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Energy saving in a residential building using occupancy information

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Abstract— Occupancy-based control systems for floor heating can lead to energy saving in a residential building. This study focuses on the energy consumption in a half-duplex residential house located in Edmonton, Alberta. A 3D energy model was developed for the house. The energy consumption was simulated with and without considering occupancy information using EnergyPlus software. The actual energy consumption of the house was obtained from the gas meter and occupancy information was collected from two Passive Infrared (PIR) sensors and the time sheets filled by the occupants. The results showed the potential for energy savings by considering occupancy information. The simulation results indicate 9.5% to 18.2% energy saving, depending on the occupancy-based control methods. This study highlights the importance of considering occupancy information in reducing energy consumption in residential buildings.

Keywords-component; Occupancy-based control; Energy saving; Residential building; Energy simulation model

I. INTRODUCTION

Residential and commercial buildings are the largest energy-consuming sector in the world. They are responsible for 40% of all primary energy usage in the US and EU [1]. In Canada, the residential and commercial/institutional sectors consume around 30% of the total energy consumption in the country. Among all the energy users in buildings, space heating and cooling account for 66% and 59% of the energy usage in Canadian residential and commercial buildings, respectively [2, 3].

Despite efforts in the building industry to reduce energy consumption and emission production, the building sector is still responsible for one-third of the greenhouse gas emissions worldwide [4]. While new projects like energy-zero buildings and green buildings have increased energy efficiency, but due to rapid growth in the building sector and world population, energy consumption in the building sector is still expected to increase globally for the next 30 years by 1.3% [5]. Thus, methods and tools to decrease building energy consumption are highly needed.

One of the effective methods in a Building Energy Management (BEM) system to reduce heating/cooling load is detecting occupancy in a building and adjusting Heating, Ventilation, and Air Conditioning (HVAC) operation accordingly [6]. Occupancy-based control systems in buildings can significantly reduce energy consumption. A study in [7] showed the possibility of up to 80% savings in energy consumption through an occupancy-based feedback control system. Another study reported a 30% energy saving by using occupancy patterns in a commercial building conference room [8].

The temperature range for comfortable occupancy in a space depends on factors like relative humidity, activity level, clothing, etc. According to the ASHRAE 55 standard, the comfortable temperature range is from 19.5°C to 27°C with relative humidity being less than 65% [9]. Although it is difficult to find a unique thermostat temperature for unoccupied buildings during the cold season, the temperature range between 12 °C to 16 °C is commonly used to avoid any damage to the building (e.g., avoid pipeline freezing) and save energy [10, 11]. This can reduce the heating load while the building is not occupied.

Despite numerous studies conducted for commercial/educational buildings to investigate energy saving by implementing building occupancy information, residential buildings have not received the same attention in the literature. Fig. 1 compares the number of studies that use residential and non-residential buildings as their testbed.

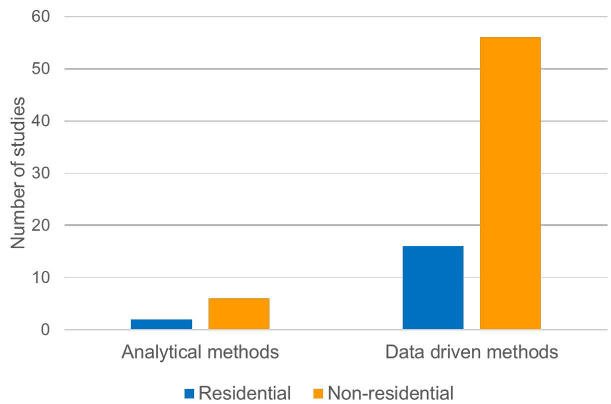


Figure 1: Comparison of the number of the studies using occupancy detection methods in residential and non-residential buildings. The data is from [13].

Residential buildings consume more energy than commercial and institutional buildings [12]. Fig. 2 depicts that non-apartment buildings account for over 85% of energy consumption in the residential sector. These facts highlight the need for further research on low-cost methods to reduce energy consumption in residential buildings, particularly in non-apartment dwellings.

In this study, a 3D model of a half-duplex residential house located Southwest of Edmonton, Alberta was created and used to simulate the energy consumption in the building. After validating the simulation model, the house's HVAC energy consumption was investigated with and without considering the occupancy information. Given the availability of low-cost occupancy sensors in the market, the results from this study can be utilized to realize substantial energy savings in residential buildings.

The structure of the paper is as follows. Section II describes the testbed of the study, the data collected for this study, and the data collection process. Section III explains the 3D model,

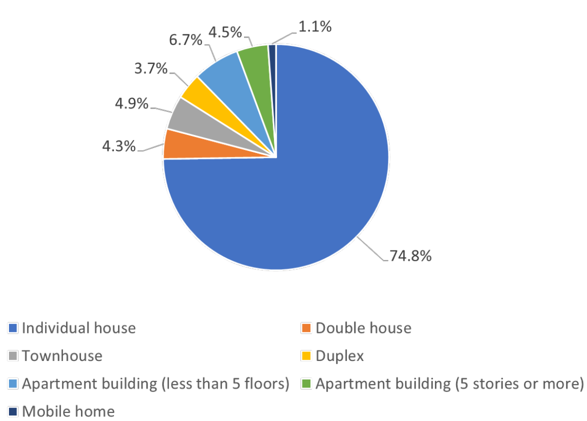


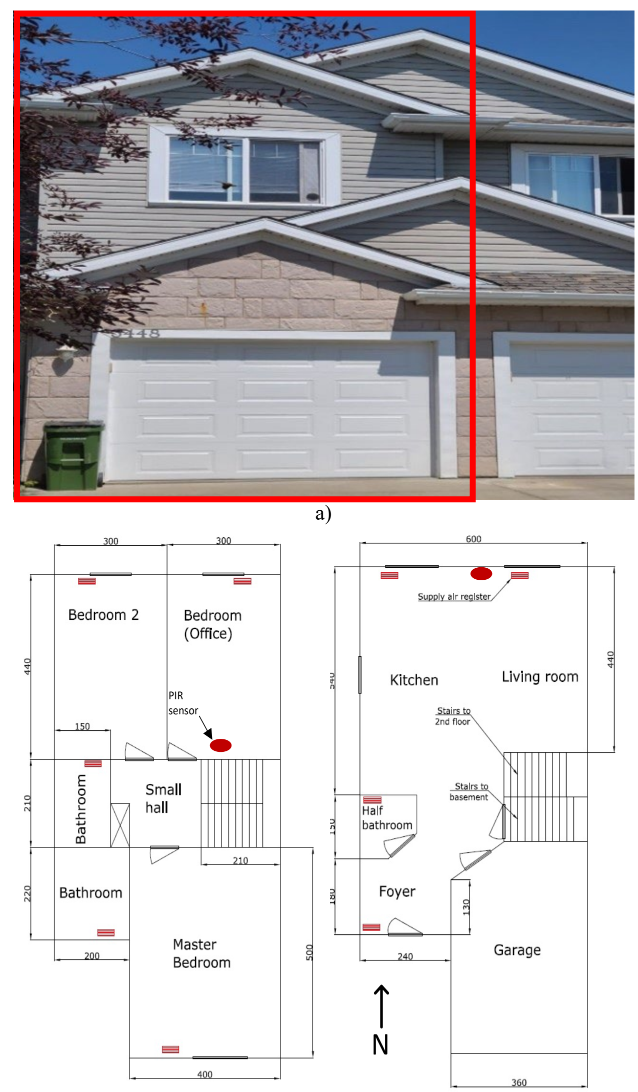
Figure 2: Total energy consumption in Canadian residential households in 2019 based on the type of dwelling. Created based on data presented in [14].

energy simulation of the building and its validation. Section IV discusses the possibility of energy saving in the building by considering occupancy information. Finally, Section V discusses the summary and conclusion of the study.

II. Testbed and Data Collection

The testbed in this study is a half-duplex residential house located at Southwest of Edmonton, Alberta. Fig. 3 presents a schematic of the house and its floor plans.

The building is equipped with a NEST thermostat E, installed in the foyer area, that controls the temperature of the building by turning on/off a TRANE Upflow left-induced draft gas furnace (Model: TUE1B080A9361A) that works with natural gas. Table 1 shows the specification of the heating system. In addition, two Monnit wireless PIR motion detection



b)

Figure 3: a) North view of the house, b) Floor plan, supply air registers' locations, and PIR sensor location in the building. (All dimensions are in cm)

Table 1: Heating system specifications.

TRANE Upflow left-induced draft gas furnace (Model: TUE1B080A9361A)	
Furnace rating	
Input (kJ/H)	84,000
Capacity (kJ/H)	66,500
Temp. rise (Min-Max) °C	16 - 33
Blower Drive	
Motor (kW)	0.25
R.P.M	1075
Volts/Ph/Hz	115/1/60

sensors are installed on the first and second floors to track the occupancy activity in the building. The PIR sensor on the main floor can cover the entire main floor including the kitchen and living room while they are occupied.

Table 2a presents the specifications of the NEST thermostat. The NEST thermostat is equipped with a motion sensor to detect occupancy and decrease the set temperature automatically during no occupancy. However, it only collects the occupancy information in its surrounding area, part of the main floor, not the entire building. PIR sensor specification is presented in Table 2b. Of the three bedrooms that are located on the second floor two of them are mostly occupied during the night, but the other one also is used for other purposes and could be occupied during the day. This room is equipped with the second PIR sensor. So, to track the occupancy on the second floor the information from the PIR sensor has been used in combination with a data sheet defining the occupancy by the occupant.

Table 2: a) Nest Thermostat E and b) Monnit wireless PIR motion detection sensor specifications.

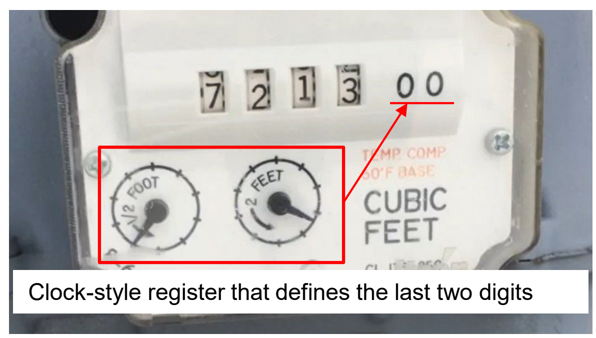
a)

 **Google Nest Thermostat E**	
Sensors	Temperature, Humidity, Proximity, Motion, Ambient light, Magnetic (for thermostat ring position)
Memory	256 MB
Operating	Temperature: 0°C to 40°C (32°F to 104°F) Humidity: Up to 90% RH unpackaged Pressure: Up to 10,000 ft altitude
Compatibility	he Nest Thermostat E works with 85% of 24 V heating and cooling systems, including gas, electric, forced air, heat pump, radiant, oil, hot water, solar and geothermal.

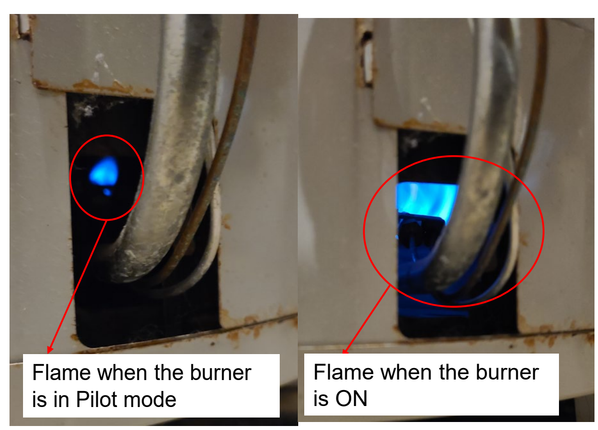
b)

 **Monnit wireless PIR motion detection sensor**	
Data logging	On Wi-Fi disruption, the unit will log the first 50 readings and transmit them when Wi-Fi connection is re-established
Wireless range	Up to 30 m
Sensor warmup time	30 Seconds
Sensing Technology	Passive infrared
Sensing range	5 m

The main heating energy consumption includes the use of natural gas in the house gas furnace and the water heater. To determine accurate and real-time natural gas consumption, two cameras recorded videos of the gas meter of the house and the burner of the water heating system. The first camera recorded the real-time natural gas consumption in the house (Fig. 4a), and the second camera recorded the state of the water heating system burner at each time (Fig. 4b). Both heating and water heating systems have only two states, On or Pilot. When the burner is in Pilot state, it is not completely Off, but it only consumes a low amount of energy and makes it easier to turn the burner On again when the heat is needed. The actual natural gas consumption by



a) Gas meter



b) Water heating system's burner in Pilot mode (left) and On (right)

Figure 4: Snapshots of the a) Gas meter, b) Water heating system's burner status (when the burner is on more blue flame is visible in the video as can be seen in the picture on the right

these systems was calculated by comparing and syncing the recorded videos and the state of the heating system's furnace, provided by the NEST thermostat.

III. 3D MODEL, ENERGY SIMULATION AND VALIDATION

The building that is used in this study shares the east wall with its neighbor (Fig. 3a) and is exposed to the outside air from the other sides. As the temperature of the neighboring building cannot be monitored, it has been assumed that there is not a significant difference between the temperature in both buildings; thus, during simulation, the east wall has been defined as an adiabatic wall (no heat transfer between both sides of the wall). In total there are 39.2 m^2 of conditioned surface on the main floor and 61.5 m^2 on the second floor.

The 3D model of the building was created using Sketchup, and this model was then imported into OpenStudio to specify building envelope parameters, weather information, number of occupants, occupancy schedule, equipment and their schedule, lighting and HVAC system. Finally, EnergyPlus was used to solve the energy model and calculate the energy consumption in the building (Fig. 5).

Table 3 presents the thermal properties of the components that were used in the energy simulation model.

To validate the developed energy model, it was necessary to measure the actual energy consumption in the building. This process is described in section II. The set temperature for the heating system and the time that furnace was On/Off were obtained using the NEST App. The data extracted from the NEST App were used to define the schedule for the furnace to validate the energy model and calculate the actual natural gas consumption of the building.

By syncing the data collected from the water heating system's burner and the heating system's burner, four distinct periods of natural gas consumption were defined:

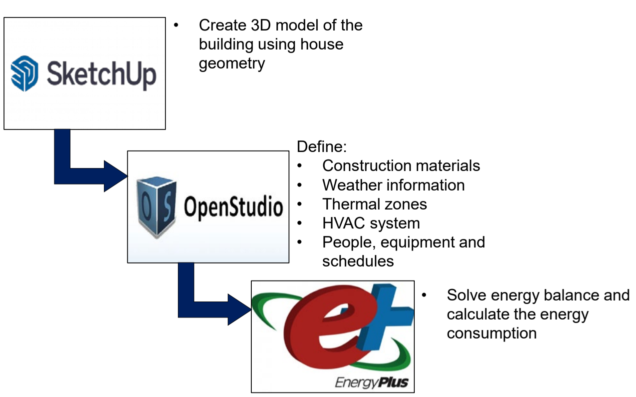


Figure 5: The process used to create the building energy consumption model.

1. Heating system and Water Heating system On
2. Heating system On, Water Heating system on Pilot
3. Heating system on Pilot, Water Heating system On
4. Heating system and Water Heating system on Pilot

Finally, the consumption rate for each of these four periods was calculated by considering the video of the gas meter. These rates can be seen in Table 4.

For a 15-day period between April 3, 2022, and April 17, 2022, the rates in Table 4 were used to calculate the heating system's natural gas consumption on a daily basis.

To validate the model, two indexes, Normalized Mean Bias Error (NMBE), and Root Mean Square Error (RMSE) were selected to compare the accuracy of the simulation [15].

$$NMBE = \frac{1}{\bar{m}} \times \frac{\sum_{i=1}^{n}(m_i - s_i)}{n-p} \times 100\% \quad (1)$$

$$RMSE = \frac{1}{\bar{m}} \times \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n-p}} \times 100\% \quad (2)$$

Where, m_i is the measured value, s_i is the simulated value, $\bar{m}$ is the mean of measured values, n is the number of measured data, and p is the number of adjustable model parameters which are considered to be zero in (1) and is equal to one in (2) [15].

Fig. 6 compares the energy consumption for the heating system based on the measured data and the result of the energy model. Both NMBE and RMSE satisfy the criteria of acceptance

Table 3: Building components thermal properties used in the building energy model

Building component	Material Layers	Thickness (m)	Thermal conductivity (W/(m.K))	Thermal resistance (m^2.K/W)
Exterior walls	1IN Stucco	0.025	0.692	
	8IN Concrete	0.203	1.730	
	Wall Insulation-36	0.057	0.043	
	1/2IN Gypsum	0.013	0.160	
Exterior floors	4 HW Concrete	0.102	1.311	
	CP02 Carpet Pad			0.10
Exterior roofs	Membrane	0.010	0.160	
	Insulation-21	0.211	0.049	
	Metal Decking	0.002	45.006	
Interior walls	G01a 19mm gypsum board	0.019	0.160	
	F04 Wall air space resistance			0.15
	G01a 19mm gypsum board	0.019	0.160	
Interior floors	F16 Acoustic tile	0.019	0.060	
	F05 Ceiling air space resistance			0.18
	M11 100mm lightweight concrete	0.102	0.530	
Ground floors	4 HW Concrete	0.102	1.311	
	CP02 Carpet Pad			0.10
Windows	Theoretic Glass-202	0.003		
Doors	F08 Metal surface	0.001	45.280	
	I01 25mm insulation board	0.025	0.030	

Table 4: Consumption rate for the heating and water heating systems when they are On or in Pilot mode.

Start time	End time	Heating system status	Water heating system status	Gas Consumption (m^3)	Duration (min)	Consumption rate (m^3/hr)
10:05	10:12	On	Pilot	o.25	7	2.18
10:12	11:36	Pilot	Pilot	0.02	84	0.01
11:36	11:52	Pilot	On	0.25	15.5	0.99
11:52	11:54	On	On	0.14	2.5	3.4
11:54	12:05	On	Pilot	0.5	14	2.21
14:30	14:31	On	On	0.03	0.5	3.23
14:31	16:29	Pilot	Pilot	0.02	118	0.01
16:29	16:30	On	Pilot	0.04	1	2.38
16:30	16:41	Pilot	Pilot	0.01	11	0.01
16:41	17:15	Pilot	On	0.58	33	1.05

of the model [15] and show that the energy model simulates the energy consumption in the building with good accuracy with NMBE of 2% and RMSE of 9%.

IV. Energy Saving by Knowing the Occupancy

After validating the energy model, the occupancy information of the building for four weeks between March 21, 2022, and April 17, 2022, was added to the model and the energy consumption in the building was simulated for four different cases.

- Case 1: Simple rule-based model with the fixed set temperature at 23 °C for the whole building
- Case 2: Occupancy-based model with the fixed set temperature at 23°C during the occupancy and 13.5 °C while the house is not occupied.

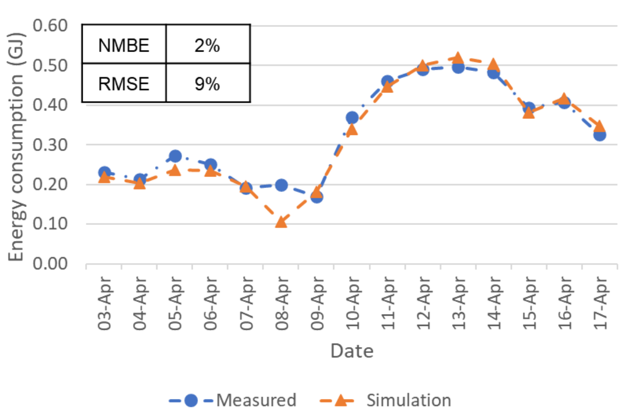


Figure 6: Energy consumption for the heating system from measured data and simulation between April 3, 2022, and April 17, 2022, used for validating the energy model.

- Case 3: User-defined set temperature that has been set by the occupants through Google NEST thermostat. In this case, occupants were asked to compromise their comfort level to save energy by setting the NEST thermostat temperature to lower than 23°C when possible (e.g., by putting on more cloth than usual).
- Case 4: Occupancy-based model that follows a user-defined set temperature explained in case 3 during the occupancy period and uses the set temperature of 13.5 °C when the house is not occupied based on the actual occupancy information collected from PIR sensors and time sheets filled by the occupants.

Without considering saving energy as a priority the occupants preferred 23°C as their desired temperature so this temperature was considered as the set temperature for both cases 1 and 2. Also, 13.5 °C was maintained as the set temperature when the building was not occupied in cases 2 and 4 to avoid any damage to the building pipeline in winter [8, 9].

Case 3 simulates the energy consumption when occupants were asked to adjust the set temperature manually using the Google NEST thermostat and its mobile App to save energy by using the lower temperature when they are away or compromising their comfort level for energy saving whenever possible. In addition, the NEST thermostat used its motion sensor and decrease the set temperature to 13.5 when detected no occupancy in its surrounding area. The temperature schedule that was defined by the occupants for April 16, 2022, is presented in Fig. 7. case 4 follows the set temperature defined by the occupants in case 3 while dropping the set temperature to 13.5 °C when the building was not occupied according to the occupancy information collected by PIR sensors and time sheets filled by the occupants.

Table 5 presents the total energy consumption during the test period and energy saving for all four cases. Case 1 is considered the baseline and all energy-saving values are compared with that. It shows using occupancy information in the heating control system can save up to 18.2% in energy consumption of the building.

The percentage of energy saving for cases 2 and 3 shows that using occupancy information with a simple occupancy-based control system that maintains the building temperature at the desired temperature of its occupants in case 2, provides more energy-saving opportunities compared with case 3 where occupants compromise their comfort level by lowering the set temperature to save energy.

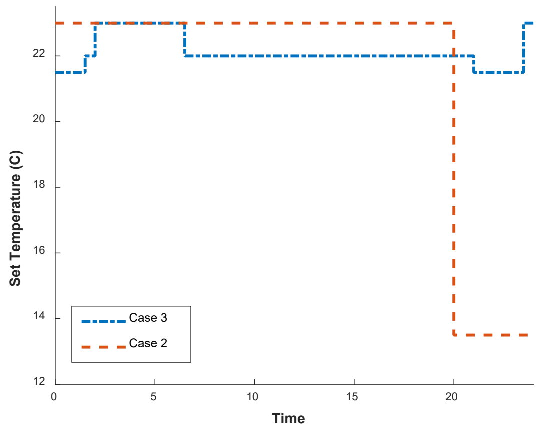


Figure 7: Set temperature for case 2 and case 3 on April 16, 2022.

V. SUMMARY AND CONCLUSION

For this study an energy model was developed to simulate the energy consumption in a residential building. The validation results showed good accuracy for the energy model by calculating NMBE and RMSE at 2% and 9% respectively. The results of this study illustrated occupancy information can reduce energy consumption of a residential building up to 18.2%.

The time period of this study was March and April 2022 with relatively higher ambient temperatures compared to winter time (Nov.- Feb.) in Edmonton. In addition, during this study one of the occupants was working from home; thus, the home was not empty during the working hour. To this end, the energy saving by using occupancy data is expected to increase for an entire winter season with normal occupancy schedule of the studied residential building.

Further studies could be conducted to find a low-cost occupancy detection system that can be used in residential buildings. In addition, in this study, building occupancy was only used to control the heating system for the whole house; however, zonal occupancy control, which maintains the desired temperature in the occupied room/zone instead of the whole building could be investigated to maximize energy saving in future research.

Table 5: Energy consumption and energy saving for four different cases. All values have been calculated for four weeks between March 21, 2022, and April 17, 2022

	Total Energy consumption (GJ)	Energy Saving (%)
Case 1	9.72	NA
Case 2	8.72	10.3
Case 3	8.80	9.5
Case 4	7.95	18.2

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