Techno-economic feasibility of hybrid energy systems for small-scale space heating applications in Canada

by

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ABSTRACT

Given the large energy consumption for space heating demands in Canada, renewable energy heating systems are becoming increasingly more popular and more important for small scale applications. However, these face tough challenges for applicability in cold climate regions due to various physical and economic limitations. Two studies presented here were designed to explore the feasibility of using renewable energy hybrid heating systems in the Canadian climate. The purpose of the first study was to evaluate the techno-economic feasibility of applying air-source heat pump (ASHP) technology to single-detached homes in Canada through combination with traditional furnaces in a hybrid space heating system. Support vector machines were used to develop a series of regression models capable of estimating exposed surface areas of homes in five Canadian cities: Vancouver, Toronto, Montreal, Edmonton, and Yellowknife. Heating load analysis was then conducted on all of the homes with the help of the predicted areas. An initial technical evaluation involved a comparison of the heat loss rate with the heat supply rate of market-available ASHPs. The bin method was used to assess the energy consumption, seasonal operating cost, and greenhouse gases (GHG) emissions on an annual basis for furnace-alone and furnace/ASHP hybrid systems. Results show that cities such as Vancouver and Toronto can achieve economic and low GHG emission benefits from utilizing ASHP technology due to their relatively warm climates and good renewable electricity generation mixes. Meanwhile, Edmonton and Yellowknife would struggle to see any substantial benefits in residential heating operational changes due to their harsh climates and lacking renewable energy infrastructures. Regardless, the technology shows signs for potential future success if these locations implement shifts towards renewable electricity generation.

The second project aimed to perform a similar analysis for an indoor farming facility in a northern climate. The study presented a framework for designing a retrofitted hydroponics facility intended to improve access to fresh and cost-effective food in northern Canadian rural communities. The framework outlined the key design features required for the indoor environment, such as temperature, humidity, airborne carbon dioxide, and how to size and select energy conversion devices to meet those demands. The use of a renewable energy-assisted heating system was proposed, and a genetic algorithm multi-objective optimization was used to determine the most cost-effective and least greenhouse gas (GHG) emitting control strategy for the system. As a result, the annual performance of the facility could be evaluated in comparison to the traditional food supply chain through life cycle cost and food-miles assessments. The proposed design protocol was showcased on a case study building in northern Alberta, Canada. The building was a light industrial fish plant that was proposed for retrofit and conversion to a farming facility, using a commercial hydroponics package, for the local community in Fort Chipewyan, Alberta. The hybrid renewable energy system consisted of a biomass cordwood boiler, a ground-source heat pump (GSHP), an onsite solar photovoltaic (PV) array, a gas furnace and water heater, and electric humidity control equipment. Overall, the facility showed cost savings as compared with produce found in the local grocers. However, GHG emissions from local production seemed to exceed those from conventional transport from southern California. The most limiting factor of the facility was found to be the considerable reliance on local diesel generated electricity, even with a tremendous benefit from the onsite solar PV. Once again, this study proved that hybrid space heating systems utilizing renewable technologies; mainly heat pumps, have the capability to provide noticeable benefit to modern built environments, but continue to be limited by the traditional infrastructures of today's communities.

PREFACE

The content of the study presented in Chapter 2 was published as Udovichenko, Artur and Lexuan Zhong. 2020. "Techno-Economic Analysis of Air-Source Heat Pump (ASHP) Technology for Single-Detached Home Heating Applications in Canada." *Science and Technology for the Built Environment,* Vol. 26 (10): 1352-1370. Also, in Udovichenko, Artur and Lexuan Zhong. 2019. "Application of Air-Source Heat Pump (ASHP) Technology for Residential Buildings in Canada." *IOP Conference Series: Materials Science and Engineering* 609: 052006. The data used in Chapter 2 was publicly available online through an open-source platform.

The content of the study presented in Chapter 3 was published as Udovichenko, Artur, Brian A. Fleck, Tim Weis, and Lexuan Zhong. 2021. "Framework for Design and Optimization of a Retrofitted Light Industrial Space with a Renewable Energy-Assisted Hydroponics Facility in a Rural Northern Canadian Community." *Journal of Building Engineering* 37: 102160. Also, in Udovichenko A., Fleck, B., Weis, T., Zhong L. (2021) "Retrofitting a Light Industrial Space with a Renewable Energy-Assisted Hydroponics Facility in a Rural Northern Canadian Community: Design Protocol", *2021 ASHRAE Virtual Winter Conference*, February 9-11. The data used in Chapter 3 was available through industry collaboration with Green Planet Energy Analytics.

I was responsible for the literature review, data analysis, and manuscript composition in both chapters. Professor Lexuan Zhong was the supervisory author and was involved with concept formation and manuscript composition in both studies. Professors Brian A. Fleck and Tim Weis provided feedback on the final manuscripts of the journal and conference papers published on some of the content of Chapter 3.

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Finally, I would like to express my utmost gratitude to my family and friends. Specifically, my mother, to whom I dedicate this thesis, for providing unconditional love and never-ending support throughout this journey and my life.

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CHAPTER 1: Introduction

1.1 Background

Greenhouse gas (GHG) emissions are the primary contributor to climate change (Environment and Climate Change Canada 2009). In 2018, Canada's total emissions were 729 MtCO2e, which is a 15 Mt increase from the previous year. While most of Canada's emissions came from the oil and gas (26 %) and transportation (25 %) sectors in 2018, buildings were responsible for 13 %, making this economic sector the third-largest contributor to total emissions (Environment and Climate Change Canada 2020). In residential applications, 61 % of energy is used for space heating (Natural Resources Canada 2019). Similarly, 55 % of commercial and institutional energy use is space heating. Furthermore, emissions associated with heating saw a 5.1 Mt increase from 2017, which made it responsible for a third of the increase in emissions in 2018 (Environment and Climate Change Canada 2020). The reason heating makes up most of the mentioned requirements is due to the harsh winter climate, which tends to bring about extreme outdoor temperatures that linger for long parts of the year in many urban areas (Environment and Climate Change Canada 2020). Coupled with the fact that over half of the household energy consumption comes from natural gas (Statistics Canada 2015), household heating becomes very GHG emissions intensive. Therefore, it is evident that to meet regulations and legislation regarding the reduction of emissions, such as the Paris agreement to reduce total emissions by 30 % below 2005 levels by 2030 (Environment and Climate Change Canada 2016), the space heating application needs to be improved. Especially given the fact that 2018 levels have only achieved a reduction of 0.1 %. The Pan Canadian Framework on Clean Growth and Climate Change has identified a clear approach for improving the built environment by: (1) making new buildings more energy efficient; (2) retrofitting existing buildings; (3) improving energy efficiency for appliances and equipment; and (4) supporting building codes and energy efficient housing in indigenous communities.

Therefore, placing greater emphasis on the improvement of buildings in Canada.

1.2 Hybrid and Renewable Systems for Space Heating

Net zero energy buildings (NZEBs) are a new concept of building science that aims to limit the carbon footprint and overall energy consumption. While the exact definition has been found to vary somewhat in the literature, it is well accepted that their goal is to result in net-zero energy consumption by utilizing various key energy efficient technologies. More specifically, the net zero concept refers to when the building must generate as much energy on-site as it consumes during the operating year, which is the reason why many cases tend to include onsite PV generation (Krarti and Ihm 2016; Awad and Gül 2018). In addition, these styles of homes include high performance appliances to reduce energy consumption, such as heat recovery ventilators (Li, B., Wild, and Rowe 2019), high efficiency furnaces, boilers, and air-conditioners (Thomas and Duffy 2013), and air-source heat pumps (ASHPs) and ground-source heat pumps (GSHPs) (Wu, Skye, and Domanski 2018). When coupled with passive energy saving strategies, such as high efficiency envelopes and building structures (Fanney et al. 2017), the result is a highly sophisticated building design with an equally sophisticated heating, ventilation, and air-conditioning (HVAC) system optimally sized to meet demands with a selection of devices. While retrofits of existing homes into NZEBs exist (Miller et al. 2018; Moran, O'Connell, and Goggins 2020), this is typically difficult to achieve due to the inherent limitations of the existing building envelope and structure and systems (Asaee, Ugursal, and Beausoleil-Morrison 2019). Meaning that close to an entire overhaul of the building would be required, which explains the priority of improving new buildings as laid out in the Pan-Canadian framework.

At the same time, the HVAC technologies and systems proposed for these buildings are an extremely valuable component and a promising idea for achieving significant energy efficiency and emissions improvement even in the cases where net zero energy status is unrealistic. With over 60% of electricity generation in Canada coming from hydropower for a total of 80 % of the electricity generating from non-GHG-emitting sources (Natural Resources Canada 2019), there is great potential to utilize electric heating systems and to move away from traditional fossil fuels. Furthermore, the vast and diverse landscape has opportunities for harnessing many natural resources, such as ground, solar, and biomass. This means that new technologies and renewable energy sources must be prioritized, and the use of traditional fuels needs to be reduced, which can be achieved with the use of multiple HVAC systems for independent and detached buildings in Canada.

There have been numerous studies found in the literature that propose hybrid energy systems for improving energy generation and use with the goal of achieving lower environmental impact. Specifically, the hybrid systems explored in this work are defined as an HVAC design that incorporates multiple active energy conversion devices. These devices typically include, but are not limited to, a mixture of renewable and traditional systems for the purpose of grasping the benefits of all systems while still being able to meet the requirements. Such cases include biogas generation coupled with ground and solar heating (Esen and Yuksel 2013); a gas boiler and a solar-photovoltaic-assisted ASHP with a thermal energy storage tank (Zanetti et al. 2020); solar and ASHP water heating for a greenhouse (Tang et al. 2020), and combined cooling, heating, and power generation system, featuring solar PV and heat collection, gas boiler, and a combination of chillers (Yang and Zhai 2019; Wang, X. et al. 2020). The goal of these systems is to achieve better performance than would otherwise occur by a traditional system or by any of the system components independently. More specifically, better performance could be defined by a selection of metrics, such as cost, greenhouse gas (GHG) emissions, energy use, or other, application-specific, parameters (Wang, J. et al. 2020; Kusiak, Tang, and Xu 2011). On the other hand, these parameters would be governed by external variables that would be used as inputs to the system model, including temperature, humidity, contaminant concentrations, energy prices, and solar activity (Pallante et al. 2020; Cheng et al. 2019). Based on instantaneous values for these parameters, the control strategy for individual components in the system would be adjusted to meet the required demands, but with minimal deviation from optimal performance. In the context of building operation, one strategy could include switching between two sources of heat depending on the physical capacity, as governed by variations in outdoor conditions, or the operating expenses, as governed by fuel price, of the two devices. As a result, this strategy can help lower emissions and costs of heating system operation by prioritizing energy use of renewable fuel components, while reducing consumption of traditional sources.

It has been noted that a limited amount of research on these systems focuses on cold climate regions such as Canada. Some moderate and cold climate regions referenced were in the Atlantic regions of Canada (Kamel and Fung 2014; Demirezen, Ekrami, and Fung 2019), and did not span the greater landscape of Canada, which varies not only by climate, but also by urban infrastructure. This thesis is aimed to address the scarce amount of literature on hybrid energy system applications for space heating demands in cold climate regions. The intent is to contribute to the scientific body of knowledge by presenting a design framework and feasibility assessment of hybrid energy space heating systems for different indoor applications in Canada.

1.3 Space Heating Load Analysis

Space heating is considered any method of maintaining thermal comfort. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) is an organization that contributes tremendously to the understanding, design, and operation of building systems across the globe. Many of its publications are used for setting minimum requirements for system operation, as well as also outlining procedures for analysis and verification of compliance with those requirements. For residential and traditional commercial spaces, this involves maintaining a temperature that would allow occupants to be comfortable, which according to ASHRAE 62 is around 21 °C (ASHRAE 2016). Design of space heating systems involves an initial sizing calculation, during which, a worst-case heat loss rate is calculated, and a system is selected to meet that capacity. This procedure involves a careful analysis of the various forms of heat loss from the space. Conduction is the transmission loss through physical surfaces denoted by surface area, thermal transmittance, and temperature difference. On the other hand, convection consists of two components; infiltration and ventilation, which are dependent on flow rates of outdoor air in and out of the space, both natural and controlled, respectively. These of course are only sensible, which means that latent loads can also be used in sizing systems for applications where humidity is an important condition to be maintained. However, in situations where heating is a major energy consumer and restrictions on indoor humidity are lenient, sensible heat takes the focus when establishing an energy estimate. Once the system is sized and selected, the actual operation of the system can be simulated and analyzed based on actual operating requirements and indoor conditions. Here, the same forms of heat loss are considered, but this time the conditions are not worst-case; they are the actual temperatures that would be experienced in a typical year. Furthermore, any gains associated with indoor equipment and the sun are included in determining actual energy consumption, and subsequently, greenhouse gas emissions and operating cost. While this is laid out for a heating system, the analysis is similar when a cooling analysis is done for sizing or simulating air conditioning systems in warmer climates, or during warm seasons. Given that the topic of this thesis is centred around cold climate regions, the heating load methods outlined here are relied upon quite heavily during the research.

1.4 Economic and Emissions Analyses

In this thesis, space heating systems are analyzed from a techno-economic perspective. This involves estimating the overall effects of the heating systems in specific applications on the operating cost and emissions, which are compared with alternative or traditional operations. In general, this involves consideration of the cost of fuels for the energy systems being considered, as well as emissions factors. According to the tabulated data from national regulatory bodies, emissions factors are generated based on local energy generation, extraction, and transmission practices. Given the country's large and diverse landscape, with various opportunities for energy generation, the availability and therefore, cost and emissions factors can differ drastically by region. Much of the northern Canadian landmass is sparsely populated and sees a major lack of development for the many rural communities who live there. Many of these communities live off the grid and rely on diesel fuel for electricity generation, unlike the many metropolitan centres near the border. This could lead to drastically different conclusions about technology usage and potential for different locations in a country that has already seen limited appearance in the literature on this topic. Data from national archives such as Statistics Canada (2017) and the National Inventory Report (Environment and Climate Change Canada 2020) play a major role in estimating emissions of system operation based on the fuels proposed for the systems.

1.5 Objectives

This thesis contributes to the field of knowledge surrounding space heating technologies in northern climates by assessing the feasibility of several operational and technological improvements to residential and industrial applications. As such, the purpose of this thesis is to explore the techno-economic feasibility of hybrid renewable energy space heating systems in Canada. This focus has been executed in the following ways:

- Development of a set of numerical models for the estimation of residential building parameters to aid in energy demand assessment.
- Techno-economic analysis of an ASHP-furnace hybrid heating system for cold-climate regions across five Canadian cities, based on operating costs and greenhouse gas (GHG) emissions.

- Framework for design and optimization of a hybrid energy system for a retrofitted industrial building into a sustainable food production centre in a northern rural community.
- Life cycle cost assessment of the operation of a hybrid energy system for a commercial food production centre based on grown produce and comparison with existing food supply chain costs.
- Greenhouse gas (GHG) emissions mitigation assessment by import substitution with the use of a hybrid energy system for an industrial food production centre.

1.6 Thesis Outline

Chapter 1 consists of providing background information on the topic of space heating technologies in Canada, as well as the current state of energy generation and use and emissions. Furthermore, this section intends to establish the basic knowledge of heating load analysis heavily relied upon in the studies presented here. This also includes analysis from the economic and emissions perspective. Chapter 2 details the research conducted on the development of the architectural parameter estimation model and assessment of an ASHP-furnace hybrid heating system for homes across five Canadian cities. Chapter 3 breaks down the research performed on the design and optimization of a hybrid heating system for industrial space in a rural northern community, as well as the findings related to the life cycle impact assessment of the buildings operating and comparison of energy consumption, cost, and emissions relative to an alternate food sourcing strategy. The fourth and final chapter summarizes the research conducted, including the methods and the findings, as well as some concluding discussion and ideas for further enhancement on the research.

CHAPTER 2: Techno-economic feasibility assessment of air-source heat pump (ASHP) technology for residential heating in Canada

2.1 Introduction

Air-source heat pump (ASHP) technology is one type of technology that is ideal for hybrid system application due to their electric power consumption, which is especially beneficial when pairing with solar PV systems, and their overall low capital cost, as compared with ground-source heat pump (GSHP) devices. It is a proven technology that is very practical in many mild-climate places, such as Saudi Arabia and Italy (Alshehri et al. 2019; Grossi et al. 2018). The downside, however, is that ASHP efficiency decreases and frost accumulation occurs on the evaporator-side heat exchanger with outdoor temperature decrease (Bertsch and Groll 2008), which pose an issue in cold-climates. As a result, the ASHPs hardly supply enough heating loads of residential buildings in Canada.

Research has been found on the application of ASHPs, supplemented with additional devices or systems, either traditional or renewable, with the intent of identifying potential energy savings and improved performance of ASHPs in cold climate regions. These include homes operated with an ASHP and supplemented with a photovoltaic (PV) collector (Kamel and Fung 2014), an ASHP and a furnace with on-site solar PV generation (Demirezen, Ekrami, and Fung 2019), an ASHP water heater (Amirirad, Kumar, and Fung 2018); all in Ontario. Additionally, a mid-rise apartment building in northern Canada simulated with heat pumps (Kegel et al. 2016), and an apartment building simulated with a heat recovery ventilator (HRV) and ASHP under the conditions of several Canadian cities (Li, Wild, and Rowe 2019).

Although such efforts have been made to expand the potential application of hybrid ASHP systems in cold regions, most of the studies were based on specific building features and climatic conditions. Thus, the results may not be applicable to diverse building construction and varying locations. This absence of a broad view of technical feasibility and economic benefits of utilizing ASHP technology in the residential sector of cold climates may impede the application of ASHP hybrid heating systems. In order to quantify the discrepancy between the energy demands of existing Canadian homes and the heat capacity of on-shelf ASHPs, the overall residential energy demand across Canada is necessary to be quantified.

Support vector regression (SVR) is known to be a very powerful modelling algorithm, which is based on developing a linear relationship with the use of nonlinear functions (Vapnik, Golowich, and Smola 1997; Parveen, Zaidi, and Danish 2019), constrained by carefully selected hyperparameters (Laref et al. 2019). SVR has been implemented and verified in some studies: forecasting building electricity load (Chen et al. 2017; Goudarzi et al. 2019), predicting building energy consumption based on outdoor conditions and various building characteristics (Wang, R., Lu, and Li 2019; Ma, Ye, and Ma 2019), and forecasting cooling load of a commercial building (Li, Q. et al. 2009; Xuan et al. 2019). In this paper, given the diversity of building architecture and envelope systems across Canada, SVR is a tool to predict building exposure areas that considerably influence energy loss.

The objectives of this study are: (1) to develop and train SVR models from a Canadian housing database for predicting the exposure areas of a random single-detached home in five Canadian cities: Vancouver, Toronto, Montreal, Edmonton, and Yellowknife; (2) to evaluate the technical feasibility of the ASHP-furnace hybrid heating systems in Canadian residential buildings by comparing the energy demands of homes with heat capacities of selected ASHPs; (3) to conduct economic and GHG emission analysis to quantify the differences between traditional furnace heating system and ASHP-furnace hybrid heating system; and (4) to predict GHG emission changes on a municipal level if half or all homes in each city adopt the ASHP technology. This study provides a clear statistical view of the applicability of the ASHP technology for five Canadian cities, which may help governing organizations update building codes for energy-saving and facilitate HVAC manufacturers to improve availability of ASHP-furnace hybrid systems.

2.2 Methodology

2.2.1 Canadian Single-Detached Housing Database

House data used for this study was acquired from the Canadian Single-Detached and Double/Row Housing Database (CSDDRD) (Swan, Ugursal, and Beausoleil-Morrison 2009) that has proven to be useful in other studies (Di Placido, Pressnail, and Touchie 2014). The raw database lists various architectural, physical, and geometric information about 16,952 Canadian homes of varying style, vintage and location in the country.

Through preliminary descriptive inspection of the database, it was found that the most common style of home in Canada can be described according to the characteristics listed in Table 2.1. Given that more than half of all occupied dwellings in Canada are single-detached homes (Statistics Canada 2017), focusing on this style of home has relevant implications. The data was filtered to only include single-detached homes, and the data size was reduced from 16,952 to 10,075. Furthermore, due to some cases listing invalid or missing quantities that are relevant to heating load calculation in this study, the final total number of homes used for heating load analysis was reduced to 9,920.

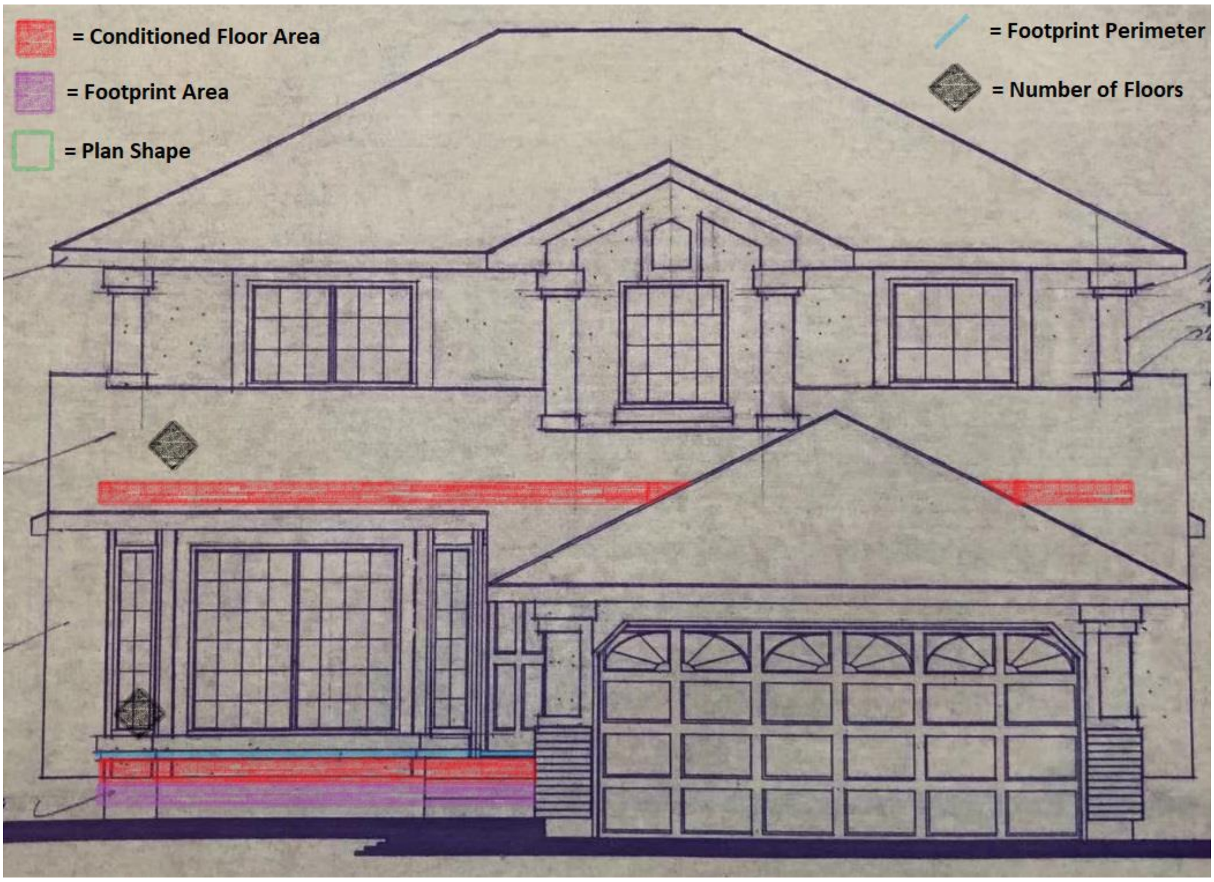
Table 2.1 Characteristics of homes represented by data.

Component	Description
Foundation Type	Basement
Attachment	Detached
Roof Type	Sloped Attic
Occupancy	Single-family
Vintage Range	1900-2003

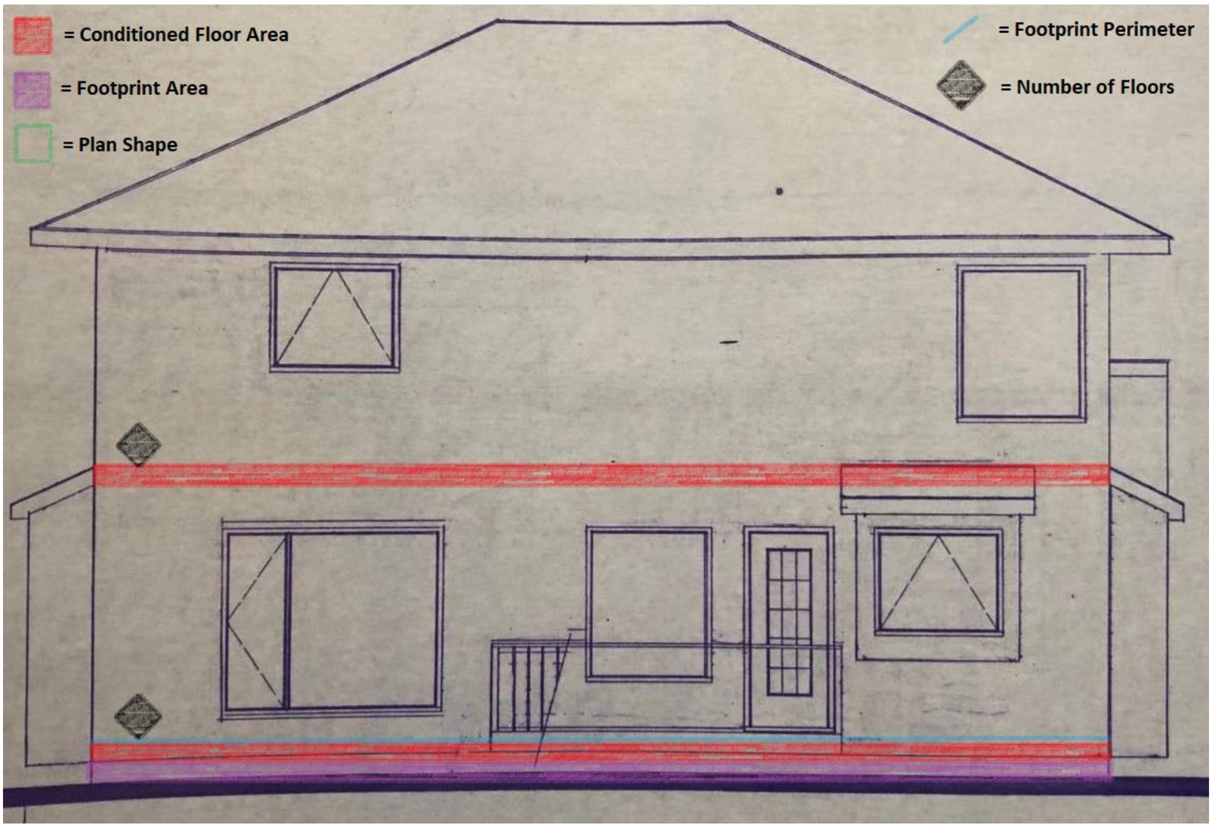
Some calculations for the raw database were made to expand the necessary variables. For example, the exterior wall area was not explicitly stated in the data file, but other similar geometric parameters such as perimeter and wall height of each storey were included. The new variable of the gross exterior wall area was used in subsequent analyses and modelling procedures. The number of bedrooms was not a known parameter in the database, so it was approximated by considering the number of occupants instead under the assumption that one bedroom is equivalent to two occupants and any subsequent occupants occupy one bedroom. Other useful parameters listed in the database include plan shape, conditioned floor area, and footprint characteristics.

The plan shape is a categorical variable, which means that it takes numeric value to represent a characteristic that is entirely independent of the numeric value. In this case, it describes the shape of the house's footprint on grade, i.e. rectangular, T-shaped, L-shaped, or other complex layouts. The conditioned floor area includes the interior floor area of the residence above the ground. Also, the perimeters and areas of the house footprint refer to the measurements made on-grade and around the base of homes. Figure 2.1 presents a visual description of these variables in a sample home. It is crucial to note that all the data, organization, labelling, and any other details found in the files were assumed to be correct and legitimate.

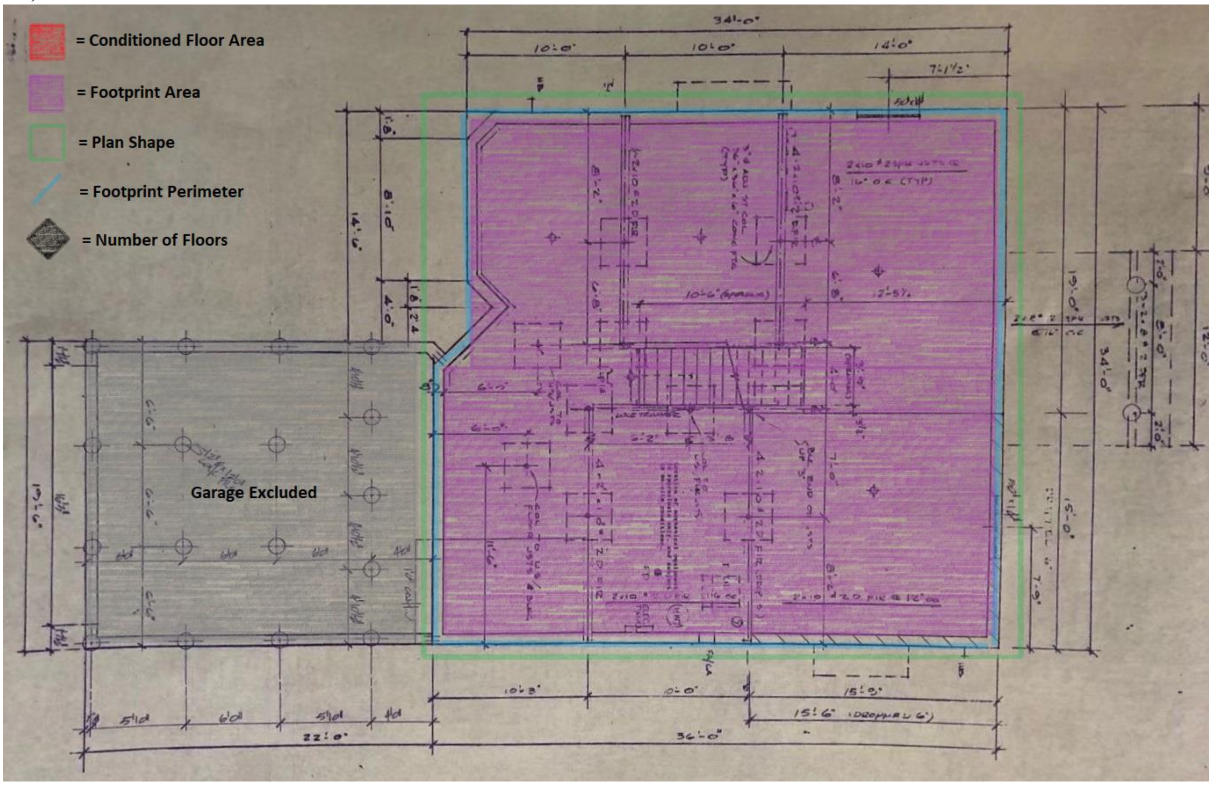
a)


= Conditioned Floor Area
= Footprint Area
= Plan Shape
= Footprint Perimeter
= Number of Floors

b)


= Conditioned Floor Area
= Footprint Area
= Plan Shape
= Footprint Perimeter
= Number of Floors

c)



d)

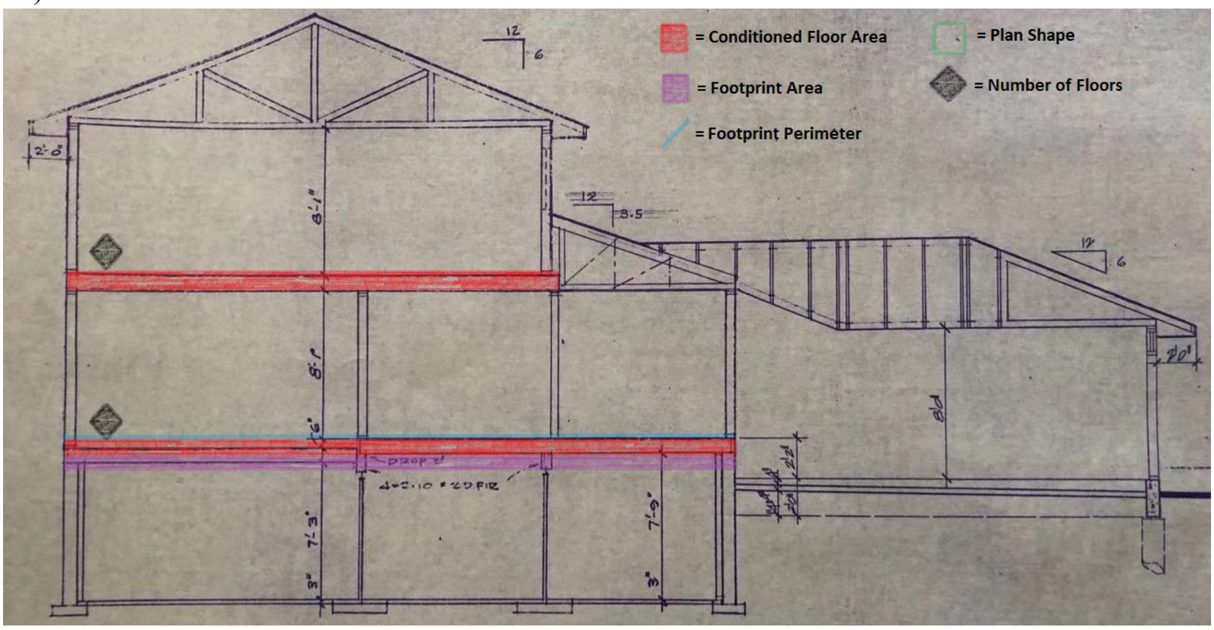


Figure 2.1(a-d) Architectural drawings of case study Edmonton home, with physical characteristics annotated.

2.2.2 Cluster Analysis

It has been assumed that houses built in different geographical locations during the past century will have different space heating energy demands due to varying outdoor conditions as well as construction standards and practices. To group by zone, the house records were manually categorized based on the city they were built in, and which zone that city belonged to, resulting in five zone data subsets.

On the other hand, the years in which the homes were built did not have preassigned grouping criteria. So, the K-means cluster analysis was used to group all records into various numbers of vintage groups based on the year-variation of all housing parameters. Cluster number ranging from two to six was explored. In addition, the one-way ANOVA test was performed to select the best cluster number that showed the largest statistical significance of yearly variation, as well as to identify which housing parameters had significant variation throughout the years. IBM's SPSS software was chosen for this operation since it allowed the cluster membership numbers to be saved to the dataset, such that the groups were easily identifiable in subsequent analyses.

This procedure identified ten housing parameters that have statistically significant variation by the year the home was built, and it grouped housing records into three year-bins. A second ANOVA test was conducted amongst these unique variables by zone. Table 2.2 shows the numerical breakdown of the database used in this study by the fifteen unique year bin and zone scenarios. It also lists the descriptive statistics of the ten housing parameters identified as having variation by year and by zone.

Table 2.2 Cluster results for zone and year (vintage) bin.

		Zone 4			Zone 5			Zone 6			Zone 7			Zone 8		
	Year Bin	n	Mean	Std. Dev.	n	Mean	Std. Dev.	n	Mean	Std. Dev.	n	Mean	Std. Dev.	n	Mean	Std. Dev.
Area of Footprint, m^2	1900-1938	13	127.99	41.13	280	102.80	46.14	243	93.87	37.98	323	100.52	77.07		N/A	
	1939-1971	58	119.63	31.90	1320	121.12	46.96	1305	109.54	44.27	1048	110.47	73.05	6	100	8
	1972-2003	73	127.49	43.12	1620	124.25	41.67	2403	110.35	38.36	1371	118.67	40.56	12	90	33
	Total	144	124.37	38.72	3220	121.10	44.67	3951	109.07	40.56	2742	113.40	59.96	18	93	28
Perimeter of Footprint, m	1900-1938	13	50.16	10.67	280	42.00	9.51	243	40.35	8.96	323	40.29	10.20		N/A	
	1939-1971	58	45.35	6.06	1320	45.30	8.76	1305	42.97	7.71	1048	42.50	8.52	6	41	2
	1972-2003	73	48.60	8.34	1620	45.97	8.02	2403	43.20	7.59	1371	44.59	7.48	12	38	8
	Total	144	47.43	7.90	3220	45.35	8.53	3951	42.95	7.75	2742	43.28	8.37	18	39	6
Number of Bedrooms	1900-1938	13	2.15	1.14	280	2.40	1.15	243	2.26	1.04	323	1.90	1.19		N/A	
	1939-1971	58	2.38	1.30	1320	2.31	1.15	1305	2.16	1.18	1048	2.03	1.19	6	2	1
	1972-2003	73	2.64	1.42	1620	2.61	1.11	2403	2.29	1.14	1371	2.21	1.23	12	1	1
	Total	144	2.49	1.35	3220	2.46	1.14	3951	2.25	1.15	2742	2.10	1.21	18	1	1
Plan Shape (categorical)	1900-1938	13	5.23	2.24	280	3.60	1.96	243	3.49	1.95	323	3.59	1.79		N/A	
	1939-1971	58	4.10	1.70	1320	3.13	1.68	1305	3.03	1.60	1048	3.35	1.58	6	3	1
	1972-2003	73	4.41	2.24	1620	3.66	2.08	2403	3.12	1.79	1371	3.79	2.01	12	4	2
	Total	144	4.36	2.05	3220	3.44	1.93	3951	3.11	1.75	2742	3.60	1.84	18	4	2
Number of Floors	1900-1938	13	1.77	0.44	280	1.78	0.42	243	1.88	0.32	323	1.48	0.50		N/A	
	1939-1971	58	1.14	0.35	1320	1.23	0.42	1305	1.23	0.42	1048	1.11	0.31	6	1	0
	1972-2003	73	1.53	0.50	1620	1.68	0.46	2403	1.36	0.48	1371	1.26	0.44	12	1	1
	Total	144	1.40	0.49	3220	1.51	0.50	3951	1.35	0.48	2742	1.23	0.42	18	1	0
Conditioned Floor Area, m^2	1900-1938	13	204.68	78.92	280	140.24	56.97	243	140.84	41.82	323	103.38	32.67		N/A	
	1939-1971	58	127.74	45.05	1320	120.20	44.30	1305	111.31	34.99	1048	101.34	25.13	6	95.93	8.57
	1972-2003	73	179.14	67.71	1620	173.61	58.98	2403	122.31	41.36	1371	120.06	33.42	12	106.40	16.47
	Total	144	160.75	66.56	3220	148.82	59.05	3951	119.82	40.08	2742	110.94	31.76	18	102.91	14.93
Gross Wall Area, m^2	1900-1938	13	215.81	73.63	280	171.34	52.87	243	167.84	41.91	323	130.58	38.95		N/A	
	1939-1971	58	135.16	46.43	1320	128.79	43.90	1305	119.39	34.38	1048	109.03	22.98	6	98.52	5.80
	1972-2003	73	185.05	61.98	1620	182.05	52.89	2403	135.11	46.55	1371	131.40	41.01	12	137.50	23.73
	Total	144	167.73	63.58	3220	159.29	55.62	3951	131.93	44.19	2742	122.76	36.57	18	124.51	27.05
Basement Floor Area, m^2	1900-1938	13	115.29	44.35	280	78.92	31.08	243	72.44	22.59	323	68.80	18.93		N/A	
	1939-1971	58	100.28	29.28	1320	94.85	28.54	1305	89.89	25.56	1048	88.45	21.94	6	89.25	7.79
	1972-2003	73	111.38	40.94	1620	99.85	31.03	2403	88.66	24.79	1371	95.03	24.49	12	82.96	25.83
	Total	144	107.26	37.21	3220	95.98	30.58	3951	88.07	25.24	2742	89.43	24.33	18	85.05	21.42
Basement Wall Area, m^2	1900-1938	13	113.32	29.58	280	76.14	20.64	243	71.59	19.24	323	73.22	15.36		N/A	
	1939-1971	58	102.95	23.33	1320	93.12	21.44	1305	89.24	19.63	1048	89.45	17.08	6	91.61	7.92
	1972-2003	73	109.96	27.92	1620	102.20	21.32	2403	94.18	18.18	1371	98.68	18.43	12	91.44	20.04
	Total	144	107.44	26.41	3220	96.21	22.60	3951	91.16	19.53	2742	92.15	19.37	18	91.50	16.69
Ceiling Area, m^2	1900-1938	13	128.01	42.41	280	88.51	34.01	243	84.83	27.21	323	80.98	25.40		N/A	
	1939-1971	58	118.09	27.35	1320	104.38	31.67	1305	98.01	36.60	1048	97.79	34.60	6	95.93	8.57
	1972-2003	73	126.12	44.40	1620	111.64	32.21	2403	97.39	26.23	1371	107.27	30.73	12	85.08	26.46
	Total	144	123.05	38.20	3220	106.66	32.81	3951	96.83	30.26	2742	100.55	32.80	18	88.70	22.41

Note: n refers to the number of house records.

2.2.3 Support Vector Regression (SVR) Model

2.2.3.1 Output Selection

In order to estimate the energy requirements of large housing datasets without an architectural analysis of the engineering parameters of each residence, the SVR models were designed to predict the gross exterior wall area (above ground), ceiling area, and basement wall and floor areas of a random Canadian home. These exposure areas were defined as the SVR model outputs since the heat conduction through the building envelope systems dominate energy losses in cold regions and, most importantly, energy losses exhibit a linear relationship with the exposure areas. The fenestration areas were considered as targets for SVR modelling, but no significant relationships were identified during cluster analysis. Hence, during subsequent analyses, these parameters were obtained from the database directly.

2.2.3.2 Input Selection

Ideally, the input parameters would have been almost entirely trivial and easy to describe a house. A two-tailed Pearson correlation test was conducted across the twelve variables displayed in Table 2.2 to determine how the four target variables are affected by the remaining eight. The correlations with the highest coefficients were prioritized for input selection. Table 2.3 shows that the perimeter and area of the house footprint have high and positive correlations with most of the target variables. Figure 2.2 shows the target variables and the inputs selected for the development of four SVR models.

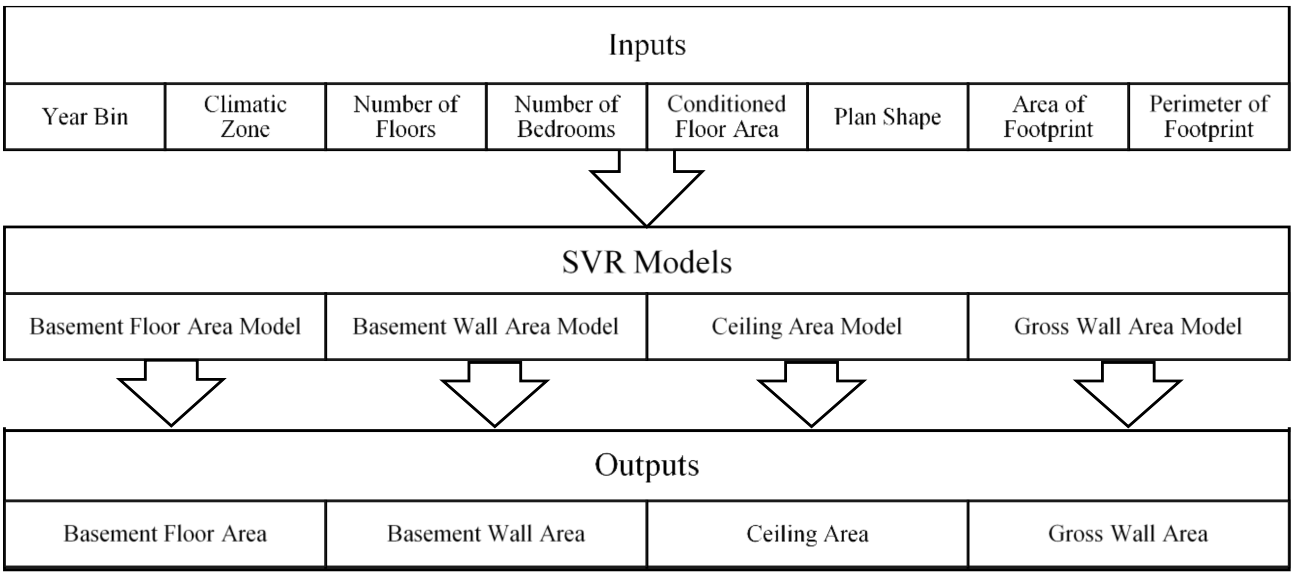


Figure 2.2 Inputs and outputs of SVR models.

Table 2.3 Pearson correlation coefficient between inputs and outputs of SVR models. All correlation is significant at the $p<0.01$ level (2 tailed).

	Basement Floor Area	Basement Wall Area	Ceiling Area	Gross Wall Area
Perimeter of Footprint	0.645	0.578	0.622	0.252
Area of Footprint	0.536	0.445	0.520	0.189
Plan Shape	0.230	0.269	0.253	0.303
Conditioned Floor Area	0.487	0.416	0.522	0.898
Number of Bedrooms	0.082	0.103	0.070	0.171
Number of Floors	-0.239	-0.187	-0.149	0.812
Climatic Zone	-0.113	-0.099	-0.099	-0.298
Year Bin	0.165	0.306	0.146	0.126

2.2.3.3 Model Training and Evaluation

The model development procedures broke down as follows:

- Assignment of input and target variables listed in Figure 2.2. Each of the four models was executed separately; the same version of the MATLAB script was used for each run and only the one output variable was implemented.
- Division of the whole dataset into training and testing subset according to a random 80/20 split. The training set was used for development via optimization, cross-validation, and training. The test data set served as a final test to ensure that over-training had not occurred.
- Optimization of all hyperparameters based on the training subset. The parameters include box constraint (C), epsilon (ε), kernel function (Gaussian, linear, or polynomial), and polynomial order (only if kernel function = polynomial). This step was performed with the 'Bayesian' optimizer and with 10-fold cross-validation on the training subset.
- Training of the learner with the best observed (according to the algorithm) selection of hyperparameters on the training subset.
- Prediction of results in both training and testing data subsets.

- Evaluation of results in both data subsets by comparison with observed values according to the following performance measures: correlation coefficient (R^2), mean absolute error (MAE), root mean squared error (RMSE), mean absolute percentage error (MAPE), and Willmott's index of agreement (WI).
- In order to generate a range of uncertainty in the result, the mean absolute error (MAE) of the testing subset of each model was propagated through the heating load analysis for the case study home. So, when the predicted area of each model was carried through subsequent calculations, its error was applied accordingly to provide an error range on the final energy consumption result.
- Ensure that effective training has been achieved by comparing the errors between the training and testing set. If training error is significantly greater than testing error, then the model was over-trained. Also, by checking how close Willmott's index approaches 1, it can be found out if the model has good generalization and can make an accurate prediction on new data.

The generated files can predict each of the four output variables once a new set of input variables is known.

2.2.4 Heating Load Analysis

To assess the performance feasibility of ASHPs in existing homes across Canada, fundamental heat transfer principles were followed to quantify the energy demands of single-detached houses in five cities: Vancouver, Edmonton, Toronto, Montreal, and Yellowknife. These cities were chosen because they represent populous regions with distinctly unique climate conditions. The heating load of each house in the database was evaluated under its corresponding outdoor conditions (99 % worst-case design temperature) and other descriptive parameters listed in Table 2.4.

Table 2.4 Canadian cities used for analysis.

Location	Vancouver, BC	Toronto, ON	Montreal, QC	Edmonton, AB	Yellowknife, NWT
Climatic Zone[1]	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
Heating Degree Days @ 18.3 °C[1]	2911	3518	4146	5198	8159
Heating Outdoor Design Temperature (°C) [1]	-3.4	-13.7	-19.2	-25.8	-38.3
Electricity Utility Rate ($/kWh)[2]	0.10	0.10	0.06	0.12	0.29
Electricity Consumption Emission Factor (gCO_2/kWh)[3]	10.9	35.0	1.6	860.0	267.5
Electricity Generation Mix (% renewable)	89 %	93 %	99 %	9 %	37 %
Traditional Fuel Option			Natural Gas		Light Fuel Oil
Traditional Fuel Utility Rate ($/GJ)	1.91[4]	3.66[4]	3.24[4]	1.98[4]	27.68[5]
Traditional Fuel Emission Factor[3] @ 15°C and 101.325 kPa	1926 gCO_2/m^3	1888 gCO_2/m^3	1887 gCO_2/m^3	1928 gCO_2/m^3	2.753 tCO_2/m^3
Housing Stock[6]	282,355	846,405	564,230	287,775	3,210

Note: 1. (ASHRAE 2017)

2. (Rylan Urban 2019)

3. (Environment and Climate Change Canada 2019)

4. (Statistics Canada 2020a)

5. (Statistics Canada 2020b)

6. (Statistics Canada 2017)

Furthermore, the analysis procedures for heating load evaluation were also taken from ASHRAE documentation referenced by the National Energy Code for Buildings (National Research Council of Canada 2017). The main forms of sensible heat loss considered in this study were conduction, infiltration, and ventilation; latent losses were not considered. As such, residential heat loss analysis was reduced to the set of governing parameters shown in Table 2.5. Conduction heat loss is a product of thermal transmittance of each exposed surface, its area, and the temperature difference across the boundary. Similarly, the convective loss is a function of flow rate, temperature difference between indoor and outdoor air. An indoor setpoint temperature was assumed to be 21°C based on typical indoor conditions from ASHRAE (2017). The developed SVR models were used to predict the areas of the four main components of heat conduction through the envelope. To obtain the correct heating load analysis of the Canadian housing stock, data about fenestration, insulation values, and airtightness were taken from the CSDDRD. Since the thermal transmittance of windows was not specified, a typical double-pane vinyl/wood frame window was assumed for all cases. ASHRAE Standard 62.2 (2016) was consulted to approximate minimum ventilation flowrate depending on residence floor areas and the number of bedrooms. The resulting heat loss rates were integrated over a typical meteorological year; based on hourly temperature occurrence data from ASHRAE resources (2017), which allowed us to visualize the total annual energy demand in addition to the average heat loss rate for homes in each city.

Table 2.5. Resources consulted to find parameters needed for heat loss analysis.

	Conduction	
Component	Surface Area	Thermal Transmittance
Above-grade Wall	SVR Model [Fig. 1]	CSDDRD
Above-grade Roof	SVR Model [Fig. 1]	CSDDRD
Below-grade Wall	SVR Model [Fig. 1]	CSDDRD
Below-grade Floor	SVR Model [Fig. 1]	CSDDRD
Window	CSDDRD	(ASHRAE 2017)
Door	CSDDRD	CSDDRD
	Convection	
Component	Flowrate	
Infiltration	CSDDRD	
Ventilation	(ASHRAE 2016)	

2.2.5 Thermal Balance and Energy Consumption

Three commercially available heat pumps and two furnaces were examined in this feasibility study. These were selected based on a previous study, in which three models of heat pumps and three furnaces were compared and the best combination was found (Udovichenko and Zhong 2019). Table 2.6 shows a basic description of the two heating devices. First, the ASHP output capacity and residential heating load were compared as a function of outdoor temperatures, which was a means to identify the thermal balance point to switch from an ASHP to a furnace. Next, the total seasonal energy consumption of each heating system or combination was compared, which was computed based on the previously determined total annual heating energy demand using the hourly bin temperature data, mentioned earlier. Four scenarios were assumed: a baseline case using only the furnace-alone (furnace A or B in Table 2.6) and three cases of a hybrid system composed of one ASHP with a furnace when needed. Since the natural gas furnace is not a common heating system in Yellowknife, an oil heating furnace (furnace B) was used as the traditional heating device in both the baseline and hybrid system cases for this city. In addition to the heat loss rate from each residence, the following parameters were calculated for each hour bin: heat loss from the residence, heat pump input and output, and supplemental heating amount (if any). Since the furnaces and heat pumps differ by energy type, no direct comparison was performed, but this analysis was used as an intermediate step to determine the final operating cost and GHG emissions results. However, a breakdown of system operation for the full year was determined, in which various stages of operation were added up based on the hourly count at each outdoor temperature occurring in the year. The stages of operation were split into the following cases: independent heat pump operation at part load with no supplemental heating (denoted as ASHP 'ON' and ASHP 'OFF' to account for cycling effects), full load operation with supplemental heating (denoted as ASHP 'ON' + Supplemental heating), and the case when the heat pump could not physically operate (denoted as ASHP 'OFF' + Supplemental heating).

Table 2.6. Basic specifications of heat pumps and furnaces to be used.

ASHP:	A[1]	B[2]	C[3]	Furnace:	A[4]	B[5]
Rated heating capacity @ 8°C	12 kW	7 kW	16 kW	Fuel Type	Natural Gas	Light Fuel Oil
Outdoor operating temperature range (Lo/Hi)	-35°C/15°C	-20°C/18°C	-13°C/30°C	Annual Fuel Utilization Efficiency (AFUE)	97%	95%
Coefficient of performance (COP) (Lo/Hi)	0.9/3.5	1.43/5.65	2.53/5.16	Heating Value of Fuel	39 MJ/m^3	39 GJ/m^3

Note: 1. (Mitsubishi Electric 2020)
2. (Goodman 2020)
3. (Bosch 2020)
4. (Armstrong Air 2020)
5. (Adams Manufacturing 2020)

2.2.6 Model Verification

A local Edmontonian home, which fits the description in Table 2.1, was used as a case study to validate the SVR predictions as well as the calculation of overall annual energy consumption. The house was selected because it was an appropriate representation of the homes analyzed in the database. Additionally, all the information about its architectural characteristics and historical energy use was locally and easily accessible. The inputs for the SVR models are shown in Table 2.7. Energy gas bills from the year of 2018 were analyzed to give the energy consumption of the natural gas furnace (80% AFUE) for space heating only. The indoor heating setpoint in this home was 18.5°C in 2018, so a minor scaling adjustment had to be performed to stay consistent with the assumption of a 21°C setpoint. As mentioned in the SVR training, an uncertainty analysis was included to propagate the MAE associated with the SVR model predictions. In generating a comparable heating load, the insulation values and air change coefficients were necessary to be known, but they were not identified in the architectural drawings. To be consistent with the evaluation method for the homes in the database, the thermal transmittance and infiltration property were taken as the average value of year bin (1972-2003) and zone (7) from the CSDDRD.

Table 2.7. Input variables of a case study in Edmonton.

Parameters	Value
Conditioned floor area	183.2 m^2
Perimeter of house footprint	41.4 m
Area of house footprint	107.0 m^2
House plan shape	Rectangular
Number of floors (above ground)	2
Number of bedrooms	3
Climatic zone	7
House vintage	1994

2.2.7 Economic and Emissions Analysis of Heating Systems

Once the total energy consumption of the heating systems was known, the economic and emissions analysis could be performed. The seasonal operating costs were calculated based on the utility costs associated with the two heating systems for each city. Similarly, GHG emissions associated with heating the residence were determined as a product of seasonal energy consumption and emission factors of the used energies. The utility costs for electricity, natural gas, and oil, as well as the emission factors, were found from websites of utility companies (Rylan Urban 2019), national statistics archives (Statistics Canada 2020), and the national inventory report (Environment and Climate Change Canada 2019), respectively. The values shown in Table 2.4 were taken as an average over the last four years. This analysis does not include costs associated with utility transport and installation or maintenance of the equipment.

The GHG emissions results were expanded to a municipal level by considering the total housing stock (2017 census data from Statistics Canada) of each city. The total seasonal emissions for a city were estimated by the average of the emission results for each home in the database, multiplied by the total number of single-detached homes. This procedure assumes that the single-detached home database is statistically representative of the single-detached housing stock. In order to obtain a clear view about benefits of ASHP implementation, three scenarios were considered: A baseline, in which all homes are assumed to be using the traditional furnaces, either natural gas or fuel oil; a second scenario assumes half of the homes own an ASHP hybrid system; lastly, all homes in a city operate the hybrid system.

2.3 Results and Discussion

2.3.1 SVR Model Results

The hyperparameter optimization of each model resulted in the optimal parameter values shown in Table 2.8. The programmed optimization procedure tested different kernel functions and determined that the linear function was the most feasible for this type of data. Performance evaluation results for the four building-area models are displayed in Table 2.9. The gross wall area model was found to be the most accurate with a correlation coefficient of 0.96 and 0.95 for the train and test datasets, respectively, and with the lowest percentage errors. Meanwhile, the basement wall area showed moderate accuracy. However, all four models had MAPEs below 15% and the values of Wilmott's index of agreement above 0.75, indicating good generalization capability.

Table 2.8. Optimal parameters of SVR models.

	Basement Floor Area	Basement Wall Area	Ceiling Area	Gross Wall Area
Epsilon (ε)	7.0288	4.2888	0.39952	0.46439
Box Constraint (C)	966.92	2.8495	26.584	0.063781
Kernel Function	linear	linear	linear	linear

Table 2.9. Performance evaluation results of four SVR models.

	Basement Floor Area		Basement Wall Area		Ceiling Area		Gross Wall Area	
	Train data	Test data	Train data	Test data	Train data	Test data	Train data	Test data
R^2	0.87	0.86	0.77	0.71	0.81	0.87	0.96	0.95
MAE (m^2)	9.28	9.49	9.16	9.56	8.57	8.68	8.16	8.78
RMSE (m^2)	13.58	14.08	13.23	14.88	19.29	15.44	13.68	15.56
MAPE (%)	11.47	11.22	10.88	10.87	9.62	13.85	5.41	5.71
WI	0.82	0.95	0.76	0.94	0.85	0.96	0.92	0.98

Comparing engineering drawing-based calculation areas with the predictions for the case study home, SVR models showed a good prediction capability in Table 2.10 for most outputs except for the basement floor area whose prediction error exceeded the MAPE of the developed model. All other models achieved prediction errors below 10%. Overall, the gross above ground wall area model outperformed the other models based on R^2, MAPE, WI, and prediction error.

Table 2.10. Model verification results (Case study).

	Actual	Predicted	% Error
Gross Wall Area, m^2	189.0	191.7	+1.4
Ceiling Area, m^2	107.0	103.9	-2.9
Basement Wall Area, m^2	98.0	92.7	-5.4
Basement Floor Area, m^2	107.0	91.0	-14.9

2.3.2 Model Verification Results

The case study home was utilized to ensure that the procedures of energy consumption estimation following building-area prediction were valid in this study. The actual space heating load and the estimated consumption using ASHRAE procedures are compared in Figure 2.3. There was a good agreement between the actual and calculated energy consumption per month in 2018. The overall annual energy use of 102.0 GJ from the utility bill was comparable with

99.5 ± 1.5 GJ from the energy calculation, confirming that the house parameters predicted by the SVR models and the subsequent heat analysis were appropriate to be used in this study.

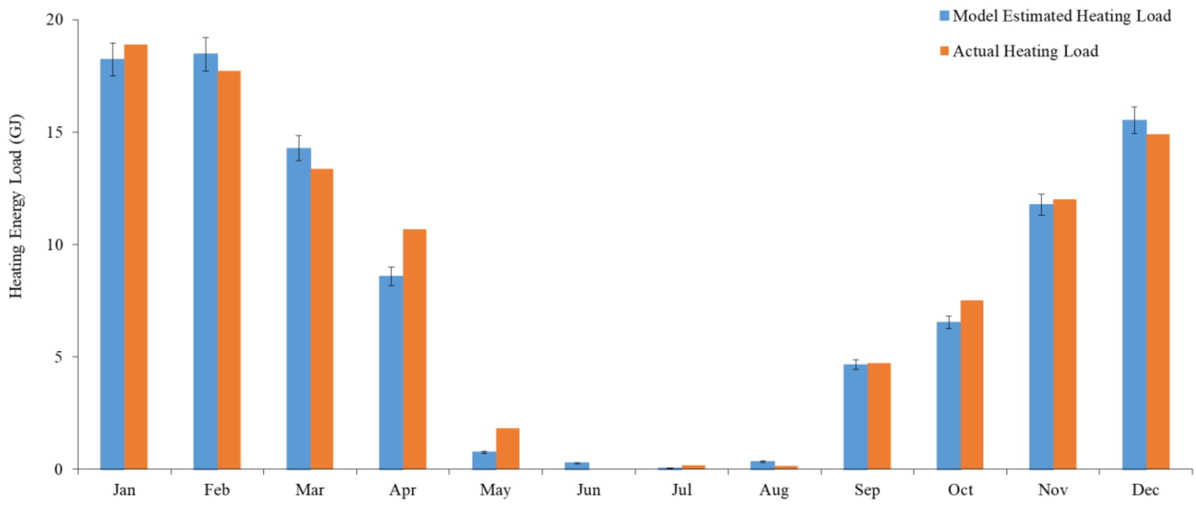


Figure 2.3. Monthly space heating energy consumption of case study home.

2.3.3 Heating Loads

As expected, the design heating loads for the cities worsen with harsher climate zones, as shown in Figure 2.4. Fundamentally, the colder cities experience higher design heating loads due to the lower design temperatures. 50% (25^{th} – 75^{th} percentile) of the homes in Yellowknife have a design heating load in the range of 23-39 kW due to the design temperature of -38.3 °C. Meanwhile, the same fraction of homes in Vancouver would experience a heat loss rate of 7-14 kW at a temperature of -3.4 °C. Surprisingly, the design temperature decrease between Toronto at -13.7 ° C, Montreal at -19.2°C, and Edmonton with -25.8 °C results in fairly constant heating loads for the 25^{th} – 75^{th} percentiles of 10-19 kW, 8-18 kW, 10-19 kW, respectively.

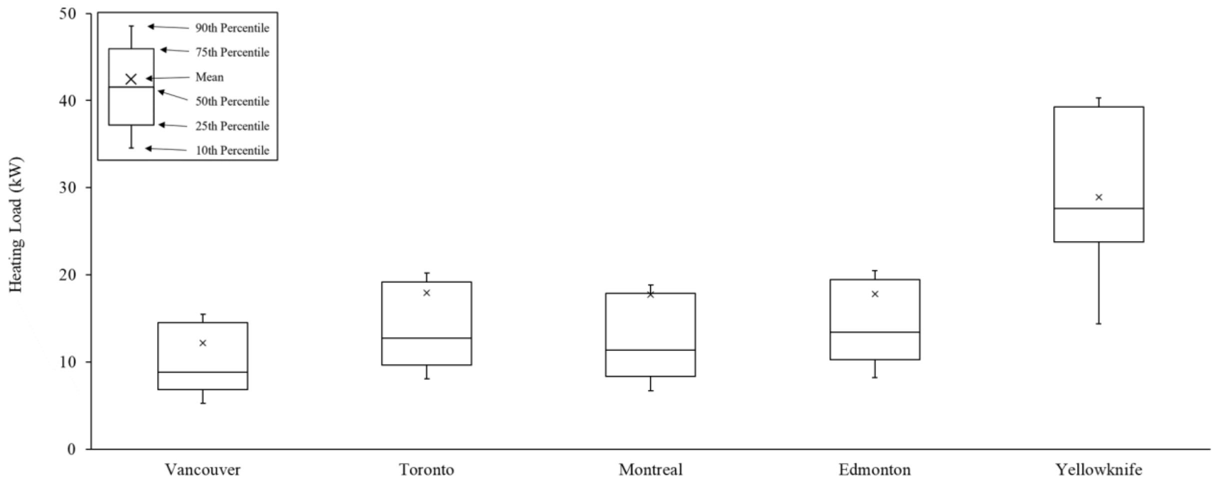


Figure 2.4. Design heating loads for five Canadian cities.

Since thermal resistances (Figure 2.5) for different components across the zones are relatively constant, these results could be attributed to the exposed surface areas. For example, Vancouver's (zone 4) mild design temperature is countered by its larger exposure areas, which results in the heating load stated above. Table 2.2 shows a decreasing trend of house sizes from Vancouver (zone 4), Toronto (zone 5), Montreal (zone 6) to Edmonton (zone 7), which is the reason for the similar heating loads in these cities. In Yellowknife (zone 8), the extreme outdoor conditions coupled with a noticeable reduction in below-ground component insulation values result in much harsher design loads. Even though the housing component areas are lower for Yellowknife, this change is not enough to counter the magnitude of heat loss occurring.

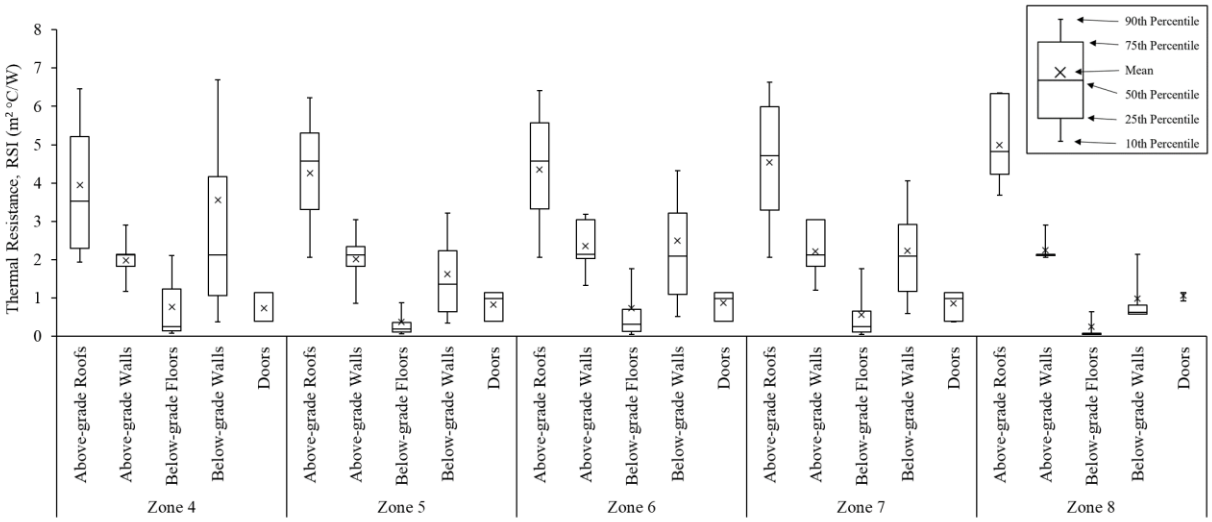


Figure 2.5 R-values of exposure components listed in the CSDDRD database.

Figure 2.6 presents a set of cumulative results deduced from the heating loads, on a vintage basis over the last century. The total annual energy demand in each city was plotted based on year bin clusters. In general, the magnitude of energy consumption in each city closely resembles the trends of design-case heat loss in Figure 2.4. Yet, now there is evidence of older homes having higher energy needs as compared with more modern homes. In Vancouver, compared with homes built between 1900-1938, mid-century and late-century homes consume 91 % and 82% as much energy, which showcases noticeable improvements in housing quality towards the end of the century. Similarly, homes built in Toronto between 1939-1971 and 1972-2003 have achieved energy consumptions of 92 % and 88 % as large as homes built at the start of the century, respectively. Montreal and Edmonton have seen diminishing results, with mid- and late-century homes achieving energy consumptions of 87 % and 83 % in Montreal, and 95 % and 96 % in Edmonton as high as homes built between 1900-1938 in those locations. Since the reduced dataset lacked early century homes for Yellowknife, less can be analyzed about this city. Newer homes appear to have higher energy consumptions (19 % increase) than older homes. Overall, this is evidence of noticeable innovation with regards to housing technologies and practices having taken place over the last century. However, a more drastic reduction was expected.

Figure 2.6. Annual space heating energy consumption of a single-detached home using the best hybrid system in each city (natural gas furnace/ASHP-C in Vancouver, Toronto, Montreal, and Edmonton; oil furnace/ASHP-A in Yellowknife) based on vintage of home. No data was available for homes in Yellowknife in the '1900-1938' bin.

2.3.4 Thermal Balance and Energy Consumption

Figure 2.7-Figure 2.11 present the heating loads of each city as a function of outdoor temperature, as well as the temperature-dependent heat capacity of three ASHPs. The intersection of the average heating load curve and the capacity curve signifies the average thermal balance point of the ASHP operating in that location. The temperature bin plots are meant to breakdown the various stages of heating system operation that would occur for an average home, heated with hybrid systems consisting of each of the heat pumps and the corresponding furnace for each city. This information is also summarized as a total for each system on an annual basis.

For Vancouver, the mild conditions allow all three ASHPs to operate at all outdoor temperatures. This means that, in general, all three models can provide heat without operational limitations. However, the heat capacity is limited for all three models, and supplemental heating is required for all homes except the bottom ~50 %, whose energy demands can be fully covered by A- and C- ASHPs (Figure 2.7). Furthermore, an average home in Vancouver could be heated only with ASHP C; at part load and without supplemental heating, for the entirety of the 4757-hour heating season, while only operating for 1500 hours (22 % of the time). In contrast, ASHP B would have to be 'on' for 2830 hours in the winter, including 872 hours (13 % of the time) that would require supplemental energy. Overall, this suggests that in the warmest city in Canada, most of the currently available ASHPs possess the heat capacity to satisfy the heating requirements of ~50 % of the homes at an outdoor temperature of -3.4 °C, with minimal or no supplemental heat.

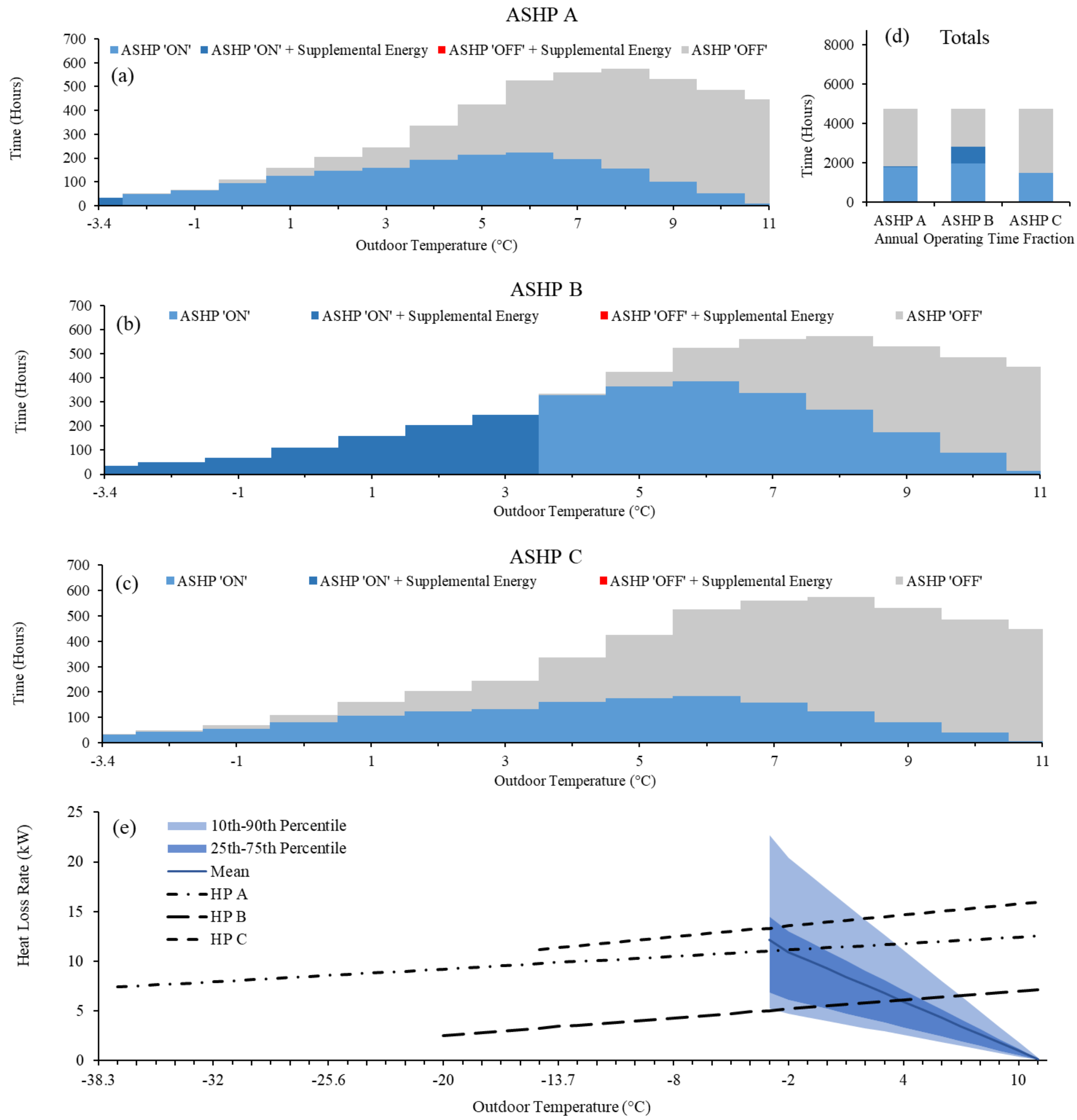


Figure 2.7. Annual heating temperature bins for all ASHPs (a-c), and operating time fraction (d) of the three ASHPs for an average home. Heating load and ASHP capacity as a function of outdoor temperature for Vancouver (e).

The results are noticeably worse for Toronto (Figure 2.8); all the models can function, but supplemental energy is required for all of them. Only the bottom ~25 % of homes with the lowest heating loads can be satisfied with the best heat pumps (ASHPs A & C) operating independently of auxiliary systems. If ASHP B were to be used, that fraction would go down to far below 10 % of homes. ASHP operating time during the 4750-hour heating season would range between 2488 hours (37 %) in total, including 520 hours (8 %) of supplemental heating for ASHP C and 3683 hours (55 %) in total with 2433 hours (36 %) of supplemental heating for ASHP B. It is evident that these operating time variations are what create a large impact on the final energy consumption, and therefore, heavily impact cost and emissions savings.

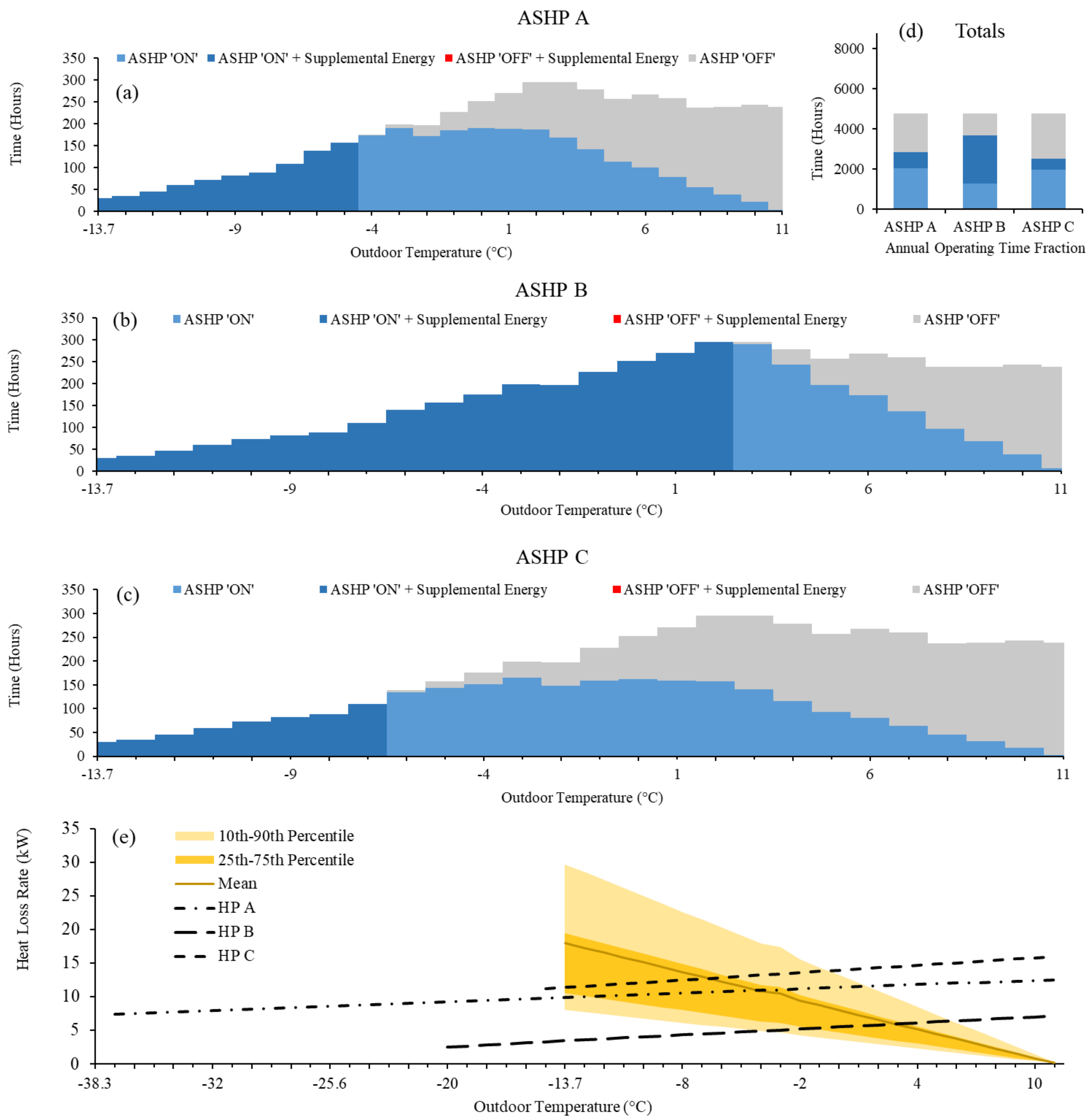


Figure 2.8. Annual heating temperature bins for all ASHPs (a-c), and operating time fraction (d) of the three ASHPs for an average home. Heating load and ASHP capacity as a function of outdoor temperature for Toronto (e).

As the locations get colder, the limitations of the heat pumps become more prevalent. Montreal and Edmonton’s conditions are too harsh for some ASHP models to function year-round (Figure 2.9-Figure 2.10). However, the insulation and surface area trends, discussed previously, result in these two locations having operating time fraction comparable to that of Toronto. A high-capacity model (ASHP C) would have to operate independently for 1980 hours (29 %), in dual-device operation for an additional 584 hours (9 %) and would be physically incapable of operating for 198 hours (3 %), which would have to be entirely supported by the furnace. On the contrary, ASHPs A and B would have no physical limitations, but would have to operate at full load for much longer; 2046 hours (30 %) independently plus 1052 hours (16 %) with supplemental energy for ASHP A, and 1146 hours (17 %) independently and 2870 hours (42 %) with supplemental energy for ASHP B.

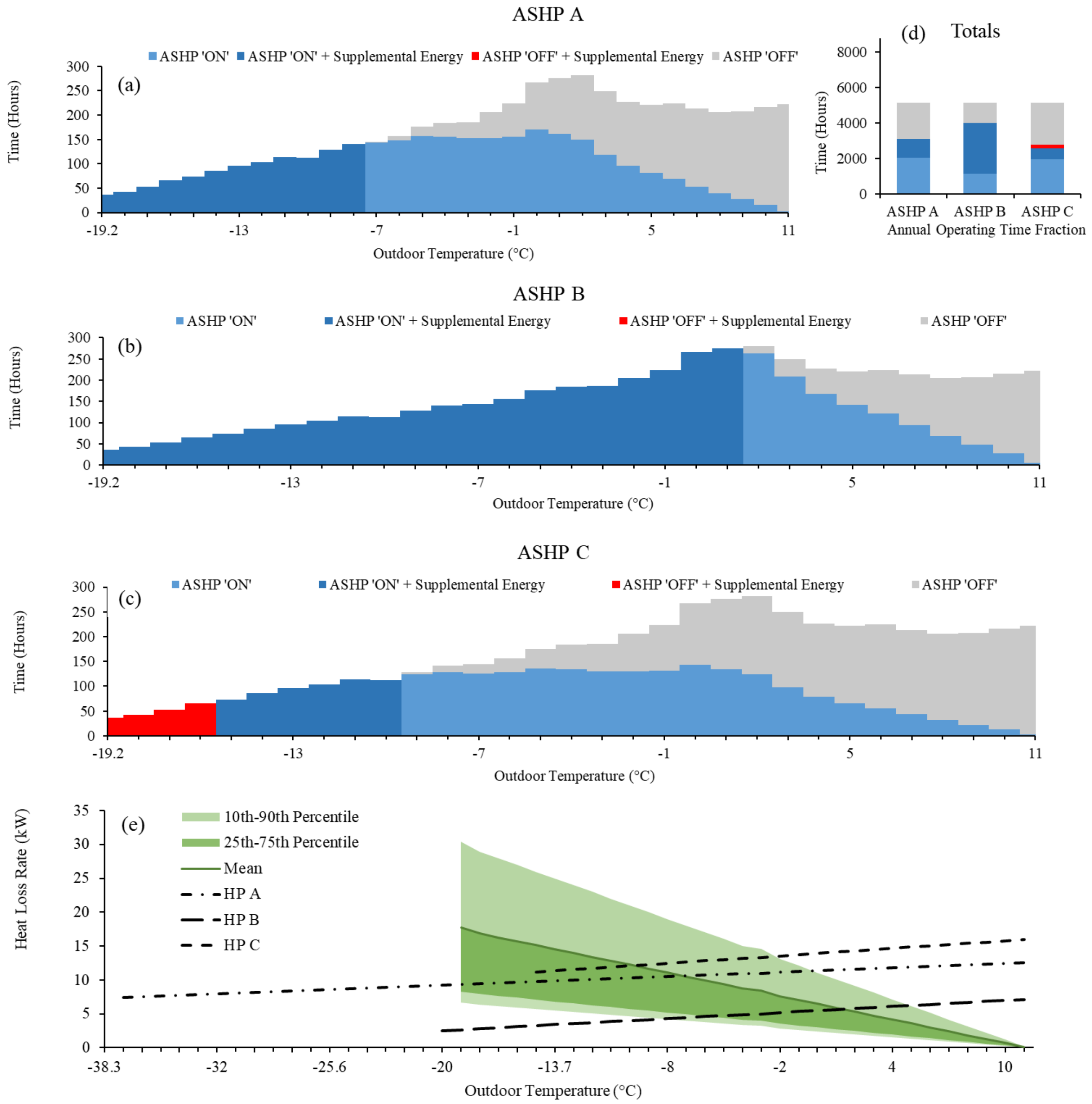


Figure 2.9. Annual heating temperature bins for all ASHPs (a-c), and operating time fraction (d) of the three ASHPs for an average home. Heating load and ASHP capacity as a function of outdoor temperature for Montreal (e).

For Edmonton, ASHP B's 1515 hours (22 %) in part-load operation, 2691 hours (40 %) with auxiliary heating and 240 hours (4 %) in shut off mode, showcases the obvious weakness of a low-capacity model with an intermediate operating temperature range. In total, the operating times of the three units (A, B, C) are 3098, 4016, and 2561 hours in Montreal, and 3358, 4206, and 2397 hours in Edmonton, which is consistent with the total heating hours of 5137 and 5897 for an average residence in the two cities, respectively. Furthermore, one advantage of ASHP A's low operating temperatures, is that it is the only model that can support a fraction of homes with no need for supplemental systems, even though that fraction is ~25 % in Montreal, and ~10 % in Edmonton.

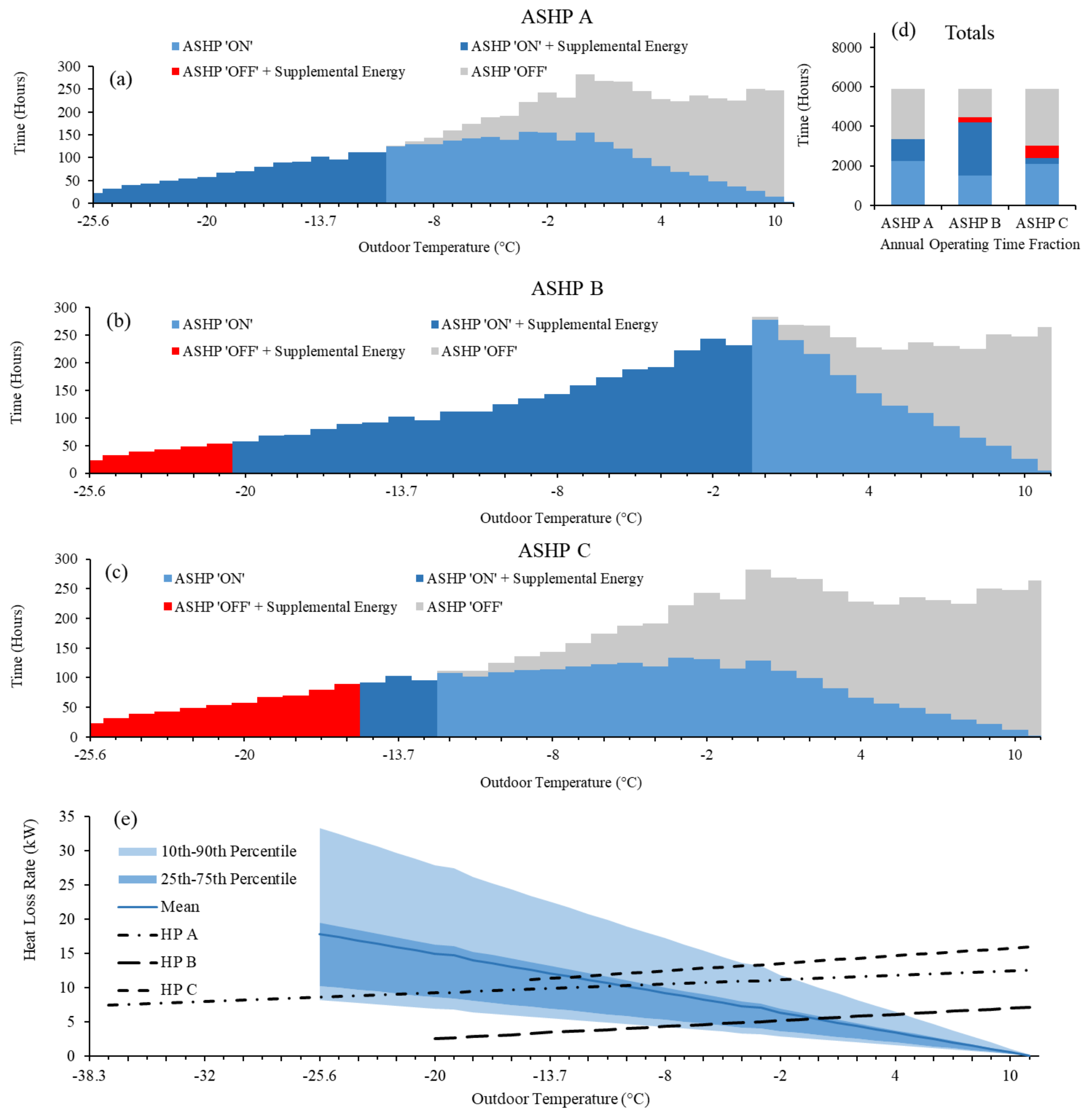


Figure 2.10. Annual heating temperature bins for all ASHPs (a-c), and operating time fraction (d) of the three ASHPs for an average home. Heating load and ASHP capacity as a function of outdoor temperature for Edmonton (e).

Unsurprisingly, all three systems will struggle in Yellowknife, so there are no homes that can run solely on electric heat pump heating during the 6750-hour heating season (Figure 2.11). Supplemental energy operation would have to occur for 2371 hours (35 %) for ASHP C to 33 hours (0.5 %) for ASHP A. In this case, independent heating time becomes irrelevant and focus shifts to finding the ASHP model that can achieve greater operating times with auxiliary energy. Even though ASHP-C has a lower switch temperature of -5.5 °C than ASHP-A's -2.3 °C, the latter has a much greater presence in the heating season due to its ability to stay active at extremely cold temperatures. Therefore, ASHP-A can supply low quality heat for a greater portion of the heating season than its counterparts, even if only to satisfy a part of the required load. However, the quality of heat provided by ASHP-A at most of these temperatures can be minimal, as compared with the overall greater output from ASHP-C, as can be deduced from inspection of the heat capacity outputs in the bottom of Figure 2.11. This dynamic between the heat pump models can result in vastly different cost and emissions implications depending on various external factors, such as energy availability, cost, and emissions factors.

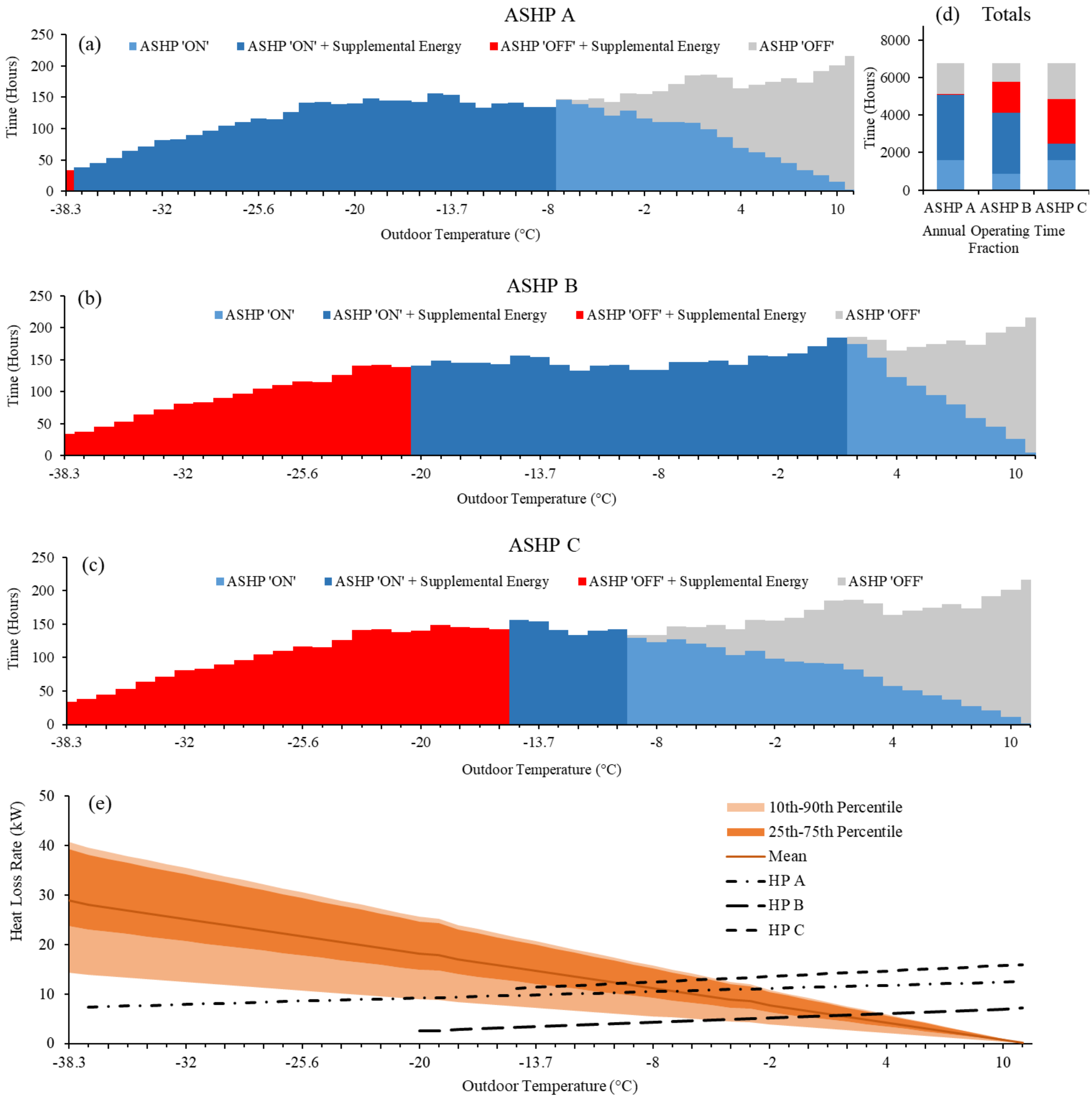


Figure 2.11. Annual heating temperature bins for all ASHPs (a-c), and operating time fraction (d) of the three ASHPs for an average home. Heating load and ASHP capacity as a function of outdoor temperature for Yellowknife (e).

Figure 2.12 shows the ranges of annual heating energy required for a home in each city using the four heating systems. Furthermore, the hybrid system that shows the lowest energy consumption (natural gas furnace/ASHP-C in Vancouver, Toronto, Montreal, and Edmonton; oil furnace/ASHP-A in Yellowknife) can be broken down into its components, as shown in Figure 2.13. These plots can be used to show the overall mixed source energy supply to the system from the end user perspective. However, the since these are a combination of primary and secondary energy sources, conclusions cannot be drawn regarding energy savings. Instead, these are directly linked to the economic and emissions results computed later.

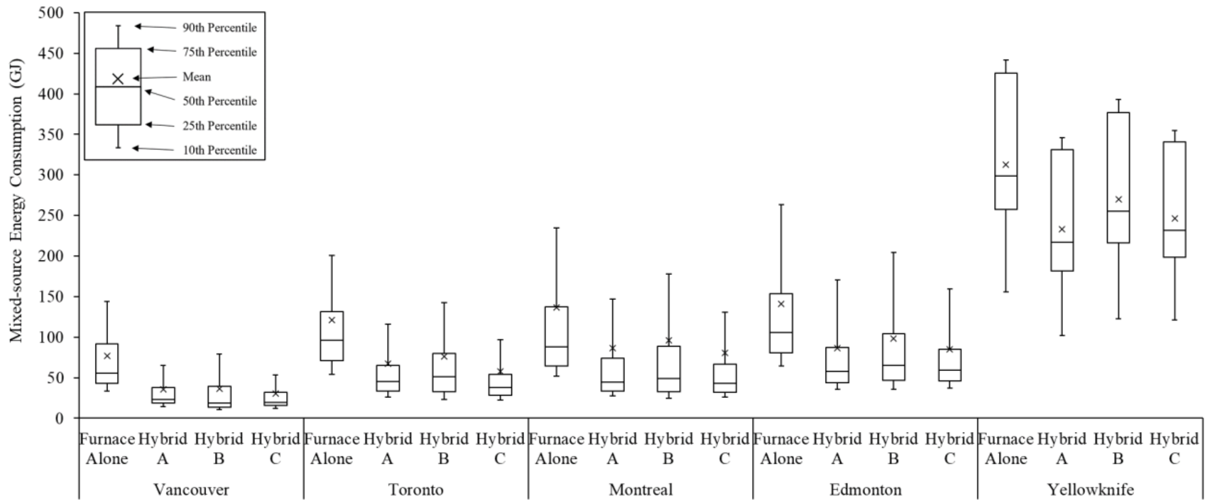


Figure 2.12 Annual space heating mixed-source end-user energy consumption of a single-detached home using different heating systems: furnace-alone system, hybrid A, hybrid B, and hybrid C.

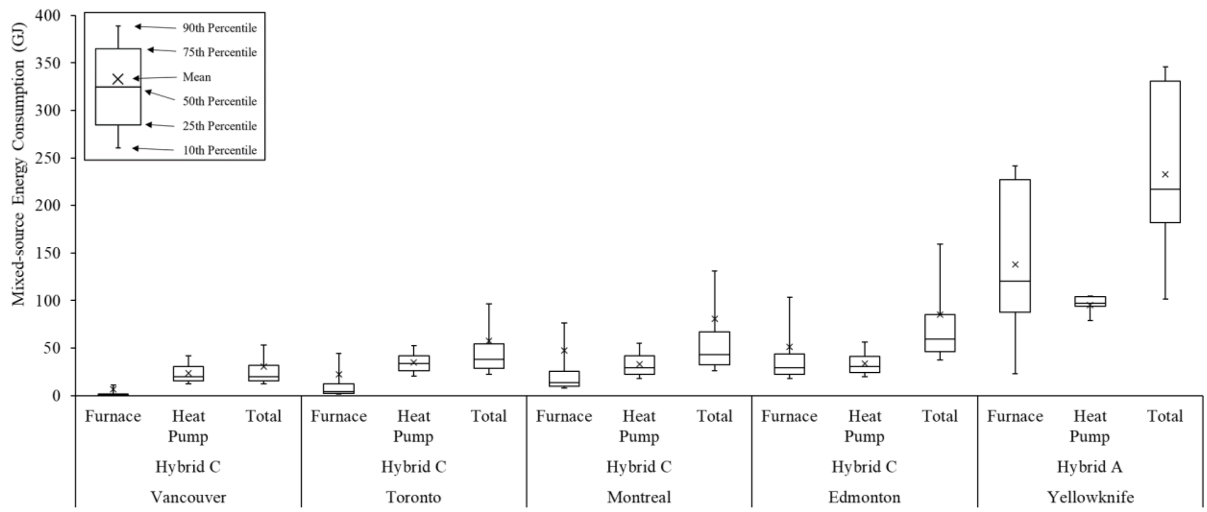


Figure 2.13 Breakdown of annual space heating mixed-source end-user energy consumption of a single-detached home using the best hybrid system in each city (natural gas furnace/ASHP-C in Vancouver, Toronto, Montreal, and Edmonton; oil furnace/ASHP-A in Yellowknife).

2.3.5 Economic and Emissions Feasibility

Annual operating emissions and costs are shown in Figure 2.14 and Figure 2.15. Operating the hybrid system is expected to provide a reduction in seasonal emissions in the homes of Vancouver of 71-89 %, with hybrid system C providing the greatest benefit. Similarly, homes in Toronto could reduce their emissions by 50 % if ASHP B is used, 71 % if ASHP A is used, and by 76 % if ASHP C is used. The superiority of heat pumps A and C, which was partially evident during thermal balance and operating time analysis, is further reinforced by the results of Montreal. The average home in this city could reduce its operating emissions by at least 45% with hybrid system B, and at most by 69 % with hybrid system A. This effect is associated with the generation mix of electricity supplied to these locations. For example, 99% and 90% of the electricity produced in Quebec and British Columbia, respectively, comes from renewable sources such as hydro, tidal, solar, and wind (National Energy Board 2018). In Ontario, that number is only 33%, but an additional 60% comes from nuclear steam turbine generation (National Energy Board 2018). In large contrast, Edmontonian homes would experience an emissions increase of 25 % (hybrid system B), 35% (hybrid system C), and 52 % (hybrid system A). This is due to the fact that 93% of electricity in Alberta is generated by the combustion of fossil fuels (National Energy Board 2018); an issue that is currently being tackled in the province's energy sector (Weis, Thibault, and Miller 2016). In the case of Yellowknife, 33 % of electricity is generated renewably (National Energy Board 2018), so the hybrid system would bring about emissions reduction of up to 24 % if hybrid system A is used (20 % for ASHP C and 13 % for ASHP B), but the magnitude of emissions far exceeds an average home in any other city due to the heavy reliance on heating oil. This result also reinforces the fact that a lower capacity ASHP A that can operate for a greater portion of the season is more beneficial than a higher capacity ASHP C, which far more limited in the operating temperature range.

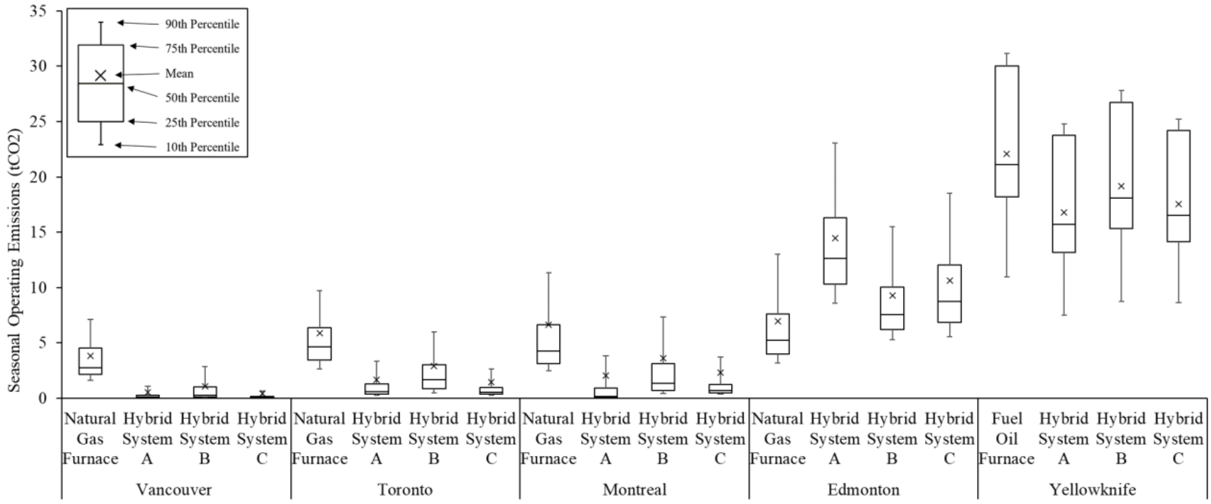


Figure 2.14. The seasonal CO2 emissions for a single-detached home in each city using the four systems.

With regard to average seasonal operating costs, the results are once again region-dependent and do not exactly parallel the results presented directly above. Operating the hybrid system would mean cost reductions of 10% or 20% if hybrid systems C and B are used, respectively. However, usage of ASHP A in conjunction with the traditional furnace in a typical Vancouver home would increase annual spending by 4%. This can be attributed to its having the lowest efficiency as denoted by its coefficient of performance (COP) in Table 2.6. This trend in operating costs extends to Toronto, where a reduction of 3 % and 8 % can be achieved with ASHPs C and B, respectively. ASHP A generates an increase of 13 % in annual operating costs. This suggests that there is currently no single system that can objectively outperform the rest by both metrics. While hybrid system C is certainly a strong choice in these locations, a decision must be made based on what the consumer values. The most positive results occur in Montreal, where electricity price is by far the lowest amongst the five cities (Hydro-Québec 2020), which leads to a reduction in costs between 27 % (ASHP B), 31 % (ASHP A), and 37 % (ASHP C). In contrast, the low cost of natural gas in Alberta signifies that the average operational cost could increase by 33-60 % in Edmonton if the average home installs hybrid systems B or C, respectively. Likewise, expenditures would increase in Yellowknife due to high electricity costs by as much as 25 % for hybrid system A. However, operating hybrid systems B and C would only increase by 1 and 2 %, respectively. As such, it is concluded that both emissions and cost reduction from the ASHP technology favour Vancouver, Toronto and Montreal. However, no single system can achieve the greatest reductions in operating GHG emissions and annual costs simultaneously.

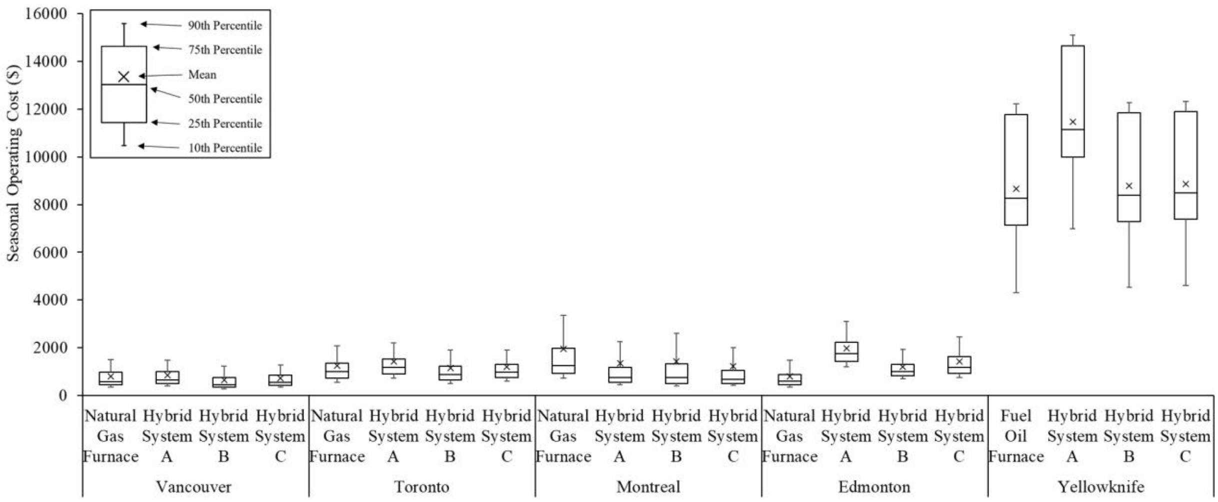


Figure 2.15. The seasonal operating cost for a single-detached home in each city using the four systems.

Although the results are not entirely favourable, the implications from emissions results are very positive, especially since the nation is aiming to reduce its emissions through various goals. Mainly, the Paris Agreement pledges to reduce national emissions by 30 % by 2030 compared to 2005 levels (Mascher 2018). Thus, a municipal-level analysis could be of use for visualizing potential emissions-reduction strategies. Figure 2.16 presents a few potential scenarios for emissions reduction on a greater scale. If every home in Vancouver were to switch to using a hybrid ASHP C-furnace system, overall annual heating emissions would reduce by 8 %. Similarly, in Montreal by 22 % with hybrid system A. With Toronto's massive population and housing stock, making the switch to all hybrid with ASHP-C systems in this city would result in the greatest overall reduction in residential heating emissions of these five communities of 32 %. By contrast, Edmonton's case would increase the CO_2 release of the cities by 5 % even if the least polluting hybrid system (B) was used in an all-hybrid scenario. Yellowknife's extreme emissions do not have such a major impact due to its relatively low population community (emission decrease of only 0.14 % for the combination of residential communities).

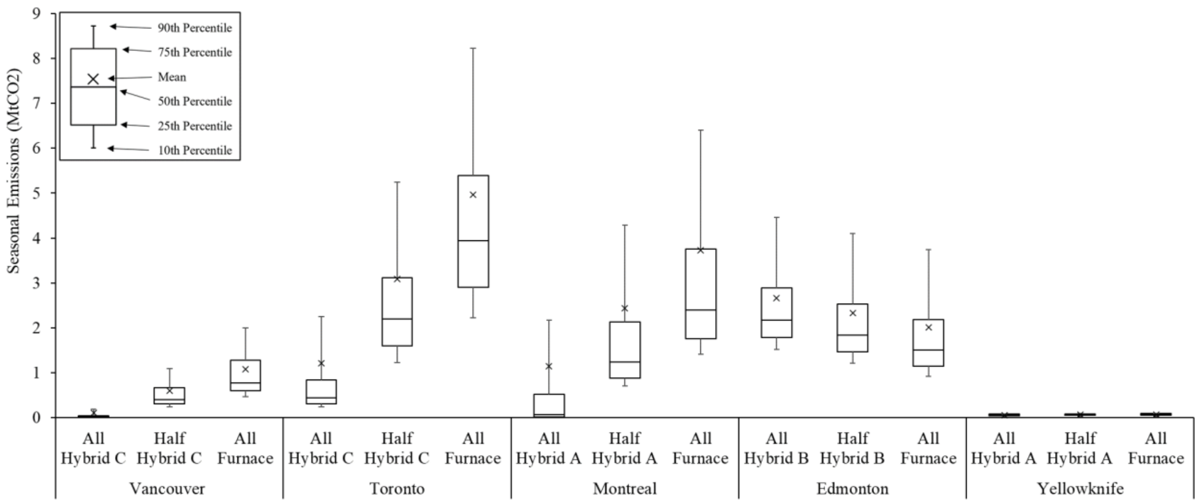


Figure 2.16. Municipal-scale GHG emissions results for all single-detached homes in each city at three heat operating scenarios.

2.4 Limitations

This study was simplified and limited in several of the following ways. Firstly, the target and input selection in this study heavily relied on the data provided from the database, so it is possible that replicating the procedure on different sets of housing data could result in different variables with better-correlating relationships. Furthermore, it is critical to note that although the original data regarding the four main components were available for use in the techno-economic analysis, prediction results from the SVR modelling were used instead. The reasoning behind this decision was to showcase the process of how the SVR predictions can be acquired and then utilized in housing energy analysis. The goal is to replicate this procedure on other datasets for different styles of homes, such as double/rowhouses, in other countries to model the necessary parameters completely. Given that the four targets tested here gave positive results, the SVR models could be expanded to other housing parameters, primarily the ones which were not feasible in this study, such as infiltration coefficients and fenestration areas. Regarding the techno-economic analysis procedure, additional steps could be taken to involve a greater level of detail in the analysis. For example, the heating load calculations may be modified to include other heat transfer effects, such as humidity, wind speed, and hourly solar irradiance. Similarly, the economic analysis in this study ignores the costs of energy transmission, as well as equipment installation and maintenance costs. Furthermore, ASHP technology can be used for cooling purposes, leading to costs and GHG emissions as well, which is beyond the scope of this study given the considerable heating demand in Canada.

2.5 Conclusion

This study analyzed the effect of utilizing electric ASHPs in combination with fossil fuel-fired furnaces as part of a hybrid energy heating system for residential homes in several Canadian cities. Prior to the feasibility analysis, SVR was applied to a Canadian housing database to generate predictive models for architectural exposure areas that were used to estimate heating energy consumption. This validated method showed reliability and consistency in analyzing large datasets. Heating load, economic and emissions analysis showed that ASHP technology would be beneficial to bring about energy source changes in the residential sector: increased use of electricity and lowered the consumption of traditional heating fuels. Moreover, the ASHP system would introduce seasonal cost reduction in Vancouver, Toronto, and Montreal. The heavily renewable generation mix and moderate utility costs, coupled with milder climates, make these locations suitable for the ASHP system and can benefit from cost and emissions reduction for space heating. Yellowknife could benefit from this system only through GHG emissions reduction, as operating costs would increase moderately. Meanwhile, currently available ASHP technology is temporarily unfeasible for use by every measurable margin in

Edmonton due to a lack of renewably generated electricity. However, some provincial governments are actively developing renewable technology to boost green electricity, such as the new solar farms scheduled for development in southern Alberta (Government of Alberta 2020), which will facilitate ASHP technology implementation in Canada.

CHAPTER 3: Framework for Design and Optimization of a Retrofitted Light Industrial Space with a Renewable Energy-Assisted Hydroponics Facility in a Rural Northern Canadian Community

3.1 Introduction

Food insecurity in remote aboriginal families was reported to be as high as 65% in 2016 (Leblanc-Laurendeau 2019). The various challenges experienced by the food supply chain; originating in warm growing climates and terminating at the hundreds of small communities scattered across Canada's north are partially responsible for this issue. The long transportation distances, some of which are not accessible year-round; not to mention the added supply chain disruptions caused by global pandemics (OECD 2020; Queiroz et al. 2020; Sophie Wirzba 2020), coupled with severe weather conditions, result in food waste, high retail costs, and decreased shelf life for commonly imported produce in northern provinces and territories (Mercier et al. 2018). A potential solution to this ongoing problem is installing medium-scale community indoor farms, such as greenhouses or plant factories, that provide fresh and cost-effective food.

Greenhouse and controlled-environment agriculture using hydroponics are becoming increasingly popular due to their capability of maintaining favourable microclimates as compared to open-field soil-based agriculture, which results in higher product quality and yield (De Gelder et al. 2012). However, these production methods have higher energy demands than open-field farming due to space conditioning, even in warm climates (Grewal, Maheshwari, and Parks 2011). The territories and northern parts of the mainland provinces experience harsher heating seasons and higher energy costs (National Energy Board 2020a), which can pose a problem for applying indoor farms. To overcome these challenges, greenhouse and hydroponic farms in northern rural communities must be designed and operated with sustainability in mind, particularly to address space heating and indoor climate control.

Various researchers have proposed unique and unconventional devices, or combinations thereof in a 'hybrid renewable energy system' (HRES), for the use in greenhouses or growing facilities. Their goal was to improve the efficiency of the heating and cooling systems and reduce reliance on traditional fossil fuels. Since many greenhouses are traditionally designed to take advantage of passive solar gain and sunlight, solar energy systems are a common point of interest in existing research. Bambara and Athienitis (2019) addressed the performance of greenhouses with roof-mounted solar PV to optimize simultaneous passive solar gain and electricity generation. Meanwhile, the case of a ground-source heat pump (GSHP) coupled with solar photovoltaics (PV) has seen success in heating greenhouses in both Turkey (Yildirim and Bilir 2017) and Italy (Russo et al. 2014). Similarly, Esen and Yuksel (2013) successfully demonstrated the potential of using a biogas, ground, and solar energy HRES for heating a greenhouse through a full winter, also in Turkey. The use of a GSHP in these cases has the added benefit of providing cooling during warmer periods, which further improves energy efficiency. Furthermore, the storage of energy using phase change material (PCM) in mild climates, such as North Africa and Turkey, has been explored for night-time heating or capturing heat from a GSHP (Baddadi et al. 2019). Overall, these studies are evidence of potential low energy consumptions of greenhouse design and operation solutions across various climates. However, three main gaps appear to be present in the research listed.

Firstly, the HRESs documented above are highly dependent on the mild climatic conditions of their locations; the cases listed were largely centred around the Mediterranean region. In the Canadian context, much less research has been found on this topic; only some passive greenhouse design technologies have been explored. For example, joining a greenhouse to a retail centre supplemented with on-site PV generation, waste heat recovery, and energy sharing was simulated to achieve net-zero performance in central Alberta (Syed and Hachem 2019) Moreover, greenhouse envelope design for the extreme arctic was reviewed, and the researcher concluded that insulating the north wall of the building, thereby optimizing heat loss and solar gain, can extend the growing season by at least a month (Henshaw 2017). In general, research tends to be limited in colder climates applications.

Secondly, there is a lack of research that utilizes optimization to determine the optimal control strategy of an HRES, which would be critical in a hybrid system that includes multiple devices dedicated to satisfying specific demands (Geleta and Manshahia 2017). While optimization has been seen used on indoor climate control of greenhouses and grow rooms (Iddio et al. 2020); with regards to ventilation and CO_2 injection, there has been a noticeable lack of studies relating to the use of optimized HRESs in the realm of controlled-environment agriculture; most of the research on HRES optimization has been found applied on standard commercial and residential buildings (Ko et al. 2015; Xie et al. 2020; Kusiak, Tang, and Xu 2011; Braun et al. 2020).

Thirdly, to be compared with the base or traditional case, the cost and emissions savings, if any, of the proposed HRES must be quantified in terms of the plant product or crop yield, which has not been seen in the research outlined so far. In other words, a comparison between local production and import of a crop can aid in choosing the most economical and least emissions-intensive option for acquiring food (Dyer et al. 2011; Michalský and Hooda 2015). To the best of the authors' knowledge, there is not enough research regarding local production as a method for import displacement, specifically targeting rural northern communities, where energy costs are higher, the climate is harsher, and transport operations are more limited.

The goal of this study is to address the lack of research regarding the application of hybrid energy systems for indoor farming in northern rural communities. More explicitly, the objectives of this chapter are two-fold. Firstly, to present a methodology for design and optimization of renewable energy-assisted hydroponics retrofitted facilities. This procedure contains the steps to review the key requirements for a hydroponics facility, optimize the operation of a hybrid energy system such that annual operating emissions and costs are minimized, and evaluate the sustainable operation of the entire facility with the proposed system by comparing its costs and emissions to traditional import. The second objective is to showcase this procedure on a case study building in a rural community in northern Alberta, Canada.

3.2 Methodology

3.2.1 Hydroponics Facility Requirements

3.2.1.1 Heating and Cooling

As with human-occupied buildings, plant growth facilities must be maintained at appropriate indoor temperatures for healthy plant growth, which tend to vary by crop type as well as stage of growth (Resh 2013). This means that temperature control equipment must be capable of combating heat losses and gains. Heat transfer can occur through typical processes, such as conduction through the exterior surfaces (floors, walls, ceiling, doors, and windows), convection (ventilation and infiltration) of outdoor air into the space, and radiation from any lights and from the sun through fenestration (ASHRAE 2017). In the case of plant facilities specifically, evaporative cooling is another energy loss to the plants that convert liquid water to vapour and must also be considered for heating system sizing (Graamans et al. 2017; McGowan 2020).

3.2.1.2 Humidity

During photosynthesis, water taken up by the roots is used to carry nutrients through the plant's core and is then evaporated into the atmosphere by stomata on the leaf surface (Jones 2005), which causes the evaporative cooling effect mentioned earlier. A carefully controlled vapour pressure deficit (VPD) drives the movement of water through the plant. High indoor humidity means a low VPD that causes plants to evaporate water more slowly, slowing down their rate of photosynthesis. Meanwhile, low indoor humidity (high VPD) can cause excessive evaporation and lead to significant dehydration (Castilla, Baeza, and Papadopoulos 2012). As with temperature, the right VPD depends on crop type and stage of growth.

3.2.1.3 Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) consumption is the method by which plants obtain carbon for growth (Jones 2005), and it is a crucial stage of the carbon cycle (Loustau and Rambal 2010). In open-field agriculture, this is not an issue as ambient outdoor air has an abundance of CO_2 that can be used to satisfy this demand. However, with indoor crop production, this resource can be quickly drained if adequate fresh air or supplemental carbon is not provided. In the case of CO_2 enrichment, elevated levels above the ambient concentration have been found to boost crop growth and yield, as well as improve quality (Resh 2013).

3.2.1.4 Lighting

One of the main drawbacks of indoor facilities for farming is the lack of natural light due to the spaces having mostly opaque envelopes to combat the harsh climate. Even in transparent greenhouses at northern latitudes, the winter months see less than the optimal 14-16 hours of light each day (Resh 2013). This issue is solved with specialized horticultural lighting options (Mitchell and Sheibani 2020), which draw a considerable amount of power and create substantial heat.

3.2.1.5 Water

Water supply is the main form of nutrient transport through the plants and is an essential part of photosynthesis (Jones 2005). Hydroponics are well known for their incredible water use efficiency as compared with soil based traditional systems (Graamans et al. 2018). Nonetheless, water consumption is high even for a small system and must operate reliably.

3.2.2 Hybrid Renewable Energy System (HRES)

3.2.2.1 System Sizing

If the existing equipment in the building cannot meet the identified requirements, new systems must be elected and sized according to appropriate design procedures and guidelines. It is also necessary to consider the available renewable energy options for the specific case. Factors such as energy availability and cost, local fuel options, available land area and resources may constrain the final selection of systems and their overall configuration.

3.2.2.2 System Modelling

The goal is to estimate the operating costs and greenhouse gas (GHG) emissions by determining the actual space demands, modelling the selected energy systems, and considering local energy and resource prices and relevant emissions factors. However, given that certain operational parameters of the facility and the energy system have not been set, variability in the result can occur.

Heating, cooling, humidity control, and CO_2 availability are all tied to how much fresh airflow is occurring and given that there are no strict code requirements for minimum ventilation of plant growth spaces, this parameter can be adjusted to achieve the most minimal energy and resource consumption. Additionally, if more than one potential energy conversion device has been selected to satisfy certain energy demand, both devices can contribute to the total load through combined part-load energy supply at variable operating fractions based on the availability of natural resources, such as sunlight or warm weather. Therefore, the optimization of such variables is very critical in this application to achieve sustainable operation. The objective functions shall be set up as the monthly cost and emissions, and the decision variables are the ventilation flow rate, and energy supply fractions for the individual demands.

3.2.2.3 Optimization of Hybrid Renewable Energy System

Since this problem will contain multiple parameters desired to be minimized, multi-objective optimization serves as the appropriate tool to perform this task. Evolutionary algorithm optimization is one method by which many studies have found the optimal operating conditions for various HVAC systems (Fadaee and Radzi 2012). These problems tend to have multiple objectives that conflict with each other, which means that a single solution cannot achieve all the goals (Gunantara 2018). Instead, the algorithm finds a range of potential non-dominated solutions along a 'Pareto-optimal front' that can be further analyzed by the user, a secondary algorithm, or other decision-making approach (Konak, Coit, and Smith 2006).

The 'gamultiobj' function in MATLAB, based on the NSGA-II algorithm (Mathworks 2020a), can be used to compute the Pareto front for each month defined by outdoor conditions. The algorithm configuration, comprised of population size, crossover fraction, Pareto fraction, and a convergence function tolerance, should be chosen to achieve a relatively quick convergence to a region near the optimal front. Followed by a secondary solver that searches more closely within the generated region to identify the best solution(s) (Mathworks 2020b). In MATLAB, this secondary solver is the 'fgoalattain' hybrid function, which is a standard algorithm that can be used to solve goal attainment (e.g., minimization or maximization) but is hindered by the fact that it requires initial guessing. Since the genetic algorithm is extremely versatile and does not require much input but is only useful for finding a collection of potential solutions, combining it with a more efficient local minimization function is a good strategy for achieving quick convergence at a global minimum.

The procedure of the custom MATLAB script, shown in Figure 3.1, is outlined as follows. First, the month number is assigned from a loop ranging from 1-12. Next, the modelling data file, which contains the necessary equations and data, is provided. The decision variable vector and corresponding constraints, which are problem-specific, must be passed to the optimization function. The algorithm proceeds by generating the first population of input vectors and evaluating the fitness function and comparing it with the convergence tolerance value. The objective space continues to be populated with increasingly improved generations of points until this tolerance is met. At which point, the final generation containing the best Pareto front of solutions is passed as the initial guess to the secondary solver. Then, the solver attempts to minimize each point on the front further by generating additional guesses and evaluating the function value along a search direction generated by the genetic algorithm. Once a function tolerance is reached and the same original constraints are satisfied, the solver stops and shows the final solution(s).

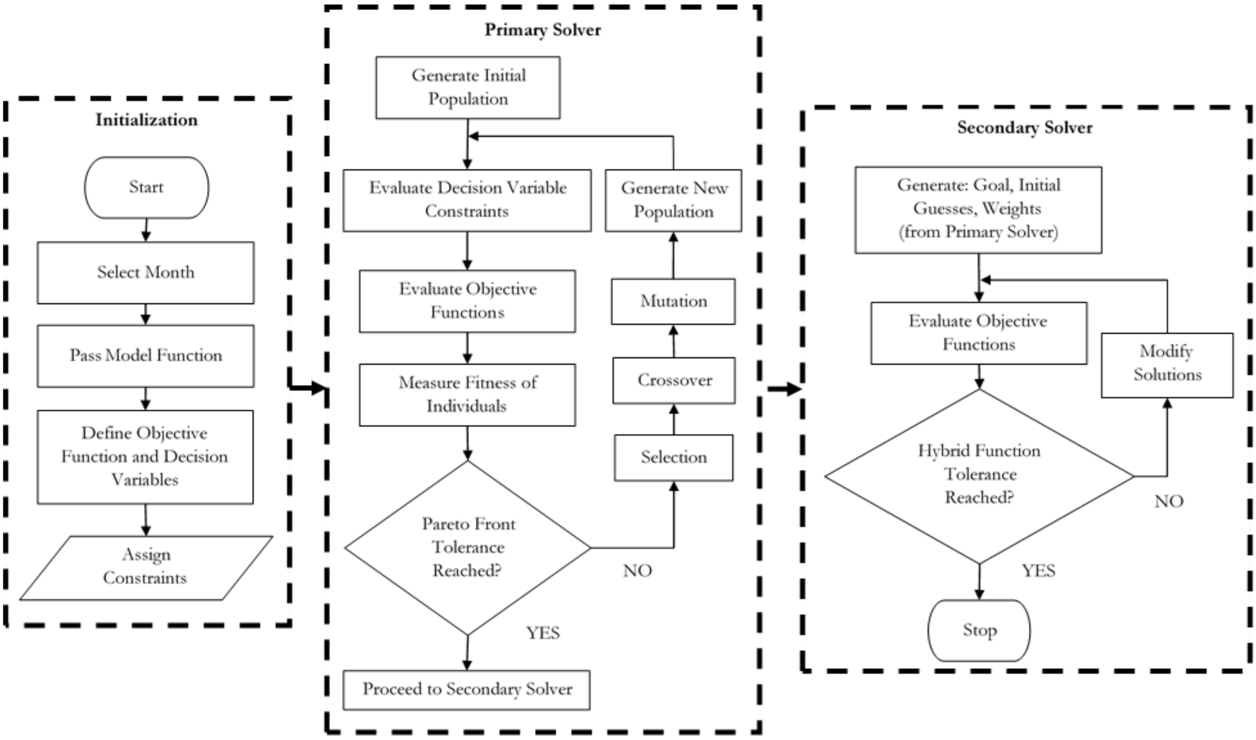


Figure 3.1. Process of the MATLAB script used for HRES optimization.

3.2.3 Comparison with Traditional Food Import

The operating cost and greenhouse gas (GHG) emissions from the optimization procedure can be used in a comparative analysis to determine if production using this method is a viable replacement for traditional import, at least on a purely quantitative basis. It should be noted that techno-economic feasibility is only one of many factors that could affect decision making in northern Canadian communities. Ultimately, every rural hamlet or community, especially that of indigenous background, would be subject to a unique set of circumstances derived from a historical issue related to colonization, which would drive choice and behaviour. In other words, the optimal low-emissions solution obtained from optimization may not necessarily coincide with a solution that supports autonomy, local employment, and training.

3.2.3.1 Life Cycle Cost

The cost analysis involves accounting for all the cost components of retrofitting the facility as well as operating it over the course of its lifetime. More specifically, the costs associated with this analysis in the current application are: 1) capital costs of all major technologies involved in the retrofit, including the energy conversion devices and the hydroponics equipment; 2) operating costs associated with consumed resources, such as energies (fuel, electricity) and miscellaneous resources (water and supplemental carbon); and 3) any additional annual expenses, such as maintenance and labour. Meanwhile, estimating the amount of product yield over the same period can help establish a cost index per quantity of produce, which can be compared with the existing cost of the same food type at the local grocer.

3.2.3.2 Food-Miles Assessment

As for emissions, the 'food-miles' assessment has been seen in literature as a method of assessing the potential for import substitution by local production (Dyer et al. 2011). For the local production case, operating emissions from energy and resource use include the consumption of resources, fuels, and electricity required for the basic operation of the facility as obtained from the annual emissions results from optimization. On the other hand, the transport case only considers total emissions from fuel use during travel, which is based on distance and size of the shipment (Kissinger 2012). The weight of the product to be transported is assumed to be equal to what is produced in a year at the local facility, which allows for a similar comparison between the two methods.

3.3 Case study

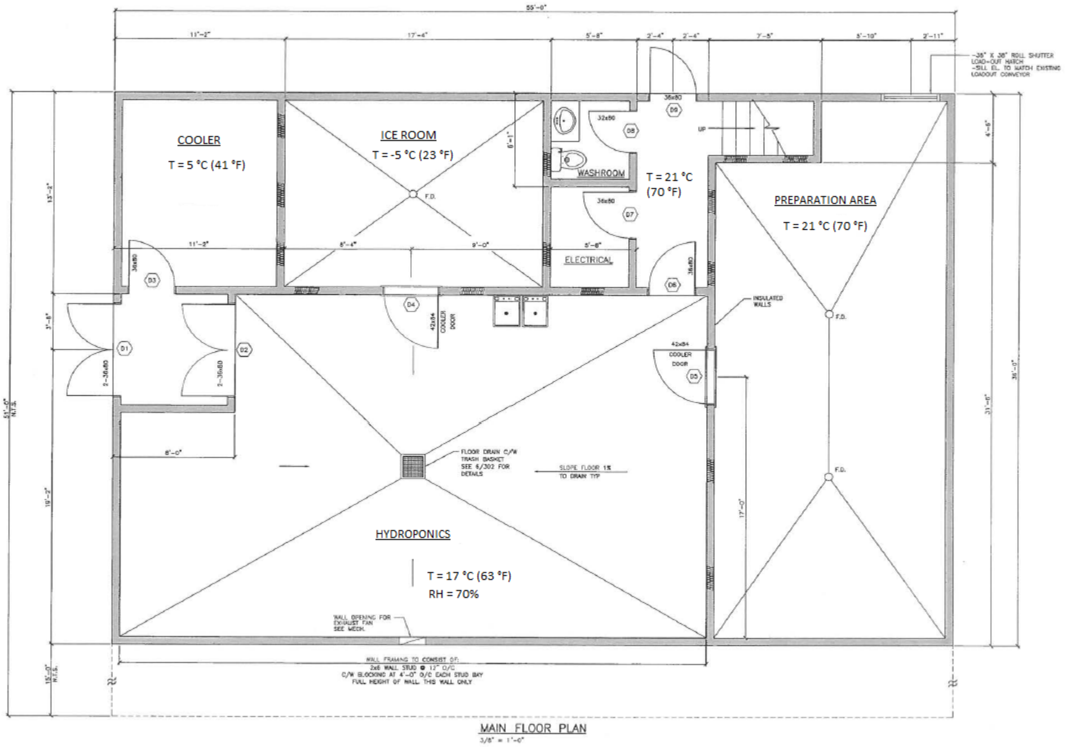
3.3.1 Existing Building Retrofit

The existing building (Figure 3.2) is a 270 m^2 commercial fish processing plant that is in Fort Chipewyan, Alberta (58.770N, 111.120W). It is a steel-frame building with RSI-4 walls and RSI-7 roof and is almost entirely opaque with only three small windows on the south-eastern side. The main space makes up most of the floor space (31 %) and was to be retrofitted with a commercial hydroponics vertical farming system designed to grow lettuce (*Lactuca sativa*). The building also included two chilled rooms, as a cooler and an ice room, as well as a food preparation area, a break room, and an office. 240 2.1 m growing towers and a combination of 24 75 W and 48 150 W variable RGB spectrum LED lights were used.

a)

b)

c)



d)

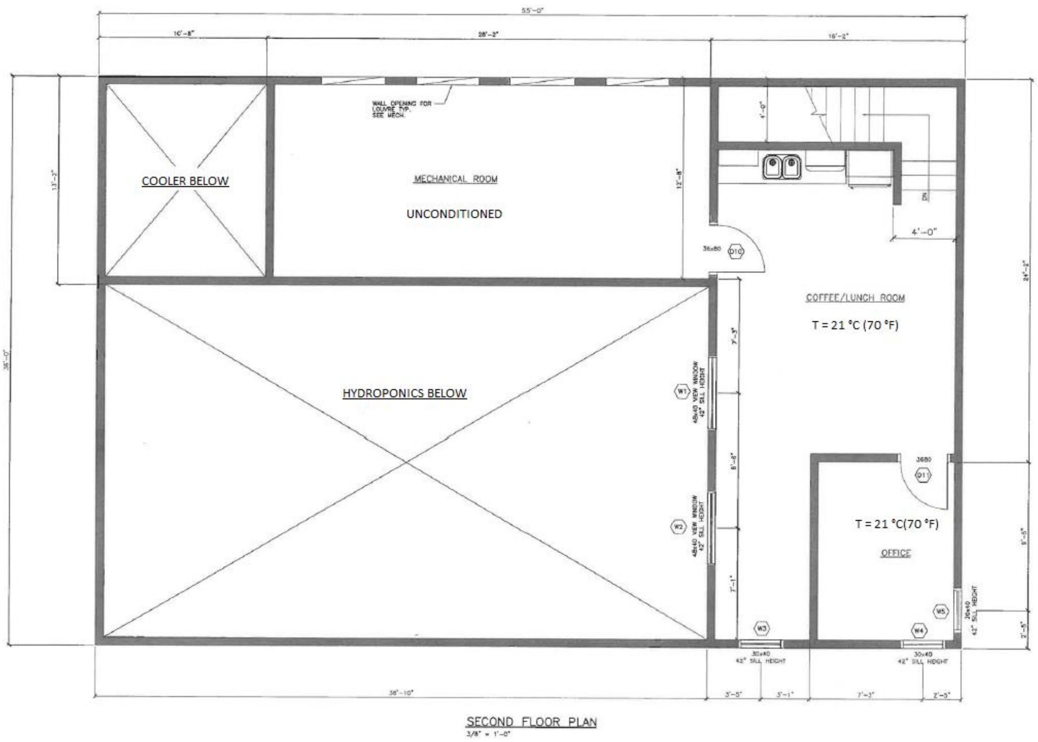


Figure 3.2. (a) Location, (b) exterior, (c) main floor plan, and (d) second floor plan of the existing fish plant building.

3.3.2 Load Calculation

Indoor plant requirement analysis was performed by applying the fundamental energy and mass transfer equations outlined in ASHRAE Handbook – Fundamentals (2017) to the case study building, and by taking into consideration the setpoints and specifications of each demand, as listed below.

3.3.2.1 Heating and Cooling

For design load calculation, the outdoor temperature was set at 99 % and 1 % worst-case dry-bulb temperatures as defined by climatic data for the weather station of Fort Chipewyan (ASHRAE 2017), and the main hydroponics space was set at 21 °C and 17 °C (Brechner, Both, and CEA Staff 2013), for heating and cooling, respectively. For the other regularly occupied spaces, the temperature setpoint was 21 °C as a typical value for human occupancy (ASHRAE 2017). The cooler and ice rooms were set at 5 °C and -5 °C, respectively. In conformance with ASHRAE standard 62.1 (2019), the break room, prep area, and office were assigned ventilation flow rates in the range of 10-30 L/s, based on regular occupancy (two in the prep area and one in the office) and floor area. The flowrate of fresh ventilation air in the main growing space was set at 7 air changes per hour (ACH), as the typical maximum greenhouse ventilation rates in the winter, according to Chapter 24 of ASHRAE Handbook – HVAC Applications (2015). Meanwhile, infiltration was assumed negligible in this building based on the assumption that an indoor plant growth facility would need to be well sealed if its purpose were controlled environment agriculture (Niu, Kozai, and Sabeh 2020). Sensible energy loss due to evaporative cooling by plants was modelled as the product of the rate of evapotranspiration and the heat of vaporization of water. For the cooling load, the peak solar heat gain into the office and lunchroom (no windows in the main growing area) through fenestration during July was modelled based on the hourly solar irradiance estimates, which were obtained from a solar position calculator (National Oceanic and Atmospheric Administration 2020) and clearness index data for the target location (HOMER Pro 2020). Furthermore, the maximum lighting heat output of standard and hydroponics lighting in the building was also considered based on typical efficiencies for high performance grow LEDs and standard fluorescent ballasts (Ahn et al. 2014; Liu et al. 2017). A safety design factor of 20 % was applied to the heating and cooling loads as a standard sizing procedure for industrial spaces.

For the performance modelling, the bin method was used to determine monthly loads based on ASHRAE provided hourly occurrence data in a typical meteorological year for the location. The actual hydroponics setpoint temperature was set to 17 °C and 20 °C for the winter and summer, respectively. The seasonal variation was introduced to ease the heating and cooling requirements, while still ensuring that the temperatures were appropriate for lettuce (Resh 2013). Meanwhile, the other spaces remained modelled at 21 °C, 5 °C, and -5 °C and the same healthy ventilation flowrates, for the regularly occupied, cooler, and ice room spaces, respectively. Flowrate of fresh air into the hydroponics space was chosen as a variable in the range of 0.1 - 7 ACH, based on the minimum ventilation for extracting contaminants generated by plants (Niu, Kozai, and Sabeh 2020; Daunicht 1997), and the maximum ventilation based on the design load. Actual lighting and solar heat gains were modelled as monthly averages based on hourly variations.

3.3.2.2 Humidity

The humidification and dehumidification requirements were determined using the 99 % and 1 % worst case outdoor humidity ratios, as listed in the climatic data for the local weather station (ASHRAE 2017), in combination with the corresponding worst-case air change flowrate of 7 ACH, and extreme indoor setpoints of 90 % RH at 21 °C (VPD = 0.2 kPa) and 50 % RH at 17 °C (VPD = 1.0 kPa) (Hanan 1998), respectively. Minimum humidifier and dehumidifier capacity were found by considering these conditions on a mass of water either removed or added per hour. This considered the approximate moisture supply to the air through plant transpiration, which was assumed equal to the watering rate; no irrigation loss or water consumption by the plants. For the other human-occupied spaces, humidity control was neglected since human comfort was not in the scope of the study.

During monthly performance modelling, the same logic was applied, except indoor setpoints of 60 % RH at 17 °C (VPD = 0.8 kPa) for the winter and 80 % RH at 20 °C (VPD = 0.45 kPa) for the summer were more realistic, and actual outdoor humidity was computed based on the hourly temperature occurrence data used in the bin method. Once again, this seasonal variation was introduced to reduce expected energy consumption by the humidity control systems, while still satisfying the requirements of the VPD.

3.3.2.3 Carbon Dioxide (CO_2) Supply

The CO_2 supply was simulated as only providing enough CO_2 to counter plant consumption and maintain a sufficient ambient concentration of approximately 400 ppm. This way, the concentration would always be constant regardless of CO_2 supply method. Plant consumption of CO_2 was taken as a value for a greenhouse 3 g/m^2 per hour (Castilla, Baeza, and Papadopoulos 2012; Nederhoff 1994), which conforms with values reported for plant factories in the literature (Graamans et al. 2018).

CO_2 consumption was modelled as inversely proportional to the average hourly indoor air change rate (ACH), such that, the time spent not ventilating the space, using a constant exhaust fan flowrate of 3780 L/s, would be supplemented by CO_2 injection, at the constant flowrate equal to plant consumption. Therefore, the higher the ventilation flowrate, the smaller the required CO_2 flowrate, and the lower the average consumption.

3.3.2.4 Water Supply

Water supply was taken as a specification from the manufacturer of the hydroponics system as 220 L/day on average. Additional water demands for other spaces in the building were estimated based on fixture layouts of one lavatory with a sink and two kitchen faucets, and the occupancy schedule. This also included water heating energy consumption, based on an average temperature rise between municipal feedwater temperature of 8 °C and boiler supply temperature of 50 °C.

3.3.2.5 Lighting

120 growing lamps with a power consumption of 9 kW, were modelled as having a 60 % efficiency with regards to heating gains used in heating and cooling loads. The operating schedule was set at 16 h / 8 h photoperiod/dark period (Frantz et al. 2004; Hiroki et al. 2014). Similarly, the hydroponics equipment (irrigation pumps) w modelled as operating 24 hours per day, and any heat gain was neglected. In the rest of the building, lighting consisted of standard 32 W ballasts operating for a typical working schedule of 8 hours a day in the occupied areas and intermittent use of 4 hours a day in the freezer and cooler.

3.3.3 Hybrid Renewable Energy System (HRES)

3.3.3.1 System Selection and Sizing

A series of energy systems were considered, both renewable and traditional, for maintaining the temperature and humidity setpoints based on locally available resources. The forced air furnace and water heater were parts of the existing system of the building with a reliable fuel source (propane) that is available locally. Additionally, a biomass boiler was sized to be used as an alternative heating system because a review of the location revealed that cordwood is an abundant local resource. Investment in this technology can provide local employment and community development, which is a benefit that cannot be accurately captured through quantitative analysis.

It was found that this location is suitable for geothermal heat exchange (Majorowicz and Grasby 2020; Mahbaz et al. 2020), and it seemed logical to utilize a heating system that could use electricity instead of traditional fuels. Also, the high efficiency and dual functionality for summertime cooling of a heat pump were deemed as major advantages over conventional fossil fuel-fired equipment. Hence, the ground-source heat pump (GSHP) was selected as an alternative heating device and the only source of cooling. This was deemed a feasible option due to the significant amount of land area around this building, which would allow for a closed-loop vertical bore system with 20 bores of 40 m depth, 6 m separation, with 25 mm high-density polyethylene (HDPE) U-tubes in 127 mm diameter bores to be installed (Kavanaugh and Rafferty 2014). Data for ground conductivity, temperature, and thermal resistance was taken as an approximation from Alberta soil surveys (Grobe et al. 2009).

Humidification and dehumidification systems for the hydroponics space were sized to meet the average daily moisture removal or addition loads operated under the worst-case design conditions, respectively. Although the GSHP is a system capable of providing dehumidification, this process can only occur when the GSHP is in cooling mode. However, there was no guarantee that the operation of dehumidification only when the GSHP was in cooling mode would have been the most cost- and emissions-friendly strategy. Therefore, the dehumidification and cooling systems were modelled independently from each other as separate units.

An indirect component of the HRES is a solar photovoltaic (PV) array, modelled as the primary source of renewable, reliable, and low maintenance electricity for the building. A total capacity of 60 kW was selected as a reasonable size for a light industrial building, for which there would be enough land area onsite. Table 3.1 lists the devices chosen to satisfy the computed loads, with details about capacity, efficiency, cost provided.

Table 3.1. Devices included in the HRES for the case study building.

Device	Fuel Type	Function	Efficiency	Capacity	System Capital Cost, CAD$
Boiler[1]	Cordwood	Space Heating	80 %	44 kW	$ 7,000
Furnace	Propane	Space Heating	80 %	35 kW	$ 0 (Existing)
GSHP[2] (w/ ground loop heat exchanger)	Electricity	Space Heating	COP = 4.0	16 kW	$ 45,800
		Space Cooling	EER = 13.7	23 kW	
Dehumidifier[3]	Electricity	Dehumidification	2.9 L/kWh	30 L/h	$ 55,440
Humidifier[4]	Electricity	Humidification	1.2 L/kWh	30 L/h	$ 3,830
Water Heater	Propane	Water Heating	92 %	17 kW	$ 0 (Existing)
Solar Photovoltaics	Electricity	Generation	Standard Module, Fixed Array, 20° tilt	60 kW DC	$ 132,600 (National Energy Board 2020b)
Hydroponics[5]	Electricity	Lettuce Farming	N/A	8440 kgs per year	$ 116,200

Note: 1. (HeatMasterSS 2020)
2. (Trane 2020)
3. (Quest Climate 2020)
4. (DHgate 2020)
5. (ZipGrow Inc. 2020)

3.3.3.2 System Modelling

The heating systems (furnace, boiler, GSHP) were set up in parallel as sources of thermal energy to the space satisfying the total monthly heating demand. Cooling, humidification, dehumidification, and water heating equipment were set up as single systems satisfying the total monthly loads. For the solar photovoltaics (PV) array installed onsite, the location-specific AC system output profile was simulated using the National Renewable Energy Laboratory's PVWatts® calculator on a monthly basis (NREL 2020), using the location of the existing plant and the proposed system size. The primary source of electricity was the local community micro-grid, which fulfilled any electric demand of the HRES not covered by electric solar PV generation, such as lights, humidification equipment, or GSHP. In other words, the purpose of the PV system was to offset the monthly import of electricity. In addition to the energy systems, the water and supplemental CO_2 usage were modelled as a total monthly consumption based on the requirements described earlier. Figure 3.3 shows the layout of the hybrid renewable energy system with energy flows from provided energy sources to the respective demands. Although the exhaust fan was not directly modelled in terms of energy use, it has been included because ventilation is a critical component of the operational strategy of the HRES.

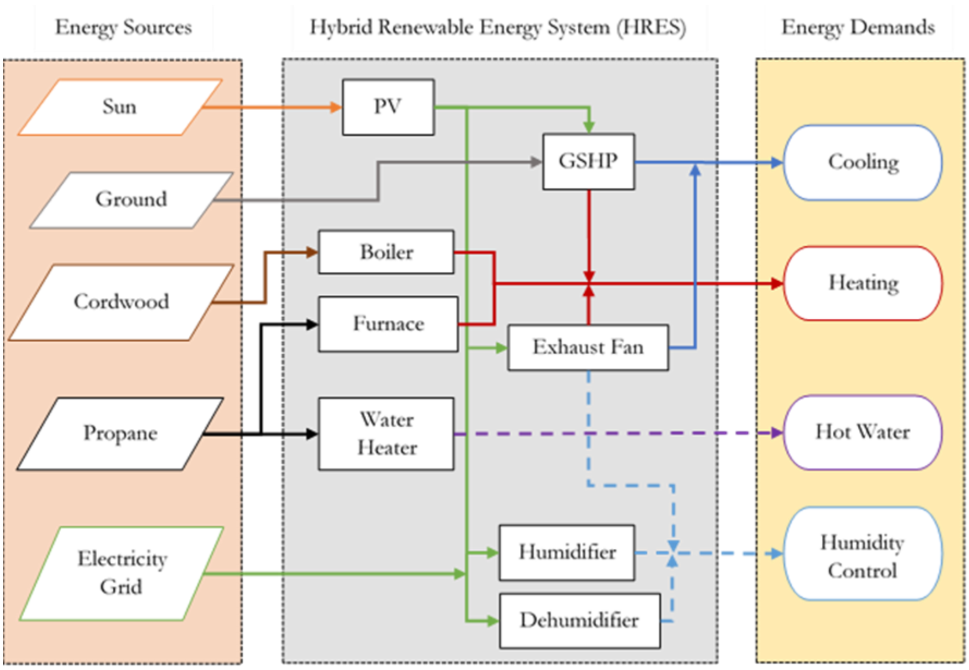


Figure 3.3. Layout of the Hybrid Renewable Energy System (HRES) in the case study.

The emissions and costs of each system were set up by using the local prices of the resource and consumption emissions factor. The general reporting guidelines listed in ASHRAE Standard 105 (2014) were used to describe energy and resource use, which considered heat content values taken from the national inventory report in terms of primary thermal energy (Environment and Climate Change Canada 2019). Table 3.2 shows the cost and emissions factors of the fuels used in the analysis. The electricity emissions factor was based on a conversion efficiency from diesel-fired generation in the community, and a value was assigned based on the average conversion efficiency found in the three Canadian territories, which most closely resemble the quality of power infrastructure found in Fort Chipewyan

(Statistics Canada 2020a; 2020b). For cordwood and propane, the emissions factors, which are based on the quantity of greenhouse gases released during combustion, in CO_2 equivalent, were taken from the national inventory report (Environment and Climate Change Canada 2019).

Table 3.2. Prices and emissions factors of fuel options used in the case study building

Fuel Option	Emission factor, gCO_2e/kWh	Fuel Cost, \$/kWh
Cord Wood	2.33 (Environment and Climate Change Canada 2019)	0.031 (Alberta Firewood 2020)
Propane	220 (Environment and Climate Change Canada 2019)	0.127 (Bluewave Energy 2020)
Electricity	784 (Environment and Climate Change Canada 2019)	0.180 (NWT Power Corporation 2020)

Meanwhile, the costs of electricity, cordwood, propane, and compressed CO_2 were found from estimates of local suppliers (NWT Power Corporation 2020; Gwich'in Council International 2017; Alberta Firewood 2020; Bluewave Energy 2020; Praxair 2020). Similarly, the water supply (Table 3.3) was calculated based on the total monthly amount of water supply for the building, including hydroponics and typical fixtures. This was combined with the fixed monthly and variable flowrate fees for the existing meter size, 38 mm, in the local municipality (Regional Municipality of Wood Buffalo 2019).

Table 3.3. Prices of material resources used in the case study building

Resource	Fixed Monthly Fee, \$/mo	Variable Cost, \$/unit
Water Supply	\$ 34.87	1.61\$/m^3 (Regional Municipality of Wood Buffalo 2019)
CO_2 Supply	-	0.77 \$/kg (Praxair 2020)

3.3.3.3 Optimization of Ventilation and HRES Control

The objective functions used in the HRES system model acted to minimize the operating cost C_{op}^i and emissions GHG_{op}^i for each month, denoted by i, as shown below:

$$C_{op}^i = min\begin{Bmatrix} m_{CO_2}^i * C_{CO_2} + m_{H_2O}^i * C_{H_2O} + E_{Wood}^i * C_{Wood} \\ +E_{Prop}^i * C_{Prop} + E_{Elec}^i * C_{Elec} \end{Bmatrix} \quad (3.1)$$

$$GHG_{op}^i = min\{E_{Wood}^i * GHG_{Wood} + E_{Prop}^i * GHG_{Prop} + E_{Elec}^i * GHG_{Elec}\} \quad (3.2)$$

where, C refers to the unit cost, shown in Tables 2 and 3, of the various resources, m, as defined by equations (3.3)-(3.4), and energies, E, as defined by equations (3.5)-(3.8). Meanwhile, GHG represents the emissions factor of each energy source listed in Table 3.2. The consumption of each energy source or material resource is governed by the monthly demand, $Load$; such as heating, cooling, humidification, dehumidification, water supply, light use, or carbon dioxide supplementation, denoted with the subscripts $Heat$, $Cool$, H, DH, H_2O, $Lights$, and CO_2, respectively.

$$m_{CO_2}^i = Load_{CO_2}^i(ACH_i) \tag{3.3}$$

$$m_{H_2O}^i = Load_{H_2O,Hydroponics}^i + Load_{H_2O,Cold}^i + Load_{H_2O,Hot}^i \tag{3.4}$$

$$E_{Wood}^i = \frac{W_i * Load_{Heat}^i(ACH_i)}{80\%} \tag{3.5}$$

$$E_{Prop}^i = \frac{P_i * Load_{Heat}^i(ACH_i)}{80\%} + \frac{Load_{H_2O,Hot}^i}{92\%} \tag{3.6}$$

$$E_{Elec}^i = \frac{Load_{DH}(ACH_i)}{2.9\ L/kWh} + \frac{Load_H(ACH_i)}{1.2\ L/kWh} + E_{GSHP}^i + Load_{Lights} - E_{PV}^i \tag{3.7}$$

$$E_{GSHP}^i = \frac{G_i * Load_{Heat}^i(ACH_i)}{COP} + \frac{Load_{Cool}^i(ACH_i)}{EER} \tag{3.8}$$

As described earlier, some of these demands are dependent on the fresh air change rate, marked with ACH_i above. In addition, the three operating fractions of the heating systems (P = propane furnace, W = cordwood boiler, G = ground source heat pump in heating mode) distribute the heating requirement between the three systems. Together, these four parameters make up the decision variable x, defined by Equation (3.9), and subject to the constraint conditions shown in Equations (3.10)-(3.14).

$$x_i = (ACH_i, P_i, W_i, G_i)^T \tag{3.9}$$

$$0.1 < ACH_i < 7 \tag{3.10}$$

$$0 < P_i < P_{max}(ACH_i) \tag{3.11}$$

$$0 < W_i < W_{max}(ACH_i) \quad (3.12)$$

$$0 < G_i < G_{max}(ACH_i) \quad (3.13)$$

$$P_i + W_i + G_i = 1 \quad (3.14)$$

Constraint (3.10) ensures that the rate of fresh air change in the hydroponics space was limited by the minimum required ventilation flowrate for enclosed plant factories (Niu, Kozai, and Sabeh 2020), and the maximum air change rate achievable for each month. Similarly, as shown in Equations (3.11)-(3.13), the operating fractions of the heating systems represented a fraction of the monthly heating load. However, these were constrained by the maximum, max, operational capacity, as defined by the monthly loads at a specific ventilation rate; they are variable based on the value of ACH_i. And, P_i, W_i, and G_i must add up to a value of one, such that the heating load in Equation (3.14) is satisfied.

For this problem, the algorithm configuration was defined by a population size of 100, a crossover fraction of 0.8, a Pareto fraction of 0.35, and a convergence function tolerance of 1e-4. Additionally, Excel was the software of choice to serve as the modelling function file, which was opened as a server within the MATLAB script outlined in Figure 3.1.

3.3.4 Comparison with Traditional Import

3.3.4.4 Life Cycle Cost

The selection of costs to consider for life cycle cost (LCC) was taken from chapter 11 of the ASHRAE textbook (Howell 2017). The capital cost component of the analysis evaluated the sum of the costs of the individual units of the systems shown in Table 3.1. The capital cost of the GSHP system included only the main unit and the ground heat exchanger loop, based on a typical construction cost of 38 $/meter of bore length (Kavanaugh and Rafferty 2014). Additionally, the building already contained a propane furnace and a water heater, so these were not proposed as retrofit options. The boiler, humidifier, and dehumidifier were priced based on the manufacturers' suggested retail prices. The service lifetime analyzed was chosen to be 20 years, based on the average lifetime of many of the devices listed, as was seen in the literature (Howell 2017). A discounted cash flow analysis was performed to estimate the life cycle cost over the time period. A real discount rate of 4 % was used to estimate the cost in 2020 dollars as per other cases found in the literature (Panagiotidou, Aye, and Rismanchi 2020; Moges 2017; Krus 2004)

Annual operating costs were comprised of the total monthly operating costs from energy and resource consumption, as determined by the optimization procedure. Labour was estimated as $20 per hour, based on data for a typical Albertan farmer's wage (Government of Alberta 2020), for two part-time workers doing a total of 16 hours per week, for 50 weeks per year. More specifically, this labour was broken down into seed germination (2 hours), transplanting seedlings into towers (6 hours), harvesting (6 hours), and routine maintenance (2 hours). The hourly breakdown was averaged over a three-week growth cycle based on the system size as defined by the number of towers. Maintenance of the HRES was estimated as a 1 % factor of the capital cost of the systems, an estimation method found in the literature (Dai et al. 2020; Tu et al. 2020; Zhang et al. 2017). Any other costs were excluded, and it was assumed that no profit was made from the operation.

3.3.4.5 Food-Miles

For this case study, it was assumed that the point of origin is Napa, California, from which a 2780 km trip by road was taken to Fort McMurray by truck (Google Maps 2020). Since Fort Chipewyan has limited road access during warmer months of the year (Regional Municipality of Wood Buffalo 2020), it was assumed that from Fort McMurray the trip was completed by airfreight over a straight-lined distance of 222 km (Distance Calculator 2020). The trucking distance also included the 6 km from the regional Fort Chipewyan airport to the town centre. The emissions factors for combustion of fuel during transport by truck and airplane were taken as 0.25 ± 0.010 kg/tonne-km and 1.18 ± 0.0795 kg/tonne-km (Dyer et al. 2011), respectively. Due to the emphasis on transport by road, the emissions factor for fuel combustion in trucks included emissions from energy used for refrigeration, including inefficiency due to refrigerant leakage of 15 %, as found in the literature (Tassou, De-Lille, and Ge 2009).

3.4 Results and Discussion

3.4.1 Design Loads

Design load calculations for heating, cooling, dehumidification, and humidification are shown in Table 3.4. Comparing the required capacities suggested that the combination of all heating equipment could satisfy this worst-case load. Similarly, the GSHP, humidifier, and dehumidifier have sufficient full-load capacities to satisfy their respective loads.

Table 3.4. Design loads of the case study building

Heating	Cooling	Humidification	Dehumidification
87 kW	20 kW	26.8 L/h	27.8 L/h

3.4.2 Optimization

Table 3.5 shows the specific optimal values selected after the optimization process for each month. An example of the Pareto front of the objective space and the final hybrid function results is shown in Figure 3.4 for January; points identified with the 'Gen' label refer to solutions identified in the main genetic algorithm and points marked with the blue diamonds refer to the final solutions determined by the secondary solver. It is important to note that while the algorithm had generated more than one unique numerical solution for many months, due to the software's extremely small numerical scale, these points can be observed to be clustered around a relatively narrow range of values. In practicality, these correspond to one general solution with some small range of uncertainty due to rounding error. As such, the error bars seen in Figure 3.5-Figure 3.8 represent maximum and minimum values due to rounding error in air change (ACH) value from the optimization procedure.

Table 3.5. Optimization results of the HRES for the case study building

Month	ACH (1/h)	F	W	GH
1	2.79	0.00	1.00	0.00
2	2.86	0.00	1.00	0.00
3	2.93	0.00	1.00	0.00
4	3.41	0.00	0.39	0.61
5	7.00	0.00	0.00	1.00
6	5.24	0.00	0.00	1.00
7	4.81	0.00	0.00	1.00
8	3.89	0.00	0.00	1.00
9	5.92	0.00	1.00	0.00
10	4.22	0.00	1.00	0.00
11	3.09	0.00	1.00	0.00
12	2.85	0.00	1.00	0.00

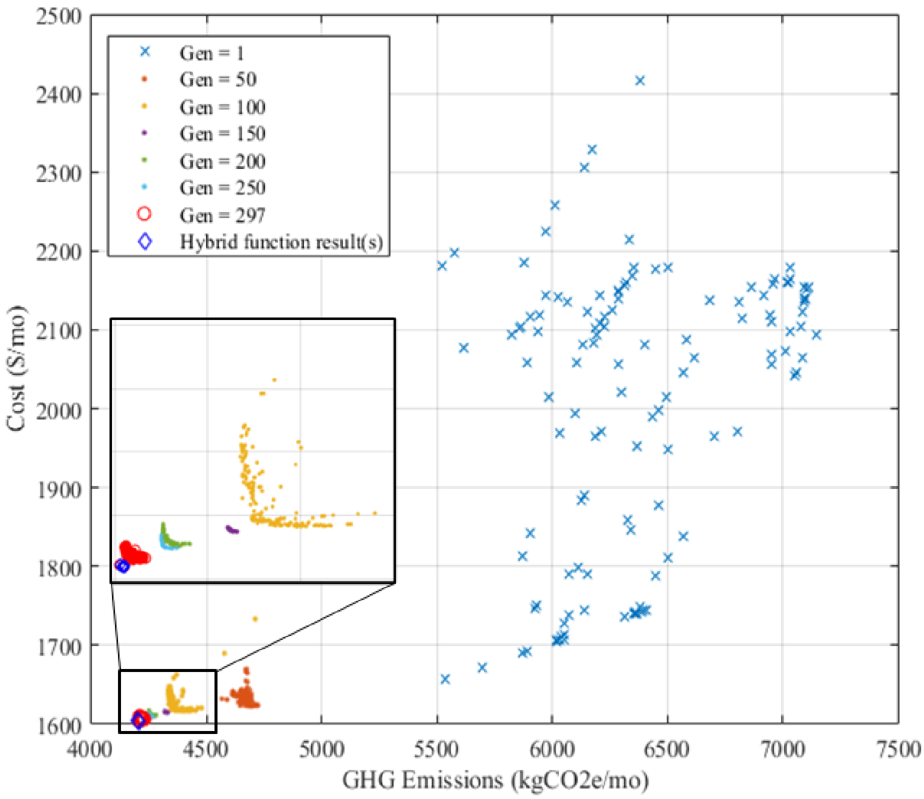


Figure 3.4. Pareto plot and generation plot of the optimization procedure of the operation of the case study facility for January.

At first glance, it is evident that ventilation flowrates (ACH) have been set much lower than what was used for design load sizing and the maximum values on the operational constraints were one for all months except for January-March and November-December for the GSHP, which were still mostly constraint-free because only the GSHP was limited to capacities close to 0.6. Since the actual operating conditions draw much lower heating demands, the selected systems do not need to operate in conjunction to meet the worst-case loads; each system can be used independently without limitations to fulfil the demands. Therefore, it is immediately evident that the heating system designated for backup, the propane furnace, was never necessary since the cordwood boiler could always handle the heating demand.

In the wintertime, between months 1-3 and 9-12, ventilation flowrate was relatively low and experienced a steady increase as the months got warmer. This could be attributed to heating energy demand (Figure 3.5) as a potential limitation for minimizing cost and emissions, especially since the low amount of solar PV generation (Figure 3.6) does not allow for a significant contribution from the GSHP, which would otherwise provide emissions-free and inexpensive heat. As a result, the entirety of the heating demand was transferred to the cordwood boiler because it was less emitting and cheaper than the furnace and the grid imported electricity required to run the heat pump; a phenomenon that has been found to apply electric space heating systems in certain Canadian regions (Udovichenko and Zhong 2019). On the other hand, the dry outdoor air in winter, brought in at these moderate flowrates, caused an appropriate moisture removal from the plants, leading to reduced additional humidity control.

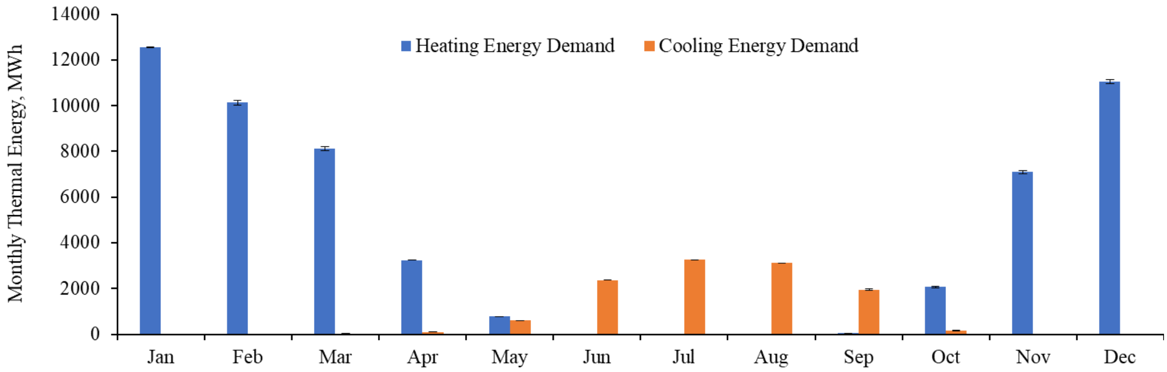


Figure 3.5. Monthly heating and cooling thermal energy transfer requirements for the case study facility with the optimized HRES.

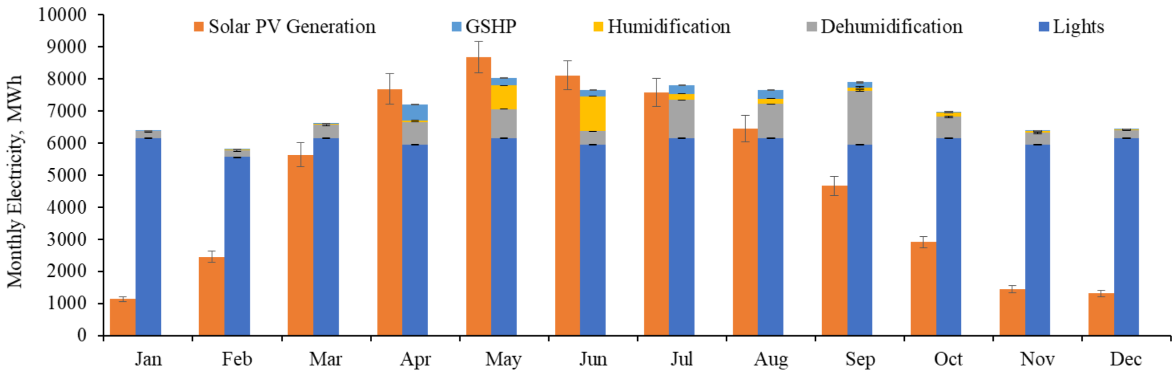


Figure 3.6. Monthly electricity requirements and solar PV generation breakdown for the case study facility with the optimized HRES.

Optimal values for ventilation flowrate appear to peak for the spring months (4-6). Due to the excess of solar PV generation, the GSHP could be used for both heating and cooling. Plus, additional imported electricity was not needed for humidity control either. So, the ventilation flowrate peaked to prioritize natural CO_2 supply in May. As a result, the humidity control systems were forced to operate more to control the humidity of the greater amount of incoming outdoor air, as seen in Figure 3.6.

During the summer months (7-8), the heating system operating fractions appear to have continued their trend of prioritizing the GSHP versus the boiler. However, given the fact that the heating loads were virtually non-existent, this ultimately did not matter. Instead, electricity consumption by the heat pump increased due to the need for cooling during this time. However, cooling was less of a priority as compared to dehumidification, as evident by the fact that the ACH values experienced a noticeable decrease during this time, and the fact that electricity usage for dehumidification is at its maximum for the late summer months. This would suggest that the dehumidification system performance outweighed the natural CO_2 supply and cooling system electricity consumption because of greater electricity consumption for dehumidification of warmer, more humid outdoor air being introduced (Figure 3.6). As a result, the summertime months that were most ideal for taking advantage of ambient outdoor CO_2; due to minimal heating loss from larger ventilation were instead the most reliant on supplemental CO_2 supply.

These behaviours ultimately influenced the monthly cost distribution, shown in Figure 3.7. Most notably, it is evident how greater solar PV generation during the early summer months aided in reducing the import of grid electricity. Especially in April - June, the facility operated with net-zero grid electricity consumption. However, Figure 3.6 also shows that lighting electricity usage was the most limiting factor, which could not be affected in this study. Since this facility is almost entirely opaque, increased summertime solar activity could not be used to reduce lighting electricity consumption. Furthermore, this design strategy would most surely affect energy consumption for heating during winter months, which are already the costliest months to operate the facility. Regardless, the electricity usage for humidity control is the highest monthly expense, which explains why the optimization procedures developed an operational strategy that varied so widely; as seen with the variation in ventilation flowrate, throughout the year in an attempt to utilize as much onsite PV generation and reduce electricity consumption for this process. Similarly, this trend is repeated in Figure 3.8, which showcases the breakdown of monthly GHG emissions. Once again, the electricity import was by far the largest emitting component. The presence of onsite solar PV generation in combination with a variable operational strategy made a significant reduction of GHG emissions due to the import of grid electricity during the summertime. As such, the cost and emissions for a full annual cycle were found to be $ 9,393 ± 8 and 24,099 ± 30 kg CO_2e, respectively.

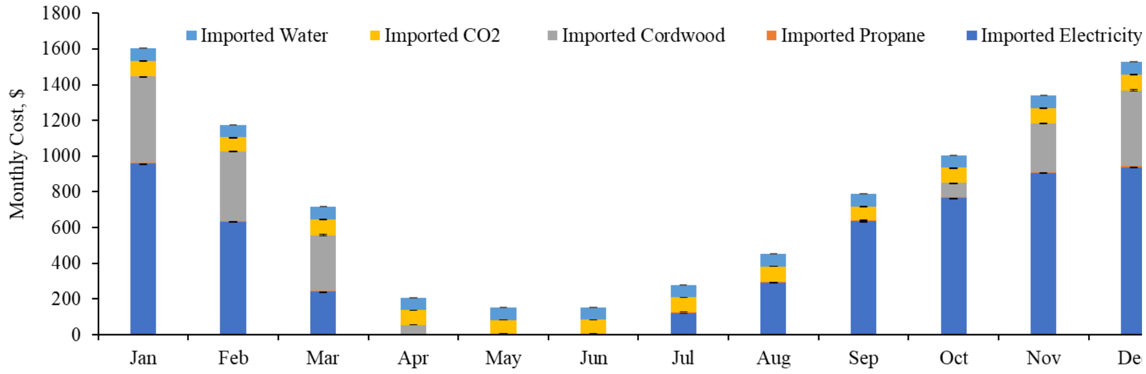


Figure 3.7. Monthly cost breakdown for the case study facility with the optimized HRES.

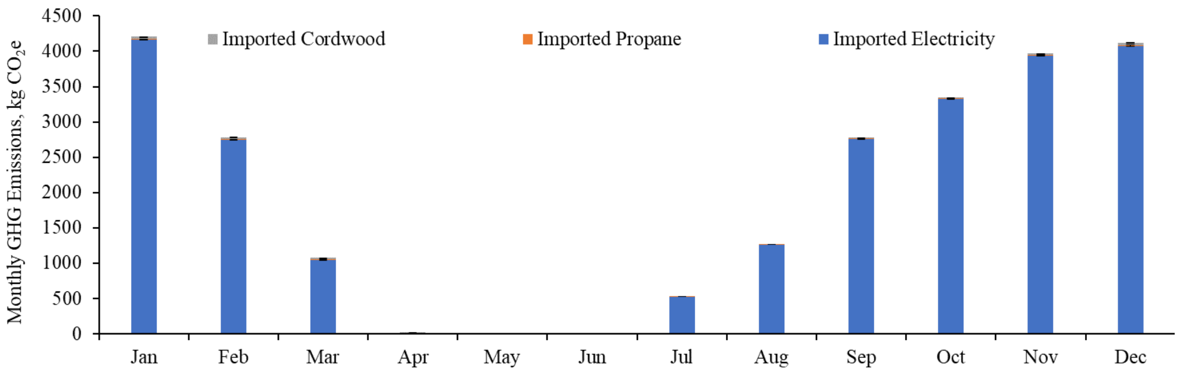


Figure 3.8. Monthly GHG emissions breakdown for the case study facility with the optimized HRES.

3.4.3 Life Cycle Cost

The life cycle cost of the proposed hydroponics facility is presented in Figure 3.9. Error bars for the proposed case represent maximum and minimum values due to rounding error in air change (ACH) value from optimization procedure. Meanwhile, error bars for the existing case represent price variation across 2018 – 2019.

Since the optimization results showed that the furnace was not used, it had zero maintenance costs. And most importantly, since it was already existing, there was no loss of capital. To be fair, it could have potentially been resold or salvaged, but this was not considered in this study. As a result, the life cycle cost of the hybrid renewable energy system over a 20-

year lifetime, including the hydroponics package, labour, maintenance, and operating resource and energy expenses came out to $ 755,259 ± 110, in present 2020 value. Based on the production cycle of three weeks, which yields 2.2 kg per vertical hydroponic tower, the entire system of 240 towers operating for 50 weeks per year was estimated to produce 8440 kg of Romaine lettuce (Table 3.1), and 168,820 kgs over the 20-year period. The unit cost of lettuce produced from this facility was therefore 4.47 ± 0.01 $/kg.

The existing local price of lettuce in the community was estimated as 5.86 ± 0.29 $/kg. No direct data were available for Fort Chipewyan, so it was based on data extrapolated for the closest city of Fort McMurray and considering the costs in Alberta's capital of Edmonton; approximately 4.28 ± 0.41 $/kg (Government of Alberta 2019; CBC News 2020). Comparing these two results, suggests that the proposed facility retrofit is competitive and could serve as a viable alternative to existing food prices caused by the long and limited supply chains. Although the savings are not tremendous, it is important to remember that this alternate method would also provide lettuce of better quality since it does not have to endure a long transport stage. A closer look at the breakdown of costs, shown in Figure 8, reveals that most of the expenses were attributed to capital and labour costs. Although the initial investment is relatively high, there is tremendous benefit from the operation of the optimized HRES; as witnessed by the reduced electricity and propane consumption, due to the solar PV onsite generation and the biomass boiler. This is especially important since fuel prices will continue to rise with carbon taxation. Moreover, Canada's north contains other communities that experience worse prices for vegetables, such as Kugaaruk (9.32 $/kg), Baker Lake (11.38 $/kg), Coral Harbour (8.52 $/kg), and Grise Fiord (7.97 $/kg) located in the territory of Nunavut (Nunavut Bureau of Statistics 2018), with which this type of facility could compete on an even greater scale.

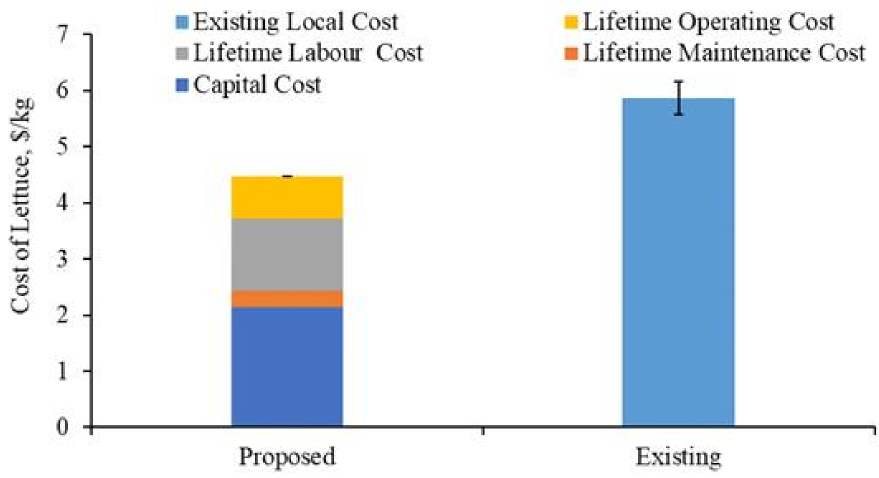


Figure 3.9. Life cycle cost breakdown for the case study facility with the optimized HRES.

3.4.4 Food-Miles Assessment

To deliver an annual equivalent quantity of lettuce (8440 kgs) to Fort Chipewyan from a traditional production location in southern USA, a total GHG emissions quantity of 8,180 ± 285 kg CO_2e would be produced during fuel combustion for transport. Meanwhile, local production in the facility would result in 24,099 ± 30 kgs CO_2e due to fuel and energy use. More specifically, GHG emissions per unit of lettuce were approximately three times higher for local production than through import; 2.86 ± 0.004 kgs CO_2e/kg hydroponic lettuce and 0.97 ± 0.034 kgs CO_2e/kg imported lettuce. Therefore, despite the investment in renewable energy technologies for the retrofitted facility, this form of local production is not an environmentally friendly alternative to traditional transport and would fail at displacing current transport emissions. As mentioned previously, this can be attributed to the tremendous emissions from local electricity consumption. Despite the fact that the onsite solar PV array helped to reduce imported electricity, as seen during the summer months, there was still a significant reliance on wintertime grid electricity for powering lighting and equipment. Given that current Fort Chipewyan electricity is reliant on diesel combustion, as are most of Canada's remote communities (Government of Canada 2011), this contributed to many GHG emissions.

3.4.5 A Note About Fort Chipewyan

Bearing in mind that this is an indigenous community, which lives under conditions that can be traced back to colonization, there are additional qualitative factors at play in this case that would require special treatment but are outside of the quantitative assessment presented here. A recently proposed and currently undergoing federally funded construction project aims to improve the local electric grid by imbuing it with a 25 % renewable electricity mix from a 2.2 MWh solar PV and storage array (ATCO 2020). This would mean that a reliable, low-maintenance displacement of diesel-fired electricity could reduce the cost and emissions of power without the need for the local solar array modelled here. Similarly, there is the possibility of cordwood having a much lower cost due to the logistics of the community's access to land and resources. The reliance on locally available fuels and resources can be beneficial in securing autonomy and community empowerment, which are concepts that ultimately lie outside of the authors' expertise. Lastly, it is important to remember that Canada's northern regions do not see the same emphasis on emissions mitigation due to the overall low physical presence by such communities in the vast arctic landscape as compared with the dense metropolises lined along the southern border. So, ultimately, the unique benefits gained from a renewable energy-assisted hybrid space heating system certainly outweigh the increase in greenhouse gas emissions.

3.5 Limitations

The analysis of the case study was simplified in several ways. Although care was taken to account for all climatic effects, wind speed and solar irradiance on opaque surfaces were neglected. During the design of the HRES, distribution equipment, such as ductwork, fans, pumps, CO_2 injection, sensors, and other equipment required for adequate climate control, were not within the scope of the analysis. For the modelling of the HRES on an annual operating basis, the emissions estimation was simplified by only considering GHG emissions expressed as equivalent CO_2 emissions. As such, biomass combustion was modelled under the assumption that it is carbon neutral when the wood is regrown sustainably (Evans, Strezov, and Evans 2010; US EPA 2003; Environment and Climate Change Canada 2019). However, if a more thorough environmental impact assessment were performed, which was not within the scope of the study, land-use change and deforestation effects, as well as particle matter (PM) and volatile organic compound (VOC) emissions, would be considered (Geng et al. 2019). Other factors excluded in the environmental analysis were packaging and waste, disposal of the system, and transport of fuel and resources. In other words, since this analysis was not a full life-cycle assessment (LCA), many stages of the whole production process were neglected. The same was true for the traditional production case in the southern USA; the use of fertilizer or pesticides and machinery were not considered. Although refrigerant leakage was considered for the effect of transport emissions, the actual environmental impact from refrigerant leakage was excluded because only combustion emissions were considered. For the financial analysis, any insurance, administrative, or disposal costs were not considered, and sensitivity analysis on any life cycle cost components was excluded from the scope. Export of electricity was not modelled, since there was no certainty that a net-metered connection would be realistic in this case. Plus, a monthly time basis was not detailed enough to accurately model the generation versus demand relationship anyway. Therefore, the analysis was limited to the case of 'net-zero' performance. Lastly, any wastewater fees were excluded as it was assumed that the water drainage from the hydroponics system was captured and reused in the community for local composting or outdoor plot farms.

3.6 Conclusion

Given the harsh conditions of northern climates, year-round horticulture can only be achieved with adequate environment control in enclosed spaces. The use of a hybrid energy system with renewable resources can help achieve efficient and sustainable space heating and climate control. As such, this study has presented a detailed design and optimization protocol for retrofitting light industrial buildings in northern Canada with renewable energy-assisted hydroponics systems. Heating, cooling, humidity control, and sufficient levels of airborne carbon are all critical factors that must be accounted for during the design of the retrofit operation. Furthermore, once the requirements are determined, it is beneficial to explore renewable energy options to aim for sustainable operation, and chosen systems must be sized according to appropriate design load evaluation procedures using in the building science industry. Depending on how complex the final system arrangement is, the operational strategy may not be trivial, and therefore, optimization by way of numerical methods could be necessary. Regardless, the proposed retrofitted facility should be compared with traditional food production methods in terms of finances and environmental impact to determine feasibility. Conversely, it is important to remember that this quantitative assessment does not have the capability to capture the decision-making values associated with the historical exploitation of northern communities due to colonization.

This procedure was performed on a 270 m^2 case study building in Fort Chipewyan, Alberta. A hybrid renewable energy system consisting of a ground-source heat pump, biomass boiler, propane furnace, solar photovoltaic array, humidifier, dehumidifier, water heater, and an exhaust fan was proposed for the building. As such, this study included the demonstration of the use of a genetic algorithm coupled with a goal attainment solver to optimize a multi-objective problem. The objectives, in this case, were operating costs and greenhouse gas emissions, which were selected to ensure that the lettuce produced from the indoor commercial farm would be a viable alternative to traditional lettuce import. For economic analysis, life cycle cost was an adequate assessment that considered lifetime expenses and food production quantity and was compared with existing prices for the same food type. An environmental impact assessment was limited to an import displacement analysis that compared operating facility emissions against the transport of an equivalent quantity of food. It was found that although the optimized hybrid renewable energy system has the potential to improve annual operating performance, this specific facility design is only feasible in the realm of cost savings for its proposed function, with an average lettuce cost of 4.47 ± 0.01 \$/kg from the proposed facility. Meanwhile, the existing price of the crop, available in the local store, was estimated as 5.86 ± 0.29 \$/kg, which would make local production in the facility a competitive alternative. However, its emissions performance is unfavourable due to an excessively high reliance on imported, diesel-generated electricity. The facility would result in 2.86 ± 0.004 kilograms of CO_2e per kilogram of lettuce produced, as compared with 0.97 ± 0.034 kilograms of CO_2e per kilogram of imported lettuce, which would effectively triple the amount of greenhouse gases emitted by local production. Regardless, this protocol has proved to be a useful method of planning retrofit projects in northern Canada that experience food supply chain disruptions, such as those brought on by the recent state of the COVID-19 pandemic.

CHAPTER 4: Conclusion and Future Work

4.1 Conclusion

In Canada, building systems could benefit from using more efficient technologies to reduce fossil-fuels for heating and the corresponding greenhouse gas emissions, which would help reduce overall national emissions given how reliant Canadians are on their space heating systems.

The use of two or more energy systems, which harness different - and preferably renewable - energy sources, in a 'hybrid system' is an idea that has received more attention from the scientific community in the last decade. One of its main strengths is that hybrid systems can achieve improved performance by capturing the strengths of multiple devices and thereby avoiding the weaknesses. It is noted that this idea does not require the development of new technology or devices, but this can be achieved with a combination of market-available products. However, there has been a noticeable lack of a thorough review of the potential of such systems in the Canadian climate. Thus, this research focused on filling in the gaps by performing a techno-economic analysis of a hybrid energy system across six different locations in Canada and two different types of buildings.

In the first part, the use of an air source heat pump-gas furnace hybrid system in the single-family, detached homes of five cities (Vancouver, Toronto, Montreal, Edmonton, Yellowknife) was evaluated. Over 10,000 homes, ranging in size, vintage, and location, were analyzed, and three different commercially available heat pump models were simulated. It was determined that cities like Vancouver, Toronto, and Montreal are most ideal for the application of such a hybrid system, and for multiple reasons: (1) the climate in these coastal regions is relatively mild in comparison to the inland cities of Edmonton and Yellowknife, which makes the heat pumps much more capable of operating for significant portions of the heating season without technical difficulties; (2) the electricity consumed by the heat pumps comes from largely renewable generating methods in these regions, which acts as an effective displacement of fossil fuel combustion in household furnace heating. However, both of these realities are inversed in Edmonton and Yellowknife. Not only are the heat pumps less reliable during the winter, making supplemental furnace heating that much more necessary, but also the cost and emissions performance of the heat pump is worse than the furnace anyway. Therefore, the application of a hybrid system in certain Canadian homes would be completely counterintuitive. However, considering the population density of these cities shows that the three coastal locations can impact emissions mitigation due to the number of homes in these regions. Adopting a hybrid system in single-family detached homes of Toronto and Montreal could reduce municipal emissions by 54 % amongst the five communities combined. Meanwhile, the relatively small community of Yellowknife has little effect on global emissions, with a potential to reduce carbon dioxide equivalent pollution by a mere 0.14 %. Furthermore, the opposite would occur for Edmonton, with a potential collective increase in greenhouse gases emitted by 5 % of the five cities. So, while it can clearly help reduce the impact of fossil fuel heating systems in some homes, the application of an air source heat pump combined with a conventional gas furnace is highly case-specific because so much is dependent on the local infrastructure of available energy sources.

The second study focused on applying a similar logic to a different set of circumstances: non-residential space heating in a rural location. It was proposed that a hybrid energy system can be an effective way to make small-scale indoor plant farming more sustainable in northern rural communities, which have historically experienced challenges with access to fresh and cost-effective nutrition options. A hybrid system consisting of a ground-source heat pump, a biomass boiler, and a propane furnace and supported by a solar PV array was proposed for a small retrofitted industrial building in Fort Chipewyan, Alberta. As before, the case was evaluated on cost and emissions terms. In short, it was found that this facility has the potential to compete with or displace the import of leafy greens, given that the life cycle cost of 4.47 ± 0.01 \$/kg of lettuce is noticeably lower than the cost of purchasing imported lettuce in the local store of 5.86 ± 0.29 \$/kg. However, in terms of emissions, the case study building is predicted to experience the same issues that Edmonton and Yellowknife would face when adopting residential ASHP technology. Operation of the facility results in 2.86 ± 0.004 kilograms of CO_2e per kilogram of lettuce produced. The reliance on diesel-generated electricity would increase overall emissions of the location by three times; emissions from the transport of lettuce were estimated at 0.97 ± 0.034 kilograms of CO_2e per kilogram of lettuce. On the other hand, the increase in emissions of this small rural town is ultimately minuscule when compared with the astronomical pollution created by the major provincial capitals. Although not an optimal choice for space heating from an emissions perspective, the hybrid system can provide a sustainable alternative economically for providing rural communities with better nutrition options. This is a cost feasible option, powered by energy options that are locally available and renewable, which embraces the philosophy of the people it provides for by supporting local employment and autonomy. This shows that the use of a hybrid energy system has other benefits when it comes to rural northern communities apart from climate change mitigation.

This thesis implies that the feasibility of such systems is highly case dependent, and that device selection for the hybrid energy system must take into consideration the resources available to the region in question. To aid help with this problem, a secondary accomplishment of this research was the development of modelling and design frameworks for the application of hybrid systems using numerical methods in both studies. A set of support vector regression models applicable to existing single detached homes across Canada was developed to aid with housing parameter estimation, which is crucial in heating load analysis on a large numerical scale. These models were verified with a case study home, and acceptable accuracy was established. Additionally, this thesis has presented a framework for retrofitting old industrial spaces into hydroponics farming facilities powered with hybrid energy systems, optimized with a multi-objective genetic algorithm. This protocol emphasizes the importance of proper load estimation based on crop requirements to help select heating, ventilation, and cooling equipment. Meanwhile, the custom genetic algorithm script is useful for finding the optimal operating strategy of the various devices in an efficient and precise manner.

4.2 Future Work

Future work in this area of research would involve addressing the various limitations outlined in the two previous chapters. (1) Validation and improvement of the model and design framework could be a tremendous addition to this narrative. More specifically, the support vector regression model developed for the prediction of architectural housing characteristics (chapter 2) was only validated using one case study home. Furthermore, the performance results were generated based on the predictions for the dataset that was used to develop the models, instead of on the original data. Although this introduced some errors, the purpose was to showcase how the models can be used in heating load analysis. Therefore, more data to replicate and test this procedure could be helpful. Similarly, the design framework for retrofit of industrial buildings into controlled-environment agriculture facilities (chapter 3) was applied to a single case study, so further testing on other potential facilities in northern Canada would be invaluable. (2) Further improvements can be made to the economic and greenhouse gas emissions analysis performed in both studies presented here. In chapter 2, a life cycle impact assessment and a life cycle cost assessment can be performed on the ASHP-furnace hybrid system to expand on the operating cost and emissions results, which would provide a more comprehensive feasibility analysis of the proposed system. Similarly, in chapter 3, a life cycle impact assessment of the proposed local production method and the traditional imported method was not considered. However, such analysis would require careful consideration of every stage of production in both cases, and when completed, could complement the life cycle cost assessment presented here. (3) In line with this logic, a sensitivity and uncertainty analysis would be essential for determining the limiting factors of the proposed hybrid systems in life cycle analysis. Especially in chapter 3, where parameters such as electricity price, wood fuel price, solar availability, indoor temperature and humidity could wildly impact the optimal operating strategy, and therefore, the final operating annual cost. As such, the inclusion of a sensitivity and uncertainty analysis would require careful integration with the optimization algorithm, and the final model could have serious implications for predicting the feasibility of hybrid renewable energy systems in rural communities. (4) Lastly, future research could include general improvements to analysis methods such as the inclusion of other climatic effects and distribution systems. Especially since this research considers multiple systems operating simultaneously, a look into the technology that would be required to physically make this happen could be of great benefit. Alternatively, this analysis can be performed with more thorough energy modelling software, which would integrate well with the support vector regression and genetic algorithm optimization models developed here.

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