Numerical study of residential Smart Dual Fuel Switching System (SDFSS) with on-site solar photovoltaic system

Saunak Shukla1,*, King Tung1, Danilo Yu2 and Alan S Fung1
1 Department of Mechanical Engineering, Ryerson University, 350 Victoria St, Toronto, Ontario, M5B 2K3, Canada
2 Department of Electrical Engineering, Ryerson University, 350 Victoria St, Toronto, Ontario, M5B 2K3, Canada
* saunak.shukla@ryerson.ca

Abstract. Building energy consumption accounts for approximately 36% of total energy consumption in the world. Since buildings are capable of on-site electricity generation and exhibiting predictive pattern of heating and cooling, the focus of this study is to investigate the Smart Dual Fuel Switching System (SDFSS), comprising a natural gas furnace and an air-source heat pump (ASHP), working in conjunction with on-site solar photovoltaic system. Base-case scenario using 1.5-ton rated capacity ASHP with 8.5 heating seasonal performance factor (HSPF) yielded only 4% cost savings and 15% greenhouse gas (GHG) emission reduction when compared to natural gas furnace space heating scenario. With an ASHP of 2-ton rated capacity and HSPF of 10 working in conjunction with solar photovoltaic (PV) system of 4.08 kWp, the cost savings of SDFSS increased to 12% and the GHG emissions reduction of 45%. SDFSS integrated with the grid is expected to yield significant benefits. It can help avoid situation of buildings drawing electricity all at once and reduce the overload on the grid. Also, it can redirect electricity generated from the solar PV system of a building for which using natural gas furnace is more economical to a building whose space heating demands can be met with this excess electricity. Higher ASHP performance and capacity, higher carbon pricing, and higher solar PV electricity generation will lead to the design of a more economical and sustainable SDFSS.

1. Introduction
The building sector is responsible for 36% of the total energy consumption and 40% of total greenhouse gas (GHG) emissions in the world [1]. Over the next 40 years, the building sector will grow by nearly 230 billion square meters which is equivalent to adding the floor area of Japan to the planet every year until 2060 [1]. For Canada, the building sector represents 26% of the total energy consumption and 65% of the energy consumed in the building sector is used for space heating [2]. In Ontario, GHG emission through the use of natural gas and electricity for space heating purposes is 50 g and 11 g per MJ, respectively [3]. Thus, on per unit energy generation for space heating basis, natural gas is 5 times more GHG intensive than electricity. By using the space heating systems more efficiently, more traditional natural gas heating demand can be offset, leading to reduced GHG emissions. The advent of strategy planning model such as smart dual fuel switching system (SDFSS) is in line with Canada’s Climate Change Action Plan (CCCAP) and the short-term goal of reducing GHG emissions by 15% compared to the level of 1990 by 2020 [4, 5].

With the improvement in air source heat pump (ASHP) and electricity being less carbon-intensive energy source compared to natural gas, in many areas of Canada including the province of Ontario, it is expected that relying on ASHP for space heating would reduce GHG emissions and total energy consumption. However, this is not the case as there are many barriers. First and foremost is the reduction in performance and capacity experienced by ASHPs during extremely cold temperatures in Canadian winter. Due to this, the electrical load demanded by the ASHP is higher and this discourages home-
owners from exploring options beyond traditional natural gas heating systems. Also, even if government policies and incentives encourage home-owners to install ASHPs, this is expected to add significant amount of load on the grid when all houses in an area are drawing electricity all at once. Moreover, during its regular operation, the operational costs of ASHP are higher than that of natural gas furnace.

While the Smart Dual Fuel Switching Systems (SDFSS), comprising two different space heating systems: ASHP and natural gas furnace, seem to solve this problem at the home-owner level, this does not fully address the problem of overload on the grid contributed by SDFSS in different houses consuming electricity all at once. This research is novel in that it aims to integrate on-site solar photovoltaic (PV) electricity generated into the smart dual fuel switching system optimal control strategy under two main incentive programs by the government: micro feed-in tariff (FIT) and net-metering scheme. This novel SDFSS considers hourly weather data, thermal load profile of the building, efficiency of the natural gas furnace, ASHP, and solar PV panel’s electricity generation. Based on these parameters, the electricity and natural gas consumption and their costs are calculated. If the electricity generated by the solar PV panel is more than the electrical load on the ASHP to meet the space heating demand, then the excess electricity generation goes towards credit for the future or gets exported to the grid. This paper starts with a brief overview of the results obtained for recent studies on these systems followed up by the description of the current case study.

2. Literature Review

Buildings are capable of storing thermal energy and exhibiting a predictable pattern of heating and cooling demand. This has sparked the interest of many scholars and thus different strategy planning models such as Load Shifting (LSH), Smart Dual Fuel Switching System (SDFSS), and Load Shifting-Smart Dual Fuel Switching System (LSHSSDFSS) have been proposed to be used in cold climate countries such as Canada [6–8]. The LSH models normally pre-heat or pre-cool during off-peak or mid-peak hours and thus reduce the energy consumption during peak hours which have different rates as defined by the local time-of-use (TOU) electricity price structure. LSHSSDFSS models would combine pre-heating/cooling with a fuel switching method. According to the study conducted by Alibabaei et al. in the City of Vaughan, LSH and LSHSSDFSS models yield the highest savings in the temperature ranges of 0°C to 12°C and 0°C to 8°C respectively [4]. The savings yielded by LSH and LSHSSDFSS models would require high thermal mass contributed by high-density materials such as concrete, bricks, and tiles used in the building. A major conclusion drawn from the study was that the buildings with light thermal mass and extreme-cold conditions would benefit the most using SDFSS model amongst the three aforementioned strategies.

The previous study looked at the efficacy of SDFSS in a net-zero energy house (NZEH) under two different switching scenarios: switching based on setpoint temperatures of -5°C and 5°C, and based on fuel costs per hour [8]. The study found that switching based on fuel costs yielded 3% cost reduction and 40% GHG reduction compared to an all natural gas space heating scenario. The switching based on fixed outdoor setpoint temperature scenario was 6% more costly than the base-case scenario of all natural gas space heating, rendering it less economical. Another study performed sensitivity analysis and assessed the efficacy of the SDFSS for NZEH as well as regular house and also considered different climatic conditions [9]. The study concluded that SDFSS yields higher cost savings for a less efficient house than NZEH. Also, the locations subject to extreme-cold conditions did not yield significant savings because ASHP would be shut off for the most time due to the poor performance at these climatic conditions. There has been little to no research done on evaluating the potential of solar PV panels operating in conjunction with the SDFSS.

3. Case Study Description

This study is performed at Toronto and Region Conservation Authority (TRCA)’s Archetype Sustainable Houses (ASH) which are built in accordance to American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards 90.1 as well as Energy Star and R2000 standards [10].

This 3-storey house, shown in Figure 1, is located in the City of Vaughan. The total floor area and volume of this house are 330 m² and 900 m³ respectively [10]. The house hosts a state-of-the-art
monitoring system and hosts more than 300 sensors as it has been used multiple times for testing multiple sustainable building technologies [6, 7, 11]. The construction of this house was made from sustainable building materials and the above grade walls are R32 (RSI 5.64), higher than the average house insulation. As can be seen from Figure 1, the house also hosts south facing solar PV panels with 30° slope and rated peak power capacity of 4.08 kWp.

![Figure 1. Location for the case study (the semi-detached house on the right) [10].](image)

Space heating equipment comprises an ASHP and a natural gas furnace. Two different types of ASHP were considered in the study: the base case scenario ASHP with 18,000 $\text{Btu/hr}$ (1.5 tons) rated heating capacity, SEER of 15, EER of 12.5, and HSPF of 8.5; high-performance case scenario ASHP with 24,000 $\text{Btu/hr}$ (2 tons) rated heating capacity, SEER of 18, EER of 14, and HSPF of 10.0. The natural gas furnace’s reported annual fuel usage efficiency is 96% and the high fire output is 28,800 $\text{Btu/hr}$.

4. Methodology
The analytics were carried out in an extensive model developed in Excel that had solar PV generation data, weather profile, space heating load profile, ASHP coefficient of performance (COP) and capacity curves plotted for the entire year for the year of 2018. The house chosen for this case study was modelled in Transient System Simulation Tool (TRNSYS) software and the simulations were carried out to obtain the thermal load of the house as well as weather profile for the 8760 hours of the year [11]. Space heating load and weather profile, as well as utility costs, were then exported to an optimization algorithm developed in Excel.

For the natural gas furnace, accounting for heat losses and combustion inefficiencies, a constant mechanical efficiency of 85% was assumed for all outdoor temperatures. For the two ASHPs (base case scenario ASHP and higher HSPF ASHP), using the known performances at certain outdoor temperatures, the COPs and maximum heating capacities were extrapolated using polynomial regression analyses. The COP versus outdoor temperature plots for base case ASHP and higher HSPF ASHP are presented in Figure 2 and Figure 3, respectively.
Electricity generated from the solar PV system was obtained through the experimental setup at the location. The measurements recorded the generation data every minute which was aggregated for an hour for the 8760 hours of the year to obtain the electricity generation profile in kWh of electricity produced. This data was exported to optimization algorithm built in Excel. The logic was built such that if the electrical load on the ASHP, after using the on-site generation electricity, at any hour yields lower space heating cost than the furnace space heating costs then it would utilize ASHP for space heating. In the end, the total space heating costs, electricity consumption, natural gas consumption, and GHG emissions were reported for each scenario on an annual basis.

Natural gas marginal cost was $0.21 per m³ [2]. The electricity marginal costs were based on the time-of-use price structure that sets on-peak (7 am to 11 am and 5 pm to 7 pm), mid-peak (11 am to 5 pm) and off-peak (7 pm to 7 am) marginal costs at $0.081, $0.111, $0.148 per kWh of electricity used, respectively [2]. The GHG emission factor, as reported by the National Energy Board, was set at 40 g per kWh electricity generation and 1860 g per m³ of natural gas burnt for space heating [3].

5. Results
The results for SDFSS for base case scenario utilizing 1.5-ton capacity ASHP and high-performance ASHP with 2-ton capacity are presented in Table 1. The government incentive programs, micro-FIT and
net-metering scheme, are also taken into consideration for the upgrade of SDFSS. The micro-FIT program currently pays $0.29 per kWh electricity generated through solar PV panel to residential homeowners and supplied to the grid [2]. The net-metering scheme takes the excess electricity generated and keeps it on the record for next year so homeowners can use the same amount of electricity within this timeframe without paying for it.

Table 1. Simulation results for different scenarios.

| Quantity                  | Unit | Natural Gas Furnace Only | Base-case 1.5-ton ASHP SDFSS | High Performance 2-ton ASHP SDFSS with Solar PV |
|---------------------------|------|--------------------------|----------------------------|-------------------------------------------------|
| Total Cost                | $    | 424                      | 421                        | 406                                            | 394                                            | 374                                            |
| GHG Emission              | kg   | 3681                     | 3424                      | 3150                                          | 2267                                          | 1995                                          |
| Natural Gas Consumption   | m³   | 1983                     | 1832                      | 1675                                          | 1182                                          | 1027                                          |
| Electricity Consumption   | kWh  | -                        | 368                       | 907                                           | 1707                                          | 2128                                          |
| Solar PV Electricity      | kWh  | -                        | -                         | 5585                                          | -                                             | 5585                                          |
| Generation                | $    | -                        | -                         | 1247                                          | -                                             | 1314                                          |
| Rebate under Micro-FIT    |       |                          |                            |                                               |                                               |                                               |
| Scheme                    | kWh  | -                        | -                         | 4302                                          | -                                             | 4531                                          |
| Future Credit             |       |                          |                            |                                               |                                               |                                               |
| under Net-metering       | kWh  | -                        | -                         | 4302                                          | -                                             | 4531                                          |

From Table 1 it can be seen that from all scenarios analysed, the GHG emission was the highest for natural gas furnace only scenario. With the base-case scenario SDFSS with solar PV, the space heating costs and GHG emissions were reduced by 4% and 14%, respectively. Using the high-performance ASHP, the operational costs were lowered and thus ASHP was used more to meet the space heating demands. Compared to a natural gas furnace, the high-performance SDFSS with solar PV scenario yielded 12% costs savings and a 45% reduction in GHG emissions. Also, under the micro-FIT scheme, it would yield a rebate of $1,314 to the homeowner. Under the net-metering scheme, the homeowner would be eligible to get credit of 4,530 kWh electricity for the next year; this is approximately 50% of the average electricity consumption in Canadian household [2]. The higher COPs in warm temperatures yielded less consumption and leading to lower electricity costs which then triggered ASHP to stay on for a longer period of time. Prior to using the 2-ton ASHP with HSPF of 10, a cold climate ASHP with better COPs at sub-zero temperatures was modelled but it did not yield significant savings as the local climatic conditions were not extremely cold [11]. The savings of this study are expected to be higher under a carbon tax scheme on a residential level.

The logic programmed into an Excel spreadsheet can be easily programmed into a server black-box and the space heating demands of the house can be met with minimal intervention, all while reducing space heating costs and GHG emissions. With the implementation of higher rated solar PV panels, the ASHP electrical load can be partially met such that electricity costs of running the ASHP are cheaper.
than that of the furnace and thus greater cost savings as well as GHG emission reduction could be achieved.

6. Conclusion
Overall, the cost savings and GHG emission reduction of the SDFSS in conjunction with solar PV panel are significant. Such optimization logic can be integrated with the grid for large building stock drawing electricity from a common utility provider. Designing for the grid would yield optimal results as it would be able to take the electricity generated from solar PV panel of buildings/houses and redirect where switching to ASHP would lower the operation costs. The efficacy of SDFSS in cost savings is heavily dependent on local climatic conditions, local utility rates, incentive programs and carbon tax schemes (if any). Sensitivity analyses and numerical studies on how combining solar PV panel with SDFSS correlates to these variables are needed to further develop the understanding of such integration. Also, the results obtained in this case study will be calibrated through the use of large monitoring system in the archetype house chosen for this study.

References
[1] International Energy Agency, “Buildings.” [Online]. Available: https://www.iea.org/buildings/. [Accessed: 02-Dec-2018].
[2] National Energy Board, “Provincial and Territorial Energy Profiles-Canada,” 2018.
[3] National Energy Board, “Canada’s Renewable Power Landscape 2017- Energy Market Analysis,” 2017.
[4] Alibabaei N, Fung A, Raahemifar K and A. Moghimi, “Effects of intelligent strategy planning models on residential HVAC system energy demand and cost during the heating and cooling seasons,” Appl. Energy, 2017.
[5] Workman C, “Minister of Environmental and Climate Change Marks Canada’s Ratification of the Paris Agreement,” 2016.
[6] Alibabaei N, Fung A and Raahemifar K, “Development of Matlab-TRNSYS co-simulator for applying predictive strategy planning models on residential house HVAC system,” Energy Build., 2016.
[7] Hajizadeh A and Golkar M, “Intelligent power management strategy of hybrid distributed generation system,” Int. J. Electr. Power Energy Syst., 2007.
[8] Tung K, Wang A and Fung A, “Numerical study on smart dual fuel switching systems in net zero energy homes Net-Zero Energy House,” pp. 232–240, 2018.
[9] Tung K, Yu D, Ekrami N and Fung A, “Experimental and sensitivity analysis of a smart dual fuel system in a net-zero energy home,” IOP Conf. Ser. Earth Environ. Sci., vol. 238, p. 012018, 2019.
[10] Zhang D, Barua R and Fung A, “TRCA-BILD archetype sustainable house - Overview of monitoring system and preliminary results for mechanical systems,” in ASHRAE Transactions, 2011.
[11] Safa A, Fung A and Kumar R, “Performance of two-stage variable capacity air source heat pump: Field performance results and TRNSYS simulation,” Energy Build., 2015.