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RESEARCH ARTICLE

Residential Smart Dual Fuel Switching System (SDFSS) for Simultaneous Reduction of Energy Cost and GHG Emissions

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Abstract

As technology shifts toward more environmentally friendly alternatives, future heating, ventilation, and air conditioning (HVAC) systems in Canada are expected to transition away from natural gas heating to electrical heating. However, a relatively rapid large-scale shift from natural gas to electricity will pose issues for utilities and consumers. In order to smooth the transition from a natural gas-dominated space heating infrastructure to an electrically powered heat pump, an intermediary solution is needed to allow society to transition efficiently and cost-effectively. The proposed intermediary technology integrates a natural gas furnace (NGF) with an air source heat pump (ASHP) and utilises a smart dual fuel switching system (SDFSS) controller. In this study, an SDFSS is implemented in residential houses to reduce greenhouse gas (GHG) emissions and overall operational costs. The heat-mapping analysis of the hybrid system with the SDFSS controller shows a clear seasonal shift in ASHP operation. During milder winter months, such as April, the ASHP operates significantly more, accounting for 57% of the total hours (414). ASHP usage drops dramatically in January, when it runs for only 2% of the hours (12 hours) due to higher operating costs in extremely cold conditions. This indicates that while the ASHP is a cost-effective option during moderate weather, the NGF is the preferred choice for the tested house during periods of extreme cold. The study also highlights that the SDFSS has the potential to reduce operational costs by up to 33% compared to the single-variable switching system.

Keywords Net Zero Energy Home (NZEH) · Energy Transition · Residential Space Heating · Greenhouse Gas Emission · Air Source Heat Pump (ASHP) · Natural Gas Furnace (NGF) · Hybrid Heating · Smart Dual Fuel Switching System (SDFSS)

1. Introduction

The residential sector is the third largest source of greenhouse gas (GHG) emissions in Canada, accounting for 13% of the GHG emissions in 2016 [1]. Within the residential sector, space heating constitutes about 60% of total energy use in Canadian households. The most significant reduction in emissions can be achieved by shifting from fossil fuel-based natural gas furnaces (NGF), used in more than half of households, to an electric heating system. This shift will change electricity demand and may affect the technical and economic aspects of the utility grid. From a technical point of view, the increase in overall electricity demand puts a larger stress on the electrical grid infrastructure whilst decreasing the demand for natural gas [2, 3]. From an economic perspective, this increase in demand will also require extra supply by additional power plants, which will increase the wholesale electricity prices. In terms of GHG emissions, a full electric system does not necessarily mean a zero-emission if the existing and added generation capacity is powered by fossil fuel.

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The Ontario electrical grid transitioned away from coal in 2014, replacing it completely with nuclear, hydroelectric, natural gas, and other non-hydro renewable sources [4]. Ontario's grid is relatively clean compared to the previous coal-fired plants. With this recent change, electricity is mostly an environmentally friendly energy alternative for residential heating systems.

Natural gas is the dominant fuel for space heating in Canada, and its combustion is a significant source of GHG emissions in this sector [5]. The Canadian Government aims to reduce GHG emissions by 80% by 2050. Canada has made strides in adopting clean technologies; however, to achieve emissions targets, a more aggressive approach across sectors is recommended [5].

A prediction by the Independent Electricity System Operator (IESO) of Ontario indicated an expected rise in energy demand across various sectors, including buildings [2, 3]. In 2019, the Canadian Government introduced the Greenhouse Gas Pollution Pricing Act, which imposes a carbon tax of $20 per tonne of CO_2 to combat climate change [6]. So, it is anticipated that natural gas will become less economical, besides its environmental impacts. The change in natural gas pricing may motivate the community to conserve energy and adopt cleaner technologies.

There are several methods to reduce energy consumption in buildings. A widely used approach for building homes involves adhering to energy guidelines established by various building codes, including the Ontario Building Code, R-2000, and Energy Star standards. These guidelines ensure that homes are constructed with energy efficiency in mind, promoting sustainability and reducing energy consumption [7-9]. On the other hand, a Net Zero Energy Home (NZEH) is a design that produces as much energy as it consumes over the course of a year [10]. According to Natural Resources Canada (NRCan), over 64% of Canada's heating demand is met using natural gas or heating oil [11]. To transition buildings towards NZEH, it is essential to develop technologies that gradually shift from fossil fuel-dependent heating systems to more environmentally friendly electrical systems.

A substantial body of research has examined emerging technologies that would be considered transitional [12-14]. The air source heat pumps (ASHPs) as a clean alternative to NGF in areas dominated by clean electricity. The emphasis on ASHPs is largely due to their high efficiency; they can generate many times more heat than the amount of electricity they consume. However, the performance of ASHPs declines significantly in extreme cold weather. Therefore, a combined heating system that utilises both natural gas and electricity could be a more viable approach in the transitioning phase than relying solely on NGF or ASHP.

An advanced controller for an integrated system is essential for optimising the energy and environmental performance of a hybrid system. One study investigated several types of switching systems, including Smart Dual Fuel Switching Systems, Load Shifting, and Load Shifting Smart Dual Fuel Switching Systems [15]. This load shifting technology can be seen as a transitional scheme for moving from a natural gas-dominated heating system to a more environmentally friendly, electricity-based system powered by clean electricity.

Most studies on advanced controllers have either not been experimentally verified or have not been conducted in extremely cold climates, such as those in Canada [16-19]. Additionally, the current literature does not consider changes in policies, such as time-of-use (TOU) electricity pricing [20], carbon pricing [21], and how these price changes may impact the effectiveness of control systems. A major challenge of hybrid heating systems is the need for an advanced multivariable control mechanism. Currently, the system employs a single-variable control that only considers outdoor air temperature for switching heating equipment. To enhance the viability of a hybrid heating system, it is crucial to consider additional variables such as TOU energy costs, weather forecasts, carbon price, and component efficiency.

This study aims to fill this research gap by thoroughly studying the impact of a smart dual fuel switching system (SDFSS) on the energy performance of a hybrid heating system. The study creates a validated model of SDFSS. The validated model demonstrated the flexibility of the SDFSS through several sensitivity analyses. This study addresses the key questions of the effectiveness of SDFSS controllers in cold climates. It also aims to evaluate how these systems perform under future high carbon pricing schemes, focusing on their impact on GHG gas emissions and the economy.

The tested and modelled hybrid system with SDFSS controller serves as a transitional technology, helping to bridge the gap between a conventional NGF and a more environmentally friendly electric alternative (ASHP). The study aims to demonstrate the advantages of using this transitional technology compared to relying solely on the manufacturer's control system or a conventional NGF for heating.

2. Methodology

The study uses a methodology that starts with a literature review to understand the challenges of adopting ASHPs in Canadian conditions. It aims to identify gaps, particularly concerning their performance in extreme weather and the economic factors influenced by carbon pricing and the province-specific TOU electricity pricing. The challenges associated with natural gas heating systems are also noted, including their inefficiency and carbon footprint. Baseline data on the selected NZEH's energy consumption, heating sources, region-specific GHG emission factors, and TOU electricity pricing are collected. Next, an experimental setup is developed, and the hybrid system with an SDFSS controller is tested. Subsequently, energy models are created, validated, and applied to perform parametric sensitivity analyses under varying conditions and to evaluate the financial and environmental implications of the transition. The methodology illustrates how a hybrid heating system with an SDFSS controller, utilising multivariable optimisation, can assist Canadian homes in selecting the most cost-effective and low-carbon heating option. A flow diagram of the adopted research methodology is shown in Figure 1.

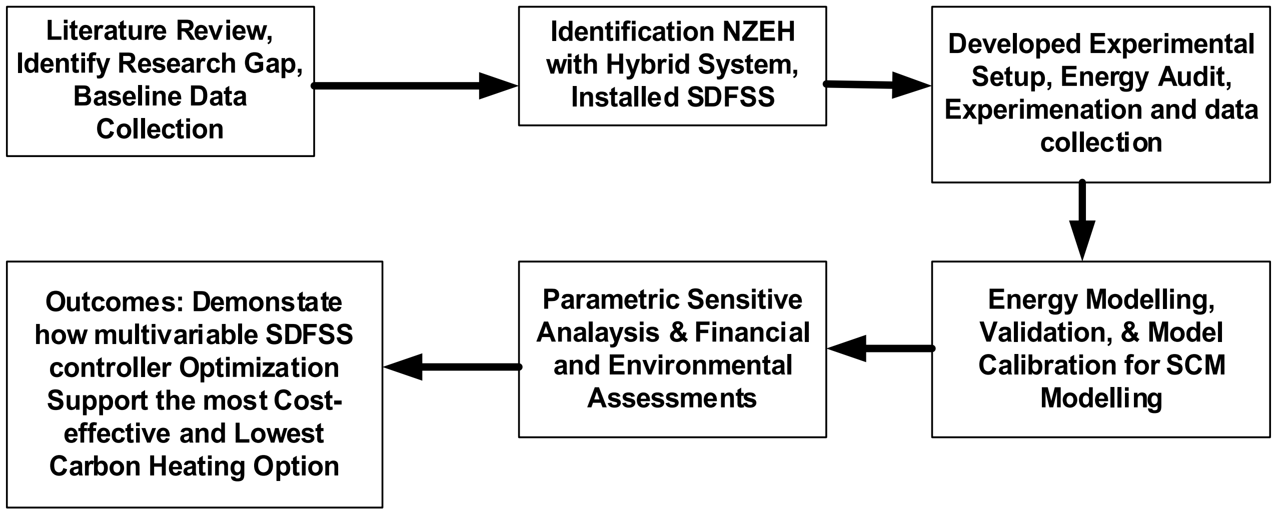

Figure 1. Flowchart outlining the research methodology

The tested house was designed and built as a NZEH with a floor area of 2,586 m^2 in Strathroy, Ontario, Canada (Fig. 2). This house was fitted with both an ASHP (rated at 3.3 Coefficient of Performance (COP) and 21 SEER) and an efficient NGF (89% efficiency) for space heating and cooling. To offset electricity consumption, a roof-mounted photovoltaic (PV) system (8.745 kWp installed capacity) was installed. In addition, an enthalpy recovery ventilation system (ERV) with a sensible recovery efficiency of 75% at 0 °C, and a drain water heat recovery system (DWHR) rated at 53.3% efficiency were also used. For domestic water heating, a high-efficiency instantaneous water heater was installed.

The SDFSS is an advanced controller developed at Toronto Metropolitan University for hybrid natural gas and electric heat pump systems [14, 15]. It utilises real-time data on electricity prices, outdoor temperatures, and the performance parameters of heat pumps and NGF to determine the most appropriate heating fuel and system for a specific time of day.

The two simulation models, the Transient System Simulation Tool (TRNSYS) [22] and Switching Control Model (SCM), are used to assess the technical and economic performance of the hybrid system with SDFSS controller for a selected house and major cities in Ontario. These models evaluated the techno-economic and environmental performance of the hybrid system with an SDFSS controller for the NZEH in Strathroy.

Figure 2. The front and side views of Strathroy's Net Zero Energy House

2.1. Simulation Models

Two computer models are developed to simulate the natural gas consumption, electricity consumption, operating cost, and GHG emission for six different heating scenarios. The selected scenarios are (1) SDFSS controller, (2) manufacturer fuel switching at -5 °C, (3) manufacturer fuel switching at -15 °C, (4) natural gas-fired heating only, (5) 100% electricity resistance baseboard only, and (6) ASHP with 100% resistance backup with -15 °C manufacturer switching.

The heating demand is first simulated with the TRNSYS building model. Afterwards, the overall results for each scenario are simulated with SCM. For the sensitivity analysis, the model is re-initiated with each of the changed parameters. In the post analysis, the results of the different scenarios and sensitivity analyses are compared. The energy cost savings and GHG emission reduction compared to the natural gas-fired heating-only system.

2.1.1. TRNSYS building model The TRNSYS building model is a simulation model that calculates the heating demand of the house for a given set of parameters. The house specifications were obtained from the builder's specifications. Additionally, a full ASHRAE level II energy audit was performed on the house. The energy audit included a verification of envelope dimensions, plug load audit, lighting audit, combustion test and blower door depressurisation test. This information was collected, analysed, and used to construct the benchmark TRNSYS model.

A CAD simulation model was created using TRNSYS-SketchUp based on detailed building information, including dimensions, infiltration rates, wall insulation, window characteristics, and occupant behaviour. Additional modules were added to simulate the surrounding environment and building components. The TRNSYS model primarily simulated annual space heating demand and was calibrated with experimental data. The output results serve as input for SCM modelling.

The tests were performed to validate the effects of different switching systems. A data acquisition (DAQ) system was built based on the required parameters and requirements of the SDFSS. The data were collected every two minutes, and for analysis, they were consolidated to hourly intervals. The NGF operation was tested for two weeks, followed by an additional two weeks of standard manufacturer heat pump switching tests.

The sensors with error ranges installed at the house are listed in Table 1. The error was calculated as the difference between the experimental heating demand and the calibrated TRNSYS model regression, using the root-mean-square error (RMSE) method. Using the regression model, hourly energy consumption was simulated for the chosen temperature range. Using these RMSE values, the calibrated linear model was then used in the SCM modelling.

Table 1. List of Sensors

Electricity Consumption/Generation Sensors	Natural Gas Consumption Sensors	Indoor Parameters	Outdoor Parameters
ASHP (W) (0.5% Error)	Natural gas-fired furnace (m^3) (0.05m³ Drive)	Main floor temperature (°C) (±0.3°C)	Ambient outdoor air temperature (°C) (±0.3°C)
Air handling unit (W) (0.5% Error)	Instantaneous domestic hot water boiler (m^3) (0.05m³ Drive)	Basement temperature (°C) (±0.5°C)	Global horizontal radiation (W/m^2) (±5%)
Enthalpy recovery ventilator (W) (0.5% Error)	Whole house natural gas consumption (m^3) (0.05m³ Drive)	Supply air temperature (°C) (±1.0°C)	
Whole house consumption (W) (1% Error)		Return air temperature (°C) (±1.0°C)	
Photovoltaic system (W) (0.5% error)		Main floor relative humidity (%) (±2%)	
		Basement relative humidity (%) (±1%)	

2.1.2. Switching Control Model (SCM) The SCM is an Excel-based model for different space heating system scenarios. The model simulated the effects of the heating system for 2018 across six scenarios (Section 2.1). A model was developed for each of the different heating system scenarios to control the fuel switching. The SDFSS mathematical and optimisation models determine the optimal switching point for a dual fuel system. Since the mathematical model relies on various input parameters, these parameters are illustrated and presented as well. One key parameter that needs to be estimated and calculated is the hourly GHG emissions associated with electricity generation in Ontario. The following equations outline the costs involved: Equation 1 demonstrates the hourly electricity consumption cost if the residential heating system operates in ASHP mode, while Equation 2 details the hourly cost for natural gas consumption if the NGF operates independently.

$$\boldsymbol{e_c = E \times P_e} \tag{1}$$

Where: $e_c = Hourly\ cost\ of\ electricity$ (\$)
$E = ASHP\ electricity\ consumption\ (kWh)$
$P_e = Marginal\ pricing\ of\ electricity\ per\ kWh\ (\$/kWh)$

$$\boldsymbol{n_c = N \times P_n} \tag{2}$$

Where: $n_c = Hourly\ cost\ of\ natural\ gas$ (\$)
$N = Furnace\ natural\ gas\ consumption\ (m^3)$
$P_n = Marginal\ price\ of\ natural\ gas\ per\ m^3 (\$/m^3)$

The ASHP electricity consumption and the furnace natural gas consumption can be derived as follows:

$$\boldsymbol{E = \frac{H}{COP}} \tag{3}$$

Where: $H = Space\ heating\ demand\ (kWh)$
$COP = Coefficient\ of\ performance\ for\ ASHP$

$$\boldsymbol{N = \frac{H}{U_n} \times \frac{1}{\eta_n}} \tag{4}$$

Where: $U_n = Natural\ gas\ energy\ density\ (kW/m^3)$
$\eta_n = Efficiency\ of\ natural\ gas\ furnace$ (%)

The two costs (natural gas and electricity) were simulated and compared on an hourly basis. The following constraint in Equation 5 must be satisfied for the HVAC system to use the ASHP heating, as the cost would be lower than the NGF. This inequality constraint incorporates Equations 1 to 4.

$$\frac{H}{COP} \times P_e < \frac{H}{U_n} \times \frac{1}{\eta_n} \times P_n \quad (5)$$

Depending on the fuel selected, the hourly energy cost will be different. To calculate the total electricity consumption, the hourly cost for both electricity and natural gas is summed together. The total annual operational cost is described as follows:

$$C_T = \sum e_e + \sum n_e \quad (6)$$

Where: $C_T = Total\ annual\ operating\ cost$
$e_e = Effective\ electricity\ cost$
$n_e = Effective\ natural\ gas\ cost$

The effective electricity cost, e_e, is the hourly cost of electricity during the hours the ASHP was used. The effective hourly cost of natural gas n_e is the hourly cost of natural gas when used. The total cost C_T is the summation of all the effective costs.

Since this study also takes into account the hourly GHG emissions, this calculation is also performed similarly to the operational costs. Equation 7 calculates the hourly GHG emission for the natural gas consumption. Similarly, Equation 8 calculates the hourly GHG emission for electricity consumption.

$$GHG_n = D_{NG} \times N \quad (7)$$

Where: $GHG_n = Hourly\ GHG\ emission\ from\ natural\ gas\ consumption\ (kg)$
$D_{NG} = GHG\ density\ for\ natural\ gas\ (kg/m^3)$

$$GHG_e = D_E \times E \quad (8)$$

Where: $GHG_e = Hourly\ GHG\ emission\ from\ electricity\ consumption\ (kg)$
$D_E = GHG\ density\ for\ electricity\ consumption\ (kg/kWh)$

If the ASHP is being used instead of the NGF, there will be no GHG emissions from the consumption of natural gas. Similarly, if the NGF is used instead of the ASHP, the GHG emissions from the consumption of electricity will be zero.

Equation 9 calculates the total GHG emissions from both the natural gas and electricity consumption.

$$GHG_{Total} = \sum GHG_n + \sum GHG_e \quad (9)$$

Where: $GHG_{Total} = Total\ Greenhouse\ Gas\ Emission$

The total GHG emissions are also calculated for the individual fuel sources to provide a comparison of the different options used in this study.

2.1.3. Combining the models The TRNSYS building models and SCMs are used in tandem to simulate the effects of a building using different HVAC systems. This involves running the models sequentially using the same input parameters; the output of the TRNSYS building model is an additional input for the SCM. An extra step is required to organise the output data from the TRNSYS building model for the SCM. The TRNSYS model generates the heating demand for the benchmark building, which serves as an input for the SCM mathematical model.

2.2. Sensitivity analysis

Three sensitivity analyses are conducted on the benchmark model to assess the impacts of altering key parameters. The analyses focus on the following factors: (1) the inclusion of carbon pricing mechanisms, (2) the selection of different cities in Ontario, Canada, and (3) TOU electricity pricing.

The sensitive analysis investigates the impacts of these parameters on the overall annual space heating energy consumption, associated cost and GHG emissions. These sensitivity analyses highlight the flexibility of the SDFSS and its performance across different parameter settings. The natural gas consumption, electricity consumption, operating cost and GHG emission of each scenario are calculated and summarised for comparison.

2.2.1. Carbon pricing In order to account for the future carbon pricing imposed by the government, this sensitivity analysis on carbon pricing was included to take into account future additional charges for natural gas from 2019-2022. According to the Canadian Department of Finance, the year 2019 had a carbon pricing inclusion of 3.91¢/m^3 natural gas consumed [21, 23]. There is an annual carbon pricing of \$10/tonne until the carbon pricing reaches \$50/tonne in 2022. The cost breakdown is shown in Table 2 and has been incorporated into the analysis.

Table 2. Canadian federal carbon pricing breakdown

	Year				
	2018	**2019**	**2020**	**2021**	**2022**
Carbon Pricing (\$/tonne)	0	20	30	40	50
Carbon Pricing (\$/m^3)	0	0.0391	0.0587	0.0783	0.0979

2.2.2. Different Canadian cities In addition to Strathroy, four cities in Ontario (Toronto, Ottawa, Windsor, and Thunder Bay) were selected for the sensitivity analysis and site-specific performance comparison. Due to varied local conditions in different regions, the weather and the electricity and natural gas prices differ from region to region [24-28]. Two separate scenarios within this sensitivity analysis are explored: (1) ignoring fuel pricing for different regions, and (2) replacing the fuel pricing to match the respective region. The first scenario aims to show the impact of site-specific outdoor temperatures. The second scenario aims to show the real effects when the fuel pricing difference is accounted for.

2.2.3. Time-of-use (TOU) pricing The Ontario government introduced TOU pricing for electricity to encourage end users to consume electricity during off-peak hours and minimise demand during peak hours [20]. This will incentivise residential buildings to use electricity as a fuel source for space heating by reducing the operating cost during the night.

2.3. Overall Process Flow

Figure 3 presents the flow chart of the SDFSS implementation, highlighting essential parameters that influence optimisation decisions. Time, date, and location determine the applicable electricity and natural gas prices, while carbon pricing and rate structures further modify these costs. Outdoor temperature and building characteristics drive the space-heating demand and influence heat pump performance. Furnace efficiency and cost tolerance shape the cost comparison between the two heating technologies. All of these inputs feed into the SDFSS system, which evaluates real-time operating costs and selects the most cost-effective heating option. These prices, along with outdoor temperature and heat pump specifications, are integral for calculating the COP of the heat pump.

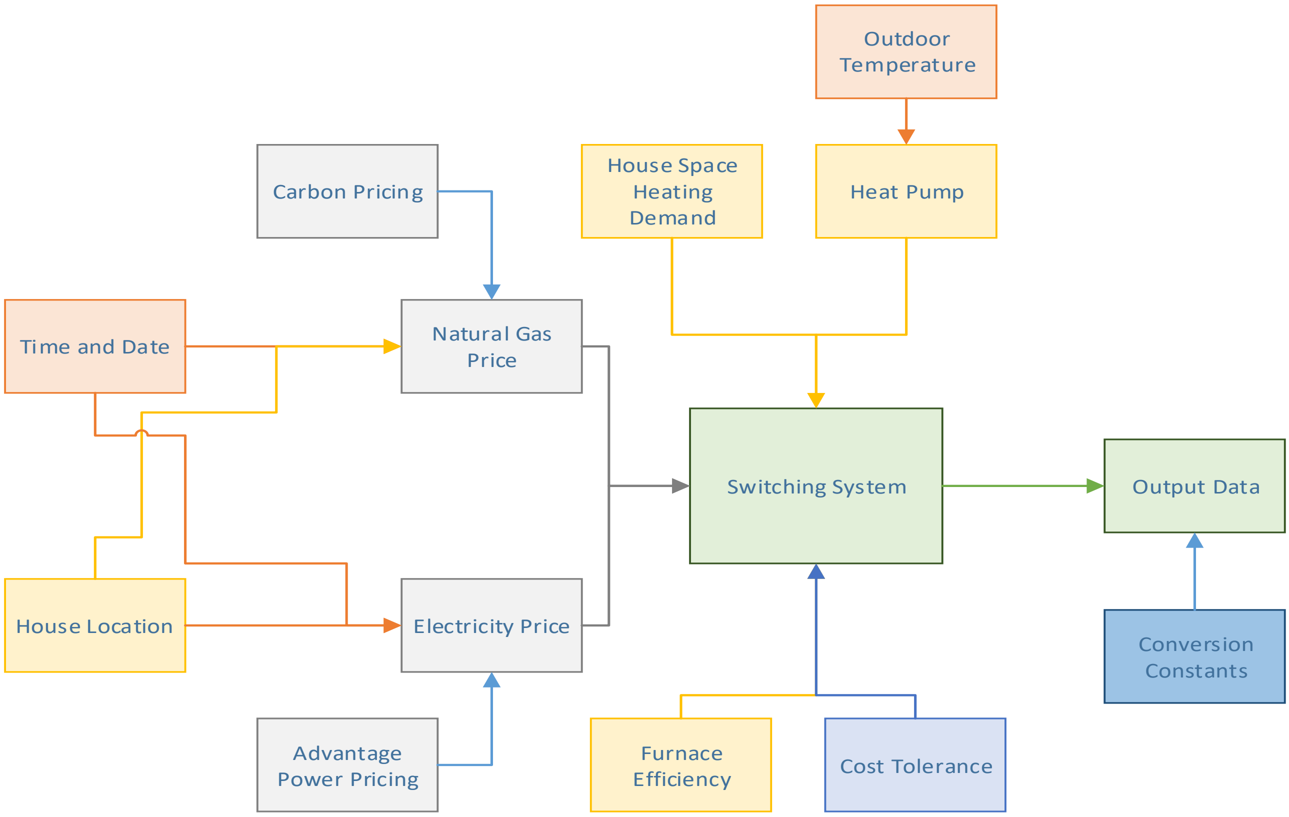

Figure 3. Flow chart illustrating the simulation model of SDFSS

3. Models Input data

The model input parameters include building specifications such as building parameters, infiltration rates, and heating set points, which are calibrated using energy audit data. Additionally, weather data from a Typical Meteorological Year (TMY) file and energy consumption metrics are included to evaluate the ASHP performance and to calculate overall operating costs and emissions. This will be discussed further in the following sections.

3.1. TRNSYS model parameters

The house parameters used to create the model are listed in Tables 3 and 4. The infiltration rate was modified to calibrate the model.

Table 3. List of building parameters

Building Parameters		Weather Data	Heating Schedule	ERV
Insulation	Occupants	Temperature		
Infiltration	Heating Set-point	Humidity	Heating Schedule	Return and Supply Air
Windows	Lighting Schedule	Solar Radiation		

Table 4. Building specifications and design values

Building Specifications	Design Values	Building Specifications	Design Values	Building Specifications	Design Values
Main Floor Wall	R34 Nominal	**Infiltration Rate at 50Pa**	0.526 ACH	**Occupants**	2 Retired Couple
Basement Wall	R34 Nominal	**Main Floor Windows**	Triple Glazed Low-e Solar Glass R-value: 4.73 Nominal	**Lighting Schedule**	Standard Work-Lighting Schedule
Basement Floor	R10 Nominal	**Basement Windows**	Triple Glazed Low-e Solar Glass R-value: 3.55 Nominal	**Annual Plug Load Consumption**	4457 kWh
Ceiling	R60 Nominal	**Heating Set-point Temperature**	23°C	**Annual Lighting Electricity Consumption**	609 kWh

The infiltration rate was recorded from the depressurisation test performed during the energy audit. The set-point temperature, occupant number and lighting schedule were obtained from the occupant interview. The plug load consumption was measured from the energy audit and was then estimated for the year. Similarly, during the energy audit, the power rating for the lighting fixtures was accounted for, and an estimated annual consumption was calculated to be 609 kWh.

The weather data files are publicly available in the format of a TMY file [28] and used for simulation purposes. The London weather data showed that the maximum outdoor temperature was found to be 33.1°C and the minimum outdoor temperature was found to be -24.6°C. The selected heating season is set from 1 hour to 3408 hours (January 1st to May 22nd) and from 6575 hours to 8760 hours (October 1st to December 31st) [12].

3.2. SCM model parameters

The SCM utilises several parameters in order to determine the operating cost for different fuel options. For the calculations, several temporal parameters are needed, including ones that are location-based, equipment-based, and fuel pricing-based (Fig. 4). The SCM is able to calculate the electricity consumption, natural gas consumption, annual operating cost and GHG emission for different combinations, including the SDFSS.

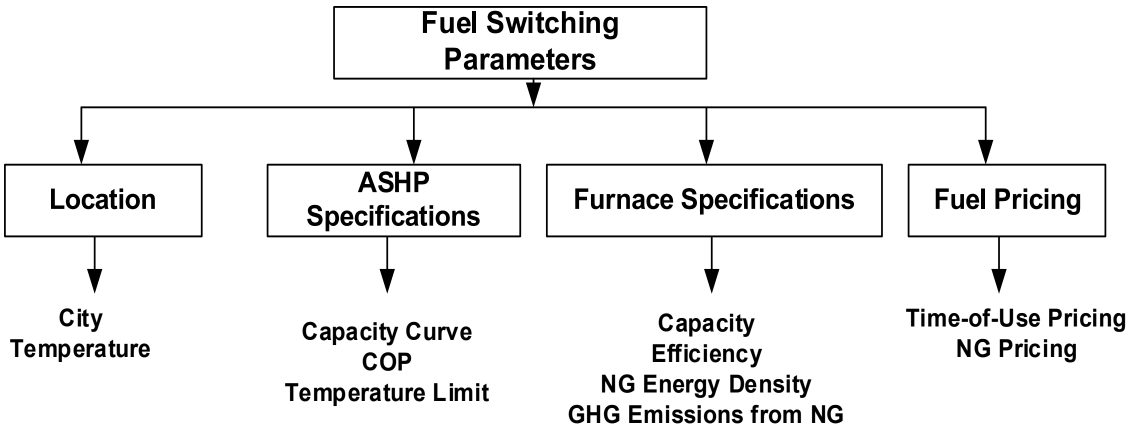

Figure 4. List of switching parameters

The performance of an ASHP depends on the outdoor temperature. The ASHP heating capacity and COP for specific temperatures are obtained from the manufacturer's specifications. The information is then used to develop performance curves for both the heating capacity and COP for the heat pump. Figs. 5 and 6 depict the ASHP capacity and COP versus outdoor temperature.

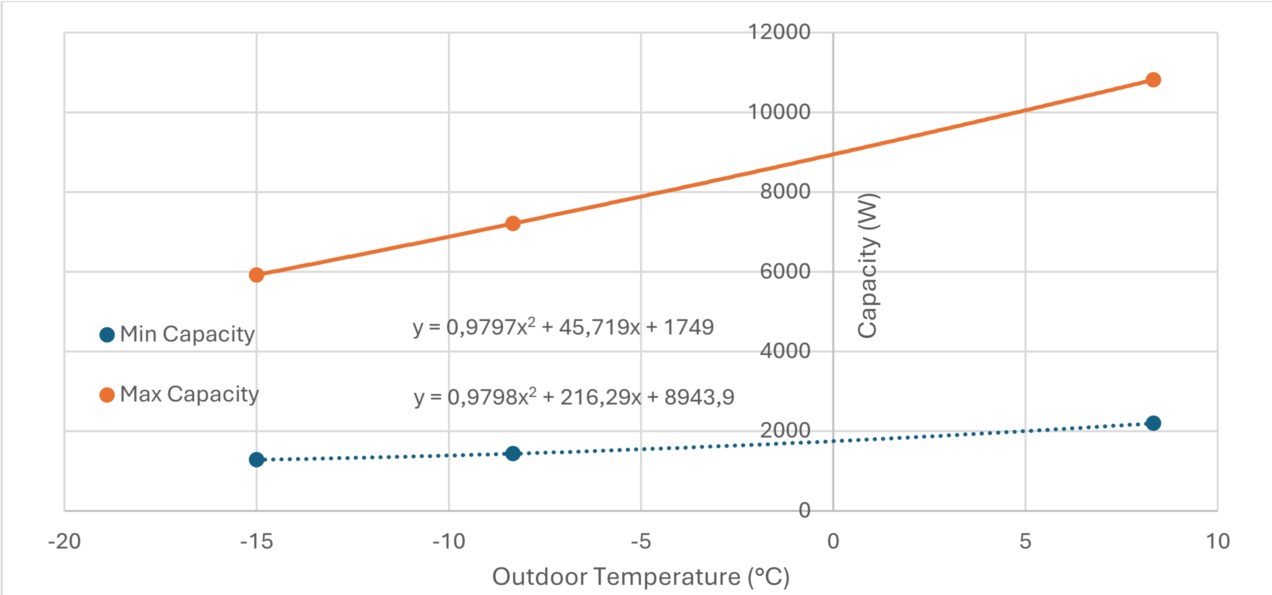

Figure 5. Heat pump capacity curve compared to temperature

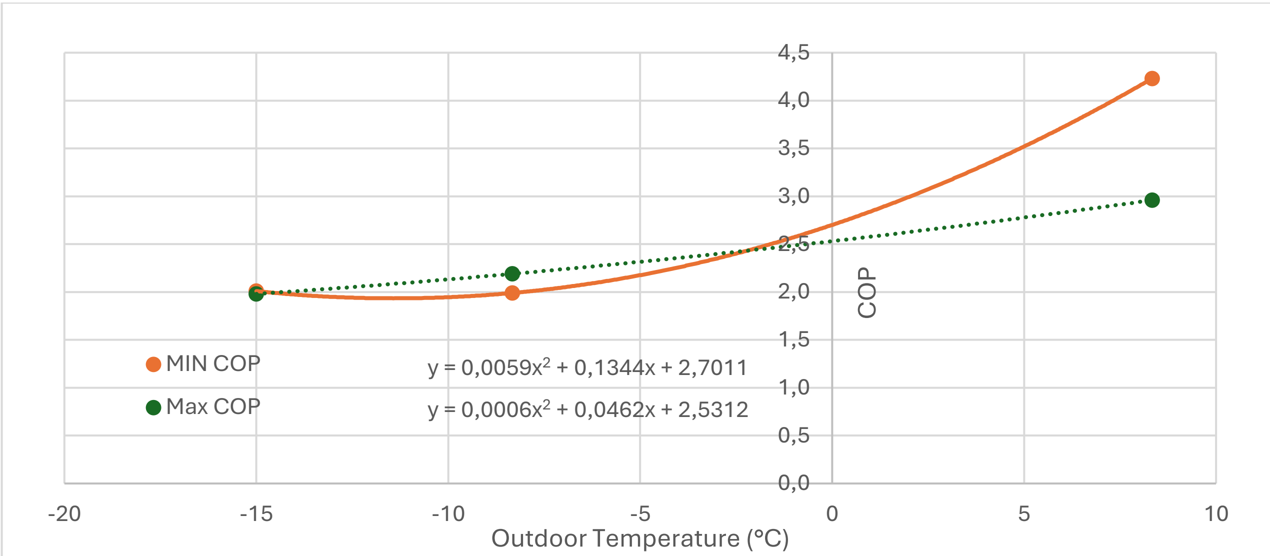

Figure 6. Heat pump COP curve compared to temperature

The ASHP used for this study is a modulating heat pump; the COP is constantly changing depending on the outdoor temperature, and the capacity should match the required heating demand of the house. The ASHP has a maximum capacity and a minimum capacity curve, with the maximum COP and minimum COP curves associated with it. The simulated hourly space heating demand from the TRNSYS model will be used to determine the heating demand ratio from the maximum capacity for the given outdoor temperature. The ratio is used on the COP curve to determine the associated COP for the required capacity and outdoor temperature. The mathematical model to find the actual COP is illustrated.

$$\frac{COP_{Actual} - COP_{Min}}{H - Cap_{Min}} = \frac{COP_{Max} - COP_{Min}}{Cap_{Max} - Cap_{Min}} \tag{10}$$

Where: COP_{Actual} = *Actual COP for the temperature*
H = *Space heating demand*
Cap_{Min} = *Capacity for the temperature using the minimum capacity curve*
Cap_{Max} = *Capacity for the temperature using the maximum capacity curve*
COP_{Min} = *COP for that temperature using the minimum COP curve*

$COP_{Max} = COP\ for\ the\ temperature\ using\ the\ maximum\ COP\ curve$

The above equation was rearranged for the actual COP.

$$COP_{Actual} = (H - Cap_{Min})\frac{(COP_{Max} - COP_{Min})}{(Cap_{Max} - Cap_{Min})} + COP_{Min} \tag{11}$$

The furnace is fully modulating and will be able to provide heating with a wide range of capacities. The efficiency of the furnace was found to be an average of 89% with the combustion analyser during the energy audit. The test was performed multiple times to verify the efficiency. Since the performance of the NGF is not highly dependent on the outdoor temperature, the heating demand is compared with the maximum and minimum heating capacity to ensure the ASHP is able to meet the heating requirement. The equivalent energy is calculated using the energy density of natural gas and is used along with the equipment efficiency to calculate the natural gas consumption. The GHG emissions were calculated with a similar method by considering the GHG emission factor for NG.

The TOU electricity pricing is obtained from the local utility company for the selected cities. In the case of the benchmark model, the marginal electricity and natural gas prices were used for simulation. TOU is the commodity price of electricity alone and does not include costs such as transportation and distribution charges, and other regulatory charges. The price of electricity is consistent for all cities within Ontario; however, the other surcharges vary from different distributors. Since the surcharge pricing is calculated per unit of electricity used, the simulation needs to account for these costs as well. The marginal price is substantially increased and will affect the simulation results. The different marginal price tiers for Strathroy, Ontario, are shown in Table 5.

Table 5. Marginal retail TOU electricity prices for the Strathroy

Off-Peak Marginal Price	Mid-Peak Marginal Price	On-Peak Marginal Price
\$0.092/kWh	\$0.124/kWh	\$0.163/kWh

The marginal price of natural gas was also calculated with additional surcharges. The cost decreases as the homeowner uses more natural gas. The price of natural gas is taken as \$0.262/m³ for the first 100 m³ and will decrease for higher natural gas consumption as per Table 6.

Table 6. Marginal price for natural gas

First 100 m³	Next 150 m³	Over 250 m³
\$0.261746/m³	\$0.258763/m³	\$0.251053/m³

Average hourly GHG emission factors for electricity were retrieved from IESO data [29, 30]. The different electricity generation and its emission factor were used to estimate the average hourly GHG generation rate. In order to estimate the GHG emissions, the following conversion rates were needed: Equivalent electricity for natural gas: 10.395 kWh/m³ [31]. GHG conversion for natural gas: 1.863 kg/m³ [32].

3.3. Sensitivity analysis parameters

As mentioned, three sensitivity analysis scenarios were performed to determine the effects of changing specific parameters. The different scenario includes the addition of carbon pricing, different cities, and a different electricity TOU pricing plan.

3.3.1. Breakdown of carbon pricing As mentioned earlier, during this work frame, the Canadian federal government imposed carbon pricing to disincentivise the use of fossil fuels, such as natural gas. This added cost will affect the cost-effectiveness of the SDFSS and will highlight the economic and environmental benefits. The carbon pricing imposed by the government starts at \$20/tonne of CO_2 in 2019, and the cost will increase by \$10/tonne per year, reaching \$50/tonne in 2022, reaching \$170/tonne in 2030. Since the carbon price is dependent on the amount of GHG emissions, the natural gas price will be significantly affected [6]. The cost breakdown and the impact of carbon pricing are shown in Table 2.

3.3.2. Breakdown of parameters for different cities Another sensitivity analysis was performed to determine the effects of operating systems in different cities. One parameter that varies across cities is HDD. Since the fuel price is different for different cities, a secondary analysis is performed using the marginal fuel cost for each city. The fuel pricing will affect the effectiveness of the SDFSS, and the benefits could change drastically. A summary of the input parameters (HDD, marginal electricity price, and marginal natural gas price) for different cities is illustrated in Table 7.

Table 7. Different utility costs for cities [24-27, 33]

	Cities														
	Strathroy			*Toronto*			*Windsor*			*Ottawa*			*Thunder Bay*		
HDD (°C-Day)	3810			3873			3409			4477			5683		
Marginal Electricity Pricing (\$/kWh)	Off-Peak	Mid-Peak	On-Peak	Off-Peak	Mid-Peak	On-Peak	Off-Peak	Mid-Peak	On-Peak	Off-Peak	Mid-Peak	On-Peak	Off-Peak	Mid-Peak	On-Peak
	0.0922	0.1226	0.1625	0.0922	0.124	0.163	0.0972	0.1277	0.1676	0.0972	0.1277	0.1676	0.0931	0.1236	0.1635
Marginal Natural Gas Pricing (\$/m^3)	0.3038			0.3645			0.3038			0.3645			0.3848		

As seen in Table 7, Thunder Bay shows the highest heating degree days HDD and Windsor is found to have the lowest HDD. The fuel pricing is also presented for the different electrical TOU electricity schemes corresponding to different cities. The electricity price for Thunder Bay is relatively low when compared to Ottawa and Windsor, even though the HDD is higher.

4. Results and Discussion

The upcoming sections will provide a comprehensive analysis of the simulation results from both TRNSYS and SCM. The section will explore the complexities of these simulations, highlighting their findings and implications.

4.1. TRNSYS Simulation Results and Calibration

The model was created using the information collected from the energy audit. A 3D model was first created using SketchUp with the TRNSYS 17-SketchUp toolbar [22, 34] (Fig. 7(a) and Fig. 7(b)). Using the special TRNSYS plugin, the appropriate air nodes, windows and doors of the house were modelled in SketchUp. In order to calibrate the model, experimental data during daily operations were collected. Calibrating the model will help fine-tune the model to take into account the occupant behaviour and unforeseen discrepancies.

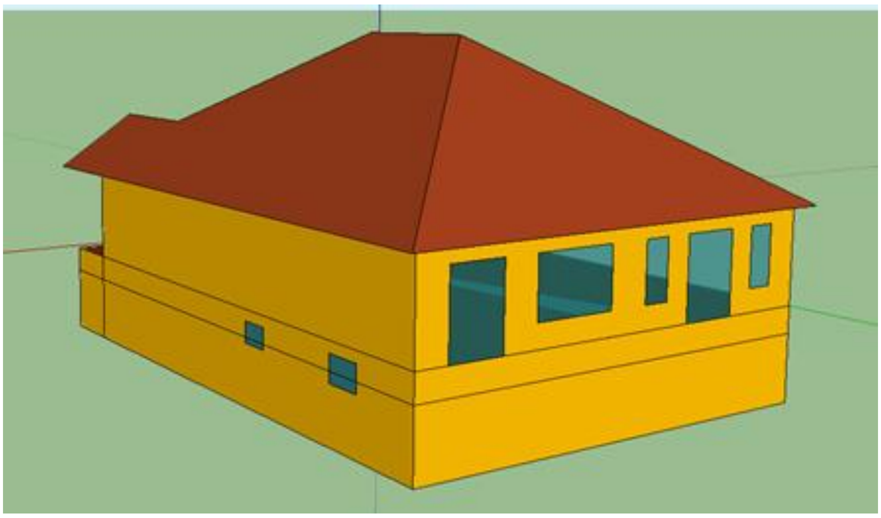

Figure 7(a). East side view of the NZEH

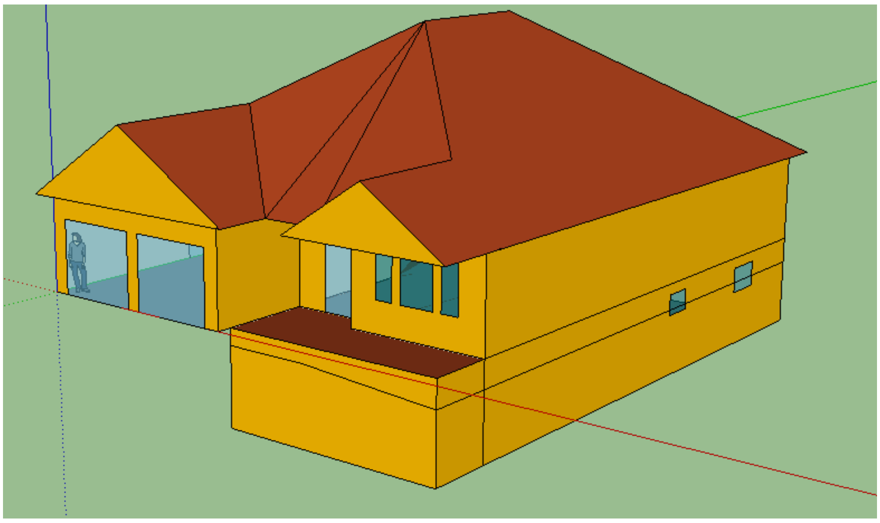

Figure 7(b). West side view of the NZEH

The simulation model needed real data in order to calibrate the model accurately. Due to the inaccuracy of the occupancy behaviour, real experimental data is required in order to fine-tune the simulation. Using the data collected from mid-February 2018 to November 2018, described previously, the graph was generated, and a regression line was produced. Using the heating demand line from the experimental results, the TRNSYS simulation model can be calibrated to better reflect the actual results. During the extensive energy audit, it was found that under the depressurisation test, a damper in the basement allowed makeup air into the building. This was initially ignored when creating the model. The assumption was that the makeup air intake effect was negligible.

When analysing the data, the experimental data showed that the heating demand was higher with the experimental data when compared with the simulation model. It is believed that this difference is due to the lack of fresh air intake in the simulation model. In the Strathroy house, the range hood is on when the homeowner is cooking. Since the house is extremely airtight, the range hood was sufficient to depressurise the house enough to allow makeup air to flow in through the dampers. In the heating demand of the calibrated model with the addition of the fresh air intake, the simulation model is relatively close to the experimental line. The calibrated model was closer when the regressions were compared against each other (Figure 8).

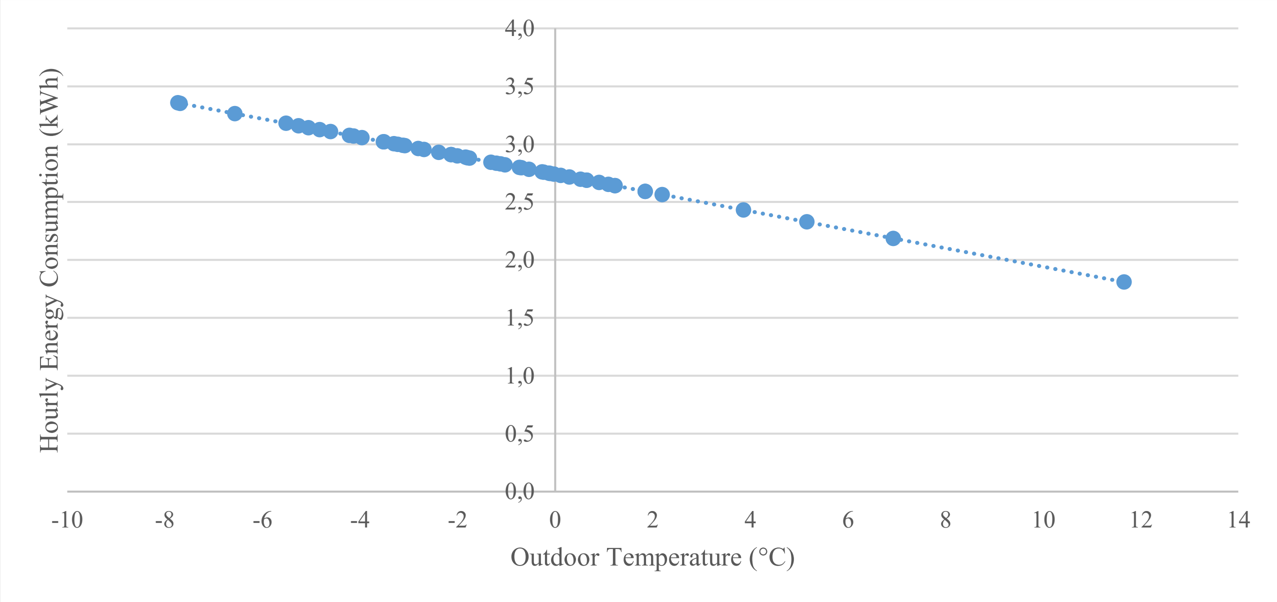

Figure 8. Calibrated TRNSYS house thermal simulation model result

Figure 9 illustrates three different regression lines of the experimental data, the original TRNSYS model and the calibrated TRNSYS model. The original TRNSYS model was shifted up a bit to obtain the calibrated TRNSYS model due to the addition of the makeup air. The results of the original TRNSYS simulation model, the calibrated TRNSYS simulation model, and the experimental results are shown together in Figure 9.

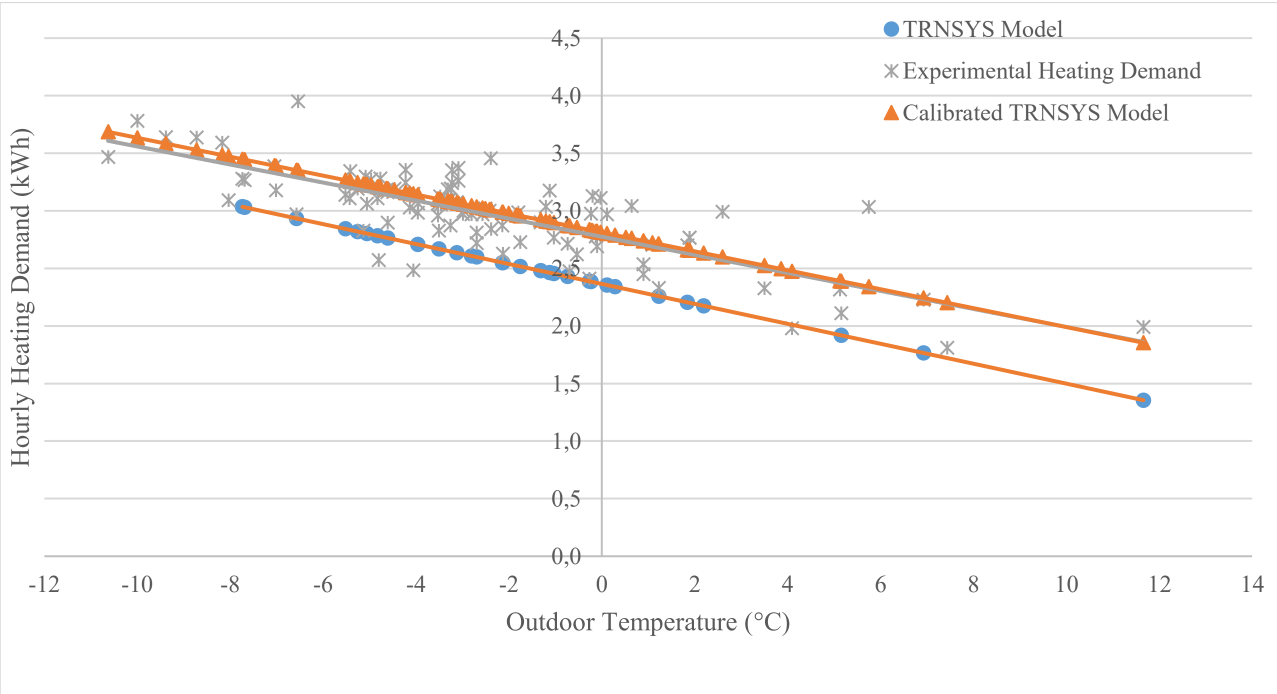

Figure 9. House space heating demand in relation to outdoor temperature from experiment, original and calibrated TRNSYS models

The error was calculated between the experimental heating demand and the calibrated TRNSYS model regression using the root mean square error (RMSE) method. Using the regression model, hourly energy consumption was simulated for temperatures of -13°C to 11.5°C with 0.5°C intervals. Using these values, the RMSE was found to be 0.05 kWh. This calibrated linear model was then used in the SCM.

The calibrated simulation model was simulated again with the TMY data for London, Ontario. The results of the simulation showed that the annual total heating demand was 14 MWh and the peak heating load was found to be 4.71 kWh (Figure 10).

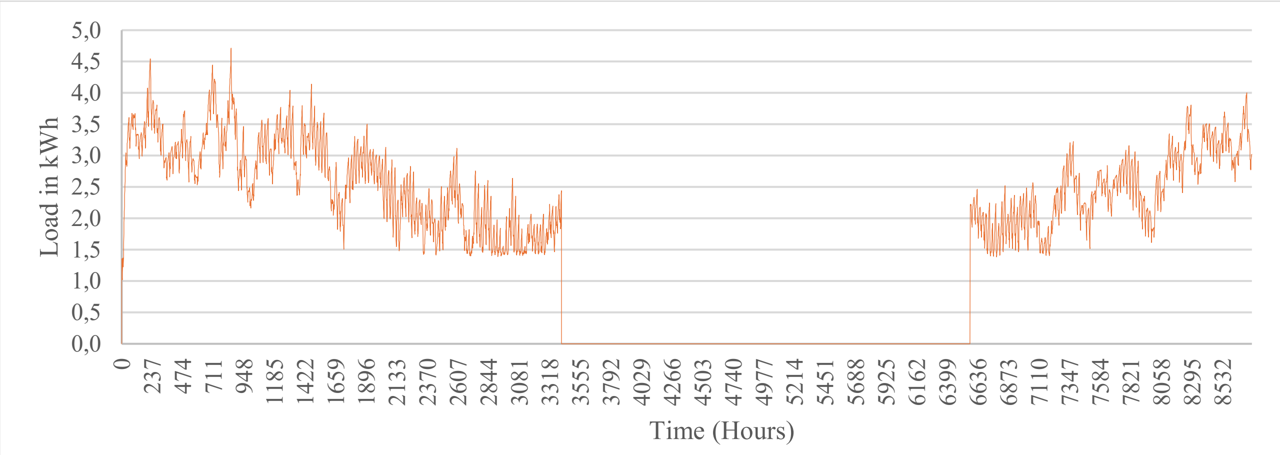

Figure 10. TRNSYS simulated hourly space heating load vs time for the Strathroy house

The combination of the outdoor temperature and hourly space heating load graphs is shown in Fig. 11. This shows the relationship between the outdoor temperature and the hourly heating demand. As the outdoor temperature increases, the heating demand decreases. The opposite can be seen when the outdoor temperature decreases.

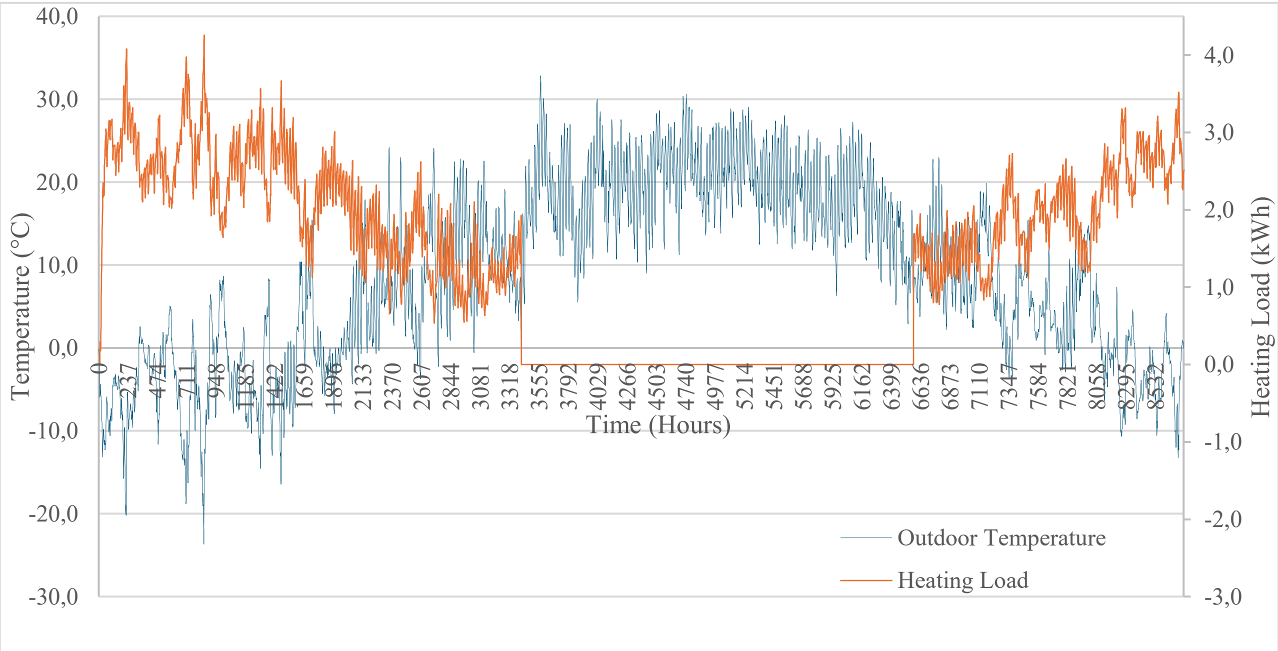

Figure 11. Comparing hourly space heating load and outdoor temperature of the NZEH for the London weather

4.2. SCM Results

The SCM uses the hourly space heating demand simulated from the calibrated TRNSYS model to estimate the annual natural gas consumption, electricity consumption, GHG emission and operational cost. As mentioned earlier, six main configurations simulated are (1) SDFSS, (2) manufacturer fuel switching at -5 °C, (3) manufacturer fuel switching at -15 °C, (4) natural gas furnace heating only, (5) 100% efficiency electricity resistance heating, and (6) ASHP with 100% efficiency electric backup with -15 °C manufacturer switching. Table 8 summarises the results of the simulated six configurations.

Table 8. Summary of results of the benchmark building scenario

	SDFSS	NGF Only	Manufacturer Switching at -5°C (Furnace)	Manufacturer Switching at -15°C (Furnace)	Manufacturer Switching at -15°C (100% Efficiency Electric Backup)	100% Efficiency Electric Heating
Natural Gas Consumption (m³)	1086.26	1306.77	374.31	24.06	0.00	0
Electricity Consumption (kWh)	491.00	0	2942.45	4498.86	4721.42	12089.679
Total Energy Cost ($)	331.52	342.04	420.24	496.87	514.43	1321.52
GHG Emission (kg)	2039.46	2434.52	812.89	216.90	181.17	461.40

Table 8 shows that the total annual energy cost for the SDFSS is lowest when compared to the other configurations. The SDFSS configuration has an annual operational cost of 3% lower and an annual GHG emission 16% lower than the NGF only option. This cost and GHG emission reduction is due to the SDFSS's lower natural gas consumption in exchange for a more efficient electrical ASHP option. The manufacturer's switching system switches from the ASHP to NGF when the outdoor temperature drops below the set-point temperature.

In this study, two different set-point temperatures were investigated: (1) -5 °C, (2) -15 °C. The results of the SCM show that the annual operating cost of the SDFSS is significantly lower than both of the manufacturer switching options. SDFSS annual cost savings are over 21% and 33% compared to that of the manufacturer switching system at set-point temperatures of -5 °C and -15 °C, respectively. This cost difference is mainly due to the manufacturer switching system only using simple switching parameters, such as the outdoor temperature. The manufacturer switching system will continue to operate using the ASHP as the main heat source even when the price of electricity is high and/or when the performance of the ASHP is poor. On the other hand, the SDFSS not only accounts for the outdoor temperature, but it also takes into account temporal equipment efficiencies, capacities, and energy prices. This allows the SDFSS to provide the same amount of heat with the more economical fuel option.

The GHG emission for the SDFSS is higher compared to the two fixed set-point switching systems. This is because the GHG emissions from consuming electricity are much lower than those from burning natural gas. Though the manufacturer switching systems have a higher annual operating cost than the NGF only configuration and the SDFSS configuration, the GHG emissions are significantly lower due to the higher usage of electricity. However, since the SDFSS is a flexible system, the inclusion of a carbon tax will further increase the cost difference between the SDFSS and the other configurations. A carbon tax inclusion will not only lower the annual operating cost for the SDFSS, but it also lowers the GHG emission which is the intended goal.

To better describe the effects of the SDFSS, a heat map shown in Table 9 was developed to illustrate the distribution of the heat pump operating status. The data was organised with columns listing the heating months. Each hour of the day is listed as a row. The sum of all days within the month and hour that the ASHP was on. For example, for February at 4 am, there are only two days within the month that the ASHP was in operation. Table 9 shows that in the month of April, the ASHP is operated more frequently (a total of 414 hours or 57%), whereas in January, the ASHP is rarely used (12 hours or 2%) due to the higher cost for the ASHP to operate in colder outdoor temperatures. This table illustrates a transition from red to green, indicating an increase in the percentage of heat pump operation. The heat pump is cost-effective during milder winter months, while an NGF remains the better option during extreme cold months.

Table 9. Heat pump operation mapping for the heating season

	1	*2*	*3*	*4*	*11*	*12*	
yr 2018	January	February	March	April	November	December	
0	1 dy 3.2%	3 dy 10.7%	6 dy 19.4%	17 dy 56.7%	16 dy 53.3%	1 dy 3.2%	44 hr 1.0%
1	1 dy 3.2%	4 dy 14.3%	5 dy 16.1%	17 dy 56.7%	14 dy 46.7%	1 dy 3.2%	42 hr 1.0%
2	1 dy 3.2%	3 dy 10.7%	4 dy 12.9%	15 dy 50.0%	12 dy 40.0%	2 dy 6.5%	37 hr 0.9%
3	1 dy 3.2%	3 dy 10.7%	4 dy 12.9%	16 dy 53.3%	11 dy 36.7%	1 dy 3.2%	36 hr 0.8%
4	1 dy 3.2%	2 dy 7.1%	4 dy 12.9%	14 dy 46.7%	11 dy 36.7%	1 dy 3.2%	33 hr 0.8%
5	1 dy 3.2%	2 dy 7.1%	4 dy 12.9%	14 dy 46.7%	11 dy 36.7%	1 dy 3.2%	33 hr 0.8%
6	1 dy 3.2%	2 dy 7.1%	5 dy 16.1%	14 dy 46.7%	12 dy 40.0%	1 dy 3.2%	35 hr 0.8%
7	0 dy 0.0%	1 dy 3.6%	2 dy 6.5%	6 dy 20.0%	2 dy 6.7%	0 dy 0.0%	11 hr 0.3%
8	0 dy 0.0%	1 dy 3.6%	3 dy 9.7%	10 dy 33.3%	2 dy 6.7%	0 dy 0.0%	16 hr 0.4%
9	0 dy 0.0%	1 dy 3.6%	3 dy 9.7%	11 dy 36.7%	2 dy 6.7%	0 dy 0.0%	17 hr 0.4%
10	0 dy 0.0%	2 dy 7.1%	2 dy 6.5%	12 dy 40.0%	5 dy 16.7%	2 dy 6.5%	23 hr 0.5%
11	0 dy 0.0%	2 dy 7.1%	6 dy 19.4%	22 dy 73.3%	13 dy 43.3%	2 dy 6.5%	45 hr 1.0%
12	0 dy 0.0%	2 dy 7.1%	6 dy 19.4%	22 dy 73.3%	13 dy 43.3%	3 dy 9.7%	46 hr 1.1%
13	0 dy 0.0%	2 dy 7.1%	7 dy 22.6%	21 dy 70.0%	15 dy 50.0%	3 dy 9.7%	48 hr 1.1%
14	0 dy 0.0%	2 dy 7.1%	9 dy 29.0%	22 dy 73.3%	16 dy 53.3%	3 dy 9.7%	52 hr 1.2%
15	0 dy 0.0%	2 dy 7.1%	10 dy 32.3%	22 dy 73.3%	15 dy 50.0%	2 dy 6.5%	51 hr 1.2%
16	0 dy 0.0%	2 dy 7.1%	9 dy 29.0%	22 dy 73.3%	14 dy 46.7%	2 dy 6.5%	49 hr 1.1%
17	0 dy 0.0%	2 dy 7.1%	5 dy 16.1%	11 dy 36.7%	4 dy 13.3%	2 dy 6.5%	24 hr 0.6%
18	0 dy 0.0%	2 dy 7.1%	4 dy 12.9%	10 dy 33.3%	4 dy 13.3%	2 dy 6.5%	22 hr 0.5%
19	1 dy 3.2%	3 dy 10.7%	9 dy 29.0%	26 dy 86.7%	17 dy 56.7%	2 dy 6.5%	58 hr 1.3%
20	1 dy 3.2%	3 dy 10.7%	8 dy 25.8%	25 dy 83.3%	14 dy 46.7%	2 dy 6.5%	53 hr 1.2%
21	1 dy 3.2%	3 dy 10.7%	8 dy 25.8%	23 dy 76.7%	14 dy 46.7%	2 dy 6.5%	51 hr 1.2%
22	1 dy 3.2%	3 dy 10.7%	6 dy 19.4%	21 dy 70.0%	15 dy 50.0%	1 dy 3.2%	47 hr 1.1%
23	1 dy 3.2%	3 dy 10.7%	6 dy 19.4%	21 dy 70.0%	14 dy 46.7%	1 dy 3.2%	46 hr 1.1%
Monthly Total	12 hr 1.6%	55 hr 8.2%	135 hr 18.1%	414 hr 57.5%	266 hr 36.9%	37 hr 5.0%	919 hr 21.3%
							4321 hr

4.3. Calculating the optimal switching temperature

The SDFSS is a flexible system designed to account for various temporal parameters in order to estimate fuel consumption. While the system is adaptable, the current base-case simulation model can be simplified to three fixed set-point temperatures based on the electricity price structure. By utilising the space heating demand mathematical model and the specifications of ASHP performance curves, the analysis can identify three optimal switching temperatures, one for each electricity pricing tier. These switching temperatures can determine the optimal switching temperature for any given hour.

The idea of the SDFSS is to use the most cost-effective fuel source available. The NZEH for the base-case analysis used both ASHP and an NGF. As long as the equation (Equation 12) holds true, the ASHP will be in use. If the equation shows false, the natural gas-fired furnace will be used.

$$\frac{H}{COP} \times P_e < \frac{H}{U_n} \times \frac{1}{\eta_n} \times P_n \qquad (12)$$

The space heating demand (H) can be replaced with the linear mathematical model of the calibrated TRNSYS model.

$$H = -0.0822t + 2.8125 \qquad (13)$$

Where $t = Hourly\ temperature\ (°C)$

Equation 5 can be simplified using the parameters.

$$\frac{P_e}{COP_{Actual}} = \frac{P_n}{0.89 \times 10.395} \tag{14}$$

$$COP_{Actual} > \frac{P_e}{P_n} \times 9.25155 \tag{15}$$

$$COP_{Actual} > P_e \times 30.4528 \tag{16}$$

Using Equation 5 and Equation 16, and the three electricity marginal prices (Table 7), three separate Equations 17, 18, and 19 can be created for each of the three electricity pricing tiers. These equations illustrate the range of COP_{Actual} of ASHP for various electricity pricing slabs. During On-Peak hours, the system should operate with a COP_{Actual} greater than 4.964 to justify it; otherwise, it will switch to an NGF. ASHP operation is justified for Mid-Peak pricing with a COP_{Actual} range of 3.776 to 4.964. For Off-Peak pricing, the COP_{Actual} should range from 2.802 to 3.776. The COP_{Actual} equation is then solved to find outdoor air temperature ranges to justify the operation of ASHP for various electricity price slabs, and the results are given in the following equations along with COP_{Actual}.

$$\textit{On-Peak: } COP_{Actual} > 4.964;\ t > 11.5141°C \tag{17}$$

$$\textit{Mid-Peak: } COP_{Actual} > 3.776;\ t > 7.2257°C \tag{18}$$

$$\textit{Off-Peak: } COP_{Actual} > 2.802;\ t > 2.3925°C \tag{19}$$

The illustration on **Error! Reference source not found.** to **Error! Reference source not found.** show the three optimal switching temperatures for on-peak, mid-peak and off-peak. The SDFSS is able to calculate these optimal switching temperatures using the input parameters and effectively switch the fuel source.

5. Sensitivity analysis

To further estimate the effects of varying parameters, several sensitivity analyses are performed. These sensitivity analysis scenarios are procured to predict the foreseeable changes due to climate change regulations. The choice of sensitivity analysis parameters, particularly carbon and TOU pricing and varying cities, is crucial for evaluating heating systems. Carbon pricing aligns with government strategies to reduce emissions, making it vital for assessing anticipated future costs and carbon footprints. The main goal of TOU pricing is to regulate the province's overall electricity demand, particularly during peak hours. Additionally, differences among cities highlight the varying climate impacts on heating requirements, as each location has its own HDD.

5.1. Carbon price increase

The government is currently implementing a carbon pricing scheme for fossil fuel usage in Canada. This additional cost on high-carbon sources will significantly alter the operating expenses associated with heating that relies on natural gas. In the future, using electricity for heating could become a more cost-effective alternative. Table 10 summarises the results from the operation of the heating system under various federal carbon price rates.

Table 10. Summary of results for different carbon prices

Smart Switching (SDFSS) with ASHP Heating						
	No Carbon Price	*$10/tonne Carbon Price*	*$20/tonne Carbon Price*	*$30/tonne Carbon Price*	*$40/tonne Carbon Price*	*$50/tonne Carbon Price*
Natural Gas Consumption (m³)	1086.26	1030.63	950.01	874.74	789.16	689.87
Electricity Consumption (kWh)	491.00	647.69	893.44	1138.80	1433.62	1797.18
Total Energy Cost ($)	331.52	353.89	374.83	394.14	411.56	427.09
GHG Emission (kg)	2039.46	1941.04	1799.71	1668.69	1519.60	1347.93
NGF Only						
	No Carbon Price	*$10/tonne Carbon Price*	*$20/tonne Carbon Price*	*$30/tonne Carbon Price*	*$40/tonne Carbon Price*	*$50/tonne Carbon Price*
Natural Gas Consumption (m³)	1306.77	1306.77	1306.77	1306.77	1306.77	1306.77
Electricity Consumption (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
Total Energy Cost ($)	342.04	369.55	397.06	424.57	452.08	479.59
GHG Emission (kg)	2434.52	2434.52	2434.52	2434.52	2434.52	2434.52
Default Manufacturer Switching at -5 °C (NG furnace)						
	No Carbon Price	*$10/tonne Carbon Price*	*$20/tonne Carbon Price*	*$30/tonne Carbon Price*	*$40/tonne Carbon Price*	*$50/tonne Carbon Price*
Natural Gas Consumption (m³)	374.31	374.31	374.31	374.31	374.31	374.31
Electricity Consumption (kWh)	2942.45	2942.45	2942.45	2942.45	2942.45	2942.45
Total Energy Cost ($)	420.24	428.12	436.00	443.88	451.76	459.64
GHG Emission (kg)	812.89	812.89	812.89	812.89	812.89	812.89
Default Manufacturer Switching at -15 °C (NG furnace)						
	No Carbon Price	*$10/tonne Carbon Price*	*$20/tonne Carbon Price*	*$30/tonne Carbon Price*	*$40/tonne Carbon Price*	*$50/tonne Carbon Price*
Natural Gas Consumption (m³)	24.06	24.06	24.06	24.06	24.06	24.06
Electricity Consumption (kWh)	4498.86	4498.86	4498.86	4498.86	4498.86	4498.86
Total Energy Cost ($)	496.87	497.37	497.88	498.38	498.89	499.40
GHG Emission (kg)	216.90	216.90	216.90	216.90	216.90	216.90

Table 10 (Cont.). Summary of results for different carbon prices

Default Manufacturer Switching at -15 °C (100% Efficiency Electric Backup)						
	No Carbon Price	*$10/tonne Carbon Price*	*$20/tonne Carbon Price*	*$30/tonne Carbon Price*	*$40/tonne Carbon Price*	*$50/tonne Carbon Price*
Natural Gas Consumption (m³)	0.00	0.00	0.00	0.00	0.00	0.00
Electricity Consumption (kWh)	4721.42	4721.42	4721.42	4721.42	4721.42	4721.42
Total Energy Cost ($)	514.43	514.43	514.43	514.43	514.43	514.43
GHG Emission (kg)	181.17	181.17	181.17	181.17	181.17	181.17
100% Efficiency Electric Heating						
	No Carbon Price	*$10/tonne Carbon Price*	*$20/tonne Carbon Price*	*$30/tonne Carbon Price*	*$40/tonne Carbon Price*	*$50/tonne Carbon Price*
Natural Gas Consumption (m³)	0.00	0.00	0.00	0.00	0.00	0.00
Electricity Consumption (kWh)	12089.68	12089.68	12089.68	12089.68	12089.68	12089.68
Total Energy Cost ($)	1321.52	1321.52	1321.52	1321.52	1321.52	1321.52
GHG Emission (kg)	461.40	461.40	461.40	461.40	461.40	461.40

The results of the sensitivity analysis show that the SDFSS will continually be cost-effective compared to the other systems. The higher carbon pricing increases the NGF substantially when compared to the SDFSS. Both the manufacturer switching showed an increase similar to the natural gas-only system. This is because the manufacturer's switching system does not take into account any cost parameters. The manufacturer switching system was more cost-effective than the natural gas system with a $50/tonne carbon price increase. This shows that the SDFSS is effective even with the newly imposed carbon pricing.

5.2. Different Canadian cities

To demonstrate the effect of the SDFSS for different cities, several cities located in Ontario were selected for this sensitivity analysis. The selected cities are larger cities with different climates in order to investigate the impact of temperature changes. The summary result is presented in Table 11.

Table 11. Summary of results for climatic differences with different cities

Smart Switching (SDFSS) with ASHP Heating					
	Strathroy	*Toronto*	*Windsor*	*Ottawa*	*Thunder Bay*
HDD (°C-Day)	3810	3873	3409	4477	5683
Natural Gas Consumption (m³)	1086.26	1158.59	976.43	1280.43	1482.56
Electricity Consumption (kWh)	491.00	394.89	580.45	318.07	200.63
Total Energy Cost ($)	331.52	341.25	311.27	365.81	407.13
GHG Emission (kg)	2031.86	2162.75	1831.16	2387.07	2757.85

Table 11 (Cont.). Summary of results for climatic differences with different cities

	Strathroy	*Toronto*	*Windsor*	*Ottawa*	*Thunder Bay*
NGF Only					
Natural Gas Consumption (m³)	1306.77	1335.71	1238.49	1421.71	1565.02
Electricity Consumption (kWh)	0.00	0.00	0.00	0.00	0.00
Total Energy Cost ($)	342.04	349.62	324.17	372.13	409.64
GHG Emission (kg)	2425.37	2479.07	2298.63	2638.69	2904.67
Default Manufacturer Switching at -5 °C (NG furnace)					
Natural Gas Consumption (m³)	374.31	428.12	230.62	678.64	948.39
Electricity Consumption (kWh)	2942.45	2897.93	3079.62	2389.78	2071.10
Total Energy Cost ($)	420.24	430.66	396.08	441.81	474.42
GHG Emission (kg)	810.27	907.27	546.14	1348.17	1834.10
Default Manufacturer Switching at -15 °C (NG furnace)					
Natural Gas Consumption (m³)	24.06	36.27	5.82	145.62	354.23
Electricity Consumption (kWh)	4498.86	4643.83	4072.91	4788.08	4755.72
Total Energy Cost ($)	496.87	514.90	444.48	558.81	614.75
GHG Emission (kg)	216.73	244.29	166.76	452.25	837.94
Default Manufacturer Switching at -15 °C (100% Efficiency Electric Backup)					
Natural Gas Consumption (m³)	0.00	0.00	0.00	0.00	0.00
Electricity Consumption (kWh)	6405.40	6858.69	5213.19	8668.26	10845.19
Total Energy Cost ($)	696.46	742.40	566.63	939.22	1184.60
GHG Emission (kg)	242.10	256.75	199.06	335.20	427.80
100% Efficiency Electric Heating					
Natural Gas Consumption (m³)	0.00	0.00	0.00	0.00	0.00
Electricity Consumption (kWh)	12089.68	12357.36	11457.91	13153.02	14478.85
Total Energy Cost ($)	1321.52	1349.67	1250.85	1436.11	1583.88
GHG Emission (kg)	461.40	468.74	435.94	501.04	556.74

Table 11 shows the results of the different scenarios when the temperature changes (HDD). It is evident from the results shown that the temperature greatly affects the operational costs. However, when comparing the different switching systems, the savings are similar in proportion. This shows that the SDFSS system is effective regardless of the colder outer temperature.

Even though the commodity pricing of Ontario is consistent within the province, as mentioned earlier, different regions in Ontario have different utility pricing due to their regulatory and transportation pricing. By including this cost, the operating cost of the selected cities will reflect better to the realistic cost. Table 12 Summarise of results for different cities when including both climatic differences and utility pricing. With the inclusion of the utility cost, the SDFSS can still optimise the operating cost to provide the lowest cost compared to the other scenarios, as recorded in Table 10.

Table 12. Summary of results for climatic differences and utility pricing

Smart Switching (SDFSS) with ASHP Heating					
	Strathroy	*Toronto*	*Windsor*	*Ottawa*	*Thunder Bay*
Natural Gas Consumption (m³)	1086.26	1127.94	1016.02	1148.08	1302.26
Electricity Consumption (kWh)	491.00	476.84	474.50	712.68	769.49
Total Energy Cost ($)	331.52	418.35	313.88	442.36	520.57
GHG Emission (kg)	2039.46	2116.68	1908.42	2161.84	2449.71
NGF Only					
	Strathroy	*Toronto*	*Windsor*	*Ottawa*	*Thunder Bay*
Natural Gas Consumption (m³)	1306.77	1335.71	1238.49	1421.71	1565.02
Electricity Consumption (kWh)	0.00	0.00	0.00	0.00	0.00
Total Energy Cost ($)	342.04	430.78	324.17	458.52	536.44
GHG Emission (kg)	2434.52	2488.42	2307.30	2648.65	2915.63
Default Manufacturer Switching at -5 °C (NG furnace)					
	Strathroy	*Toronto*	*Windsor*	*Ottawa*	*Thunder Bay*
Natural Gas Consumption (m³)	374.31	428.12	230.62	678.64	948.39
Electricity Consumption (kWh)	2942.45	2897.93	3079.62	2389.78	2071.10
Total Energy Cost ($)	420.24	507.59	411.60	495.07	553.22
GHG Emission (kg)	812.89	910.27	547.76	1352.92	1840.74
Default Manufacturer Switching at -15 °C (NG furnace)					
	Strathroy	*Toronto*	*Windsor*	*Ottawa*	*Thunder Bay*
Natural Gas Consumption (m³)	24.06	36.27	5.82	145.62	354.23
Electricity Consumption (kWh)	4498.86	4643.83	4072.91	4788.08	4755.72
Total Energy Cost ($)	496.87	598.68	465.00	591.74	647.95
GHG Emission (kg)	216.90	244.55	166.80	453.27	840.42
Default Manufacturer Switching at -15 °C (100% Efficiency Electric Backup)					
	Strathroy	*Toronto*	*Windsor*	*Ottawa*	*Thunder Bay*
Natural Gas Consumption (m³)	0.00	0.00	0.00	0.00	0.00
Electricity Consumption (kWh)	4721.42	4979.38	4126.78	6135.29	8032.94
Total Energy Cost ($)	514.43	628.97	470.19	699.00	882.60
GHG Emission (kg)	181.17	187.66	157.63	236.87	316.65
100% Efficiency Electric Heating					
	Strathroy	*Toronto*	*Windsor*	*Ottawa*	*Thunder Bay*
Natural Gas Consumption (m³)	0.00	0.00	0.00	0.00	0.00
Electricity Consumption (kWh)	12089.68	12357.36	11457.91	13153.02	14478.85
Total Energy Cost ($)	1321.52	1566.74	1308.60	1502.27	1597.56
GHG Emission (kg)	461.40	468.74	435.94	501.04	556.74

5.3. Different pricing profile

The part of the sensitivity analysis performed is to determine the impact of the new advantage power pricing (APP). This new pricing plan aims to reduce the electricity cost during the overnight off-peak hours. Table 13 shows the four different costs associated with the new APP pricing plan.

Table 13. Different pricing tiers and their marginal prices

Pricing Tier	Pricing per kWh
Off Peak	9.22 ¢
Mid Peak	12.05 ¢
On Peak	21.61 ¢
Super Off-Peak	4.49 ¢

This new pricing was included in the simulation, and in addition to analysing the price change to the benchmark scenario, the new pricing was also implemented to simulate the effect in combination with the upcoming carbon pricing.

The results show (Table 14) that with the SDFSS option, the new APP reduces the operational cost. The default manufacturer switching system set at -15°C did not benefit from this change as much as the SDFSS, since the system is operating the ASHP majority of the time and the lower cost during the night does offset the high cost during the day. The natural gas-only scenario was not affected since changing the cost of electricity does not impact a natural gas-fired furnace. As expected from the previous analysis, as the carbon pricing increases, the operating cost for all the scenarios increases. However, with this added APP, the operating cost comparison between the natural gas only option and the SDFSS showed a constantly increasing cost reduction. This analysis shows the effects of the foreseeable changes in the tax pricing and the electricity pricing.

Table 14. Summary of results with the new APP, also looking at the inclusion of carbon pricing

Smart Switching (SDFSS) with ASHP Heating						
	No Carbon Price	*$10/tonne Carbon Price*	*$20/tonne Carbon Price*	*$30/tonne Carbon Price*	*$40/tonne Carbon Price*	*$50/tonne Carbon Price*
Natural Gas Consumption (m^3)	893.87	847.71	785.78	730.49	666.58	594.76
Electricity Consumption (kWh)	1251.24	1379.94	1565.82	1742.72	1958.71	2216.32
Total Cost ($)	310.68	329.10	346.35	362.38	377.00	390.25
GHG Emission (kg)	1702.35	1620.76	1512.50	1416.64	1305.69	1182.11
NGF Only						
	No Carbon Price	*$10/tonne Carbon Price*	*$20/tonne Carbon Price*	*$30/tonne Carbon Price*	*$40/tonne Carbon Price*	*$50/tonne Carbon Price*
Natural Gas Consumption (m^3)	1306.77	1306.77	1306.77	1306.77	1306.77	1306.77
Electricity Consumption (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
Total Cost ($)	342.04	369.55	397.06	424.57	452.08	479.59
GHG Emission (kg)	2434.52	2434.52	2434.52	2434.52	2434.52	2434.52

Table 14 (Cont.). Summary of results with the new APP, also looking at the inclusion of carbon pricing

Default Manufacturer Switching at -5 °C (NG furnace)						
	No Carbon Price	*$10/tonne Carbon Price*	*$20/tonne Carbon Price*	*$30/tonne Carbon Price*	*$40/tonne Carbon Price*	*$50/tonne Carbon Price*
Natural Gas Consumption (m^3)	374.31	374.31	374.31	374.31	374.31	374.31
Electricity Consumption (kWh)	2942.45	2942.45	2942.45	2942.45	2942.45	2942.45
Total Cost ($)	396.32	404.20	412.08	419.96	427.84	435.72
GHG Emission (kg)	812.89	812.89	812.89	812.89	812.89	812.89
Default Manufacturer Switching at -15 °C (NG furnace)						
	No Carbon Price	*$10/tonne Carbon Price*	*$20/tonne Carbon Price*	*$30/tonne Carbon Price*	*$40/tonne Carbon Price*	*$50/tonne Carbon Price*
Natural Gas Consumption (m^3)	24.06	24.06	24.06	24.06	24.06	24.06
Electricity Consumption (kWh)	4498.86	4498.86	4498.86	4498.86	4498.86	4498.86
Total Cost ($)	458.07	458.58	459.09	459.59	460.10	460.61
GHG Emission (kg)	216.90	216.90	216.90	216.90	216.90	216.90
Default Manufacturer Switching at -15 °C (100% Efficiency Electric Backup)						
	No Carbon Price	*$10/tonne Carbon Price*	*$20/tonne Carbon Price*	*$30/tonne Carbon Price*	*$40/tonne Carbon Price*	*$50/tonne Carbon Price*
Natural Gas Consumption (m^3)	0.00	0.00	0.00	0.00	0.00	0.00
Electricity Consumption (kWh)	4721.42	4721.42	4721.42	4721.42	4721.42	4721.42
Total Cost ($)	472.17	472.17	472.17	472.17	472.17	472.17
GHG Emission (kg)	181.17	181.17	181.17	181.17	181.17	181.17
100% Efficiency Electric Heating						
	No Carbon Price	*$10/tonne Carbon Price*	*$20/tonne Carbon Price*	*$30/tonne Carbon Price*	*$40/tonne Carbon Price*	*$50/tonne Carbon Price*
Natural Gas Consumption (m^3)	0.00	0.00	0.00	0.00	0.00	0.00
Electricity Consumption (kWh)	12089.68	12089.68	12089.68	12089.68	12089.68	12089.68
Total Cost ($)	1219.29	1219.29	1219.29	1219.29	1219.29	1219.29
GHG Emission (kg)	461.40	461.40	461.40	461.40	461.40	461.40

5.4. SDFSS Versus Other Heating Options

Using electricity as the main fuel source to replace natural gas will greatly reduce the GHG emissions from residential space heating. The current pricing model and available switching control do not justify the increased cost of implementing an electric heat pump. The simulation results highlighted that the operating cost of using the manufacturer switching in general is costlier compared to the natural gas-only option. Moreover, the impact of several factors in the foreseeable future shows the disadvantage of the higher operating cost of the manufacturer's switching system. Though the operating cost of the manufacturer switching is significantly higher than the natural gas-fired furnace option, the GHG emission is greatly reduced when the switching system is implemented.

A moral and economic dilemma exists between the reduction of GHG emissions and the lowering of operational costs. Residential homeowners are less likely to increase their operational cost for the sole purpose to reduce GHG emissions. Because of this, there is a lack of urgency to convert the NGF-dominated heating system to a more environmentally friendly option, such as the electric heat pump. The SDFSS incentivise the inclusion of heat pumps by theoretically lowering the operating cost while reducing the GHG emissions. Though the GHG emission reduction is not as high as the result of operating the system under the manufacturer's switching system, the GHG emission is still significantly lower than that of a natural gas-only system. The simulated results show that the SDFSS potentially provide up to 19% cost saving and GHG emission reduction of 51% when a $50/tonne carbon pricing is implemented compared to a natural gas-only system.

6. Conclusion

This study presents simulated results of SDFSS with a hybrid system and highlights its key parameters, which can be used to evaluate operating costs and GHG emissions for various locations and utility prices. The findings suggest that the SDFSS control system may become increasingly beneficial in the coming decades, even with added carbon pricing and new electricity tariffs. The SDFSS reduces costs and lowers GHG emissions, especially for mild winter conditions, compared to NGF. In the benchmark scenario, the SDFSS achieved a 3% cost reduction and an 18% decrease in GHG emissions compared to NGF. It also resulted in a 21% cost saving compared to the manufacturer switching system, increasing to 33% at set-point temperatures of -5 °C and -15 °C, respectively. However, GHG emissions from the SDFSS were significantly higher than the manufacturer's set point systems at these temperatures.

Despite the higher emissions, the cost savings incentivise users to transition from natural gas heating to an ASHP hybrid system. The SDFSS facilitates this shift by enabling integration with older systems and providing a low-emission heating alternative. Furthermore, the SDFSS's connectivity and flexibility allow integration with utility demand response, photovoltaic systems, ASHP water heaters, and temperature predictions. This comprehensive assessment enables the SDFSS to optimise switching criteria and, in the future, potentially manage other heating systems.

Limitations The key limitations of this study arise from its reliance on a single net-zero energy home in southwestern Ontario and modelling simulations for four other Ontario cities, which restricts the generalizability of its findings to other climates, house types, and occupancy patterns. Key modelling assumptions can also impact accuracy. The performance curves for ASHP, which are based on manufacturer data, may only provide approximations, especially under part-load and cold-weather conditions. Additionally, relying on static or region-specific electricity and natural gas price data can further limit precision. Moreover, more real-time data from diverse situations is necessary to enhance the models' accuracy and the results of the parametric analysis. These constraints suggest that while the results are promising, they should be interpreted cautiously and validated through broader, more detailed modelling.

Abbreviations ASHP: Air Source Heat Pump; COP: Coefficient of Performance; GHG: Greenhouse Gas Emissions; HDD: Heating Degree Day; HVAC: Heating, Ventilation, and Air-Conditioning; IESO: Independent Electricity System Operator; NGF: Natural Gas Furnace; NZEH: Net Zero Energy Home; RSME: Root-Mean-Square Error (RMSE); SCM: Switching Control Model; SDFSS: Smart Dual Fuel Switching

System; TMY: Typical Meteorological Year; TOU: Time-of-Use; PV: Photovoltaic; TRNSYS: Transient System Simulation Tool

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Data Availability Data is confidential and will be made available on request.

Declarations

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Environment and Climate Change Canada. (2023). Greenhouse gas sources and sinks in Canada: National inventory report 1990–2016. Government of Canada. https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/sources-sinks-executive-summary-2023.html

[2] Independent Electricity System Operator. (n.d.). Long-term energy plan. https://www.ieso.ca/en/Sector-Participants/Engagement-Initiatives/Engagements/Long-Term-RFP

[3] Independent Electricity System Operator. (n.d.). Ontario planning outlook. https://www.ieso.ca/en/Sector-Participants/Planning-and-Forecasting/Annual-Planning-Outlook

[4] Government of Ontario. (2018). Archived – The end of coal. https://www.ontario.ca/page/end-coal

[5] Natural Resources Canada. (n.d.). Canada's GHG emissions by sector, end use and subsector – Including electricity-related emissions. http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=HB&sector=aaa&juris=ca&rn=3&page=0

[6] Environment and Climate Change Canada. (2024). Ontario and pollution pricing. https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work.html

[7] Government of Ontario. (2014). Ontario Regulation 332/12: Building Code (Building Code Act). https://www.ontario.ca/laws/regulation/120332

[8] Natural Resources Canada. (2018). Details of the R-2000 standard. https://www.nrcan.gc.ca/homes/learn-about-professional-opportunities/become-energy-efficient-builder/details-r-2000-standard/20588

[9] Natural Resources Canada. (2014). ENERGY STAR® for new homes standard (Version 12.6). https://www.nrcan.gc.ca/energy/efficiency/housing/new-homes/energy-starr-new-homes-standard/energy-starr-new-homes-standard-version-126/14178

[10] Delisle, V. (2011). Net-zero energy homes: Solar photovoltaic electricity scenario analysis based on current and future costs [Conference presentation]. ASHRAE Conference, Montreal, Canada. https://natural-resources.canada.ca/sites/www.nrcan.gc.ca/files/canmetenergy/files/2011-040.pdf

[11] Natural Resources Canada. (2018). Residential sector Canada: Heating system stock by building type and heating system type (Table 27). http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=res&juris=ca&rn=27&page=0

[12] Safa, A. A., Fung, A. S., & Kumar, R. (2015). Comparative thermal performances of a ground source heat pump and a variable capacity air source heat pump systems for sustainable houses. Applied Thermal Engineering, 81, 279–287. https://doi.org/10.1016/j.applthermaleng.2015.02.039

[13] Udovicenk, A., & Zhong, L. (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, 26(9), 1352–1370. https://doi.org/10.1080/23744731.2020.1787083?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle

[14] Demirezen, G., Fung, A. S., & Deprez, M. (2020). Development and optimization of artificial neural network algorithms for the prediction of building-specific local temperature for HVAC control. International Journal of Energy Research, 44(11), 8513–8531. https://doi.org/10.1002/er.5537

[15] Alibabaei, N., Fung, A. S., Raahemifar, K., & Moghimi, A. (2017). Effects of intelligent strategy planning models on residential HVAC system energy demand and cost during the heating and cooling seasons. Applied Energy, 185, 29–43. https://doi.org/10.1016/j.apenergy.2016.10.062

[16] Peng, W., Hisham, Z., & Pan, J. (2010). Household-level fuel switching in rural Hubei. Energy for Sustainable Development, 14(3), 238–244. https://doi.org/10.1016/j.esd.2010.07.001

[17] Strbac, G. (2008). Demand side management: Benefits and challenges. Energy Policy, 36(12), 4419–4426. https://doi.org/10.1016/j.enpol.2008.09.030

[18] Klein, K., Herkel, S., Henning, H.-M., & Felsmann, C. (2017). Load shifting using the heating and cooling system of an office building: Quantitative potential evaluation for different flexibility and storage options. Applied Energy, 203, 917–937. https://doi.org/10.1016/j.apenergy.2017.06.073

[19] Robillart, M., Schalbart, P., Chaplais, F., & Peuportier, B. (2019). Model reduction and model predictive control of energy-efficient buildings for electrical heating load shifting. Journal of Process Control, 74, 23–34. https://doi.org/10.1016/j.jprocont.2018.03.007

[20] Government of Ontario. (2025). Electricity price plans. https://www.ontario.ca/page/electricity-price-plans

[21] Government of Canada, Department of Finance. (2018). Backgrounder: Fuel charge rates in listed provinces and territories. https://www.canada.ca/en/department-finance/news/2018/10/backgrounder-fuel-charge-rates-in-listed-provinces-and-territories.html

[22] TRNSYS. (n.d.). Suite of tools – Features: Transient system simulation tool. https://www.trnsys.com/features/suite-of-tools.php.html

[23] Environment and Climate Change Canada. (2019). The federal carbon pollution pricing benchmark. https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/carbon-pollution-pricing-federal-benchmark-information.html

[24] Entegrus. (2019). Electricity rates. https://www.entegrus.com/electricity-rates-0/

[25] Toronto Hydro. (2019). Residential electricity rates. https://www.torontohydro.com/for-home/rates

[26] ENWIN Utilities. (2019). Regulatory information. https://enwin.com/regulatory-information/

[27] Synergy North. (2019). Residential electricity rates. https://synergynorth.ca/residential/billing/rates/

[28] U.S. Department of Energy. (2019). EnergyPlus weather data sources. https://energyplus.net/weather/sources

[29] Gordon, C., & Fung, A. S. (2009). Hourly emission factors from the electricity generation sector: A tool for analyzing the impact of renewable technologies in Ontario. Transactions of the Canadian Society for Mechanical Engineering, 33(1), 1–16. https://doi.org/10.1139/tcsme-2009-0010

[30] Gordon, C., & Fung, A. S. (2011). Analysis of time-dependent valuation of emission factors from the electricity sector. In M. Nayeripour (Ed.), Sustainable growth and applications in renewable energy sources. https://www.intechopen.com/chapters/24436

[31] Enbridge Gas. (2019). Conversion factors. https://www.enbridgegas.com/storage-transportation/doing-business-with-us/unit-measure-conversion-information

[32] Government of Ontario. (2019). Guide: Greenhouse gas emissions reporting. https://www.ontario.ca/page/guide-greenhouse-gas-emissions-reporting

[33] Ontario Energy Board. (2019). Natural gas rates. https://www.oeb.ca/consumer-information-and-protection/natural-gas-rates

[34] Tung, K., Wang, A., Ekrami, N., & Fung, A. S. (2018, May 9–10). Numerical study on smart dual fuel switching systems in net zero energy homes [Conference paper]. Proceedings of eSim 2018, IBPSA-Canada, Montreal, Canada. https://publications.ibpsa.org/proceedings/esim/2018/papers/esim2018_1-3-B-5.pdf