Occupant-based HVAC Set Point Interventions for Energy Savings in Buildings

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Abstract– **Energy savings and occupant thermal comfort are the two most important factors in controlling heating ventilation and air conditioning (HVAC) operation in buildings. Typically, it is found that thermal comfort is not always met in buildings. Hence, there is still an opportunity to improve indoor thermal comfort, and at the same time save energy by controlling HVAC set points. The objective of this paper is to propose a method to obtain energy savings by adjusting HVAC set points based on occupant comfort measured using Predicted Mean Vote (PMV) and occupancy information. The idea is to calculate hourly PMV values based on real-time occupancy information, indoor temperature set points and humidity in a building. Then, a new set of temperature set points that can maintain occupant comfort, i.e., PMV = 0, is derived. To evaluate the effectiveness of the proposed method, a building model is developed in eQUEST using the information from a real-world building located in Alexandria, VA. Research findings indicate that HVAC electrical consumption savings of 14.58% is achieved when the proposed set point adjustment method is implemented as compared to that of the base case. To study the impact of adding occupancy information on HVAC energy savings, another scenario is simulated where HVAC set point is increased when the building is unoccupied, e.g., during lunchtime or holidays. Research findings indicate that additional HVAC electrical consumption savings of 8.79% is achieved when taking into account occupancy information in HVAC control.**

Index Term **– Thermal Comfort, Predicted Mean Vote (PMV), eQUEST, Occupant - based HVAC Set Point Interventions, energy savings**

I. Introduction

Nowadays people in developed countries spend more than 90% of their activities indoors, and indoor conditions have broad implications for public health, general welfare and performance [1]. Providing indoor comfort requires a considerable amount of energy, and indeed buildings take up a large part of the world's total energy consumption. In the U.S., 41% of U.S. primary energy was consumed by the buildings sector, compared to 30% by the industrial sector and 29% by the transportation sector [2]. Sixty percent of power consumption in buildings is consumed by HVAC and lighting systems [3]. The quality of living for occupants in buildings is mainly determined using three basic factors: thermal comfort, visual comfort, and indoor air quality comfort [4]. In this research, thermal comfort is of focus, because it is the factor determining the use of HVAC systems in buildings. Based on ISO Standards, the definition of thermal comfort is “a condition of mind which expresses satisfaction with the thermal environment” [5].

PMV (Predicted Mean Vote) is the most well-known and standard indicator for thermal comfort. There are several parameters needed to obtain PMV values, including air temperature, radiant temperature, air velocity, relative humidity, metabolic rate, and clothing isolation [6]. Sensors are required to obtain the value of these parameters.

Many researchers have conducted research on the relationship between occupant behaviors and energy savings. Authors in [7] determine energy saving through occupancy control by decamping the lights and validating the data with actual photometric measurements. Authors in [8] model human behavior patterns and use the information to regulate building energy consumption to achieve the best trade-off between user comfort and energy efficiency. Authors in [9] minimize power consumption by calculating the probability of usage of appliances using Bayesian Algorithm. Authors in [10], in order to get significant amount of energy savings, collect the sensor data (including occupancy sensors) and program a microcontroller to control lighting intensity. Authors in [11] detect and forecast the building-level occupancy to control the operation of HVAC and lighting systems for energy savings without affecting occupant comfort. Then Authors in [12] propose an adaptive HVAC control method for multi-zone shared spaces in buildings using Interval Type-2 Fuzzy Logic System (IT2FLS). This research is unique in that it shows the impact of the thermal comfort and number of occupants on HVAC energy consumption in a building.

In this research, PMV is used to determine whether the use of HVAC in the building is efficient. Since both thermal comfort and occupancy numbers have an impact on electrical energy consumption of HVAC units, this paper presents a method to save energy by performing on-demand HVAC set point interventions based on thermal comfort and real-time occupancy information and demonstrates how HVAC electrical consumption can be reduced. It gives an insight into the impact of thermal comfort and occupancy levels in reducing the HVAC electrical consumption. A commercial building located in Alexandria, VA, USA is used for analysis.

II. PMV as an Index for Thermal Comfort

Determining occupant thermal comfort is one of the challenging tasks for researchers. Thermal comfort is determined by using a combination of many other parameters, other than air temperature [13]. Therefore, researchers are interested in identifying parameters that affect thermal comfort. At the beginning of the 20th century, one of the first results in the thermal comfort research is the chart that determines the comfort zone proposed by the American Society of Heating and Ventilating Engineers [14]. In 1930s, the authors in [15,16], undertook a new empirical study of comfort. In the 60s, authors in [17] used participants to assess their thermal sensations in relation to certain thermal situations. Based on this study, Fanger [24] defined in 1970 the equation that describes occupant comfort based on six parameters: activity, clothing level, air temperature, average temperature of radiation, air velocity and air humidity. This equation is then standardized and has become a universal comfort equation called the Predicted Mean Vote (PMV) index. Various other methods for thermal comfort evaluation have been conducted at the same time, a comprehensive summary is provided in [18].

Currently, thermal comfort can be calculated according to different standards, including the standard ANSI/ASHRAE 55 [19], EN 1525 [20], and ISO 7730 standard [21]. Among these indicators, the PMV index is the most well-known and widely used example and has been applied for almost 40 years across different building types. It includes all major variables that affect thermal sensation and provide a more objective evaluation [22].

PMV is a prediction index that can be used to calculate thermal comfort by using a model that can predict the average value of a large group of people. This refers to a thermal scale that extends from cold to hot. This scale was developed by Fanger and adopted as an ISO standard (ASHRAE standard scale) as shown the table below [23].

TABLE I. FANGER'S THERMAL COMFORT SCALE

Value	Sensation
-3	Cold
-2	Cool
-1	Slightly Cool
0	Neutral
1	Slightly Warm
2	Warm
3	Hot

The recommended PMV value is between -0.5 and +0.5 for an interior space [6]. The mathematical expression for PMV calculation is expressed in (1) [21-22, 24-25]:

$$PMV = [0.303e^{-0.036M} + 0.0275] \times \{M - W - 3.05[5.733\; 0.007(M - W) - Pa] - 0.42(M - W - 58.15) - 1.73 \times 10^{-2} M \times (5.867 - Pa) - 0.0014M \times [34 - ta - 3.96 \times 10^{-8} \times f_{cl} |(t_{cl} + 273)^4 - (tr + 273)^4| - f_{cl} hc(t_{cl} - ta)]\} \quad (1)$$

Where:

e = Euler's number (2.718)

M = the metabolic rate (W/m2)

W = the effective mechanical power (W/m2)

Pa = water vapor partial pressure (KPa)

fcl = the clothing surface area factor

tcl = the clothing surface temperature (°C)

tr = the mean radiant temperature (°C)

Icl = the clothing insulation (m2 · K/W)

ta = the air temperature (°C)

hc = the convective heat transfer coefficient [W/(m2 · K)]

In (1) the water vapor partial pressure, Pa, and the effective mechanical power, W, are calculated using (2) and (3):

$$Pa = RH\ x \exp\left[16.6536 - \frac{4030.183}{ta+235}\right] \quad (2)$$

$$W = \eta M \quad (3)$$

Where RH is measured in % and η is the effective utilization coefficient of the mechanical work. The clothing surface area factor or fcl, is determined as shown in (4).

$$fcl = \begin{cases} 1.00 + 1.290Icl, & Icl \leq 0.078m^2.K/W \\ 1.05 + 0.645Icl, & Icl > 0.078m^2.K/W \end{cases} \quad (4)$$

The clothing surface temperature or tcl, is calculated using (5):

$$Tcl = 35.7 - 0.0275(M-W) - rcl\{(M-W) - 3.05[5.73 - 0.007(M-W) - Pa] - 0.42[(M-W) - 58.15] - 0.0173M(5.87 - Pa) - 0.0014M(34 - ta) \quad (5)$$

Where the value of rcl is determined in (6):

$$rcl = 0.155\ Icl \quad (6)$$

The convective heat transfer coefficient or hc, is determined as follows:

$$hc = \begin{cases} 2.38(tcl - ta)^{0.25}, & 2.38(tcl - ta)^{0.25} > 12.1va^{0.5} \\ 12.1\ va^{0.5}, & 2.38(tcl - ta)^{0.25} > 12.1va^{0.5} \end{cases} \quad (7)$$

where va is the air velocity (m/s)

In this study, the environment variables (ta and tr) were set equal to the temperature set point in eQUEST; the air velocity (va) was set to 0.15 m/s based on ISO 7730: 2005 [20]; and the relative humidity (RH) was set to 45-50%. The parameters M, Icl and η are constants, and are obtained from [20, Tables B.1 and C.1].

III. EXPERIMENT SET UP TO CAPTURE OCCUPANCY INFORMATION

To capture occupancy information, an experiment was conducted to obtain occupancy readings in a laboratory environment. The experiment was carried out for the period of three months, and hourly occupancy information was recorded.

A. RFID-based Occupancy Sensor

The following components were integrated together to build a Radio-Frequency Identification (RFID)-based occupancy sensor (as shown in Fig 1):

- RFID RC 522 sensor was used as the occupancy sensor, sending data to Raspberry Pi for recording.
- Raspberry Pi 3 Model B v1.2 was used to process and record the data from the RFID RC 522 sensor.

- S50 White Card was used to tap to the RFID sensor for occupancy count.
- Key Fob was also used for occupancy count.
- Jumper Wires
- USB A to micro USB as a power cable
- LAN Cable (Straight) as a communication channel between the Raspberry Pi and the computer
- Micro SD 32 GB to install the raspberry OS

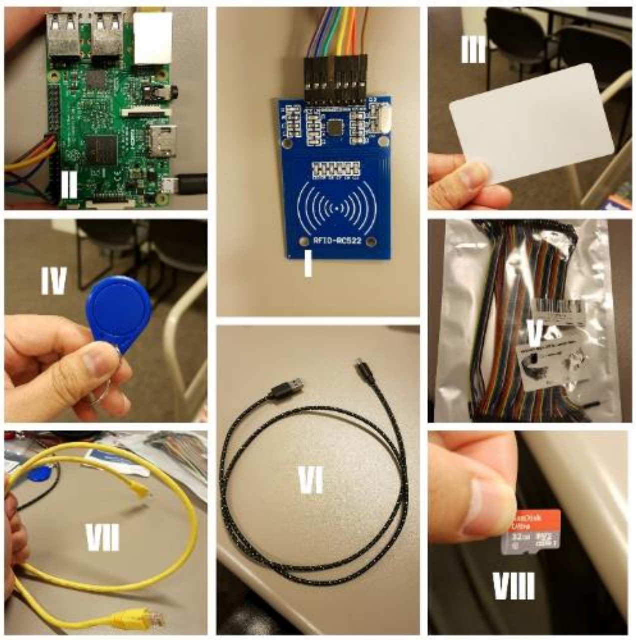

Figure 1. Components of the RFID-based occupancy sensor.

B. *Occupancy Detection*

For the measurement, there are steps to follow in order to get the occupancy data as shown in Fig. 2.

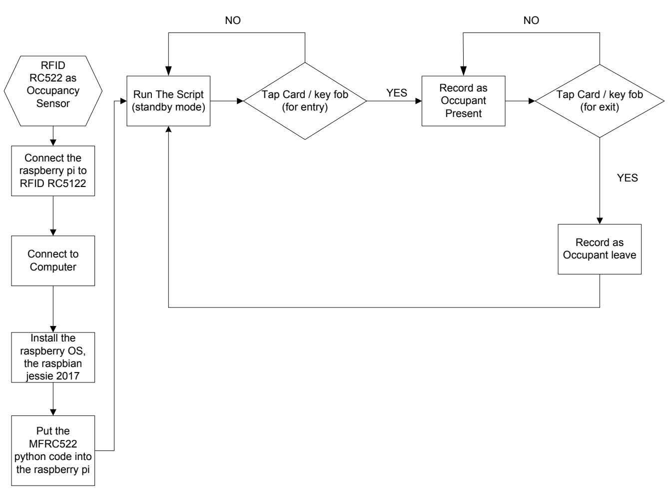

Figure 2. Steps to make RFID into occupancy sensor.

In order to get occupancy data, the RFID RC 522 sensor was connected to the Raspberry Pi, which acts as the brain of the sensor. Three white cards and three key fobs were used as an input to the sensor. Each card and key fob has a unique address. The Raspberry Pi was connected to the computer for OS installation. In this study, 2017-04-10-raspbian-jessie was used. After the OS was installed, the MFRC522 script [26] for reading and writing RFID cards was installed. Then, the script was run in a standby mode to record the occupant entry information when a card or a key fob is brought to the RFID sensor. If the same card/key fob with the same address is brought to the RFID sensor, the occupant exit information is recorded. When a different card/key fob with a different address is brought to the sensor, the sensor considers this as the presence of another occupant.

Fig. 3 depicts the readings from the RFID-based occupancy sensor (from midnight to midnight) for the period of data collection, i.e., three months.

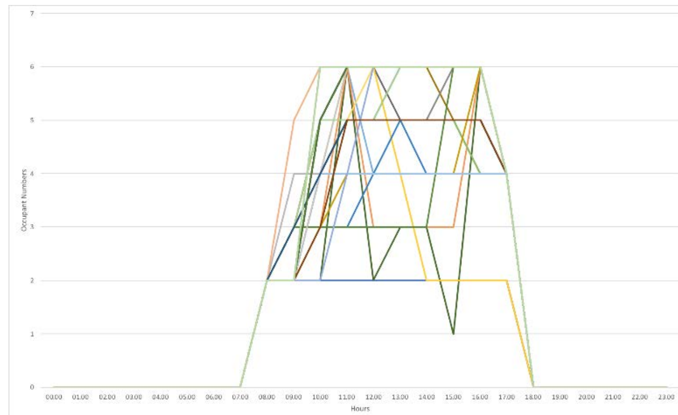

Figure 3. Number of occupants recorded by the RFID sensor over the three-month period.

It can be seen that most people are present between 8:00 and 17:00, and the maximum occupancy is six.

IV. Building Model Development in eQUEST

This section discusses building model development in eQUEST [27] – a building energy simulation tool provided by US. Department of Energy.

A. *Building Model Development*

To determine the HVAC electrical consumption and its potential energy savings in a building based on occupant comfort and occupancy level, a simulation was conducted using eQUEST.

A commercial building located in Alexandria, VA was used as a case study. The building has three activity areas, which are office, storage and warehouse.

- **Building physical parameters:** The building is south-facing with the area of 8,991 ft^2. It has 9 doors, made of wood, glass and steel. The roof construction is 2-inch concrete; the wall construction is 12-inch concrete masonry unit (CMU); and the ground construction is 8-inch concrete.
- **Weather:** The building is located in Alexandria, VA, then one-year weather data at this location was used. The weather data was obtained from National Centers for Environmental Information (NCEI). NCEI is under Department of Commerce, USA.
- **HVAC unit:** In this building, the HVAC system is of DX coil type for cooling and of furnace type for heating.

- **Set points:** It is assumed that the base HVAC set point of the eQUEST model is 72.5oF during occupied period, which is the set point recommended by ASHRAE 55. The unoccupied set point is assumed at 86oF**.**
- **Load densities:** For lighting power density, the building has three activity areas: office, warehouse and storage. The lighting power density in the office area is assumed to be varied as follows: the lobby area 1.77 W/sqft; the mechanical/electrical room 0.81 W/sqft; kitchen and food preparation 1.19 W/sqft; general purpose area 1.24 W/sqft; exhibit/display area 1.03 W/sqft power density; then open-plan office 1.24 W/sqft. The lighting power density of the warehouse and storage areas are assumed at 1.19 W/sqft.
- **Building operations:** This building operates from 8 am to 5 pm for weekdays and is closed on weekends.
- **Occupancy information:** The occupancy measurements from the RFID-based occupancy sensor (described in the previous section) were used to indicate occupancy information in the eQUEST software.

Based on the above sets of inputs, a building model was developed in eQUEST. The 3D model of the developed building is shown in Fig. 4.

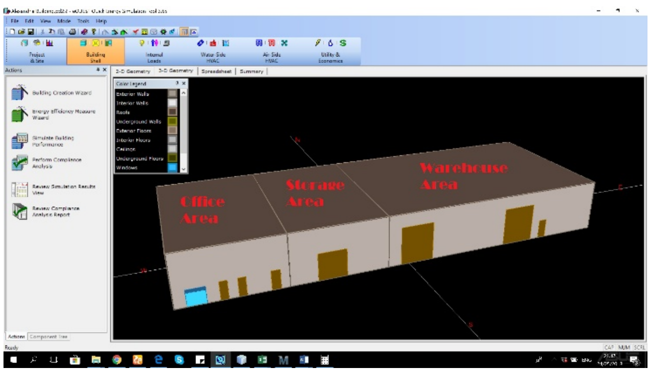

Figure 4. 3D model of the building model developed in eQUEST.

B. HVAC Energy Consumption

The developed eQUEST model was simulated. The monthly HVAC energy consumption of this building is depicted in Fig. 5.

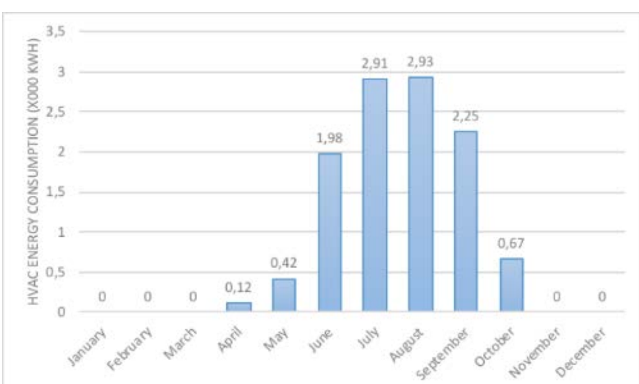

Figure 5. Monthly HVAC energy consumption from the simulated building in eQUEST.

Based on Fig. 5, it can be seen that the HVAC unit works between April and October and the total HVAC electrical consumption is **11,279 kWh.**

C. PMV values

The hourly PMV values of the above building were determined using (1) – (7), using the following parameters.

- The AC set point in eQUEST of 72.5°F was used for air temperature and radiant temperature.
- Relative humidity was set around 45-50%
- A constant air velocity of 0.15 m/s was used based on ISO 7730: 2005 [17].
- The activity "Sedentary activity (office, dwelling, school, laboratory)" with the metabolic rate of 70 W/m^2 or 1.2 Met [28] was used.
- The cloth type "Typical Summer Indoor" with the cloth insulation value of **0.5 Clo or 0.078 m^2. K/W** [29] was used.

The hourly PMV values calculated based on the above assumptions for this building is shown in Fig. 6 for a one-week period.

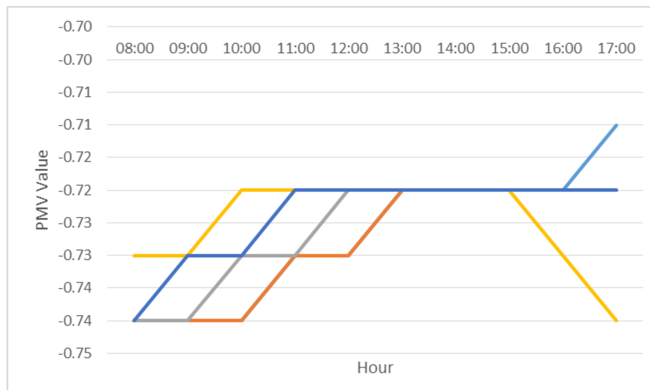

Figure 6. Hourly PMV values on June 18-June 22.

According to Fig. 6, the PMV value is observed between -0.74 and -0.71. This implies there is a potential to reduce the HVAC electrical consumption in this building.

V. Energy Savings From Comfort Adjustment And Occupancy Information

To understand the relationship between HVAC consumption and occupant comfort in a building, two simulations must be conducted to obtain HVAC energy consumption using the base case set point and the new set points that can maintain occupant comfort, i.e., PMV = 0.

To understand the relationship between HVAC consumption and occupancy level, HVAC consumption is determined using the base case occupancy level and the new occupancy level taking into account lunch breaks and holidays.

A. Determine Set Points at PMV = 0

After the original PMV value is obtained (discussed in Section IV(C), the next step is to calculate the temperature set points that can maintain occupant comfort, i.e., PMV = 0. Using (1) – (7), the new set points are determined, as shown in Fig. 7.

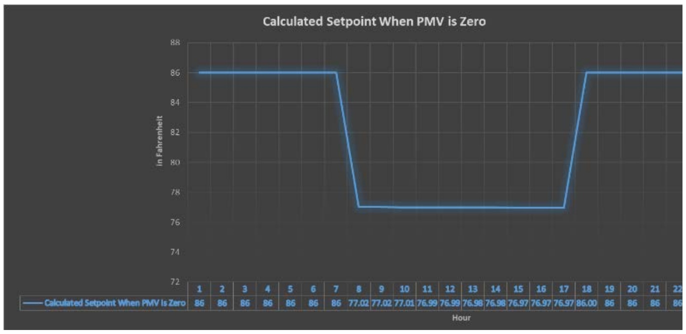

Figure 7. Calculated set points when PMV is zero.

B. *HVAC Energy Consumption (PMV = 0)*

The new set points were inputted to eQUEST to obtain the new HVAC energy consumption at PMV =0. The simulation result is shown in Fig. 8 for monthly HVAC consumption. As shown, the annual HVAC electrical consumption when PMV is set to zero is **9,635 kWh.**

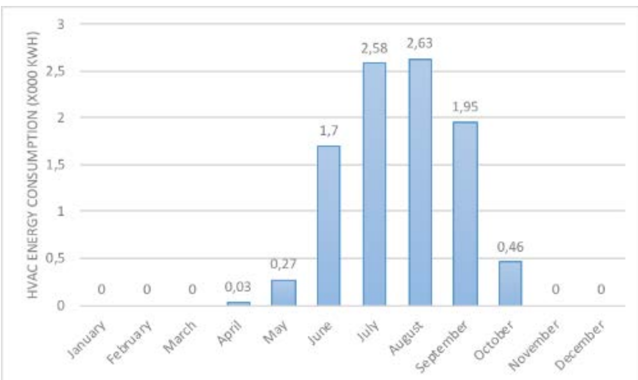

Figure 8. Monthly HVAC energy consumption from the simulated building (PMV=0).

C. *HVAC Energy Consumption (PMV = 0) Considering Occupancy Information*

To study the impact of occupancy level on HVAC electrical consumption, it is assumed that the occupancy level is reduced to zero at lunch time and on holidays. Using the set point temperature when PMV is zero, the revised occupancy information was entered into eQUEST accordingly. The result illustrating monthly HVAC consumption with no occupancy during lunch time and on holidays is shown in Fig. 9.

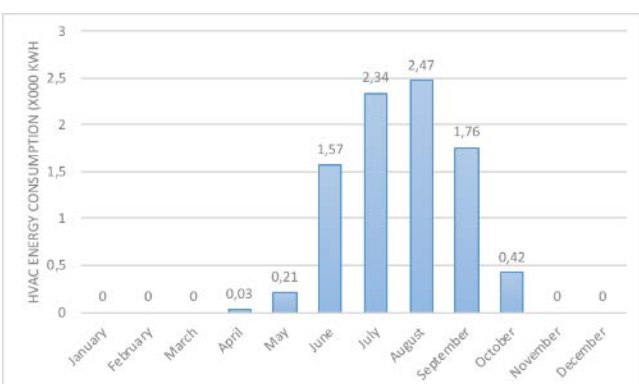

Figure 9. Monthly HVAC energy consumption from the simulated building (PMV=0, no occupancy during lunch/holidays).

The annual HVAC electrical consumption when taking into account occupant comfort (PMV = 0) and occupancy information is **8,788 kWh**.

VI. RESULTS & DISCUSSION

Fig. 10 compares HVAC energy consumption among three cases: (i) base case; (ii) consider occupant comfort (PMV = 0); and (iii) consider occupant comfort (PMV = 0) and occupancy information.

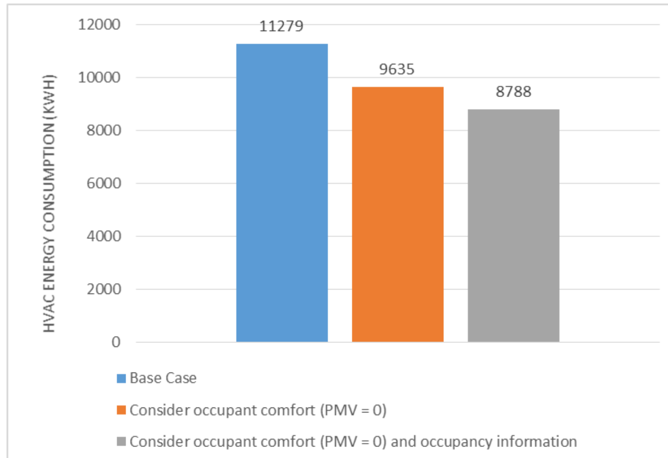

Figure 10. Comparison of HVAC energy consumption.

From these three simulations, it can be concluded that the thermal comfort condition based on PMV value can reduce HVAC electrical consumption by **14.58%**. And, the decrease in occupant numbers in a building can provide additional savings in HVAC electrical consumption by **8.79%.**

VII. CONCLUSION

This paper studies how thermal comfort and occupancy numbers have an impact on HVAC electrical energy consumption. It presents a method to save energy by performing HVAC set point adjustments based on thermal comfort and considering occupancy information. It gives an insight into the impact of thermal comfort and occupancy in reducing the AC electrical consumption in a building.

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