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Economical and environmental data analysis of hybrid HVAC system of air source heat pump and natural gas furnace for cold climate - Canada

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Abstract

This preliminary study is part of a bigger cloud-based Smart Dual Fuel Switching System (SDFSS) for hybrid heating, ventilation and air conditioning (HVAC) systems. The SDFSS being developed enables flexible and cost-optimized control between the natural gas furnace and air source heat pump (ASHP), allowing simultaneous reduction in energy costs and greenhouse gas (GHG) emissions. To meet the optimal energy consumption requirements and satisfaction of the residents, the employment of smart sensors and software are broadly used. By using experimental data retrieved from an actual near net-zero energy house (nNZEH), this study investigates the GHG emissions as well as the energy costs from the combined electricity consumption of the ASHP and the natural gas consumption from the furnace. The results demonstrate the potentials for large-scale implementation and deployment of such smart control strategy for hybrid residential HVAC system of natural gas furnace and air source heat pump in reducing overall GHG emission in a cost-effective manner in cold climate of province of Ontario, Canada where relatively expensive but clean source of electricity is available. These results demonstrate the potential for large-scale implementation and deployment of a SDFSS in colder climates such as in Canada.

Keywords: ASHP;greenhouse gas emissions; hybrid HVAC system; natural gas furnace; data analytics

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1. Introduction

To minimize the negative impacts of climate change, the United Nations Framework Convention on Climate Change (UNFCCC) developed the Paris Agreement [1]. This Agreement aimed to unite all countries to mitigate the impacts of and to adapt to climate change and find ways to reduce greenhouse gas (GHG) emissions. After signing this Agreement, Canada also introduced the Pan-Canadian Framework on Clean Growth and Climate Change (the Pan-Canadian Framework) to help address the impacts of climate change nationwide. Similar to the Paris Agreement, the Pan-Canadian Framework encourages innovation and the development of technology to find efficient energy solutions to help minimize climate change impacts. Additionally, the Federal Government of Canada has recently introduced taxes for carbon pollution. Moreover, the Pan-Canadian Framework has set an ambitious target to reduce GHG emissions by 30% by 2030 and by 80% by 2050, relative to 1990 levels [2].

A breakdown of Canadian GHG emissions by sector is shown in Figure 1, demonstrating that the residential sector produces a significant portion of GHG emissions. Moreover, Canada Green Building Council (CaGBC) established a building code to reduce energy use by 50% for one million homes in Toronto while working to meet Canada's 2030 goals of constructing net-zero energy buildings (NZEB)s. To achieve this goal, one of

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Canada’s strategic plans for promoting systems and technologies that minimize natural gas and fossil fuel usage while increasing the use of clean electricity.

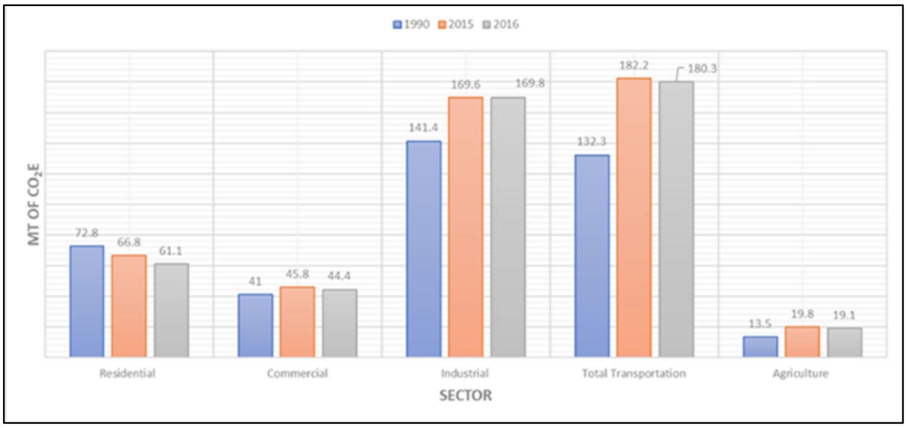


Fig. 1. Breakdown of Canadian GHG emissions by sectors [3]

Buildings are Ontario’s third-largest source of emissions, representing about 19% of the province’s total GHG emissions. Additionally, the residential sector’s heating demand contributes to 80% of the total household energy consumption [3]. This suggests that energy consumption in buildings is a key contributor to GHG emissions. Regardless of the type of fuel that is being used for space heating, energy demands are increasing in the Canadian residential sector. Meanwhile, the combination of North America’s cold climate condition and outdated HVAC control systems is contributing to higher energy consumption and increasing GHG emissions.

Even though most governments and scientists agree on being fossil-free as soon as possible, there is still room for greater technological innovation to help achieve their goal of reducing GHG emissions and energy costs. Therefore, it is important to introduce a technology that addresses this transition period before Canada becomes 100% carbon neutral.

For Canada to meet its energy reduction commitments by 2030 and 2050, low fossil fuel energy sources such as an ASHP could be considered an alternative to help reduce natural gas usage in residential buildings. However, only using electricity to meet residential buildings' heating/cooling demands is not feasible technically and economically as electricity is more expensive than natural gas in Canada [citation]. With this being said, hybrid electric ASHPs and natural as (NG) furnace systems are viewed as a lower-cost option that is better for the environment [4, 5, 6].

Although numerous research work has been conducted for managing the energy demand, smart dual fuel switching systems (SDFSS) are rarely found in the literature. The studies mentioned in [7] and [8] discussed three strategies for operating the energy demand of an archetype house through the optimal utilization of an electric air-source heat pump (ASHP) and a natural gas-fired mini-boiler using a predictive controller. To address this, a working cloud- based SDFSS prototype was implemented and tested for a one-year period in 2018 to account for the entire heating and cooling seasons. The house is located in the town of Strathroy, Ontario, Canada and is a near net-zero energy house (nNZEH). This paper studies the effects of the newly developed SDFSS system and its ability to reduce GHG emissions while considering the economic impacts of electricity and NG consumption from the HVAC equipment.

2. Case Study Description

The developed SDFSS system was implemented in a newly constructed house with 2586 sqft of conditioned living space (combined main floor and basement) and is owned and occupied by a retired couple with two dogs. A photograph of the house is presented in Figure 2. The house has a rooftop mounted PV (photovoltaic) array with a total capacity of 8.745 kWp and uses a hybrid electric ASHP, a NG furnace, and an electric enthalpy recovery ventilation (ERV) for its heating, cooling, and ventilation needs. The house uses NG for its domestic hot water production, cooking range and fireplace. The ASHP is used for both the heating and cooling needs of the house depending on the season.

Additionally, the ASHP defrost was taken into account. Hence, the ASHP was disabled to operate below the balance point temperature [13]. In this case, the NG furnace was used as an auxiliary system. The cloud-based SDFSS implemented operates based on the temporal thermal demand of the house and optimizes its HVAC operation using short-term weather forecast information to minimize the operating cost for a few hours on the cloud server. The SDFSS then communicates with the house's HVAC system via a connected smart thermostat to operate either the ASHP or the supplementary heater, and in this case, an NG furnace [9]. The ASHP operates as an air-conditioning system during the cooling season. A computer platform and a physical communication interface board were developed to mimic and observe the behaviour of the SDFSS. The developed system iterates an algorithm consisting of various temporal parameters such as time of day, TOU price of electricity, outdoor temperature, ASHP performance/capacity, NG furnace performance and thermal demand of the house to select the most cost-effective fuel source for the given hour. The TOU electricity pricing scheme is demonstrated in Figure 3. As an added benefit, this system also reduces GHG emissions since the NG furnace is optimally substituted by an ASHP powered by a relatively clean source of electricity to meet the space heating demand of the house dynamically on an hourly basis.

Fig. 2. Exterior photographs of the house

The cloud based SDFSS implemented operates based on the temporal thermal demand of the house and optimizes its HVAC operation, using short-term weather forecast information, to minimize the operating cost for the next few hours on the cloud server. It then communicates with the house's HVAC system, via a connected smart thermostat, to operate either the ASHP or the supplementary heater, in this case a NG furnace [9]. The ASHP operates as an air-conditioning system during the cooling season. In addition to computer platform developed to mimic and observe the behavior of SDFSS, the physical communication interface board was developed to test the actual system. The developed system iterates an algorithm consisting of various temporal parameters such as time and day, TOU price of electricity, outdoor temperature, air-source heat pump performance/capacity, natural gas furnace performance and thermal demand of the house to select the most cost-effective fuel source for the given hour. TOU electricity pricing scheme is demonstrated in Figure 3. As an added benefit, this system also reduces the GHG emission since the NG furnace is optimally substituted by an ASHP powered by the relatively clean source of electricity to meet the space heating demand dynamically on an hourly basis.

Fig. 3. TOU electricity pricing scheme [12]

The main focus of this study is to examine the environmental and economic impacts of implementing a cloud-based SDFSS for hybrid residential HVAC systems. By using experimental data retrieved from an actual near net-zero energy house, this study aims to investigate the reduction of GHG emissions as well as the energy costs associated with the electricity consumption of the ASHP and the NG consumption from the furnace. Therefore, a net zero energy building (NZEB) in Ontario, Canada was studied to investigate the viability of the SDFSS. The preliminary analysis demonstrated that the implemented SDFSS is a cost-effective and environmentally-friendly alternative to conventional HVAC equipment used in North American cold climates.

3. Methodology

The SDFSS modelled, developed, and implemented at the studied house accounts for the following factors in deciding whether the NG furnace or the ASHP should be operated at a specific time to meet space heating demand (HD) of the house [4]:

- π_{TOU}: TOU electricity price which changes based on hour of the day such as off-peak, mid-peak, on-peak hours [10]
- π_{NG}: Natural gas price (which is constant during the day)
- COP_{ASHP}: Coefficient of performance of the ASHP which is derived from the manufacturer's data and then calibrated with experimental data [5, 10]
- $\eta_{FURNACE}$: Efficiency of the NG furnace (89% with multiple measurements on site)
- NG energy density: 10.395 kWh/m^3 [R]
- T_{amb}: Ambient outdoor dry bulb temperature

To estimate HD of the house, a TRNSYS model was developed. This model is depicted in [10]. The curve for the COP_{ASHP} formulated from manufacturer's data and then calibrated with the experimental data is as follows:

$$COP_{ASHP} = 0.0053T_{amb}^2 + 0.0.0834T_{amb} + 2.8545 \tag{1}$$

Hourly space heating demand (HD) of the house is expressed in terms of COP_{ASHP}, $\eta_{FURNACE}$, consumption from ASHP (D_{elec}), consumption from NG furnace (D_{NG}) as the following equations:

$$D_{elec} = HD/COP_{ASHP},\ D_{NG} = HD/\eta_{FURNACE} \tag{2}$$

Based on the consumption of the equipment calculated, the total cost from ASHP operation (C_{ASHP}) and the total cost from NG furnace (C_{NG}) are defined as follows:

$$C_{ASAP} = D_{elec} * \pi_{TOU},\ C_{NG} = D_{NG} * \pi_{NG} \tag{3}$$

The SDFSS decides whether ASAP or NG furnace should be in operation based on the cheapest total cost amongst C_{ASAP} and C_{NG}. The data-driven SDFSS model consisted of an optimization algorithm which was ran hourly.

4. Results

From Equation 1, 2, and 3; CASAP, CNG, DNG, Delec are calculated for the period where the SDFSS was in operation. The first day of the data retrieval was on the 16th of February 2018. The first day of activating the SDFSS was on the 7th of November 2018, and the final day of the SDFSS experimentation was on the 6th of December 2018. The broader study also concluded on December 6th, 2018.

The average hourly GHG emission factors (in gCO_2eq/kWh) from the Ontario grid were taken from [11]. Along with the TOU dependency based on heating and cooling season, the weekends and statutory holidays are considered as the off-peak hours for the operation of the ASHP. Therefore, the day of the week and these holidays are also included in the analysis.

A detailed analysis of the outcomes of the SDFSS in terms of cost (in CAD) and GHG emissions released (in $kgCO_2$/day) from the HVAC equipment used during this period is depicted in Table 1. It is observed that on some days, only one type of the HVAC equipment was active. On other days, the switching happened during the day. So, there was both electricity and NG consumption from HVAC equipment. GHG emissions occurred from both HVAC systems. The results demonstrate that the NG furnace releases relatively more GHG emissions, but it is cost-effective. Similarly, the ASHP releases relatively less GHG emissions, but it is more expensive than NG.

Table 1. A detailed analysis on ambient temperature, cost, GHG emission, and loads from the HVAC equipment when the SDFSS in operation (from 7th of November to 6th of December 2018)

	SDFSS in OPERATION OUTDOOR TEMPERATURE (^{o}C)				HP_COST	FURNACE_COST	TOTALCOST	HP_LOAD	Furnace_LOAD		HP_GHG	Furnace_GHG	Total GHG
DAYS	AvgTemp	MinTemp	MaxTemp	SpreadingTemp	CAD	CAD	CAD	kWh	kWh	DayoftheWeek	kgCO$_2$/day	kgCO$_2$/day	kgCO$_2$/day
7	0.35	-0.70	1.90	2.60	0.78	0.26	1.04	23.19	9.47	Wednesday	0.28	1.86	2.14
8	7.85	1.20	17.20	16.00	1.47	0.21	1.68	44.39	7.58	Thursday	0.51	1.49	1.99
9	3.08	0.30	10.40	10.10	0.00	0.93	0.93	0.00	33.62	Friday	0.00	6.60	6.60
10	-0.26	-1.10	2.20	3.30	0.00	1.51	1.51	0.01	54.45	Saturday	0.00	10.70	10.70
11	-1.10	-4.60	4.20	8.80	0.32	1.01	1.33	9.82	36.46	Sunday	0.11	7.16	7.28
12	-1.53	-2.80	-0.20	2.60	0.27	0.88	1.14	8.50	31.72	Monday	0.14	6.23	6.37
13	5.64	3.40	7.10	3.70	0.04	0.62	0.65	1.11	22.25	Tuesday	0.01	4.37	4.38
14	3.32	2.30	4.80	2.50	0.00	1.40	1.40	0.00	50.66	Wednesday	0.00	9.95	9.95
15	1.77	0.30	2.90	2.60	0.00	1.37	1.37	0.00	49.72	Thursday	0.00	9.77	9.77
16	-1.55	-4.80	1.50	6.30	1.00	0.59	1.59	31.29	21.31	Friday	0.41	4.19	4.60
17	0.13	-2.20	2.70	4.90	0.74	0.03	0.76	24.17	0.95	Saturday	0.37	0.19	0.56
18	1.60	-3.20	6.30	9.50	0.16	0.98	1.14	5.09	35.51	Sunday	0.07	6.98	7.05
19	0.52	-1.90	2.70	4.60	0.00	1.18	1.18	0.02	42.61	Monday	0.00	8.37	8.37
20	-2.73	-5.60	3.80	9.40	0.59	1.02	1.61	18.52	36.93	Tuesday	0.25	7.25	7.51
21	-2.28	-4.50	-0.10	4.40	0.00	1.43	1.43	0.00	51.61	Wednesday	0.00	10.14	10.14
22	0.10	-0.60	0.50	1.10	0.02	1.87	1.89	0.51	67.71	Thursday	0.01	13.30	13.31
23	1.13	-0.10	2.40	2.50	0.28	1.13	1.41	8.50	40.72	Friday	0.18	8.00	8.18
24	-0.50	-1.80	1.30	3.10	1.15	0.01	1.16	40.78	0.47	Saturday	0.62	0.09	0.71
25	-0.83	-6.70	7.40	14.10	0.72	0.00	0.72	27.40	0.00	Sunday	0.38	0.00	0.38
26	-0.85	-5.80	2.10	7.90	1.14	0.00	1.14	28.47	0.00	Monday	0.43	0.00	0.43
27	-1.94	-5.60	0.10	5.70	0.40	1.34	1.74	12.53	48.77	Tuesday	0.15	9.58	9.73
28	-7.19	-10.70	1.30	12.00	0.00	1.58	1.58	0.02	57.76	Wednesday	0.00	11.35	11.35
29	-0.28	-6.20	8.20	14.40	0.00	1.54	1.54	0.01	56.34	Thursday	0.00	11.07	11.07
30	4.65	2.40	7.50	5.10	0.36	0.97	1.33	8.73	35.51	Friday	0.16	6.98	7.13
1	5.55	3.70	7.60	3.90	0.73	0.75	1.49	22.79	27.46	Saturday	0.37	5.39	5.76
2	2.46	1.00	3.40	2.40	0.45	0.00	0.45	19.34	0.00	Sunday	0.17	0.00	0.17
3	-1.36	-2.40	1.70	4.10	0.95	0.00	0.95	27.49	0.00	Monday	0.50	0.00	0.50
4	-1.86	-2.60	-0.90	1.70	1.03	1.05	2.08	21.55	38.35	Tuesday	0.47	7.53	8.00
5	-2.24	-3.40	-0.50	2.90	0.00	1.29	1.30	0.03	47.35	Wednesday	0.00	9.30	9.30
6	-0.38	-1.80	1.70	3.50	0.00	1.05	1.05	0.01	38.35	Thursday	0.00	7.53	7.53

To further analyse the outcomes of the SDFSS introduced, the actual loads of the HVAC equipment were analysed along with the average outdoor temperature, the average minimum temperature, and the average maximum temperature on the days when the SDFSS was in operation. This analysis is demonstrated in Figure 4. It should be noted that spreading temperature is the absolute difference of the maximum and minimum outdoor temperature of a specific day. Additionally, Figure 5 depicts the GHG emissions from the HVAC equipment when the SDFSS was in operation.

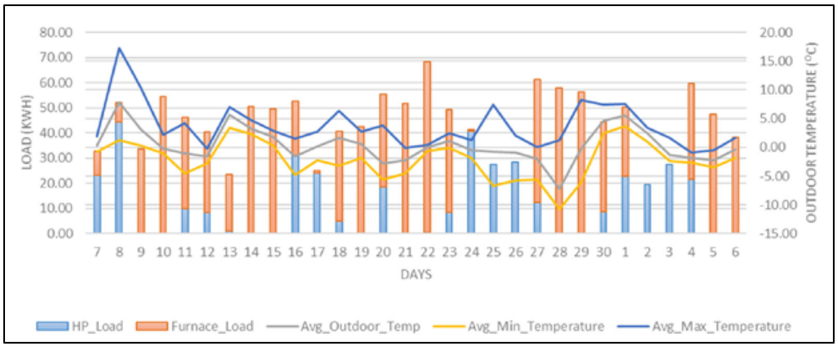


Fig 4. Ambient temperature and loads from the HVAC equipment when the SDFSS in operation (from 7th of November to 6th of December 2018)

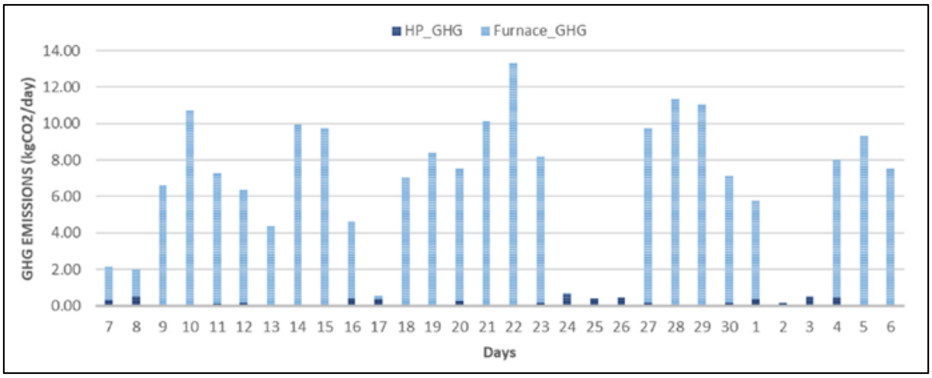


Fig 5. GHG emissions from the HVAC equipment when the SDFSS in operation (from 7th of November to 6th of December 2018)

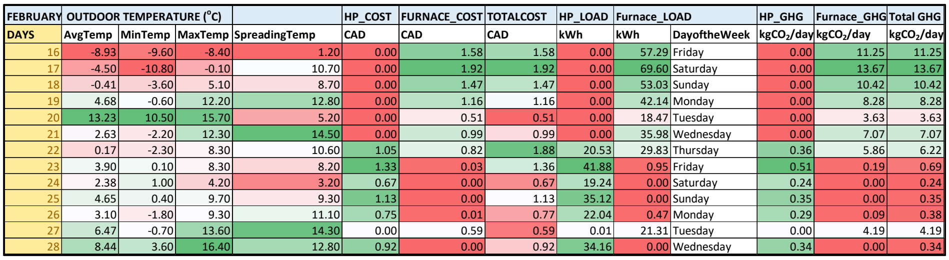
The COP and capacity of the ASHP depend on the ambient outdoor temperature, which has led HVAC manufacturers to have a built-in temperature sensor on their ASHP. The ambient outdoor temperature of the specific location of the house is required in defining and meeting the thermal demand of the house. Therefore, the ambient outdoor temperature is a pivotal factor in this analysis to observe the smart switching optimal temperatures based on the introduced algorithm of the SDFSS. Table 2 depicts the marginal TOU electricity pricing based on TOU tiers such as off-peak, mid-peak, and on-peak hours [12]. The electricity prices from the consumption of electricity from ASHP are calculated based on the criteria given in Table 2. However, NG marginal price is \$0.3038/m^3 and has been fixed.

Table 2. Marginal TOU electricity pricing

Off-peak	\$0.092/kWh
Mid-peak	\$0.124/kWh
On-peak	\$0.163/kWh

Moreover, the costs and GHG emissions released from the electricity and NG consumption by the hybrid HVAC equipment when SDFSS is active and inactive were compared. For instance, when the thermostat switching setting was fixed at 0ºC, the days with almost the same outdoor temperature conditions were analyzed. Table 3 demonstrates the analysis considered the entire month of February 2018. When the SDFSS was inactive, a fixed fuel switching temperature was introduced at 0ºC, where ASHP operated when the outdoor temperature was above 0ºC. Otherwise, when the outdoor temperature was below 0ºC, the NG furnace was operated. For the SDFSS, the ASHP was in operation during the off-peak TOU hours and when the ambient temperature was above the optimal switching points. When on-peak and mid-peak TOU hours and the ambient temperature was below the optimal switching points, the NG furnace was in operation.

Table 3. A detailed analysis on ambient temperature, cost, GHG, and loads from the HVAC equipment when the switching point was at 0ºC (from 16th of February to 28th of February 2018)



FEBRUARY	OUTDOOR TEMPERATURE (°C)				HP_COST	FURNACE_COST	TOTALCOST	HP_LOAD	Furnace_LOAD		HP_GHG	Furnace_GHG	Total GHG
DAYS	AvgTemp	MinTemp	MaxTemp	SpreadingTemp	CAD	CAD	CAD	kWh	kWh	DayoftheWeek	kgCO$_2$/day	kgCO$_2$/day	kgCO$_2$/day
16	-8.93	-9.60	-8.40	1.20	0.00	1.58	1.58	0.00	57.29	Friday	0.00	11.25	11.25
17	-4.50	-10.80	-0.10	10.70	0.00	1.92	1.92	0.00	69.60	Saturday	0.00	13.67	13.67
18	-0.41	-3.60	5.10	8.70	0.00	1.47	1.47	0.00	53.03	Sunday	0.00	10.42	10.42
19	4.68	-0.60	12.20	12.80	0.00	1.16	1.16	0.00	42.14	Monday	0.00	8.28	8.28
20	13.23	10.50	15.70	5.20	0.00	0.51	0.51	0.00	18.47	Tuesday	0.00	3.63	3.63
21	2.63	-2.20	12.30	14.50	0.00	0.99	0.99	0.00	35.98	Wednesday	0.00	7.07	7.07
22	0.17	-2.30	8.30	10.60	1.05	0.82	1.88	20.53	29.83	Thursday	0.36	5.86	6.22
23	3.90	0.10	8.30	8.20	1.33	0.03	1.36	41.88	0.95	Friday	0.51	0.19	0.69
24	2.38	1.00	4.20	3.20	0.67	0.00	0.67	19.24	0.00	Saturday	0.24	0.00	0.24
25	4.65	0.40	9.70	9.30	1.13	0.00	1.13	35.12	0.00	Sunday	0.35	0.00	0.35
26	3.10	-1.80	9.30	11.10	0.75	0.01	0.77	22.04	0.47	Monday	0.29	0.09	0.38
27	6.47	-0.70	13.60	14.30	0.00	0.59	0.59	0.01	21.31	Tuesday	0.00	4.19	4.19
28	8.44	3.60	16.40	12.80	0.92	0.00	0.92	34.16	0.00	Wednesday	0.34	0.00	0.34

After analysing the cost and GHG emission values for the days that had similar ambient temperature values, it is observed that the SDFSS cost less while preserving lower GHG emissions. For instance, on the 16th and

17th of November 2018, the SDFSS was active and on the 22nd of February 2018, the SDFSS was inactive, and the switching was at a fixed temperature of 0ºC. The days that had similar conditions were defined based on maximum difference in ambient temperatures. The overall costs and GHG emissions released these days are a significant depiction of the SDFSS better than the conventional HVAC equipment in terms of these criteria.

As previously mentioned, the electricity prices are more costly than natural gas prices in Ontario, Canada. Therefore, a supplementary analysis was conducted to exhibit the overall applicability of the SDFSS on operating ASHP. Figure 6 shows the overall cost from operating ASHP, when the SDFSS is active and inactive. Following the methodology defined above, the associated ambient temperatures were taken into account to compare them with the days when the SDFSS was operating. The operational costs from the ASHP were mapped against the days in November 2018. It is seen that when the SDFSS was in operation, the electricity cost from the ASHP was more economical than the conventional testing period. When the SDFSS was active, the cost did not exceed $1.50.

In contrast, when the SDFSS was inactive, the costs reached up to $4. The ASHP was less expensive during the operation of the SDFSS because when the extreme outdoor temperatures and the on-peak hours of electricity pricing occurred, the NG furnace was turned on for operation to meet the space heating demand. As NG furnace was not operated consistently, the SDFSS switched between the NG furnace and the ASHP. The GHG emissions were not higher than the conventional periods, where there was a fixed switching temperature at 0ºC.

The comparison of GHG emissions obtained from the operation of the ASHP between the days, when the SDFSS was in operation (in November 2018) and other days in the heating season are demonstrated in Figure 7. This comparison was performed while considering the mean difference in ambient temperatures between the days with similar weather conditions and the days when SDFSS was in operation. Based on these differences, the GHG emissions from the consumption of the HVAC equipment were compared. It is observed that in November 2018 as the SDFSS was active, the GHG emissions were relatively lower than the period, where the fixed switching temperature was in operation.

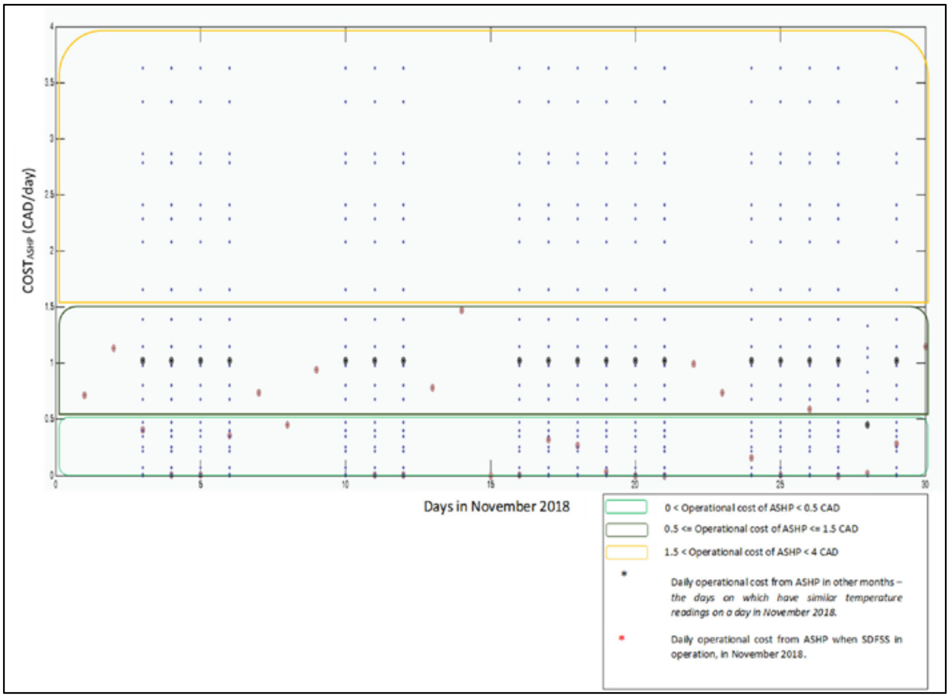


Fig. 6. Comparison of operational cost of ASHP between the days when SDFSS in operation (in November 2018) and other days in the heating season

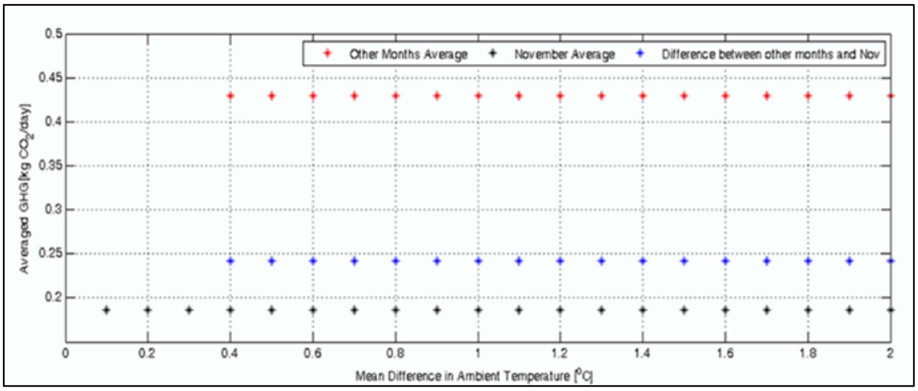


Fig. 7. Comparison of GHG emissions obtained from the operation of ASHP between the days when SDFSS in operation (in November 2018) and other days in the heating season

5. Conclusion

This study introduced a unique and innovative approach to account for the balance between economic and environmental impacts of the residential space heating in cold climates by proposing a flexible, cost effective, and clean energy solution. The technology, called the SDFSS, was developed, installed, and implemented at a Net Zero Energy House in Strathroy, Ontario, Canada. The SDFSS estimates the optimal switching point temperatures by considering various temporal factors such as TOU electricity prices, the efficiency of the NG furnace, the COP and capacity of the ASHP, and NG prices. Using Internet of Things (IoT) technologies and cloud servers, the data from the heating of the house when the SDFSS was in and out of operation were retrieved and analyzed in detail. This study focused on the environmental and economic impact of implementing these alternative technologies, called cloud based SDFSS for hybrid residential HVAC systems, in the transitioning period of prior being completely fossil-fuel free. The preliminary analysis demonstrated that the implemented SDFSS is a cost-effective, flexible, and environmentally friendly alternative to conventional HVAC equipment used in the North American cold climate.

Future work will examine the potential benefits, in terms of reduction of operating cost and GHG emissions of such cloud-based SDFSS for hybrid residential HVAC system in meeting different GHG emission reduction targets by 2030 and 2050 with the recently introduced federal carbon taxes of $20/tonne, $30/tonne, $40/tonne, and $50/tonne of CO_2 from 2019 to 2022.

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