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Experimental and sensitivity analysis of a smart dual fuel system in a net-zero energy home

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Abstract. Hybrid residential HVAC system, comprising of with a natural gas furnace and an air-source heat pump (ASHP), is gaining interest as a more environmentally friendly alternative to conventional HVAC system with a natural gas furnace and central air-conditioner. Such hybrid HVAC systems could take advantage of the relatively clean and cost competitive time-of-use (TOU) electricity pricing to meet heating demand with the ASHP during milder winter temperature and off-peak hours. Current hybrid systems rely on a pre-set outdoor temperature set point for heating source switching, thus making such system inflexible and not optimal. In the current study, the NZEH model was experimentally validated using collected data and an extensive sensitivity analysis was performed. The Smart Dual Fuel Switching System (SDFSS) was simulated to operate in different scenarios including different major cities in Ontario (Canada), different types of residential houses, operate under the proposed federal carbon tax and operate with different new time-of-use electricity pricing schemes. The different scenarios demonstrate the benefits and flexibility of such Smart Duel Switching System in terms of reducing the space heating energy consumption and associated operating cost and greenhouse gas emission on an annual basis.

1. Introduction

The global energy demand is on an increase and the global primary energy consumption rose 131 million gigawatt hours in 2009 [1]. If this trend continues to grow at the current rate, the effects of global warming will be more evident. Currently, the emerging nations are consuming more energy at a growth of 3.2% and will exceed the consumption rate of developed countries by the year 2020 [2]. Due to this frightening growth, the Canadian government responded by implementing the Canada Climate Change Action Plan (CCCAP) [3]. In response, Ontario also implemented the long-term energy plan in order to reduce the energy consumption at the provincial level [4]. Both plans aim to reduce the GHG emissions by a factor of 15% when compared to the level of 1990 by 2020. The long-term goal is to further reduce the emissions by 80% by 2050. This is implemented in hopes that it would improve the efficiency of the Ontario's energy system.

As the world strives to reduce their carbon footprint, Ontario achieved its goal of decommissioning all the coal-fired power plant in 2014 [5]. This greatly reduced the greenhouse gas emissions, but to further reduce greenhouse gas emissions, other methods must be used. A recent paper from the Journal of Renewable and Sustainable Energy Reviews found that the residential sector represents 27% of the global energy consumption and 17% of the global CO2 emissions [6]. It was also shown that the three highest global energy consumption is in the transportation, industry, and residential sectors in descending order. To achieve a grid with no GHG emissions, we must transform our existing natural gas heating systems to electric heating, however this poses some critical problems. One main problem is the price of the HVAC system will deter the residents from switching from the use of natural gas to electricity. The other main issue is the utility will not be able to provide enough electricity to meet the increased demand. This project explores an intermittence solution that will act as a transition to full electricity.

This paper discusses the results of the study on a dual fuel system that uses an air source heat pump (ASHP) system, with a natural gas burning furnace as a supplemental fuel source. Current switching systems use one preset balance outdoor temperature point which makes this default system inflexible. This study focuses on a smart dual fuel switching system (SDFSS) developed by Ryerson University that allows the HVAC system to switch its fuel source depending on a few time-variant parameters. This SDFSS communicates with the HVAC system to gather hourly data and weather forecasts. With the collected data from the HVAC system, the SDFSS calculates the most cost-effective fuel source. This system reduces the operation cost which provides an incentive for the homeowner. Additionally, it shifts the electricity demand to natural gas during high electricity peak hours. This allows the electric utility to slowly adapt to the increase of electrical demand.

2. Background Information

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

Net zero energy house (NZEH) is a reoccurring theme within the energy efficient topic. The house is modelled in this paper is located in Strathroy and is built to achieve a net-zero house status. This building is built to with high insulation and low infiltration. Table 1 shows the R-Values of the insulation in the house.

The house's infiltration rate at 50Pa was specified to be 0.53 ACH by the designer. To verify the specification, a depressurization test concluded that at 50Pa, the infiltration rate is 0.54 ACH. The difference between the designed value and the experimental value is very minimal. The depressurization test confirms that the infiltration rate at 50Pa matches the builder's specification. The supplementary natural gas furnace used was rated to be 90% efficiency. This efficiency is maintained consistently throughout the simulation and the sensitivity analysis. The second house used is for the sensitivity analysis is a previously studied house in Toronto and Region Conservation Authority (TRCA) Kortright Center, located at Vaughan, Ontario [7].

3. Air Source Heat Pump

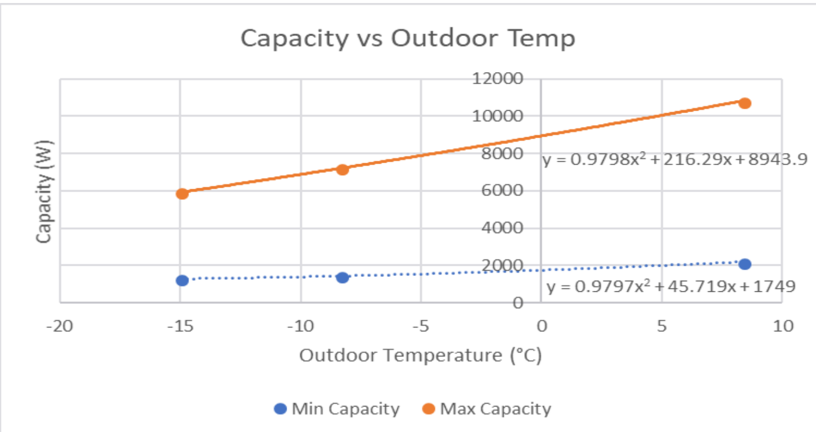

Figure 1:. Chosen ASHP Capacity Vs Outdoor Temperature

The ASHP used in the study is a variable capacity heat pump which can provide the appropriate amount of heating and cooling without constantly turning on and off. Heat pump technology has improved and matured over the past two decades [8]. In this paper, the COP will change according to the partial load at a given outdoor

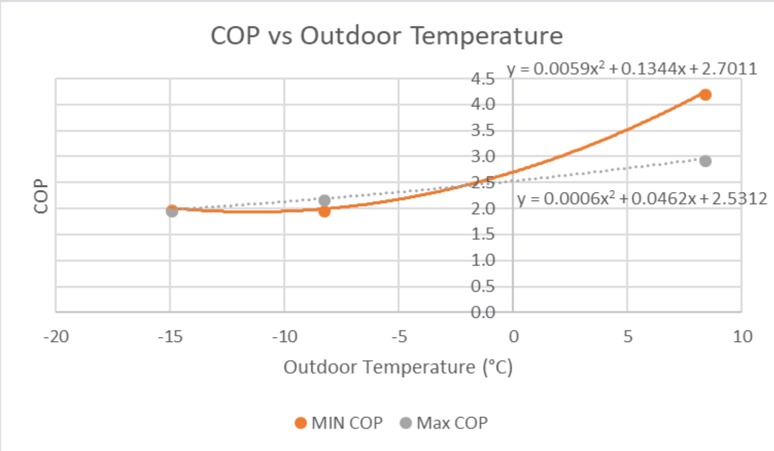

Figure 2. *Chosen ASHP COP vs Outdoor Temperature*

temperature. The rated heating and cooling capacity of the ASHP is 24,000 BTU/hr (7 kW), EER of 13 and SEER of 21.

Figure 1 shows the heat pump capacity versus the outdoor temperature. The numbers and values for the graph are obtained from the manufacturer testing data. Figure 2 shows the minimum and maximum capacity curves. The two graphs are used to calculate its estimated energy consumption. The ASHP information is used as an input for the SDFSS and it takes account of the maximum and minimum capacity along with the maximum and minimum COP to decide the main fuel source. The COP for each required heating demand was interpolated proportionally according to the capacity graphs.

4. Simulation

Table 2. Time-Of-Use Electricity Pricing Scheme

Price Tiers	Current Price	New APP
On-Peak	13.2 ¢	18.3 ¢
Mid-Peak	9.5 ¢	9.2 ¢
Off-Peak	6.5 ¢	6.5 ¢
Super Off-Peak		2 ¢

A previous study modelled a net-zero energy house located at Strathroy, 35km west of London, Ontario, in TRNSYS to simulate the heating demand [9]. The paper also discussed the potential of the SDFSS in different scenarios and cases. Using the aforementioned model also with the data collected from the detailed energy audit and the installed sensors, the model is calibrated to better reflect the data collected.

The calibrated model was used to compare different scenarios in the sensitivity analysis. The sensitivity analysis was performed to compare the effects of the SDFSS for several different Ontario cities and for different house types. Two different electricity pricing schemes and four different carbon tax pricing schemes are also analysed along with the scenarios for different cities and different house types. The results highlight the difference in performance for buildings located in a different climate. Different houses in these climates will also be investigated to represent standard houses.

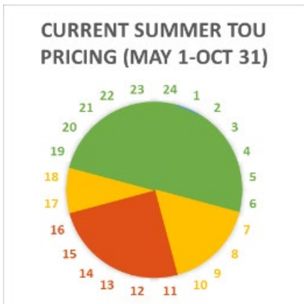

Figure 3. Current Summer TOU Pricing

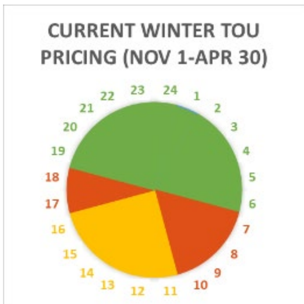

Figure 4. Current Winter TOU Pricing

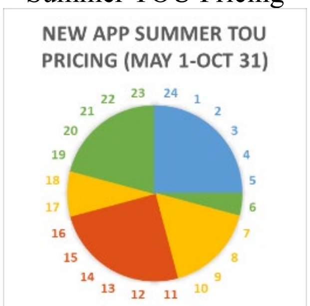

Figure 5. New APP Summer TOU Pricing

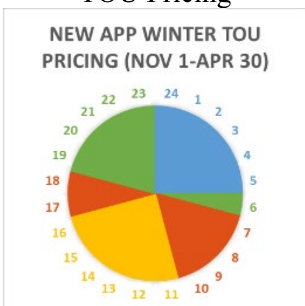

Figure 6. New APP Winter TOU Pricing

The simulations use the time-of-use (TOU) pricing from early 2017 along with the new Advantage Power Pricing (APP) proposed and tested by a local electricity utility company. Figure 3 and Figure 4 shows the current TOU pricing time for summer and winter seasons. Similarly, Figure 5 and Figure

6 shows the TOU pricing scheme for the new APP TOU pricing for summer and winter seasons. Both sets of these time schemes are only valid for weekdays. The weekend and holiday pricing scheme are the same for both pricing plans at the off-peak price. Table 2 shows the cost of each of the different price tiers. The TOU cost was taken from the Ontario Energy Board [10]. Depending on the local distributor, the marginal electricity cost was calculated. The new APP scheme introduces a new price tier called Super Off-Peak which occurs in the hours between midnight to 6 am [11]. The price at these hours is heavily reduced but the price difference is made up by increasing the price during peak hours.

5. Calibration of Model

To calibrate the model, the collected data from the sensors were analysed to identify the estimated space heating demand of the house. Since the initial TRNSYS model did not consider the makeup air in the basement for the range hood, the model was calibrated using the makeup air. Additionally, the heating set point temperature was increased to 23°C from the homeowner's original set point temperature of 20°C. The overall calibrated model better reflected the collected data. The experimental data used to compare the original simulated model is from the month of February to the end of May 2018. The results of the simulated model marginally lower than the experimental results.

The furnace natural gas consumption was collected along with the outdoor temperature. This experimental data was analysed per operating cycle. The consumption was summed for the duration of the cycle and the equivalent hourly consumption was calculated. The temperature is averaged between the interval of the cycle. The original TRNSYS model was used to simulate the energy consumption and a regression line was created. The regression line of the simulated model was compared with the experimental data.

Figure 7 shows the regression of the experimental results and the TRNSYS simulated results. To calibrate the model, the TRNSYS inputs were modified to better represent the experimental findings. One of the main changes to the simulation model was the heating set point temperature. During the extensive energy audit, the homeowner stated that the heating set-temperature was 20°C. When analysing the collected data, the indoor temperature was found to range from 21°C to 23°C. The TRNSYS simulation model was set to 23°C to reach the approximate heating demand of the experimental data.

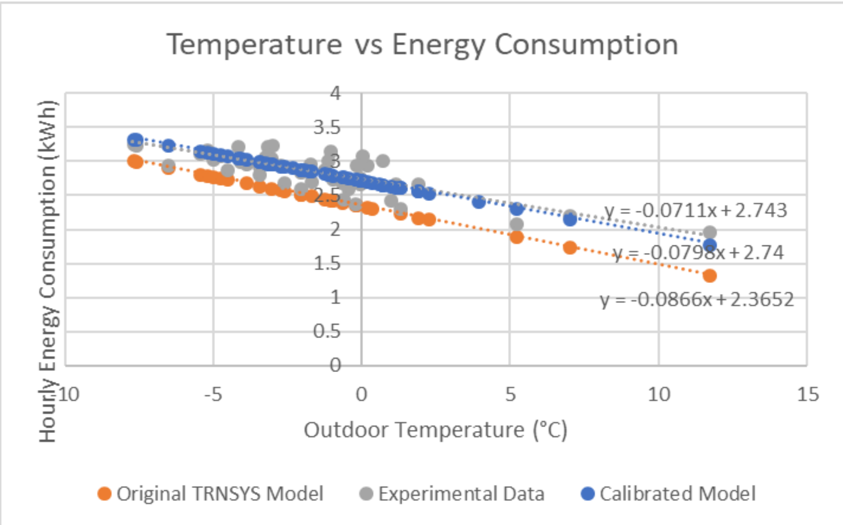

Figure 7. Simulation and Measured Energy Consumption vs Outdoor Temperature

Additionally, due to the kitchen range hood, make-up air is added into the house through the basement as fresh intake air. During the energy audit, it was found that there is a damper located in the basement that adjusts the amount of intake of fresh air. The model was modified to add 10 kg/hr of ventilation air which adjusted the simulation close to the experimental results. Figure 7 also shows the newly calibrated model compared with both the experimental data and the original model. The calibrated model is used for the SDFSS simulation to provide a more accurate simulation of the switching system.

6. Results

The first simulation scenario uses the calibrated Strathroy house model along with London weather data in order to set a baseline for the sensitivity analysis. The operating cost of a typical natural gas furnace and the operating cost of the SDFSS was calculated for the two different electrical pricing scheme and the carbon tax pricing of $0, $10, $25, $50 per tonne of CO2.

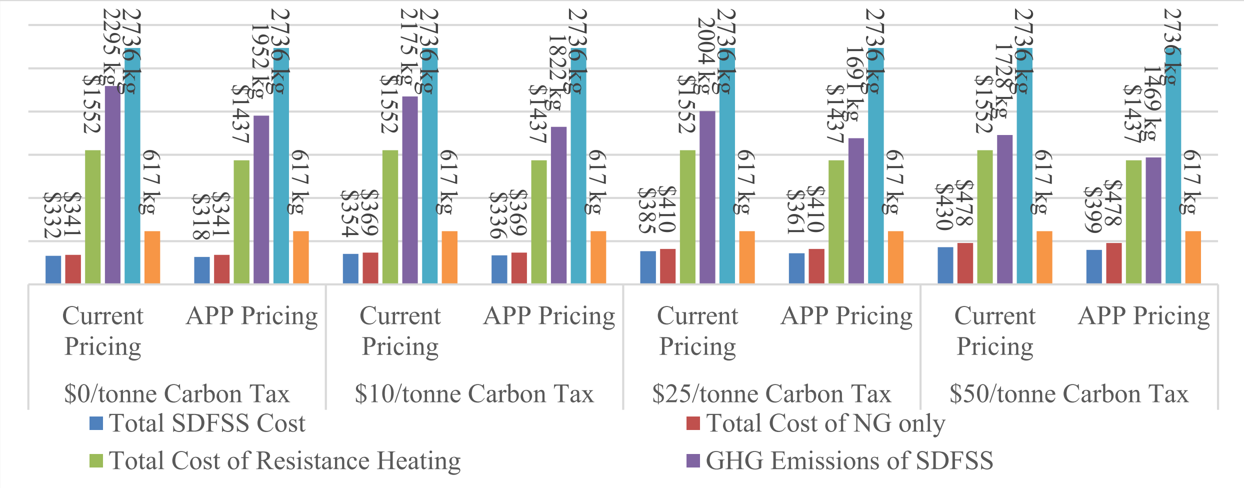

Figure 8. Switching System Different Electricity and Carbon Tax Pricing

Figure 8 shows the different cost and GHG emissions for each pricing combinations. The results show that the SDFSS provides cost reduction in all the proposed carbon tax pricing and the APP schemes. From Figure 8, the SDFSS shows potential cost savings and GHG emission reduction compared to a typical natural gas furnace system. The current pricing without carbon pricing and APP yields annual cost savings of 2.89% and 16% GHG emission reduction which is the lowest savings in all the scenarios. The highest GHG emission reduction is within the $50/tonne carbon tax scenario with an annual GHG emission reduction of 46%. The total cost and GHG emission reduction of a fully resistance heated building is also illustrated but the operating cost associated is extremely high and not economically competitive with natural gas or ASHP.

7. Sensitivity Analysis

A sensitivity analysis was performed for different Ontario cities to represent different climates. Temperature files for four cities, Windsor, Toronto, Ottawa, and Thunder Bay, was used in the simulation. The coldest city studied is Thunder Bay with 5706°C-day heating degree days in 2017 [12].

In the preliminary stage of this analysis, the electricity and the natural gas marginal cost were kept consistent with the London marginal costs while the different cities were used. It was observed in the preliminary stage that in colder climates, the effect of the SDFSS diminishes since the cost of natural gas in London is relatively low compared to electricity cost. The SDFSS utilizes the natural gas as its main fuel in these colder climates since it will be the most economical fuel source. In order to perform an accurate simulation with the different cost, the marginal cost of the different distribution company was research and collected. Table 3 summarizes the marginal cost of both electricity and natural gas.

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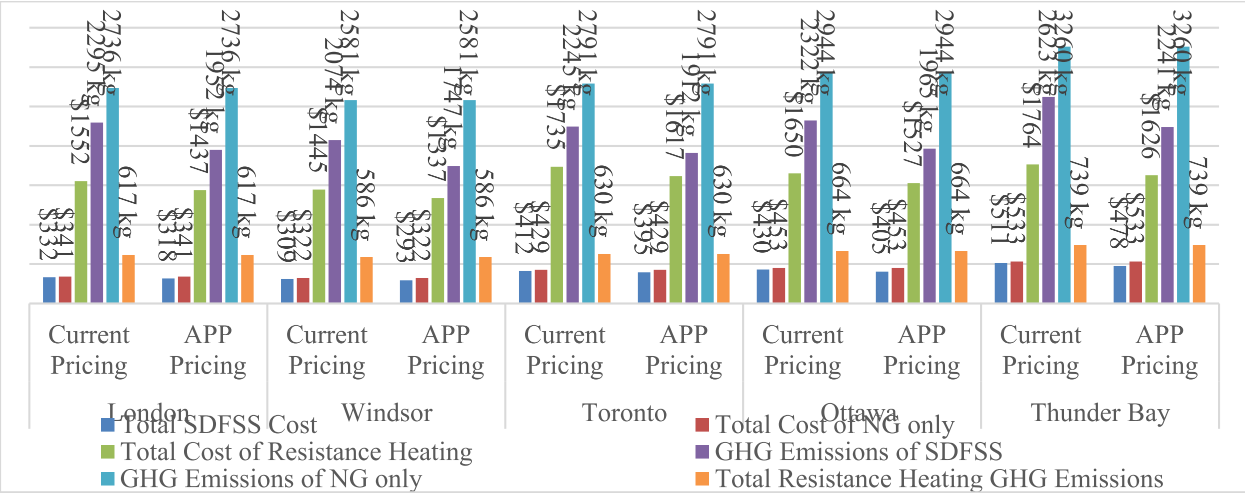

Figure 9. Comparing Different Cities with the NZEH

Table 3. Marginal Energy Prices in Different Ontario Cities

	Electricity				Natural Gas
	Off-Peak	Mid-Peak	On-Peak	Super Off-Peak	
London	$0.094	$0.124	$0.161	$0.049	23.16 ¢
Windsor	$0.093	$0.123	$0.160	$0.048	23.16 ¢
Toronto	$0.105	$0.135	$0.172	$0.060	28.54 ¢
Ottawa	$0.093	$0.123	$0.160	$0.048	28.54 ¢
Thunder Bay	$0.089	$0.119	$0.156	$0.044	30.33 ¢

Figure 9 shows the different cost and GHG emission between the 5 cities. When comparing the operating cost between the natural gas furnace only option with the SDFSS option, the potential savings of implementing the SDFSS increase in colder climate. Additionally, with the new advantage pricing plan, the savings are more evident in colder climate temperature. Due to Thunder Bay's extreme winter conditions SDFSS did not have the highest cost savings when compared with NG furnace since the ASHP cannot operate during such extreme climates. The highest savings potential is in Ottawa where the current pricing yields almost 5% annual savings while the APP scheme will yield 10.5% annual savings. Similarly, the highest GHG emission reduction is also seen in Ottawa with a 21% reduction with current electricity pricing and 33% with APP scheme. This is due to the SDFSS using the electric ASHP more frequently compared to the natural gas furnace. Using the trend from the previous Figure 8, we can also conclude that with the addition of carbon tax, the annual savings and GHG emission reduction would be increased with a higher carbon tax.

Though net-zero energy houses are efficient houses, they are not as common and cannot represent the Canadian housing stock. A presentation from Natural Resource Canada mentioned that a large percentage of current houses are built in 1970-1999 which most likely do not meet the NZEH [13]. Hence, in this study, a less efficient house was selected to be compared alongside the Strathroy NZEH. A previous study by Safa et al. [7] on the Archetype Sustainable House (ASH) at the Kortright Center located in Vaughan, Ontario was performed to identify the heating demand of the house. The study was further reviewed, where the hourly heating demand and the model were used by Raghad and Fung [14]. The hourly heating demand curve illustrated in the two pieces of literature were used as the basis of the simulation.

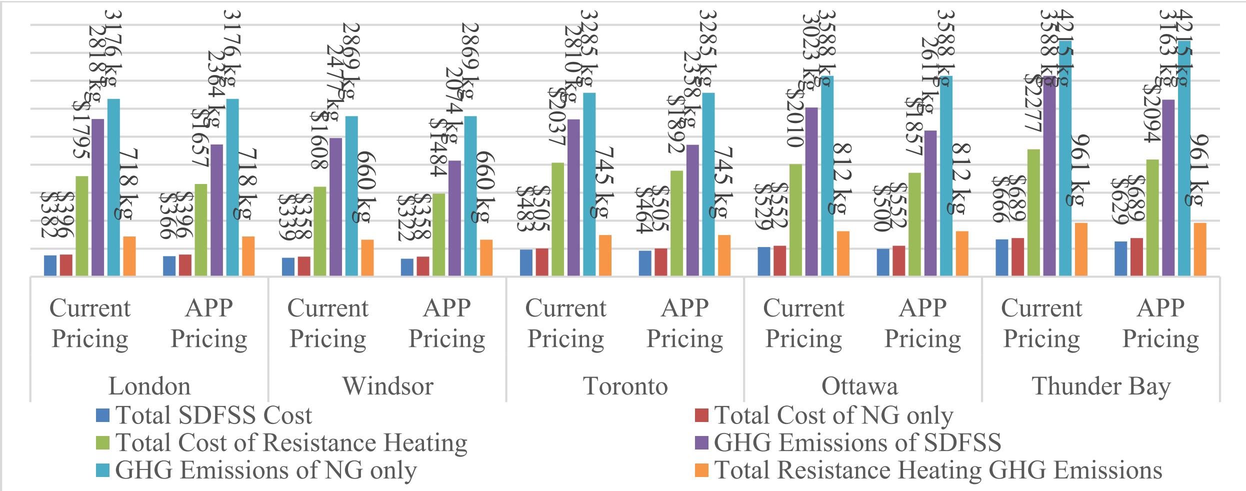

Figure 10. Comparing Different Cities and Cost Scheme with Different Building

Figure 10 shows the effects of using a different house model in the simulation. The annual operating cost of the SDFSS is consistently lower than the NG furnace in all options. When comparing the savings of switching to the SDFSS, this scenario with a less efficient house shows more potential savings of 3.6% from the 2.9% for a NZEH. For different locations, it is seen that there was a decrease in savings in Ottawa and Thunder Bay. This is due to the colder temperature with the less efficient house. Though savings increased, the GHG emission reduction potential decreased slightly where Windsor had the greatest change from 19% reduction to 14% reduction.

8. Conclusion and Implications

This study and the simulation of the Smart Dual Fuel Switching System (SDFSS) utilizing an ASHP together with a natural gas-fuelled furnace provides a transitional technology to incentivize the switch from natural gas heating to electrical heating. Not only does this technology provide a monetary incentive to the homeowner, but it also reduces the GHG emission to the environment. This technology also provides the electrical utility with a flexible system that utilizes the extraneous electricity in off-peak hours and also allowing the electrical utility to expand the facilities to accommodate the increasing electricity demand.

The SDFSS analysed shows potential savings of switching the main heating fuel source from a natural gas furnace to electrical ASHP. This study shows that potential savings increase with the addition of the Advantage Pricing Plan (APP). This new pricing plan is currently tested in select location and is very beneficial option for residential housing. An additional flexible APP is also being tested but provides a dynamic price based on the electrical demand at that hour (Alectra Utilities 2018). In future studies, this option will be evaluated to analyse the effectiveness of SDFSS in such pricing environment.

Carbon tax in Canada is an additional cost to natural gas and other fossil fuel imposed by the Federal government. It is expected that the carbon tax in 2020 will have a set cost per tonne of CO2 emitted. Though currently the cap-and-trade carbon tax has been removed, it is expected that the carbon tax will increase up to $50/tonne of CO2 in the near future. The results of this study show that such carbon tax increase will encourage residents to use electricity in tandem with natural gas to reduce the operational cost.

Though the results show an increase in savings in different Ontario cities but the local electricity and natural gas distributor price has a large impact on the annual cost. The larger the pricing difference between natural gas and electricity is, the higher the savings between the SDFSS and the natural gas furnace option will show. Similarly, the different house model used showed an increase in cost savings but the GHG emission reduction potential was decreased from the NZEH model. This is due to the lower performance of the ASHP. A subsidiary preliminary analysis showed that with an improved cold climate ASHP, the cost savings from using the SDFSS increased drastically from the current results while the

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GHG emission reduction also increased. In future work, an analysis will be performed on ASHP with different COP and capacity.

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