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Potential Heating Energy and Cost Savings of Dual Fuel Heat Pump Controls as a Residential Building Equipment Retrofit in the U.S.

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Abstract

This study investigated the energy and cost savings potential by modeling a dual fuel heat pump system with its control for a residential building in (5A) cold climate in U.S. The simulation analysis showed that the application of the DFHP system and its control to the target building can save the heating energy by 42% over a gas furnace system (baseline system). Although the HP-only system can save more heating energy (i.e., 53%) over the baseline system than DFHP system does, the DFHP with its control demonstrated the higher cost savings when a time of use electricity rate was considered.

Introduction

The new U.S. administration has set a target to reduce greenhouse gas emissions by 50%–52% by 2030 for a carbon-neutral economy by 2050. In the building sector, the primary target of the building decarbonization has been electrification of building's space heating source. However, it is challenging to convert existing natural gas (NG) systems to heat pump (HP) systems all at once. The dual fuel heat pump (DFHP) system can address this challenge and provide a unique opportunity to use both NG and HP systems. However, as the traditional control of HP systems can diminish cost and energy saving benefits, in this study, we aim to reduce cost and energy consumption through advanced DFHP control algorithm.

In many studies, the retrofits have been proposed for residential buildings. This retrofits have two categories: building envelope retrofits, and building mechanical system retrofits (e.g. HVAC). Several studies have suggested a retrofitting method that reinforces the thermal performance of the building envelope, such as installing high-performance windows and double-skin façades (Hart et al. 2019; Ascione et al. 2021; and Burgett et al. 2013).

Some studies have focused on the heating system, particularly the use of high-efficiency boilers or heat pumps. Other studies have suggested combining the solar water heating system and the renewable energy system (Teres-Zubiaga et al. 2016; Caskey et al. 2018; and Liu et al. 2021). Existing literature focused on replacing the old heating system or windows for energy saving. However, there have been limited studies considering system control, with cost and energy savings as the target analysis.

In this study, the electric HP was installed as a secondary heating system and not as a replacement for the heating system. To maximize energy and cost savings, we propose a DFHP system and its control algorithm as a retrofitting bundle.

Methods

To evaluate the impact of the DFHP system and its control algorithm, we conducted a simulation study. We used OpenStudio for geometry modeling and the U.S. Department of Energy's EnergyPlus whole building energy program for detailed simulation modeling and HVAC system modeling. We developed the control algorithm of the DFHP system using Python. Python was then linked with the EnergyPlus simulation model using the Python Energy Management System (Python-EMS) function, as shown in Figure 1.

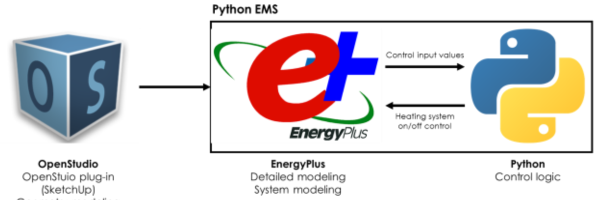

Figure 1 Simulation method

Simulation model

Simulation model description

To make the simulation model, we selected a residential building in Albany, NY as a target building. Figure 2 shows an overview of the target building, the size of which is 221.6 m^2 (2,385 ft^2). The gas furnace system served as the building's primary heating system.

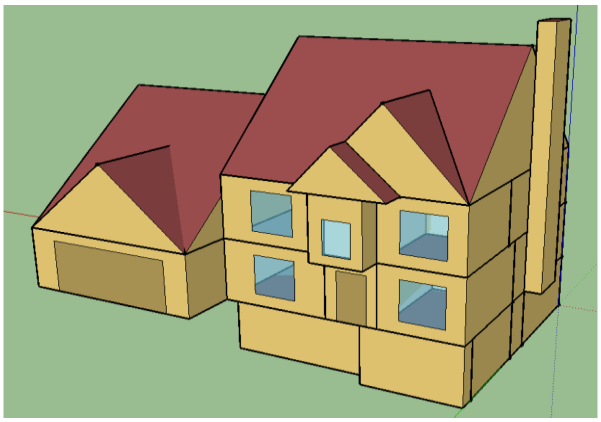

Figure 2 Simulation model

Table 1 shows input values of the simulation model which are from the building summary report. Since the building summary report did not provide the lighting power density, we used the value from the residential prototype building model based on the International Energy Conservation Code (IECC) 2015, provided by the Building Energy Codes Program website (Building Energy Codes Program, 2021).

Table 1 Simulation input values

Variables		Input value
U-value (W/m^2·K)	Exterior wall	0.42
	Roof	0.392
	Window	0.46
Infiltration (ACH)		0.205
People (#)		4
Lighting (W/m^2)		2.1*
Electric equipment (W)		124
Heating setpoint (°C)		20 (4 a.m. to 10 p.m.)
Heating setback setpoint (°C)		17.2 (10 p.m. to 4 a.m.)
Hot water setpoint (°C)		51.6
Capacity of gas furnace (kW)		24.9
Efficiency of the boiler (%)		80

Dual fuel heat pump system

The DFHP system is the proposed heating system for retrofitting residential buildings in this study. HP (i.e., air-to-air HP) was installed as another heating system. Table 2 shows the input values of the HP in EnergyPlus simulation model. This information is from the EnergyPlus simulation library.

Table 2 Input values of the Heat pump

Variables		Input value
1 Speed	Capacity (kW)	14.9
	COP (W/W)	4.35
	Air flow rate (m^3/s)	0.6135
2 Speed	Capacity (kW)	24.9
	COP (W/W)	3.96
	Air flow rate (m^3/s)	0.7551

Cost of utilities

Figure 3 shows the electricity rate on weekdays and weekends. Electricity rate varies depending on the time of usage (i.e., off-peak, mid-peak, or on-peak hours).

The DFHP control logic (see Figure 4) starts from the cost savings part where both electricity cost and gas cost are important values.

The gas price is based on the 2025 annual energy outlook reference case price for NG. (U.S. EIA, 2021). The gas rate provided by the U.S. energy information administration is \$10.15 per MMBtu (\$0.0346 per kWh).

For the electricity price, since the annual energy outlook provides the fixed averaged rate even if the electric rate varies depending on the time of usage, we used averaged electricity rate from several electricity companies which are located in different states.

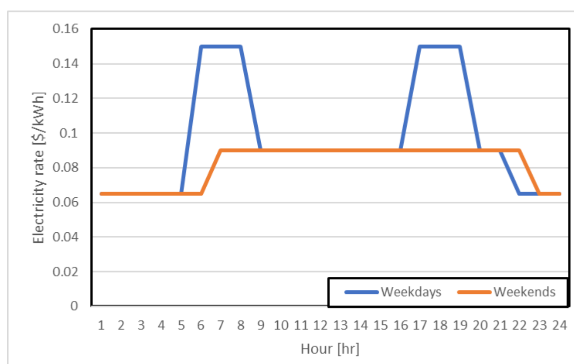

Figure 3 Electricity rate

Control logic

Figure 4 shows the DFHP control algorithm, which has three main parts: cost savings, deadband, and HP operation. The yellow-colored box in Figure 4 signifies cost savings, the blue-colored box refers to deadband, while the red-colored box pertains to HP operation.

For cost savings, the time-of-use rate for electricity and the fixed price for NG was considered. Meanwhile, 1.1

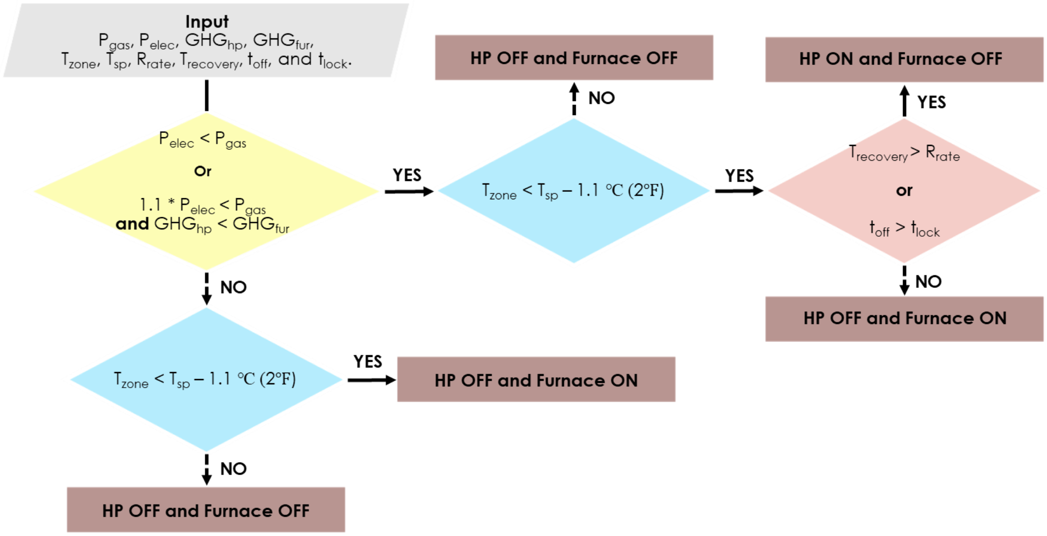

Figure 4 Dual fuel heat pump control logic

°C was set as deadband. Recovery rate, accumulation time when the HP is off, and indoor air temperature drop were considered for HP operation. If within 3 hours indoor air temperature drops more than 2.8 °C—the difference between heating setpoint and heating setback temperature—then the HP turns on. In the logic, R_{rate} refers to the recovery rate, which is 2.8 °C per 3 hours.

The timestep of the control logic is 5 mins, which is why the value of R_{rate} is 0.078 °C per 5 mins.

To maximize HP operation, if the HP turns off for more than 30 mins, then the HP turns on when heating is needed for energy savings.

Simulation cases

To determine the effect of DFHP and control logic on energy and cost savings, three cases were selected and analyzed. As described above, energy consumption saving is expected when the base case and the DFHP case are compared due to the efficiency of the HP is higher than that of the gas furnace. To confirm cost savings from the proposed control logic, we compared the DFHP case with the case where only the HP is operated.

- Base case (i.e., gas furnace only)
- Air-to-air HP only
- DFHP (i.e., air-to-air HP and gas furnace)

To estimate heating energy savings, we selected October to March as the analysis period. We calibrated the simulation model using monthly utility bills from October 2020 to March 2021. Figure 5 shows the calibration results; the X-axis indicates outdoor air temperature, while the Y-axis indicates gas consumption. The weather file (Albany NY) for the simulation was obtained from the official website of the EnergyPlus program. For the calibration process, we downloaded monthly average outdoor air temperatures from the website of the Weather Underground (Weather Underground, 2021). We could not compare gas consumption because we did not use the actual hourly weather data for the simulation. However, when we plotted gas consumption versus monthly average outdoor air temperature, we found that the monthly gas consumption pattern of the simulation model is similar to the actual monthly gas consumption.

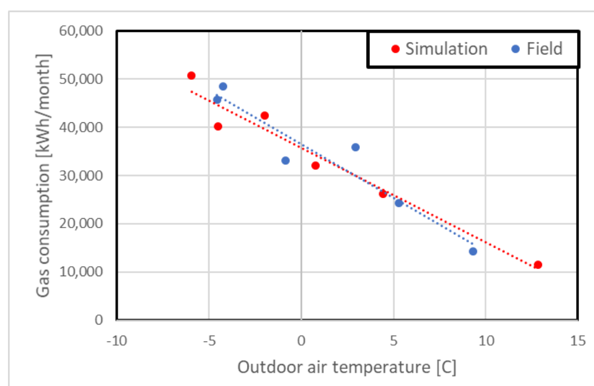

Figure 5 Comparing gas consumption with actual data

Analysis of the winter representative day

To understand how heating system works, we selected December 21 as the winter representative day. Figure 6 shows the heating energy consumption of the base case and the DFHP case on the winter representative day. Furnace in Figure 6 is the base case (i.e., gas furnace only), while DFHP is the DFHP case. While the base case consumed heating energy steadily, in the DFHP case, the heating system was turned on and off repeatedly. As previously mentioned, the DFHP control logic consists of three parts: cost saving, deadband, and HP operation. The cost saving and HP operation parts do not affect the heating system operation hours because it determined which of the two heating systems should be used.

However, deadband part affects the heating operation hours. Since deadband of 1.1℃ was set in the DFHP control logic, the heating system operated only when the indoor air temperature is lower than the heating set temperature by 1.1℃ or more. However, there was no deadband in the base case. This observation confirmed that the DFHP case operates less than the base case.

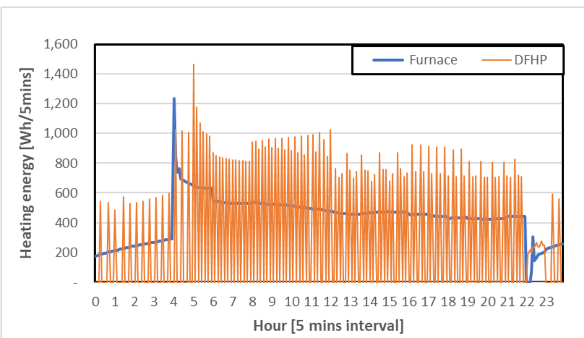

Figure 6 Heating energy consumption pattern on the winter representative day

Figure 7 shows the heating energy consumption patterns of the HP and gas furnace for DFHP case. The control logic was designed to operate one heating system at a time to ensure energy and cost savings. As can be seen in Figure 7, both systems never operated at the same time. For a more detailed analysis, we analyzed heating energy consumption patterns by control logic part.

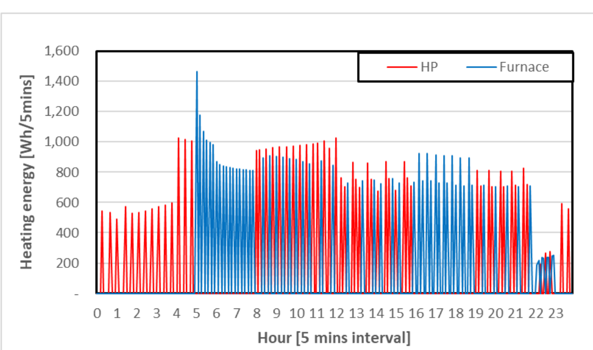

Figure 7 Heating energy consumption pattern of the DFHP case on the winter representative day

Cost savings part

Figures 8 and 9 show the heating energy consumption pattern of the HP and gas furnace on the winter representative day.

As shown in Figure 3, electricity rate is expensive during on-peak hours from 5 a.m. to 8 a.m. and from 4 p.m. to 7 p.m. The HP had no heating energy consumption during on-peak hours, while the gas furnace was used when heating is needed.

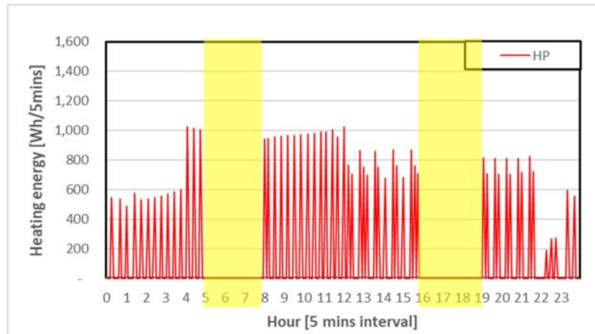

Figure 8 Heating energy consumption pattern of the HP on the winter representative day (on-peak hours)

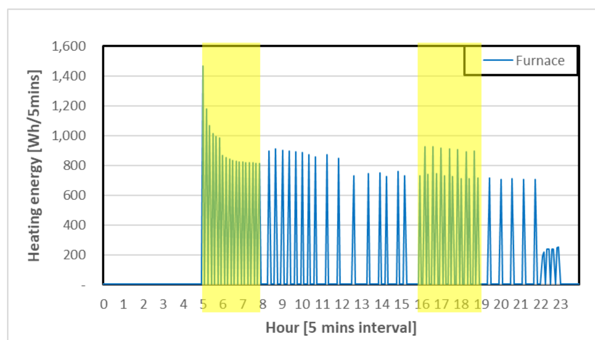

Figure 9 Heating energy consumption pattern of the gas furnace on the winter representative day (on-peak hours)

Heat pump operation part

According to the control logic, the HP needs to operate when the indoor air temperature drops more than 2.8 ℃ within 3 hours, and if HP is not operated for more than 30 minutes, HP will be operated at the next timestep when heating is needed. Figures 10 and 11 show the heating energy consumption pattern of the HP and the gas furnace from 8 a.m. to 4 p.m. and from 7 p.m. to 12 a.m.

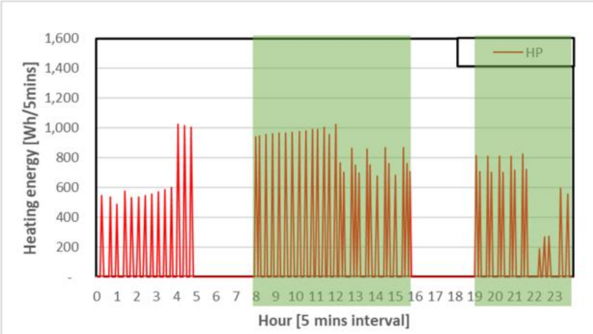

Figure 10 Heating energy consumption pattern of the HP on the winter representative day

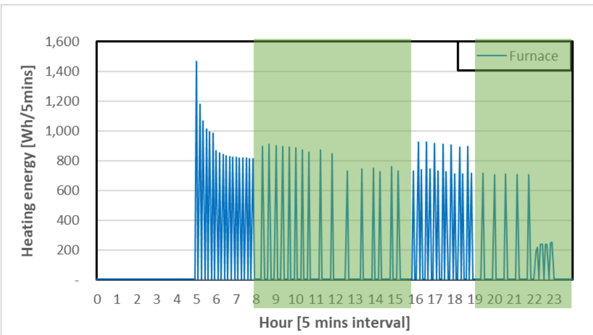

Figure 11 Heating energy consumption pattern of the gas furnace on the winter representative day

To understand HP operation, we compared $T_{recovery}$ and R_{rate}. Figure 12 shows the indoor air temperature drop ($T_{recovery}$) and recovery rate (R_{rate}) comparison. We calculated the indoor air temperature drop by subtracting the indoor air temperature in the previous timestep from the current indoor air temperature. In the control logic, the HP turns on when the indoor air temperature drop is higher than the recovery rate. One in the Y-axis in Figure 12 means that $T_{recovery}$ is higher than R_{rate}, which indicates that the indoor air temperature drop is higher than the recovery rate, and the HP must be turned on when heating is needed. Zero in the Y-axis in Figure 12 means that $T_{recovery}$ is lower than R_{rate}, which indicates that the indoor air temperature drop is lower than the recovery rate, and the gas furnace must be turned on when heating is needed.

Figure 13 shows the heating system operation from 8 a.m. to 4 p.m. The system operation pattern of the HP in Figure 13 follows that in Figure 12, which means that when the value of the indoor air temperature drop is higher than the recovery rate, the HP turns on; otherwise, the gas furnace turns on as expected.

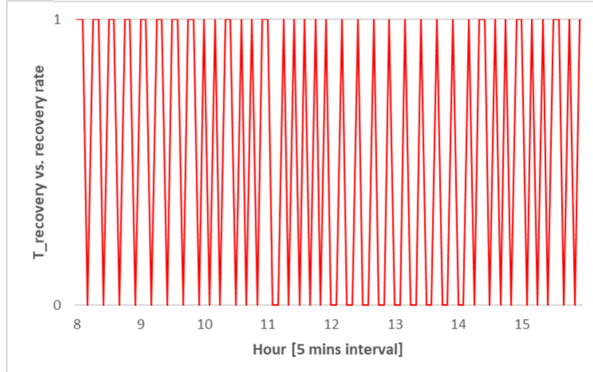

Figure 12 Indoor air temperature drop and recovery rate comparison (8 a.m. to 4 p.m.)

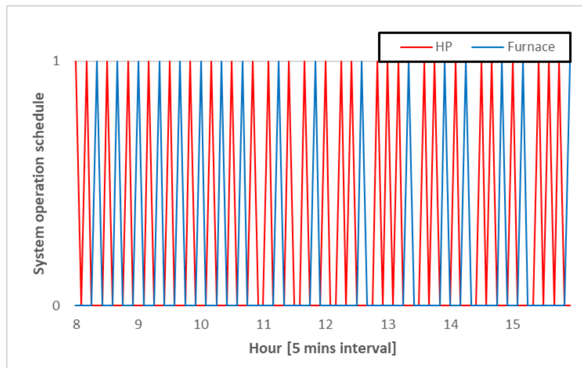

Figure 13 Heating system operation from 8 a.m. to 4 p.m.

The pattern in Figure 14 is different from the pattern in Figure 12.

Figure 14 shows the indoor air temperature drop and recovery rate comparison from 7 p.m. to 12 a.m. From 10 p.m. to 11 p.m., the indoor temperature drop was lower than the recovery rate, which means that the HP should not be turned on.

However, as shown in the heating operation from 7 p.m. to 12 a.m. in Figure 15, the HP turned on from 10 p.m. to 11 p.m. even if the indoor temperature drop was lower than the recovery rate as shown in Figure 14. This is because of the accumulation time when the HP is off (t_{off}) and the threshold for t_{off} (t_{lock}). To maximize HP operation time, if it has not been turned on for more than 30 mins, the HP is turned on when heating is needed.

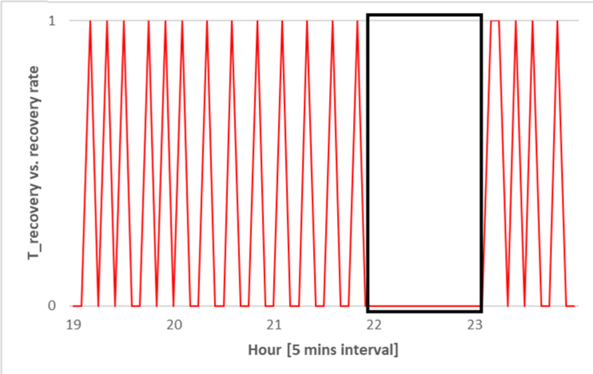

Figure 14 Indoor air temperature drop and recovery rate comparison (7 p.m. to 12 a.m.)

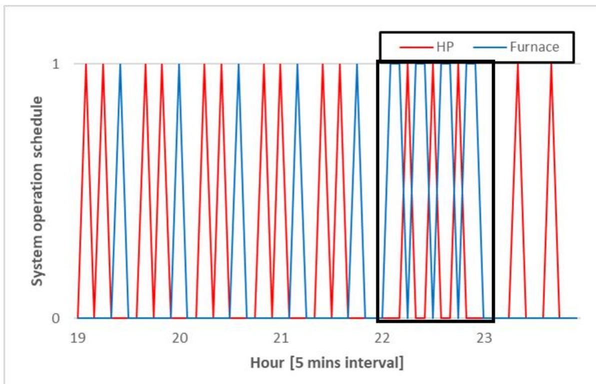

Figure 15 Heating system operation from 7 p.m. to 12 a.m.

From 12 a.m. to 5 a.m., the indoor air temperature dropped quickly, as it was cold outside. Only the HP operated during this time.

In our analysis of the winter representative day, it can be seen that the control logic implemented in Python is well connected with the EnergyPlus simulation model by Python-EMS.

Energy and cost analysis

Monthly site energy savings analysis

Figures 16 and 17 show the monthly site gas and electricity energy consumption in each case.

In both cases, the highest gas and electricity consumption was in January. In terms of gas consumption, the base case (i.e., gas furnace as heating system) consumed the most, while and the HP only case (i.e., used gas only for the gas equipment) consumed the least. In terms of electricity consumption, the HP only case (i.e., electric HP as heating system) consumed the most, whereas the base case (i.e., used electricity only for fan and electric equipment) consumed the least.

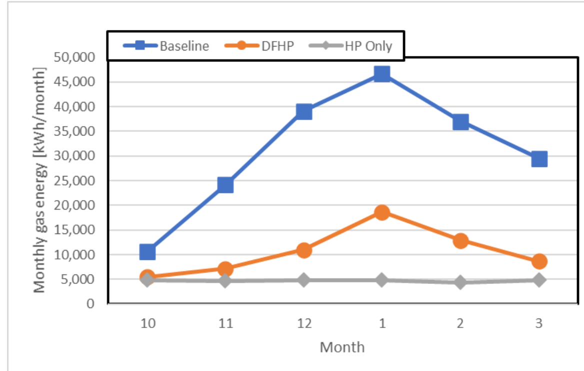

Figure 16 Monthly site energy consumption (Gas)

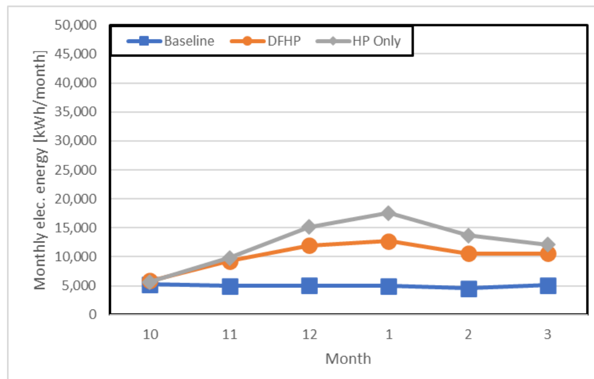

Figure 17 Monthly site energy consumption (Electricity)

Table 3 shows the total site energy consumption comparison. During the heating period from October to March, the base case consumed 186,983 kWh of gas, the DFHP case consumed 64,006 kWh, while the HP only case consumed 28,543 kWh. As for electricity consumption, the HP only case consumed 74,022 kWh, the DFHP case consumed 60,989 kWh, whereas the base case consumed 30,041 kWh.

Combining gas and electricity consumption, the base case consumed the most with 217,024 kWh. The DFHP case consumed 124,995 kWh of gas and electricity, and the HP only case consumed 102,565 kWh, it is 52.7% less gas and electricity consumption than the base case.

Table 3 Site energy consumption comparison

	Base case	**Dual Fuel Heat Pump**	**Heat Pump**
Gas (kWh/year)	186,983	64,006	28,543
Electricity (kWh/year)	30,041	60,989	74,022
Total (kWh/year)	217,024	124,995	102,565
Energy savings (%)	-	42.4 %	52.7 %

Monthly heating energy savings analysis

Figures 18 and 19 show the monthly gas and electricity energy consumption for heating in each case.

Both gas and electricity consumption patterns are the same as that of the site energy consumption. As regards gas consumption, the base case (i.e., gas furnace as heating system) consumed the most. The HP only case did not consume gas because the HP uses electricity. As regards electricity consumption, the HP only case (i.e., electric HP as heating system) consumed the most, whereas the base case, which used electricity only for the fan, consumed the least.

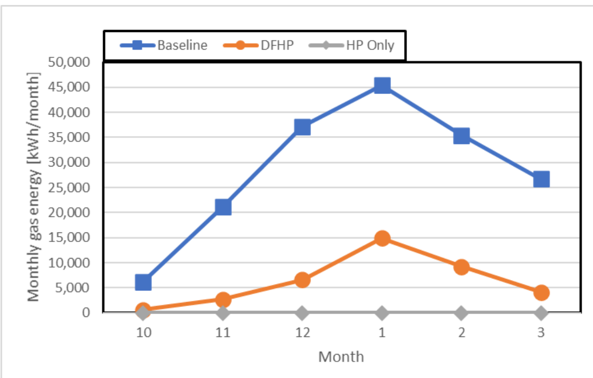

Figure 18 Monthly heating energy consumption (Gas)

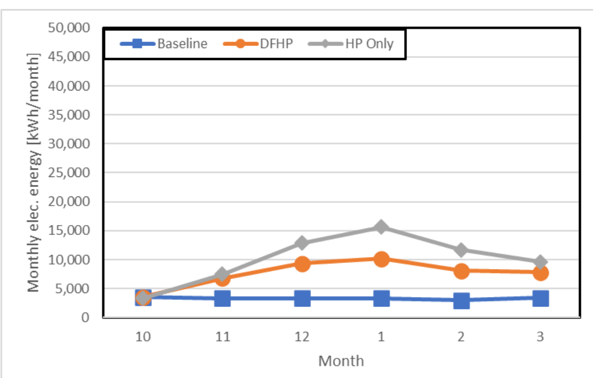

Figure 19 Monthly heating energy consumption (Electricity)

Table 4 shows the total heating energy consumption comparison. The base case consumed 172,056 kWh of gas, while the DFHP case consumed 38,511 kWh. The HP-only case did not consume any gas. As regards electricity consumption, the HP only case consumed 60,566 kWh, the DFHP case consumed 45,665 kWh, while the base case consumed 19,965 kWh.

Combining gas and electricity consumption, the base case consumed the most with 192,021 kWh. The DFHP case consumed 84,177 kWh, which is 56.2% less than the base case. The HP-only case consumed 60,566 kWh, which is 68.5% less than the base case.

Table 4 Heating energy consumption comparison

	Base case	**Dual Fuel Heat Pump**	**Heat Pump**
Gas (kWh/year)	172,056	38,511	0
Electricity (kWh/year)	19,965	45,665	60,566
Total (kWh/year)	192,021	84,177	60,566
Energy savings (%)	-	56.2 %	68.5%

Monthly operational cost savings analysis

Figures 20 and 21 show the monthly gas and electricity cost for heating in each case. Table 5 shows the gas and electricity cost comparison. As can be seen in the site energy and heating energy analysis above, both the DFHP case and the HP only case showed 50% or more energy savings than the base case. Since the base case consumed gas, which is relatively cheaper than electricity, its cost saving is around 30%, which is lower than percentage of the energy saving. In terms of energy consumption, the HP only case consumed the least gas and electricity, but since HP only case consumed electricity for heating even when electricity rates are high, the DFHP case, overall, has more cost savings.

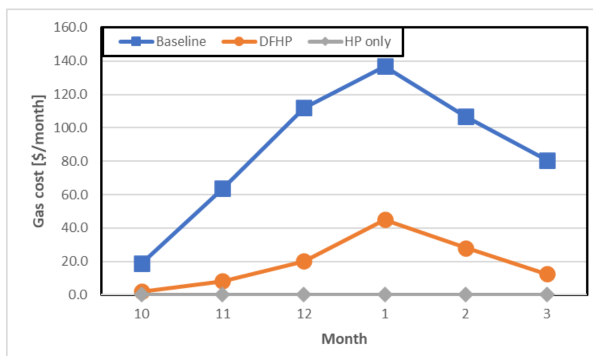

Figure 20 Gas operational cost in each case

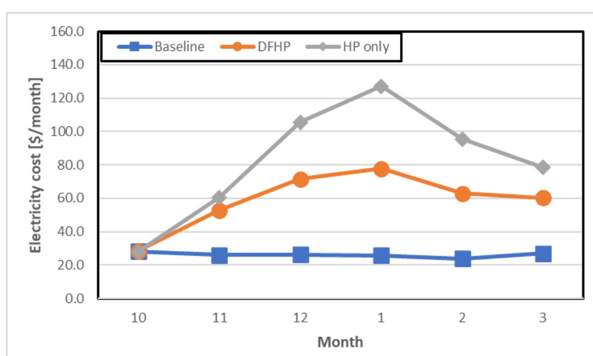

Figure 21 Electricity operational cost in each case

Table 5 Operational cost comparison

	Base case	Dual Fuel Heat Pump	Heat Pump
Gas ($)	518.89	116.14	0
Electricity ($)	157.10	354.08	494.93
Total ($)	675.99	470.22	494.93
Cost savings (%)	-	30.44 %	26.78%

Conclusion

In this study, we proposed the DFHP system and its control as a retrofit for residential buildings in cold climate zones. We calibrated the simulation model with monthly gas and electricity bills. We also applied Python-based control logic for both energy and cost savings to the EnergyPlus simulation model, and it worked as expected.

The analysis affirmed that the application of the DFHP system and its control can reduce heating energy consumption. Even if the HP-only case consumed less gas and electric energy for heating, the HP only case consumed electricity even when the electricity rate is high. For this reason, the DFHP case is the optimal case that can significantly reduce both cost and energy consumption.

In a future study, we will perform a field test with the DFHP system in the target building, and we will calibrate the simulation model using the measured data and verify the energy and cost savings. Additionally, we will conduct a greenhouse gas emission analysis.

Acknowledgment

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Nomenclatures

Nomenclature	Definition
P_{gas}	Gas price/ 0.8 (gas efficiency) ($/W)
P_{elec}	Electricity price/COP ($/W)
GHG_{hp}	Greenhouse gas emission (elec.)
GHG_{fur}	Greenhouse gas emission (gas)
T_{zone}	Indoor air temperature (℃)
T_{sp}	Heating setpoint temperature (℃)
R_{rate}	Recovery rate (0.078 ℃ within 5 mins)
$T_{recovery}$	Indoor air temperature drop (℃)
t_{off}	The accumulation time when HP is off (min.)
t_{lock}	Threshold for t_{off} (30 mins)

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