Monitoring and Evaluation of Nearly-Zero Energy House (NZEH) with Hybrid HVAC for Cold Climate – Canada

G Demirezen, N Ekrami, AS Fung, D Yu, KY Tung
350 Victoria Street, Toronto, ON M5B 2K3, Canada
gulsun.demirezen@ryerson.ca

Abstract. A Nearly Zero Energy Home (NZEH) in Strathroy, Ontario, Canada was monitored and studied to evaluate its performance for both heating and cooling seasons. The house is a new built and is equipped with an electric-natural gas hybrid spacing heating system. A high efficiency natural gas furnace and an electric air source heat pump (ASHP) were coupled to meet the space heating demand of the house. The house also benefits from on-site renewable energy generation (solar PV). The original system was controlled by a simple switch over thermostat that drives furnace or ASHP based on the outdoor temperature as a single decision-making factor. The system then was upgraded with a cloud based Smart Dual Fuel Switching System (SDFSS) controller that considers time-of-use (TOU) pricing, fuel cost, weather forecast, and equipment efficiencies and capacities. This multi-variable decision-making process defines an optimal schedule for the hybrid system to run more efficiently and more economically. A detailed monitoring system, including sensors, meters, and data acquisition system, was installed to collect all required information at a 2-minute interval. The furnace and ASHP were studied separately to verify their capacities and efficiencies. Then the overall hybrid system and its controller were monitored to identify its effectiveness. A complete model of the house and the hybrid system were developed and validated with experimental data. Thereafter, the system was run by the SDFSS controller. All of these scenarios were compared against each other and benchmarked. In addition, the factors affect indoor air quality (IAQ) were studied in detail. The preliminary result has shown that SDFSS controller provides a cost effective, feasible, cleaner and healthier IAQ options to run the hybrid system in a NZEH.

1. Introduction

Residential buildings are starting to adopt air source heat pumps (ASHP) and/or ground source heat pumps (GSHP) to reduce the operational cost of the homeowners and reduce the environmental impact of heating and cooling systems. 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 [1]. An economic issue associated with the adoption of ASHP is the higher operating cost compared to conventional heating systems that use natural gas. In addition, ASHP performance and capacity decrease when outdoor temperature drops well below freezing, thus, requiring backup/supplemental heat source under such extremely cold winter temperatures in cold climates such as Canada. Therefore, an electric-natural gas hybrid combination of mechanical system called the Smart Dual Fuel Switching System (SDFSS) was modelled, optimized and simulated in order to estimate the potential savings and the environmental benefits of the proposed hybrid system. In addition to computer platform developed to mimic and observe the behavior of SDFSS, the physical communication board was developed to test the actual system. The developed system iterates an algorithm consisting of various parameters such as time and day, time-of-use 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 hour. As an added benefit, this system also reduces the greenhouse gas emission (GHG) since the natural gas
furnace is optimally substituted by an electrically powered air-source heat pump (ASHP) to meet the space heating demand dynamically on an hourly basis. After testing and studying the data retrieved and collected, further analysis on IAQ is performed. The results demonstrate that the system introduced is not only a cost-effective alternative to the conventional systems but also environmentally considerate without sacrificing the indoor air quality and other factors which affect the comfort-level of the occupants.

2. Data Acquisition System (DAQ)
The studied house is in the town of Strathroy, Ontario, Canada. This house has a south facing solar roof and west facing front door. By performing standard HOT2000 simulation certification procedure, the house was found to be a nearly zero energy home (NZEH). A working Smart Dual Fuel Switching System (SDFSS) was implemented, tested, and evaluated in this NZEH. This SDFSS simulates the thermal demand of the house and optimizes its HVAC operation, using short-term weather forecast information, so as 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 natural gas furnace, based on the minimization of operating costs in order to meet the space heating demand of the house [2].

The house was monitored over a one-year period. A fully automated data acquisition system (DAQ) was designed based on the requirements of the project, complexity of the hybrid system, and physical limitations of the site. An online visual tool/dashboard was developed to demonstrate real-time operation and performance of the house and its main equipment as well as their historical trends. The dashboard provides all of the energy consumption and generation information without the need of extracting data from the data logger. The monitoring system was operational for a total of 295 days and collected data from 74 data points/parameters every two minutes. The monitoring period was concluded after storing 15.7 million points of data.

The data loggers used were capable of 1-second sampling rate, but the data collection was set at 2-minute to account for the latency of GSM used to transmit data from the local loggers to the cloud server. Ambient outdoor dry bulb air temperature sensor (PVmet 75) used has a wired modem. DAQ is designed to capture, store and visualise the following measured data [3]:

- Weather (ambient temperature, GHI) data,
  - In addition, forecast data from three different sources (such as Accuweather, Openweather, CanMeteo) were stored in the DAQ for comparison and analysis.
- Electricity (solar PV) generation,
- Electricity (such as ASHP, AHU, ERV, whole house) consumption,
- Temperature and humidity (first floor, basement, supply air, return air).

3. Data Analysis
The nearly-zero house in Strathroy has a natural gas furnace along with an electric air source heat pump. A full ASHRAE level III energy audit was conducted to identify major energy consumers, base loads and energy consumption of miscellaneous appliances/devices, and to perform combustion tests for both furnace and water heater, thermal imagery, blower door depressurization test, plug-load collection, and lighting end-use collection. Additionally, homeowners were interviewed in order to gather required information about the end-user’s behavior in terms of thermal comfort and energy consumption. Data from the energy audit was used to develop an initial building energy simulation model with TRNSYS software. Each of the HVAC equipment was tested individually to identify their efficiencies and coefficient of performance (COP). The individual and isolated tests provided enough information to compare the manufacturer’s nominal values and performance curves with recorded data under real-world condition. Furnace efficiency was measured during the energy audit (89%) and by analyzing the natural gas consumption of the furnace, supplied thermal energy to the house was calculated. The load
was correlated with outdoor temperature to find the thermal demand of the house in different weather condition. This experimentally calculated load was then used to calibrate and validate the TRNSYS simulation model. The air source heat pump (ASHP) was also tested separately to calculate its COP based on outdoor temperature. After both tests, the system was set on the manufacturer’s default control for electric-natural gas hybrid systems. A working prototype communication interface board of the Smart Dual Fuel Switching System (SDFSS) was developed and used to receive, intercept and send signals and commands to the hybrid system as well as send these signals to the cloud server. The SDFSS successfully controlled the ASHP and the natural gas furnace while applying an optimal running schedule for the system remotely from the cloud server. Collected data for the whole monitoring period was categorized and analyzed based on the controller settings. It was observed that the SDFSS controller provides a less expensive and relatively clean (lower GHG emission) option compared with conventional systems as well as the hybrid systems with simple/single variable controllers. The experimental results of the SDFSS test were used to fine-tune the TRNSYS simulation model and then collected weather information for a period of 30 days was applied to the model to investigate the energy and associated cost and GHG emission of each HVAC set up (SDFSS, default manufacturer setting, furnace only, and ASHP only).

Figure 1 illustrates the monthly power consumption of major consumers in the house along with on-site power generation through the PV system. The pattern of power generation shows an increase during summer season which was expected due to higher solar intensity and longer hours of operation. The whole house consumption is also shown versus different HVAC equipment.

![Figure 1. Electricity generation and consumption activities in 2018.](image)

The natural gas consumption data collected by the installed sensors are analysed in depth. These analyses are also used to help calibrate the simulation model. The natural gas furnace in this study was assumed to be a constant efficiency furnace. During the energy audit, the natural gas furnace went through combustion testing. During the test, the thermostat was adjusted to simulate maximum furnace capacity along with minimum furnace capacity and the efficiency was tested to be an average of 89%. Thereafter, natural gas consumption was converted to an equivalent energy density of natural gas using the National Energy Board’s accepted conversion rate of 10.64 kWh/m³ [4]. The overall analysis for natural gas consumption including the sources of the consumption is provided in Table 2.
Table 1. Summary of annual electricity consumption.

| Electricity Consumption & Generation Activities (kWh) | Whole House Electricity Consumption (kWh) | ASHP Electricity Consumption (kWh) | AHU Electricity Consumption (kWh) | ERV Electricity Consumption (kWh) | Whole House Electricity Consumption without ASHP, AHU, and ERV (kWh) | PV Generation (kWh) |
|-------------------------------------------------------|----------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------------------------------------|-------------------|
| Annual                                                | 10,340                                 | 1,917                           | 568                             | 274                             | 7,474                                                        | 9,746             |

Table 2. Summary of annual natural gas consumption

| Natural Gas Consumption from | Whole House | Domestic Hot Water (DHW) | Furnace | Others (Cooking + Fireplace) |
|-----------------------------|-------------|---------------------------|---------|------------------------------|
| m³                          | 794.2       | 158.9                     | 471.7   | 162.4                        |
| GJ                          | 29.6        | 5.9                       | 17.6    | 6.0                          |
| kWh                         | 8,228       | 1,647                     | 4,887   | 1,683                        |

The annual total consumption and generation is presented in Table 1, which shows a slightly lower electricity generation compared to total consumption. It was observed during the entire monitoring period that homeowners tend to consume electricity excessively since they believe they are generating a good amount of electricity. Therefore, resident’s behavior was a key factor that electricity consumption surpassed the electricity generation.

4. Analysis on indoor air quality (IAQ)
In this section, some of the factors such as indoor dry bulb temperature, relative humidity (RH), air-handling unit (AHU), energy recovery ventilator (ERV), which correspond to indoor air quality (IAQ), are examined.

![Figure 2](image-url). A portion of the analysis on electricity consumption from AHU and its potential relationship with NG Furnace/ASHP loads during the operation of SDFSS, November 2018.
For a given thermal load, ASHP requires higher AHU power, therefore the energy. In Figure 2, this expected result is observed. During the switches from natural gas furnace to ASHP, air supply temperature also increases drastically for a moment to start the ASHP cycle.

Relative humidity (RH) is the ratio of the amount of moisture present in the air due to the maximum amount of moisture the air could possibly contain at a given temperature [5]. It can be seen from Figure 3 that during the afternoon at 1:10 PM and at 6:32 PM on first of December 2018, an abrupt increase in ERV consumption is recorded. The occupants’ having a potential guest over during this weekend could explain the reason of such an immediate increase in indoor relative humidity. It is observed that ERV can handle this increase in relative indoor humidity by operating with a higher pace. In other words, without a need for a humidifier, ERV enables a comfortable indoor experience for the occupants.

**Figure 3.** A portion of the relationship between Relative Humidity [%] and mainfloor power consumption from ERV in winter season, December 2018.

Furthermore, behaviour of the temperature changes during the operation of SDFSS is studied in detail. A portion of this analysis is demonstrated in Figure 4. It is seen that the mainfloor temperature have sudden temperature rise which is unexpected. This increase can only be explained by some of the activities by the occupants such as turning on the fireplace ran by natural gas or having major cooking activities that increase the heat gain as well as makeup into basement due to kitchen exhaust fan (depressurization). Hence, such cold unconditioned outdoor makeup air into the basement caused the temperature drop. Additional analysis on air supply temperature and air return temperature changes during SDFSS was in operation is conducted. Expectedly, switches from ASHP to natural gas furnace caused drop in air return temperature.

**5. Conclusion**

The Strathroy house is a single-storey detached residential house with a basement and is currently owned and occupied by a retired couple. The house uses a high-efficiency hybrid natural-gas furnace and an electric air source heat pump (ASHP) together with an ERV for its heating, ventilation and air-conditioning needs. To help meet its nearly-zero status, a solar photovoltaic system was installed on the roof to offset energy consumption. Furthermore, a detailed analysis conducted on the factors such as indoor dry blub temperature, relative humidity (RH), air-handling unit (AHU), energy recovery
ventilator (ERV), which correspond to indoor air quality (IAQ), are examined. It is concluded that the preliminary analysis conducted for over a year of period to monitor the operation of SDFSS with a focus on heating season, is promising.

Temperature Analysis on Indoor Air Quality during SDFSS is in Operation

![Temperature Analysis on Indoor Air Quality during SDFSS is in Operation](image)

**Figure 4.** A portion of the temperature analysis during SDFSS is in operation, November 2018.

### 6. Acknowledgements

Authors would like to thank Union Gas Limited, Ontario Centres of Excellence (OCE) and MITACS for funding support.

### 7. References

[1] Safa AA, Fung AS, Kumar R. Comparative thermal performances of a ground source heat pump and a variable capacity air source heat pump system for sustainable houses. Applied Thermal Engineering. 2015 Apr 25;81:279-87.

[2] Tung K, Yu D, Ekrami N, Fung AS. Experimental and sensitivity analysis of a smart dual fuel system in a net-zero energy home. InIOP Conference Series: Earth and Environmental Science 2019 Feb (Vol. 238, No. 1, p. 012018). IOP Publishing.

[3] Demirezen G, Fung AS. Application of artificial neural network in the prediction of ambient temperature for a cloud-based smart dual fuel switching system. Energy Procedia. 2019 Feb 1;158:3070-5.

[4] National Energy Board (Canada). “Energy Conversion Tables - Canada.ca.” Retrieved from https://apps.neb-one.gc.ca/Conversion/conversion-tables.aspx?GoCTemplateCulture=en-CA#s1ss2. 2016.

[5] Zhang J, Fung AS. Experimental study and analysis of an energy recovery ventilator and the impacts of defrost cycle. Energy and Buildings. 2015 Jan 1;87:265-71.