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Numerical study on smart dual fuel switching systems in net zero energy homes

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Abstract: *Hybrid residential HVAC system having an air-source heat pump (ASHP) coupled with a natural gas furnace can use relatively clean and inexpensive electricity to meet space heating demands. Currently, the heating source switches from the air source heat pump to the natural gas furnace at a pre-set outdoor temperature, thus making such system inflexible and not optimal. A full analysis was performed on a net-zero energy house (NZEH), located near London, Ontario, to ensure it meets NZEH requirements. It consists of a smart-switching thermostat that utilizes a set of temporal parameters to continuously optimize the switching point between the ASHP and furnace to minimize the total energy cost for the homeowner. The overall system was modeled to demonstrate the potential benefits of such Smart Dual Fuel Switching System (SDFSS) in this NZEH in terms of energy demand, associated operating cost and greenhouse gas emission on annual basis.*

Keywords: *Simulation, Sustainability, NZEH, Smart Dual Fuel switching System (SDFSS), ASHP*

INTRODUCTION

Residential buildings are starting to adopt air source heat pumps (ASHP) or ground source heat pumps (GSHP) to reduce the operational cost and reduce the environmental impact. An advanced cold climate ASHP is found to be a more economical and affordable option for the Northern cold climatic conditions in Canada compared to a GSHP while also having a comparable seasonal performance (Safa, Fung, & Kumar, 2015). In this context, an ASHP is essential to reduce the energy cost of heating and cooling of residential houses. One of the issues with adapting an ASHP is the higher operating cost when compared with the typical natural gas system. Another limitation is the lower performance of the ASHP during the extreme cold winter temperatures in Canada. This also means that the ASHP might not be able to meet the heating demand during these conditions without relying on auxiliary or supplemental heat source.

This study will discuss the preliminary results of the study on a dual fuel system that utilizes a natural gas burning furnace as a supplemental fuel source with the ASHP. The current switching system in the market utilizes a pre-set balance outdoor temperature point which determines whether the ASHP or the supplementary furnace will be operating. Since this is an inflexible system, it also cost more to operate than a full natural gas system.

A system was developed by Ryerson University that utilizes the time-of-use electricity price and natural gas prices and other temporal parameters to compare the energy cost of the two fuel sources. This smart dual fuel switching system (SDFSS) will communicate with the HVAC system to operate either the ASHP or the supplementary heater depending on the operational cost. Since this system uses hourly parameters, the switching system provides an hourly update to the HVAC switching control.

An energy audit was conducted on a net-zero energy house located at Strathroy, a city 35km west of London, Ontario. A depressurization test, thermal imaging test, combustion test and full plug-load and lighting audit was conducted. The home owners were interviewed to collect usage data and all electrical plug-loads were documented. The annual electricity consumption was calculated, and the daily electricity consumption was also calculated. These daily values were used for the simulation model. A TRNSYS model was created with the dimensions and data collected through the audit. The TRNSYS model simulates the heating demand using the available weather data for London, Ontario.

A thorough analysis of the ASHP was done to create a performance and capacity curve of the ASHP. The curve was used to estimate the performance of the heat pump. The results were used along with the heating demand simulated by the TRNSYS model to calculate the optimal fuel at the hour.

This study compares different heating sources and different switching systems including standard natural gas, setpoint switching to natural gas at -5°C, setpoint switching to

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natural gas at 5°C, setpoint switching to 100% efficiency baseboard at -5°C, setpoint switching to 100% efficiency baseboard at 5°C, all 100% efficient baseboard and system with only ASHP. The SDFSS was found to reduce the energy cost when compared with the other switching systems analysed.

BACKGROUND INFORMATION

Net-Zero Energy House

The Net Zero Energy House (NZEH) is a reoccurring theme in the topic of energy efficiency. The Strathroy house studied is currently considered a NZEH. Since NZEH is still considered a newer topic without a set standard. NZEH can be defined as a building that has demonstrated through actual annual measurement that the delivered energy is less than or equal to the on-site renewable exported energy (US Department of Energy 2015). A paper in the Rehva Journal stated that a nnZEB is commonly used for nearly net zero energy buildings which is defined as "a building using 0 kWh/(m²a) primary energy." (Kurnitski, et al., 2011). Primary energy is the "energy from renewable and non-renewable sources which has not undergone any conversion or transformation process." (Kurnitski, et al., 2011).

A "nearly zero-energy building' is a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby;" (Energy Performance Building Directive, 2010). Net zero energy is purely a number-based definition. There are no specific standards for insulation or equipment efficiency but in general, in order for a building to reach NZE, it would depend strongly on the climate, the inherent energy efficiency measures in the home design, the equipment and the occupant behaviour.

Air Source Heat Pump

Heat pumps has been an existing technology for many decades. It has evolved to become a mature technology over the past two decades (Chua, Chou, & Yang, 2010).

There are many different types of heat pump and in this study, the NZEH uses an air source heat pump (ASHP) as its main source of heating. An air source heat pump (ASHP) is a system that absorbs heat from the surrounding air from the outdoor and expels the heat into the interior for heating during winter seasons. During the summer, the ASHP can reverse its operating cycle and absorb the heat in the interior and exhaust it out to the exterior.

Natural gas heating furnaces are commonly used in the residential dwellings in Ontario mainly due to the low price and broad availability of natural gas. This reduces the energy cost benefits of utilizing an electricity driven heat pump since the price of electricity is higher per equivalent energy content.

The studied house currently has an ASHP which has a rated capacity of 24,000 BTU/hr, EER of 13 and SEER of 21. The heat pump does not specify to be a cold climate heat pump but was mentioned that the balance point can be set by the user from the range of -15°C to 10°C. This balance point is an outdoor set-point temperature that controls the switching between ASHP and natural gas furnace. If the outdoor temperature is lower than the balance point, the ASHP would no longer operate and the heating is fully done by the furnace.

To model and utilize the heat pump in a simulation model, the COP and capacity curve must be created. For the heat pump installed in the studied NZEH, the published tabulated performance parameters, did not provide enough data points to create accurate heat pump performance and capacity curves. The manufacturer only provided points for -8°C and 8°C. Instead of using the incomplete data, the published specifications (capacity, COP, SEER) of a similar heat pump were compared to the installed heat pump. Using this data, the "ASHP Capacity Versus Outdoor Temperature" curve and "COP Versus Outdoor Temperature" curve were generated.

The studied ASHP is a variable capacity heat pump which changes the compressor speed during lower loads to meet the demand of the house. The COP will change according to the partial load at given outdoor temperature. To estimate the related COP for a given capacity, the COP was interpolated proportionally according to the heating capacity values. If the maximum capacity for the heat pump is sufficient to meet the demand, the maximum capacity and its COP will be used. If the maximum capacity is lower than the required heating demand of the house, the supplementary heater will be operating instead to satisfy the heating demand.

Figure 1 and Figure 2 show the chosen heat pump capacity and COP curves with trend line functions. The new capacity and COP curves as a function of outdoor temperature were taken and interpolated to estimate the actual COP at given outdoor temperature and capacity. As seen in Figure 1 and Figure 2, the trend shows that the lower the outdoor temperature, the lower the COP and capacity.

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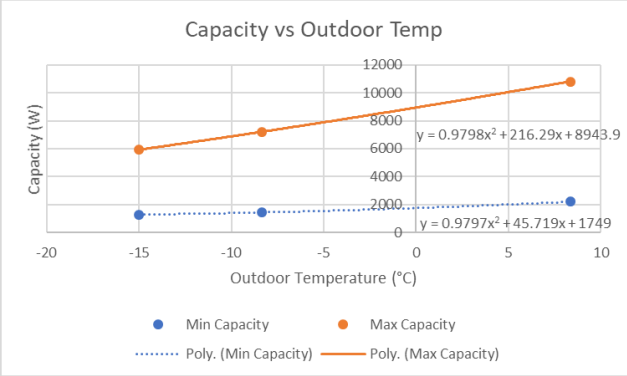

Figure 1: Chosen ASHP Capacity vs Outdoor Temperature

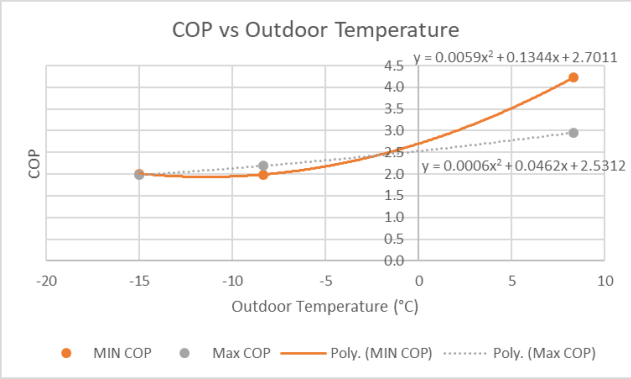

Figure 2: Chosen ASHP COP vs Outdoor Temperature

Figure 1 shows the capacity as a function of outdoor temperature as well as the range in capacity from minimum to maximum. Figure 2 shows COP as a function of outdoor temperature over the same range as the capacity. Using these functions, the COP for any given capacity within the curve can be approximated by interpolation.

Experimental data is being collected by utilizing Wattnode power meters, and natural gas meters on natural gas inlet for the furnace and the domestic hot water. First, the HVAC system will be set manually to furnace mode in order to record natural gas consumption during the heating season. Since the efficiency of the furnace is available and confirmed with on-site measurement, the heating demand can be calculated with the data. This data will be used to calculate the actual COP in the future. The COP can then be used to create a more accurate curve with multiple points.

Historical Weather Data

A typical meteorological year (TMY) is a common type of weather data used for simulation in order to assess the heating and cooling demands of the designed building. The TMY data consist of hourly data for both solar radiation and other meteorological data that allows performance comparison of different models. The TMY data is generally used to represent conditions over a long period of time.

The software that is used for this study (TRNSYS and HOT2000) utilize different weather formats. TRNSYS is able to use multiple different types of weather data. The most commonly used file types are the TMY and the EPW both of which have readily available files for the major cities.

HOT2000 utilizes a normalized monthly weather data including the solar radiation and wind speeds. The default weather data only provides one temperature data for the full month.

Currently, the experimental process is ongoing, and a dedicated weather station was installed adjacent to the house in order to record localized weather data. This can provide a better set of weather information. In the future, the collected weather data will be implemented to the model to further calibrate the model.

Creating Weather Data

The weather data required for Strathroy is not readily available. Based on available weather data, London (Ontario) weather data was selected as a close approximation to Strathroy. In this study, most of the points of the weather data was extracted from the historical weather data from Environment Canada. The study was done before the end of the year hence the weather data for the last quarter of the year is taken from the data of the previous year.

In order to use the weather data in TRNSYS, the file format must be in the required formats. The file format chosen was the epw (EnergyPlus Weather) format and EnergyPlus was used to convert the hourly weather dataset into a useable epw file.

Since HOT2000 utilizes a different weather format, the simulation results using this weather data file yielded a different result when compared with the simulation results with the actual hourly weather data from TRNSYS.

House Description

The studied net-zero energy house is located in Strathroy, Ontario, Canada. This house has a south facing solar roof and west facing front door. There is no significant shading on the house from the surrounding environment.

This newly built house was occupied starting from April 2017. It demonstrates low energy consumption and an air-tight building envelope according to the HOT2000 model provided by the building consultant.

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The studied house includes many energy efficient technology including energy efficient furnace, domestic hot water heater (DHW) and drain water heat recovery system (DWHR). This reduces the energy consumption when compared with the average household consumption. An air source heat pump (ASHP) is used as the main heating and cooling equipment. The heating system is supplemented with a natural gas burning furnace for extreme low temperature. The default switching system utilizes the outdoor set-point temperature (outdoor set-point temperature switching) to determine which heating source is used.

The R-values on the wall, windows, roof and slab was found on the building specification provided by the builder and is summarized in Table 1.

Table 1:Wall Insulation Values

Wall	Nominal R-Value
Main Floor Wall	R34 Nominal
Basement Wall	R34 Nominal
Basement Slab	R10 Nominal
Ceiling	R60 Nominal
Main Floor Windows	Triple Glazed Low-e Solar Glass R-Value: 4.73 Nominal
Basement Windows	Triple Glazed Low-e Solar Glass R-Value: 3.55 Nominal

The house infiltration rate at 50Pa was specified to be 0.53 ACH and the consultant used typical values for plug loads to generate the HOT2000 simulation model.

To verify the specifications, a full energy audit was performed to measure appropriate plug-loads, verify the mechanical equipment performance and verify the infiltration rate. These tests included the combustion test, depressurization test, thermal imaging camera, lighting and plug-load testing. These values were compared with a model that was provided by the consultant during the construction phase.

The depressurization test concluded that at 50Pa, the infiltration rate is 0.54 ACH. This confirmed that the infiltration rate at 50Pa matches the builder's specification.

The lighting and appliance usage habitats of the occupants was investigated by conducting an interview with the home owners. Since the homeowners are retired couples, the usage was lower than the consultants estimated value in the model.

Table 2: Plug Loads and Lighting Energy Consumption

	Daily Consumption (kWh/day)	Annual Consumption (kWh/year)
Lighting	1.67	609
Appliances	12.2	4457

Table 2 shows the energy consumption of the lighting and appliances calculated from the energy audit. The annual lighting usage used for calculating the energy consumption was estimated to be 1000 hours a year for each lighting fixture (Fung & Ugursal, 1996).

The values calculated and gathered from the audit were used to update the TRNSYS model to account for internal heat gains. The internal heat gains reduce the required heating load during the winter but increases the required cooling load.

Simulation

This study was started by using the case study HOT2000 model provided by the building consultant at the time of construction. HOT2000 is suitable for the HOT2000 compliance program but since uses bin method for simulation, it is not suitable for hourly analysis in this project. The details from the model and the energy audit were used as input parameters into TRNSYS to perform an accurate simulation. Comparison of HOT2000 and TRNSYS will be done for future work.

TRNSYS Model

Transient System simulation tool (TRNSYS) is a program designed to solve complex transient system problems. The program consists of multiple tools/subsystems (similar to subroutines of a programming software) that are connected together through related paths and variables. These connections combined with the different subsystems represents one model. The TRNSYS simulation was modeled with the specifications provided from the builder. The model was initially created with only the required insulation and the shape of the building. The building model consists of 5 different zones where only two of the zones are considered conditioned. The first floor and basement are considered two different conditioned zones while the garage, attic and cold room are considered unconditioned. The model was then refined with the internal gains taken from the detailed energy audit.

Figure 3 shows the TRNSYS Studio and the network of connections. The weather file created using historical weather data from statistic Canada did not have the solar

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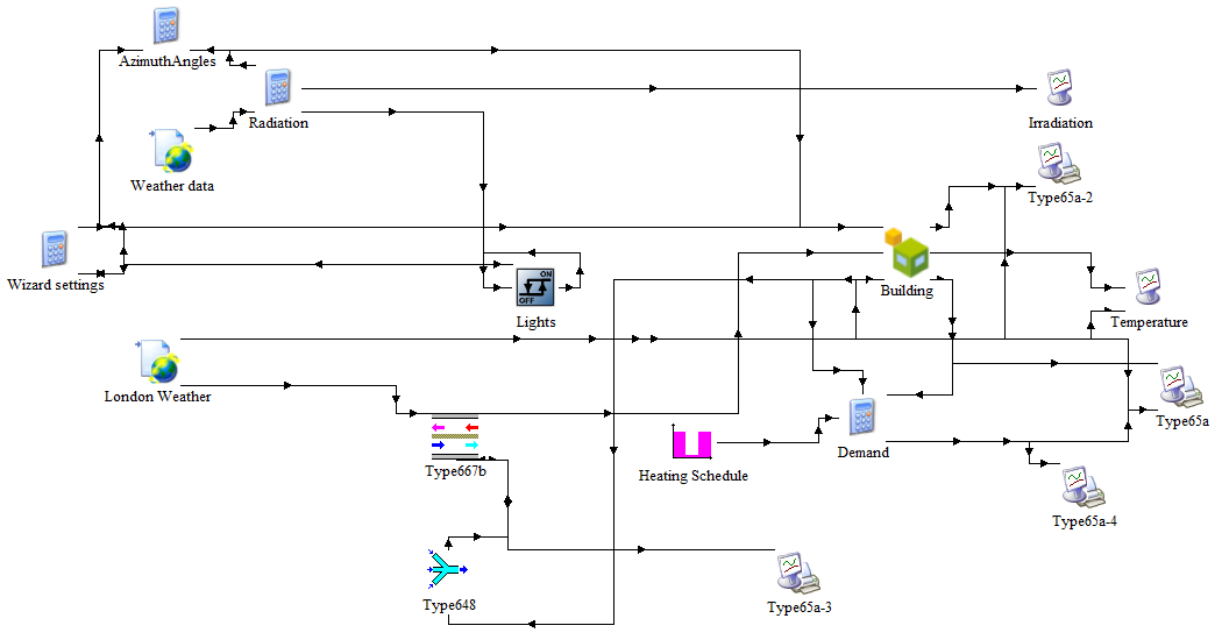

Figure 3: House Model in TRNSYS Studio

information. To account for solar gains, a separate weather file of Toronto's solar information was used. Additionally, an ERV was simulated with TRNSYS template Type 667b.

TRNSYS Methodology

A 3D model was created on SketchUp for the TRNSYS simulation. The TRNSYS program allows the user to create a 3D model using Google SketchUp and the TRNSYS Google SketchUp toolbar. The appropriate air node and windows were modeled on the house. The dimensions of the house were taken from the designer drawings. The windows and backdoor were designed to be low-solar, triple glazed glass. The TRNSYS software allows the user to change whether the windows are shaded or not. For this model, the windows were assumed not shaded.

The building also sits on uneven ground. The basement windows are sitting halfway between the grade-line. To simulate the model in TRNSYS, the walls and windows are divided into two different components. The components above the grade line is considered to have an outdoor boundary while the below grade components are adjacent to the ground instead of the outdoor air. The main door, garage door and side doors were made as a wall type with typical fibreglass material and typical garage door materials. Since the nominal RSI for these components were not provided, the material was selected from a list of TRNSYS pre-set materials. Since the garage door is in an unconditioned area, the impact of this is not critical. The doors located between the conditioned areas and the outdoor environment might affect the heating demand.

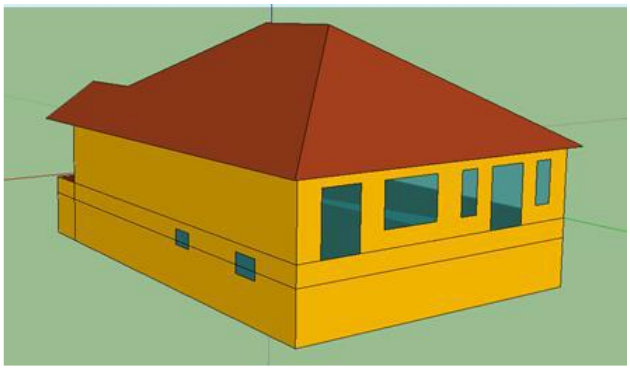

Figure 4: South-East Side of the House

The solar panel are south-facing and the back entrance is facing east. The solar panels are not modelled into TRNSYS 3D model and the power generated is factored into the calculation separately.

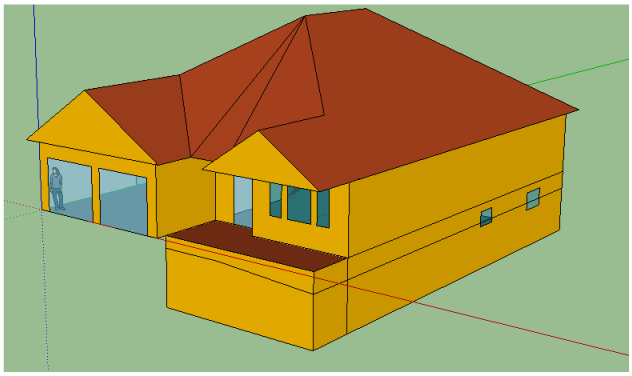

Figure 5: Front Side of the House

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Figure 5 shows the front of the NZEH model and Figure 6 shows a photograph of the house.

Figure 6: Photograph of the Net-Zero Energy House

As seen on Figure 6, the solar PV panels are installed on the south facing roof with a total of 33 solar panels are installed providing a total installed capacity of 8.745kW.

SIMULATION RESULTS

The program TRNSYS was used for the simulation of heating and cooling demands of the house. With the simulated values, an extensive Excel model was used to calculate and simulate different switching scenarios. A model of the house heated conventionally with a natural gas furnace was compared with the set-point outdoor temperature switching system with electrical and natural gas supplement, and the smart dual fuel switching system (SDFSS). The set-point temperature switching was simulated at 5°C and -5°C while the SDFSS utilizes the hourly cost of electricity to determine the most economical fuel source.

Heating Demand on TRNSYS

The studied NZEH model was simulated over a period of a year to obtain the annual heating and cooling load. Figure 7 illustrates the hourly outdoor temperature with maximum of 33.85°C and minimum of -21°C. The heating season was assumed to be from January 1st (1 hour) to May 22nd (3408 hour) and from October 1st (6576 hour) to December 31st (8760 hour). The indoor set point temperature was adjusted to 20°C for the heating season and the cooling set point temperature was adjusted to 24°C. These set point temperatures were taken from the audit response from the homeowners.

Figure 8 shows the hourly heating and cooling load for the year. The maximum summer temperature in the weather file is at 33.85°C and the lowest winter temperature is -21°C. The hourly outdoor temperature is compiled, and a graph of the data is created. The cooling load for the year is zero, hence the cooling data is removed from the graph. This aligns with the interview and audit from the homeowners. The homeowner commented that the house was extremely comfortable even during the harsh summer temperatures. During the heating season, the peak heating load was found to be 4.26 kW and by the end of the full heating season, the total heating consumption was estimated to be 12,243 kWh.

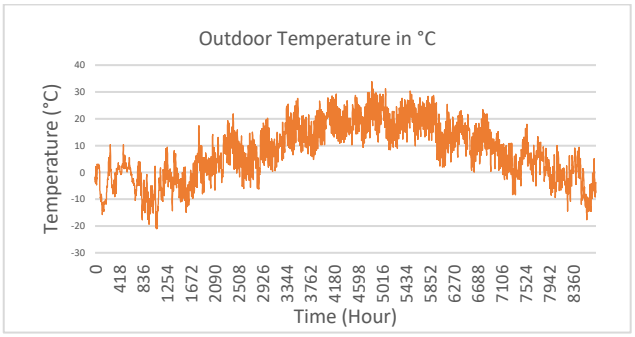

Figure 7: Annual Hourly Outdoor Temperature

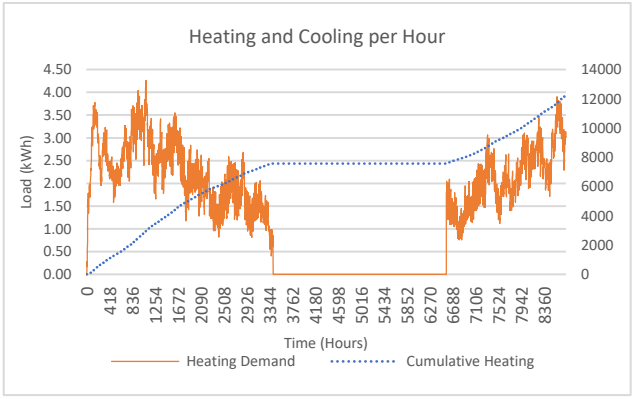

Figure 8: Simulated Hourly Heating and Cooling Load, and Cumulative Demand

Fuel Switching System Modelling

When the air source heat pump (ASHP) could not provide enough heat to meet the space heating demand of the house, a switching system changes the heating source from the ASHP to a different heating system. This system is useful since it allows the homeowners to save operational costs by selecting a better option that provides enough heating capacity at a lower energy cost.

The results from the simulation is summarized in **Error! Reference source not found.** which includes the operational costs, electricity consumption, natural gas consumption and GHG emission for heating. The results shown only takes account of the furnace or ASHP energy and does not take account of the DHW, lighting and plug load energy consumption. At the current stage of the project, the energy costs of the different switching scenarios do not take account of the potential economic benefits of the photovoltaic system. The photovoltaic panels will be monitored experimentally and will be implemented in future work.

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In this project, the installed air source heat pump switching system is a fixed set-point switching system. This means that at a pre-set outdoor temperature, the system controls the heat pump to switch the heating source from a ASHP to the supplementary natural gas furnace. The system also allows the homeowner to choose the switch over set-point temperature to any temperature from -15° to +10°C. In this project, the common comparison value of -5 was selected for the ASHP switching point. Six different models were compared: 1) set point temperature switching with natural gas furnace, 2) economically smart switching between ASHP and natural gas furnace, 3) set-point switching with electric baseboard backup (100% efficient), 4) pure natural gas furnace only, 5) baseboard only (100% efficient), 6) ASHP only.

To achieve this task, a TRNSYS model was developed and used to estimate the hourly space heating demand of the house. The result from TRNSYS was taken to an Excel spreadsheet with the hourly outdoor temperatures and time intervals used. With the trend-lines from the air source heat pump capacity and COP curves, the actual COP at a given hour was interpolated from the graphs for every interval.

The maximum capacity of the ASHP was compared with the heating demand for each hour. If the heating demand is higher than the ASHP maximum capacity, the maximum capacity will be used to calculate the electricity load. Using the capacity and COP of the ASHP curve, the electricity consumption was calculated. The calculated value was then used to calculate the cost of electricity from the ASHP. Any heating demand that exceeds the heat pump's maximum capacity is fulfilled by the supplementary heaters.

The smart switching system model investigated utilizes time-of-use electricity pricing and natural gas pricing in order to select the most optimal cost-effective heating source. When the cost to operate the ASHP is higher than that of natural gas, the system switches the source to natural gas.

The GHG emission factor for the natural gas was taken as 1860g CO_2eq/m³ as reported in the guide line version 2016 for the Greenhouse Gas Emissions reporting on Section 4(1) of Ontario Regulation 452/09 (Government of Ontario, 2016).

The results of the smart switching show that it costs 3% less than natural gas and reduces GHG emissions by 40% and it was 9% more economical than the -5°C switching setpoint temperature to natural gas system.

The results show that there are savings and reductions in both the energy cost and GHG emissions for the smart switching system. From the values, it also shows that the GHG emissions is higher for the pure natural gas system but more economical and for the ASHP with baseboard backup model has lower GHG but much higher operational cost.

According to Alibabaei et al. this smart switching method is not only used to ensure a comfortable thermal level but it also to minimizes the energy cost and energy demands associated with the ASHP (Alibabaei, Fung, Raahemifar, & Moghimi, 2017). Since this smart switching stragety utilizes the cost of operating the ASHP compared with the cost of natural gas, this smart switching method will provide the most cost savings.

Smart Dual Fuel Switching System

To model the switching systems, an Excel program was created to calculate the most cost-effective fuel source at any given hour and the greenhouse gas emission from the fuel source. Excel was used since it is a relatively simple and required less processing power compared to other software like TRNSYS. The algorithm written in Excel can easily be implemented to a server black-box for practical.

The time-of-use electricity price is taken from the Ontario Energy Board (OEB) historical pricing (Ontario Energy Board, 2017). Each hour of the day is categorized as off-peak, mid-peak and on-peak hours where the highest cost of electricity is during high-peak. Table 3 shows the time ranges during weekdays for the different peak levels in summer and winter. Holidays and weekends are considered off-peak hours. The cost of electricity for the different peak hours are changed by the OBC within the year and are also summarized in Table 3.

Table 3: Time-of-Use Hours during Weekdays

Time Range	Summer	Winter
0:00-7:00	Off-Peak (15.6¢)	Off-Peak (15.6¢)
7:00-11:00	Mid-Peak (11.9¢)	On-Peak (8.9¢)
11:00-17:00	On-Peak (8.9¢)	Mid-Peak (11.9¢)
17:00-19:00	Mid-Peak (11.9¢)	On-Peak (8.9¢)
19:00-24:00	Off-Peak (15.6¢)	Off-Peak (15.6¢)

The other electricity related charges were taken from Entegrus, the electricity distributor in Strathroy. The marginal cost of electricity takes account of the extraneous charges imposed by the distributor. Since the price of electricity changes depending on the time of day, hourly marginal electricity cost is required to calculate the pricing accurately. Since electricity production depends on the powerplant from which the electricity was generated, the GHG emissions also varies hourly.

The cost of natural gas is consistent throughout the day and the cost only varies depending on the monthly natural gas

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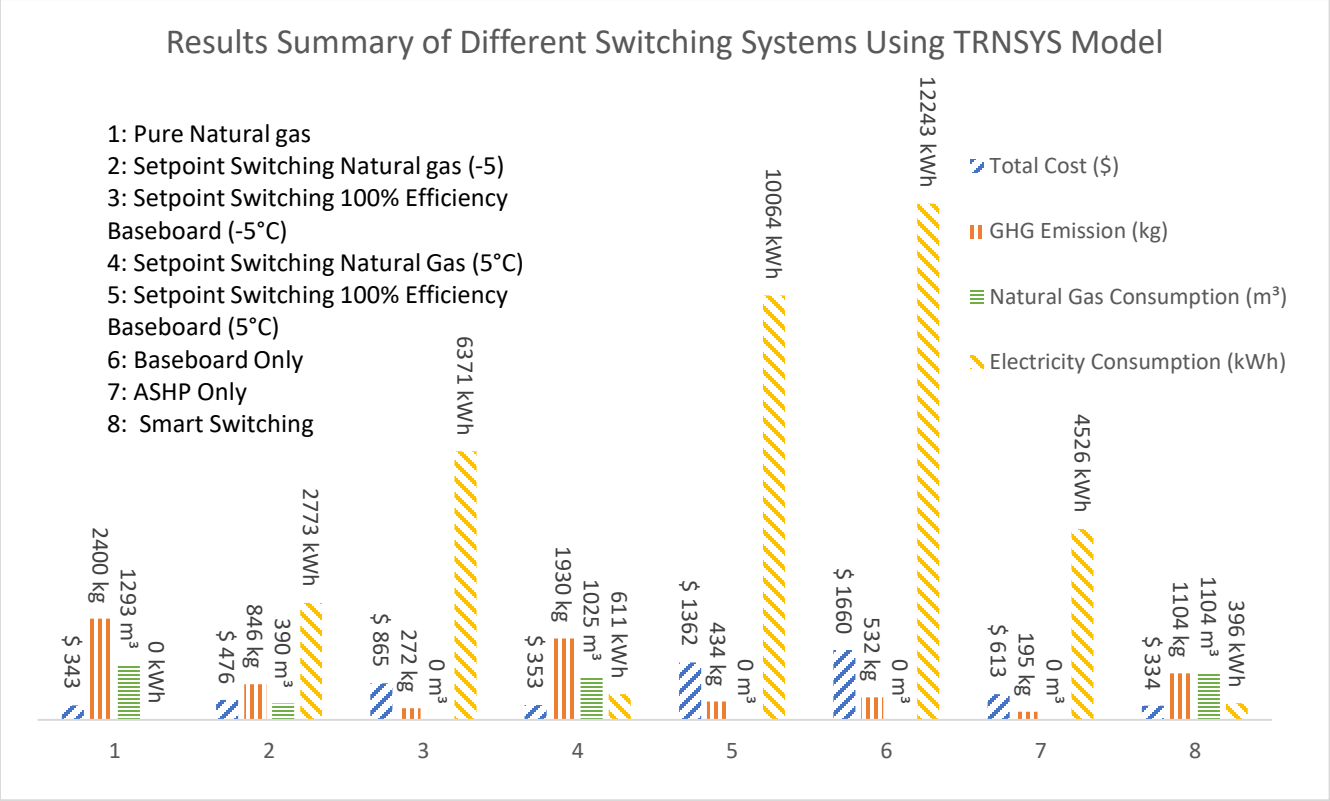

Figure 9: Switching System Comparison with Outdoor Switching Temperature of -5°C and 5°C

amount. The local distributor for the studied house is Union Gas Limited and the marginal price per m³ was calculated with the distribution cost charged by Union Gas.

CONCLUSION

This study and the simulation of a hybrid HVAC system utilizing an ASHP together with a natural gas fueled furnace has been completed to understand the baseline energy consumption an actual "Net Zero Energy House" as well as the potential reduction in energy consumption utilizing a smart dual switching control system.

The updated ASHP capacity and COP curve, shows that the ASHP in the studied house drop in performance as the outdoor temperature drops. The energy audit verified the as-built drawings and the specifications for the envelope. The plug-loads and lighting energy usage were updated for the models.

Based on London Airport 'epw' weather file, the heating demand simulation in TRNSYS was able to confirm natural gas consumption, electricity consumption, GHG emission and total energy cost under various scenarios of heating fuel source, equipment and set points. These scenarios were then exported to an Excel format to investigate the advantages of prioritizing heating source based on optimal time-of-use electricity and natural gas pricing.

The results show that smart switching based on time-of-use electricity pricing reduces energy cost in all scenarios, including purely natural gas fired heating. Though this study was done on a house with an ASHP and natural gas furnace pre-installed, there is potentially higher savings when the SDFSS is used on an older house. Other than energy savings, the SDFSS could be used to offset peak natural gas or electricity usage. If the demand for natural gas for the hour is high, the distributor could send a signal to the thermostat to switch the heating source from natural gas furnace to ASHP. The same could be done if the electricity demand is higher.

Further sensitivity analysis will be done in the future to explore the effect of the SDFSS in different Canadian cities. The weather data will be used for the different cities to verify the potential benefits of implementing the system. In addition to that, sensors are being installed at the studied house in order to monitor the house energy consumption. The collected data will be used to verify the model and to fine tune the simulation model.

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