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Determination of Effectiveness of Energy Management System in Buildings

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ABSTRACT

Building Energy Management Systems (BEMS) are computer-based systems that aid in managing, controlling, and monitoring the building technical services and energy consumption by equipment used in the building. The effectiveness of BEMS is dependent upon numerous factors, among which the operational characteristics of the building and the BEMS control parameters also play an essential role. This research develops a user-driven simulation tool where users can input the building parameters and BEMS controls to determine the effectiveness of their BEMS. The simulation tool gives the user the flexibility to understand the potential energy savings by employing specific BEMS control and help in making intelligent decisions. The simulation is developed using Visual Basic Application (VBA) in Microsoft Excel, based on discrete-event Monte Carlo Simulation (MCS). The simulation works by initially calculating the energy required for space cooling and heating based on current building parameters input by the user in the model. Further, during the second simulation, the user selects all the BEMS controls and improved building envelope to determine the energy required for space cooling and heating during that case. The model compares the energy consumption from the first simulation and the second simulation. Then the simulation model will provide the rating of the effectiveness of BEMS on a continuous scale of 1 to 5 (1 being poor effectiveness and 5 being excellent effectiveness of BEMS). This work is intended to facilitate building owner/energy managers to analyze the building energy performance concerning the efficacy of their energy management system.

KEYWORDS

Buildings; energy management system; demand controlled ventilation; supply air temperature reset; temperature setback control; monte carlo simulation

Nomenclatures

ACH	Air Change per Hour
AI	Artificial Intelligence
BE	Building Envelope
BEMS	Building Energy Management System
BMS	Building Management System
CFM	Cubic Feet per Minute
COP	Coefficient of Performance

DBT	Dry Bulb Temperature
DCV	Demand Controlled Ventilation
DOE	Department of Energy
DR	Demand Response
DRL	Deep Reinforcement Learning
DRP	Demand Response Program
EIA	Energy Information Administration
GA	Genetic Algorithm
GHG	Greenhouse Gas
HEMS	Home Energy Management System
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
LSTM	Long-Short Term Memory
MCS	Monte Carlo Simulation
MILP	Mixed-Integer Linear Programming
NN	Neural Network
OH	Operating Hour
PV	Photovoltaic
SAT	Supply Air Temperature
SHEMS	Smart Home Energy Management System
SHR	Sensible Heat Raio
TEE	Target Energy Efficiency
TL	Transfer Learning
VAV	Variable Air Volume
VBA	Visual Basic Application
WF	Weather Factor

1 Introduction

1.1 Background

The term "Energy Management" encompasses strategic planning and operation of energy generating and/or consuming units. It can be broadly defined as the systematic, organized, and proactive management of energy use in organizations, industries, or buildings to meet the economic and environmental necessities. The main aims of energy management are the conservation of the resource, protection of the climate, and saving costs. At the same time, the consumers have continuous access to the energy they require. The core principles which are generally followed for energy management include but are not limited to collecting the energy data and metering the consumption of energy, seeking opportunities to save energy, implementing actions to save energy, and making a record of the progress and ongoing improvements.

In today's world, energy management is considered the groundwork for saving energy at an organizational level. Further, due to the increasing demand and decreasing supply of non-renewable natural resources such as gasoline and coal, costs are likely to rise. Also, the standards of sustainability are pushed more to higher limits by the regulations. Managing energy use does not always involve a considerable investment of capital or complex analysis. It can be started by monitoring and evaluating the profile of energy consumption over time. Sometimes, making minor modifications to the energy spending behavior can lead to savings. Whatever the conditions, energy management is about

developing a foundation of information for intelligent decision-making and using the information to reduce energy consumption.

Since 2012, the number of facilities has grown by 6% and the floor space by 11% in the U.S. More than half of commercial buildings in the U.S. were built between 1960 and 1999, and 25% have been made since 2000. The number of buildings has increased from 3.8 million to 5.9 million, and the amount of commercial floor area has increased from 51 billion square feet to 97 billion square feet. Among all commercial buildings, 48% were represented by warehouse and storage, service, and office buildings and had 42% of total retail building floor space [1]. About 93% of the total energy consumed in commercial buildings in 2012 was electricity and natural gas. Natural gas is typically used to heat water, interior space, and operate cooling equipment in commercial buildings. About 32% of the total energy consumed in a commercial building in 2012 was from natural gas and 61% from electricity. The significant contribution to electricity in commercial buildings is due to lighting [2].

1.2 Objectives

This research aims to simulate the energy consumption of the building by varying the control aspects of the BEMS. Initially, based on the number of rooms in the building and the type of rooms, the user can input various data such as dimensions of the rooms, thermostat setting (setpoint and setback temperature) for each room. Furthermore, users can also input the geographical position, energy source for heating and cooling the building. Microsoft Excel®, based on the discrete-event Monte Carlo Simulation (MCS), is used to simulate the energy consumption pattern. A heuristic approach is used for generating random variables for occupancy. This model calculates the energy consumption rate at 30-min intervals for one year. Users can understand the energy consumption by HVAC units with the BEMS controls and compare them against their HVAC energy consumption data. Develop a Microsoft Excel-based (Visual Basic Application) Monte Carlo simulation, which can forecast the occupancy level at the different time frames of the day.

2 Literature Review

2.1 Current Scenario of Energy Consumption by Buildings

The building sector in the U.S. accounted for about 39% (38 quadrillion BTUs) of primary energy consumption in 2016. This figure is more than the other two uses: transportation (29%) and industry (32%). The commercial and residential buildings were accountable for 18% and 21% of the primary energy consumption within the building sector [3].

2.2 Study of BEMS

Jamil et al. [4] presented a paper with a review of building energy management systems. The authors emphasized that building an energy management system acts as a bridge between the electric grid and the consumer side to realize the demand response and make the dream of an intelligent grid visible. They concluded that energy management in a building can be performed economically and efficiently using available BEMS technologies. Mei [5] described BEMS as the computer-based control system that monitors and controls the electrical and mechanical aspects such as heating, cooling, ventilation, power systems, and lightings. The author also claimed that installing BEMS energy savings of 10%–20% can be achieved than stand-alone controllers. The author, however, emphasized the importance of scheduled maintenance of the BEMS system and keeping its setting up to date to match the user comfort and realize more energy savings.

Syed et al. [6] discussed the Building Energy Management System in their paper published in 2018. The authors also examined the control system, integration, and interfacing of BEMS units. Numerous benefits of the BEMS system were also delineated, including but not limited to enabling users to analyze, collate and transform the data into meaningful information, allowing them to monitor the consumption of energy and determine the waste. The authors further discussed the BEMS architecture and several energy monitoring systems such as direct, indirect, and hybrid monitoring systems. Chen et al. [7] presented a paper in the 2016 3rd International Conference on Green Technology and Sustainable Development discussing designing and implementing a Building Energy Management System. The report highlights the utilization of a considerable amount of infographic and data visualization design elements in conjunction with interactive and dynamic charts that help users gain insights into critical building performance data. The developed design has general power and demand measurement, Time of Use (TOU) metrological management, and a power quality monitoring system. Hernandez et al. [8] presented a paper regarding the review of strategies for building energy management systems. The authors concluded that most of the studies only focused on decreasing the HVAC system's energy consumption, leaving alone the other subsystems of the building, which might significantly contribute to energy consumption depending upon the building type. Djuric et al. [9] presented a paper using the BEMS data and optimization tool to estimate the heating system performance. The authors considered a building with a total area of 13,700 m^2, three floors, and a basement. The authors collected data through an on-site survey, BEMS, and additional measurements, including indoor air temperature in four offices, outdoor air temperature, ultrasound flow meter, and energy consumption by hot water using thermocouples.

2.3 Study of Control Aspects of BEMS

Pacific Northwest National Laboratory (PNNL) published a report [10] that discussed the training guide for retuning the building. The authors highlighted the re-tuning of the building based on occupancy scheduling, night, and weekend temperature setback, and cycling of supply fans during unoccupied hours. The authors claimed that if the control aspects of the building are controlled adequately during the unoccupied mode, it can significantly reduce costs in commercial buildings. The authors also claimed that with proper setback control, the difference between the baseload to the peak load can be a minimum of 30% but can be as high as 80%. These savings were also illustrated through charts for better understanding. Verma et al. [11] presented a paper that discussed controlling the lighting automatically in an optimized way in a hotel building to achieve energy efficiency. The authors described various categories for lighting control, such as occupancy-based control, schedule-based control, and daylight-based control. From the study, the authors claimed that automatic lighting control with dimming can reduce the total consumption of energy by 37% and consumption of lighting energy by 55%. Hence, the authors concluded that dimming and switching control of lighting contribute to saving energy, but the latter have more savings at the expense of occupant's comfort.

Lawrence Berkeley National Laboratory (LBNL) published a report [12] describing occupancy-based energy management in buildings. The authors conducted field studies and modeling analyses of the structure based on occupancy through the building. The authors divided the projects into three parts: Feasibility and efficacy study, refine hardware and software tools, and link with other DOE programs, and finally, implantation and testing of the prototype. The authors concluded that each zone in the building could result in an HVAC energy consumption reduction of nearly 15%. Liu et al. [13] discussed using various technologies such as building occupancy sensors and sensor networks for controlling the terminal box. The authors used building occupancy sensors to count the occupancy for all the rooms and deliver the measured data to the signal processing station through the sensor

network. The system architecture, control strategy, and available sensor technology were explained in this paper. Ardiyanto et al. [14] presented a paper discussing the energy savings in buildings through HVAC setpoint interventions based on occupancy. The authors considered occupant thermal comfort and energy savings as the two prominent aspects in controlling the HVAC operation in the building. The authors aimed to devise a method to save energy by adjusting HVAC setpoints based on comfort measured using Predicted Mean Vote (PMV) and occupancy information. The results showed that the HVAC electrical consumption decreased by 14% when the proposed HVAC setpoint adjustment method was employed.

Mandlem et al. [15] discussed using Smart Thermostat-based BEMS for energy efficiency effectiveness in a residential building. The main factors that the authors considered were occupancy of the rooms, weather factor, the volume of the space, building envelope, and thermostat set point. The model was validated against a typical household where the difference between the simulated and the actual energy consumed was 5 MMBtu with an error of 15%. A report [16] published by Iowa State University titled "Experimental and simulation study of demand-controlled ventilation" highlights the comparison of energy use and CO_2 concentration for a multizone building utilizing three ventilation control strategies. A report [17] published by Iowa State University titled "Experimental and simulation study of demand-controlled ventilation" highlights the comparison of energy use and CO_2 concentration for a multizone building utilizing three ventilation control strategies: occupancy-based DCV, constant ventilation, and CO_2 based DCV. The authors compared the building's energy consumption using these three winter, summer, and transition seasons.

2.4 Recent Development with AI and Smart Controls

Farzaneh et al. [18] introduced an evaluation framework for assessing the recent research conducted across the major AI domains, including energy, comfort, design, and maintenance. The authors reviewed the studies in application of artificial intelligence (AI) technologies in smart buildings through the concept of a building management system (BMS) and demand response programs (DRPs). Wang et al. [19] presented a multi-objective optimization method that considers two main purposes including energy consumption cost and user satisfaction. The authors developed the algorithm based on a new improved version of the butterfly algorithm for increasing the convergence speed. Himeur et al. [20] did a review of existing anomaly detection frameworks for building energy consumption based on artificial intelligence. In this study, the authors introduced a comprehensive taxonomy to classify existing algorithms based on different modules and parameters adopted, such as machine learning algorithms, feature extraction approaches, anomaly detection levels, computing platforms and application scenarios.

Elsisi et al. [21] proposed a deep learning-based people detection system utilizing the YOLOv3 algorithm to count the number of persons in a specific area. The proposed system enhances decision making about energy consumption. The number of persons and the status of the air conditioners are published via the internet to the dashboard of the IoT platform. Elnour et al. [22] proposed a neural network (NN) based model predictive control management and optimization system for the heating, ventilation, and air conditioning (HVAC) system of a sports facility. This model provides an integrated dynamic optimization method that accounts for future system behavior in the decision-making process, consisting of a prediction element and an optimizer. Elnour et al. [23] presented a review and in-depth discussion of existing solutions in building operation management and optimization for sports facilities in different climate zones.

Can Duman et al. [24] proposed a mixed-integer linear programming (MILP)-based home energy management systems (HEMS) that performs day-ahead load scheduling for cost-minimization and provides optimal demand response (DR) and photovoltaic (PV) self-consumption. The fuzzy logic-based thermostat aims efficient DR of air-conditioning and maintenance of thermal comfort. Saidu Aliero et al. [25] presented an analysis of smart home energy management system (SHEMS) with the goal to identify current trends and challenges for future improvement. The authors described opportunities for future research that ensure energy-efficient smart homes free of unnecessary energy consumption, health challenges, and cyber security attacks. Himeur et al. [26] presented a review of the applicability of transfer learning (TL) for energy systems by adopting a well-defined taxonomy of existing TL frameworks. The authors carried out an in-depth analysis to identify the pros and cons of current techniques and discuss unsolved issues. Luo et al. [27] proposed a building energy consumption forecasting system that uses hybrid genetic algorithm (GA) and long-short term memory (LSTM) neural network model for accurate and robust energy prediction. This prediction model can play an essential role in various areas, including daily building energy management, decision making of facility managers, building information model designs, net-zero energy operation, climate change mitigation and circular economy.

Lissa et al. [28] proposed a deep reinforcement learning (DRL) algorithm for indoor and domestic hot water temperature control, aiming to reduce energy consumption by optimizing the usage of photovoltaic (PV) energy production. The algorithm is calibrated to not exceed more than 1% of the time out the specified temperature setpoints. Mariano-Hernández et al. [29] presented a review of management strategies for building energy management systems for improving energy efficiency. The authors found that different management strategies can be used to achieve energy savings based on the type of the building.

Aliero et al. [30] presented an analysis of SHEMS with the goal to identify current trends and challenges for future improvement. The authors described opportunities for future research that ensure energy-efficient smart homes free of unnecessary energy consumption, health challenges, and cyber security attacks. Jradi et al. [31] proposed a software that has three major capabilities, initial BMS auditing, BMS retro-commissioning and continuous building commissioning. The software development is a part of the BuildCOM project which is driven by the industry and customer needs, and it responds to the increasing demands for energy efficiency, comfort, and safety in the building.

2.5 Research Motivation

Everyone at some point in their lives has come across the term "Energy Management," particularly in recent years, where conservation of energy is getting foremost importance for the future of organizations worldwide. Due to increased fuel cost, increasingly aggressive environmental targets, and concerns over energy security, every organization is becoming competitive to reduce its operational cost. Savings in energy cost provides the organization a competitive edge to flourish in the market.

Many organizations install BEMS for the management of energy in their buildings. The reduced cost of sensors, analytics software, and data storage has made BEMS affordable to install, even for small businesses. The sensors are used in monitoring the operational conditions of the building and building equipment, such as monitoring airflow in the building, exposure to sunlight, and temperature. Then, the controllers of the devices process all the collected data from the sensors, and the actuators perform suitable actions for optimizing the physical settings.

Installation of BEMS requires considerable capital investment, and any organization expects a lower payback period on investment through energy savings. If the operating characteristics of the

building are not correct, then the performance of the BEMS cannot be achieved as expected. There are various conditions where BEMS cannot function efficiently, such as infiltration and exfiltration of air through cracks in the building envelope, doors and windows openings, poor building insulating material, single-pane doors and windows, and excessive internal heat loads. Moreover, the BEMS also does not run effectively during poor control system operation of the thermostat, excessive ventilation to the building than required, conditioning of unoccupied spaces, and constant SAT.

The transmission loss of heat is reduced with proper insulation of the building, upgrading of windows and doors. Furthermore, the heat loss due to infiltration is also reduced by installing appropriate frames in doors and windows and other sealing cracks in the building envelope. This reduces the load on the HVAC system. Hence, it does not have to run continuously. Moreover, by upgrading thermostat controls such that setback temperature could be set during unoccupied periods, the load on the HVAC system would decrease tremendously. In addition, using a CO_2 sensor for demand-controlled ventilation, the HVAC system conditions only required amount of air to the building according to the number of occupants in the building.

2.6 Potential of Proposed Research

Currently, no literature has provided any tool to determine the effectiveness of the energy management system of the building based on varying BEMS controls. In this research work to resolve this problem, a simulation model was developed for determining the effectiveness of an energy management system for buildings. The developed model in this research is user-interactive; hence, the user can change the model's parameters to determine the effectiveness of BEMS of their building. Therefore, in this way, the potential for energy savings by using the appropriate BEMS controls was determined, and the current effectiveness of the BEMS was evaluated. This tool can also determine the peak ventilation air requirement for a building to meet the indoor air quality based on ASHRAE Standard 62.1–2019 that could help in preliminary study for sizing ventilation components of a building. Furthermore, this research also helps in the reduction of GHG emissions by exploring the ineffectiveness of BEMS operation and quantifying the amount of GHG emissions reduced in terms of pounds of CO_2 emissions saved per year.

3 Methodology

3.1 Assumptions

Several assumptions have been made during the development of this simulation program. They are listed below:

1. The time interval for the simulation has been considered 30 min. So, it will not detect any event in terms of occupancy between 0–30 min intervals.
2. The temperature of the return air is assumed to be the same as that of the room temperature.
3. The loss of energy for the return air is neglected, and the mixture of outside air and return air is considered an ideal mixture.
4. The weather condition is considered to be constant for every 8 h.
5. The values in the occupancy chart are assumed to be the same for similar types of the room but can be changed according to user requirements.
6. Relative humidity of thermal comfort conditions is assumed to be at 50 percent.
7. A natural disaster is ignored in this simulation.

3.2 Overview of Research Approach

This work involves determining the effectiveness of the BEMS system by simulation of the control aspects of the BEMS. The simulation takes information about the types of rooms in the building, the dimension of the rooms, information about the building envelope and location, setpoint, and setback temperature at each room during the summer and winter months. The research workflow can be segmented into steps and delineated in the following list:

Step-1: Select the building in terms of the number of zones and type of zones.

Step-2: Determine the operational characteristics of the building along with BEMS controls.

Step-3: Define charts for occupancy (i.e., Expected occupant percentage) based on the time of the day and day of the week for each type of zone.

Step-4: Determine various HVAC energy consumption factors such as the dimension of individual zones, thermostat settings (i.e., setpoint and setback temperatures) for summer and winter months. Further, also choose the climatic region according to the location of the building among the given nine climatic regions of the U.S. Also, specify the type of building envelope and determine the sensible heat ratio for individual zones.

Step-5: Determine the expected number of occupants at each room based on the time of the day and day of the week for each type of zone based on Monte Carlo Simulation.

Step-6: Determine the new Air Change per Hour (ACH) and outside air requirement (cfm) for every 30-min time interval for each zone. This calculation is based on the number of occupants and the area of the room.

Step-7: Calculate the HVAC energy consumption for every 30-min–for one year for each type of zone.

Step-8: Furthermore, calculate the total HVAC energy consumption of the building by the addition of energy consumption of individual rooms (Base Case).

Step-9: Furthermore, perform a similar calculation for the TEE Case where all BEMS controls are enabled with improvement in building envelope to determine the annual energy consumption of the building.

Step-10: Compare the annual energy consumption of the building for the Base Case with the TEE Case to determine the percentage change in energy consumption. Based on the difference in energy consumption between the TEE Case and Base Case, assign a rating of BEMS effectiveness on a scale from 1–5, where 1 being poor condition and 5 being an excellent condition.

Step-11: Determine the annual reduction of GHG emissions by enhancing the effectiveness of BEMS.

3.3 Case Development

Primarily, two cases, the Base Case and TEE Case, are developed to determine the BEMS system's effectiveness.

Base Case: This case is based on the building's user defined BEMS controls and building envelope level. This case gives the energy required for space cooling and heating given the present condition of the building.

TEE Case: In this case, all four BEMS controls are input to the model, and the building envelope level is in good condition, i.e., no infiltration of air, double pane windows and doors, and good building envelope insulation. The energy required for space cooling and heating obtained from this case is used

to calculate the effectiveness of BEMS of the building by comparing against the data obtained from the Base Case.

3.4 Principle of Data Analysis

The system requires some input from the user to calculate the HVAC energy consumption of the building with some BEMS controls. To be specific, the user has the option to input the total number of rooms in the building, type of individual rooms, the dimension of each room, thermostat setting for each room, geographical position according to climatic region, percentage of an outdoor air intake, BEMS controls, fuel type, and fuel cost. All these factors have been accounted as input data to the simulation. The proposed simulation is interactive, which allows its users to change the value of the variables. The simulation is performed in Microsoft Excel® based on the discrete event Monte Carlo Simulation (MCS) using the Visual Basic Application (VBA). A uniformly distributed random number will be generated in excel. To determine the expected number of occupants, heuristic rules will be applied for comparing the automatically generated random number and value from the occupancy chart.

3.5 Energy Calculation Factors

All the energy calculation factors can be divided into two categories–major factors and minor factors. Major factors are those that directly impact energy accounting. Major factors are occupancy level and type of room. On the other hand, the minor factors are the ones that are present in all different scenarios, such as building envelope, level of thermostat, area of the room, geographical location.

In this study, only 18 states were selected for the simplicity of the simulation model. Two weather stations from each of the 18 states are included in this simulation model. The user is asked to select the "state" and "nearest weather station" from the available options. Based on the chosen state, two weather stations will be available to choose from, and based on the selected weather station, the elevation (ft.), heating dry bulb temperature (DBT), cooling DBT, and humidity ratio are determined from values referenced from the 2017 ASHRAE Handbook [32].

3.6 Simulation Description

This simulation aims to determine the effectiveness of BEMS by calculating the annual HVAC energy consumption with varying BEMS controls and building operating parameters. In this research, energy consumption has been shown for one year for the given building using VBA. The program developed here is very user-interactive, where the user can select various inputs to define the scenario appropriately. Additionally, the users can change the expected occupancy levels for a more precise simulation of the building under consideration.

3.6.1 Users Inputs and Outputs

The energy consumption simulation program has been divided into five sections: User manual, Inputs, Reference, Climatic data, and Occupancy. At first, the "User Manual" sheet of MS excel describes the complete process step by step to guide the users through the simulation process. Next, the "Inputs" sheet of the Microsoft Excel software asks a user to select several rooms in the building. Additionally, the user also must provide the type of rooms, a dimension of the room, setpoint and setback thermostat temperature for summer and winter months, location of the building (Climatic Zone, State and City). The reference sheet contains information required for energy calculation based on the weather, Occupancy chart, ASHARE standard for people, and area outdoor air rate for various types of rooms and fuel types. Upon providing all the information on the input page, the program starts

the calculation and shows the expected number of occupants and outdoor air (cfm) requirements for each room. At the very end, the tool will ask for the source of energy for heating the building, the average cost of electricity ($/kWh), and an average cost of natural gas ($/MMBtu).

3.6.2 Description of Energy Consumption Calculation

In this study, user input values are taken into consideration for determining the building operating parameters. The user can also select the BEMS controls that are used in the building from the given option. Based on these inputs, the energy consumption of the building was calculated [33,34].

Air-Change per Hour (ACH): At full occupancy, the value of ACH is used according to the given ASHRAE Standard 62.1–2019 for a particular type of room. But, during part-load occupancy, the value of ACH is calculated proportionally to the level of occupancy. For example, at half occupancy, the rate of ACH is also halved. However, during no occupancy, the ACH is calculated based on dimensions of the room and area outdoor air rate.

$$ACH_{new} = \% \, \text{Occupanc} \times ACH$$

During no-occupancy:

$$ACH_{new} = \frac{A \times R_a \times 60}{V}$$

where,

A = Area of the space

R_a = Area Outdoor Air Rate

V = Volume of the Room

Supply Air Requirement: Based on the ACH_{new}, the required supply air (cfm) is determined

$$V_T = \frac{\sum_{i=1}^{n} \text{Vix} \, (ACH_{new}) \, \text{i}}{60}$$

where,

V_T = Total requirement of supply air, cfm

V_i = Volume of zone i, ft^3

n = Total number of zones

Outdoor Air Requirements: The outside air required for a specific type of space can be calculated as:

$$V_0 = \sum_{i=1}^{n} N \times Rp + A \times Ra$$

where,

V_0 = Outside Air *Required* for all the zones (cfm)

N = Number of Occupants in zone i

R_p = People Outdoor Air Rate for zone i

A = Area of the space of zone i

R_a = Area Outdoor Air Rate for zone i

Return Air Thermal Conditions: The thermal conditions (temperature and humidity ratio) of the return air are determined from two factors: temperature, humidity ratio of return air from each zone, and amount of air (cfm) returned from each zone. The temperature of the return air can be calculated as follows:

$$T_r = \sum_{i=1}^{n} T_{ri} \cdot \left(\frac{V_{ri}}{V_R} \right)$$

Here, the dry-bulb temperature of outside air is determined according to the location selected by the user.

The humidity ratio of the mixed air can be calculated as:

$$h_m = h_0 \times \left(\frac{V_0}{V_T} \right) + h_r \times \left(\frac{V_T - V_0}{V_T} \right)$$

where,

h_m = humidity ratio of mixed air

h_0 = humidity ratio of outside air

h_r = humidity ratio of return air

Here, the humidity ratio of the outside air is determined according to the location selected by the user.

Humidity Ratio of Supply Air: The thermal conditions (temperate, humidity ratio) of supply air are required to determine energy consumed by the heating or cooling unit. The supply air temperature is estimated based on the level of occupancy, building envelope condition, and weather factor [35]. The rule is designed to select SAT based on those two factors.

Sensible load calculation:

As an example, the sensible cooling load during summer months for zone 1 is calculated as:

$$Q_{s1} = \left(\frac{V_{T1} \times 60}{v} \right) \times c_p \times (T_{r1} - T_{s1})$$

where,

V_{T1} = total supply air at zone 1, cfm

v = specific volume of air at standard condition, $13.3 \text{ft}^3/\text{lb}$

c_p = specific heat of air at standard conditions, $0.24 \text{ Btu/lb} -^\circ \text{F}$

T_{s1} = dry-bulb temperature of supply air for zone 1

The sensible heating load during winter months for zone 1 is calculated as:

$$Q_{s1} = \left(\frac{V_{T1} \times 60}{v}\right) \times c_p \times (T_{s1} - T_{r1})$$

The total load for zone 1 is calculated as:

$$Q_{T1} = \frac{Q_{s1}}{SHR}$$

where,

Q_{T1} = total heating/cooling load for zone 1

Q_{s1} = total sensible load

SHR = sensible heat ratiod

Similarly, the total sensible load and total heating/cooling load for all the zones in the building are calculated to determine the total heating/cooling load of the building.

The humidity ratio of the supply air during summer months for zone 1 is calculated as:

$$h_{s1} = h_{r1} - \left(\frac{Q_{T1} - Q_{s1}}{V_{T1} \times C}\right)$$

where,

h_{s1} = humidity ratio of air leaving the cooling unit for zone 1 (lbm moisture/lbm of dry air)

h_{r1} = humidity ratio of air in the zone 1 (lbm moisture/lbm of dry air)

C = conversion constant, 4,840 $\left(Btu - min/hr - ft^3\right)$

The humidity ratio of the supply air during winter months for a zone is calculated as:

$$h_{sw1} = \left(\frac{Q_{T1} - Q_{s1}}{V_{T1} \times C}\right) - h_{r1}$$

Similarly, the humidity ratio of the supply air for all the zones is calculated.

Load on Heating/Cooling Unit: The load on the heating or cooling unit is determined based on the heating or cooling degree days for a given climatic region selected by the user. For example, during the summer months, the cooling load for the cooling unit is calculated, whereas during the winter months heating load for the heating unit is calculated.

Cooling unit load: The cooling unit load is determined by calculating the sensible and latent cooling load for the cooling and dehumidification unit. For example, the sensible cooling unit load for zone 1 is calculated as:

$$Q_{sc1} = \left(\frac{V_{T1} \times 60}{v}\right) \times c_p \times (T_m - T_{s1})$$

where,

Q_{sc1} = Sensible Cooling unit load for zone 1 (Btu/hr)

K = Conversion constant, 60 min/hr

The latent cooling unit load for zone 1 is calculated as:

$$Q_{l1} = V_{T1} \times C \times (h_m - h_{s1})$$

where,

Q_{l1} = Latent Cooling load for zone 1(Btu/hr)

Similarly, the sensible and latent cooling unit loads for all the zones are determined accordingly.

Heating unit load: The heating unit load is determined by calculating the sensible heating unit load. For example, the sensible heating unit load for zone 1 is calculated as:

$$Q_{sh1} = \left(\frac{V_{T1} \times 60}{V}\right) \times c_p \times (T_{s1} - T_m)$$

where,

Q_{sh1} = Sensible heating load (Btu/hr)

Similarly, the sensible heating load for all the zones is determined accordingly.

HVAC: The HVAC energy consumption for zone 1 can be calculated as:

During Summer Months,

$$E_{S1} = \frac{Q_{C1} \times W \times OH \times (WF + BE)}{T \times COP}$$

where,

E_{S1} = HVAC energy consumption during summer for zone 1 (kWh)

Q_{C1} = Total cooling load for zone 1 (sensible cooling load for zone 1 (Q_{sc1}) + latent cooling load for zone (Q_{l1}))

W = Tons to Kilowatt conversion constant, 3.516 kW/ton

OH = Operating hours, 0.5 for 30 min interval

T = Tons to Btu/hr conversion constant, 12,000 Btu/hr − ton

COP = Coefficient of Performance

WF = Weather Factor

BE = Building envelope factor

Here, the total cooling load is determined from the above calculation in "Cooling unit load." COP of the HVAC unit is input by the user. Similarly, the total energy consumption during summer is calculated by summation of cooling energy consumption from all the zones in the building.

During Winter Months, for electric heating system:

$$E_{W1} = \frac{Q_{sh1} \times OH \times (WF + BE)}{Eff_e \times 3,412 \text{ Btu/kWh}}$$

And for gas heating system:

$$E_{W1} = \frac{Q_{sh1} \times OH \times (WF + BE)}{Eff_g}$$

where,

E_{W1} = Heating unit energy consumption during winter for zone 1 (kWh)

Q_{sh1} = Sensible heating unit load

Eff_e = System efficiency of electrical heating system

Eff_g = System efficiency of gas heating system

Similarly, the heating energy consumption for all the zones is calculated by summation of heating energy consumption from all the zones in the building.

Hence, the total annual energy consumed by the HVAC system is determined by the summation of the energy consumed during the summer months and winter months.

$$TE = \sum_{i=1}^{n} (E_{si} + E_{wi})$$

where,

TE = Total energy consumed by the HVAC system

3.6.3 Rating for Effectiveness of BEMS

For determining the effectiveness of BEMS, two types of energy sources are considered in this simulation tool, i.e., electricity and natural gas. To normalize both kinds of energy sources for comparison, they are converted to their respective cost. The average cost of electricity ($/kWh) is used that is calculated by dividing the total electricity cost in a year by total electricity (kWh) consumption. This electricity cost includes all the expenses included in the electric bill, such as demand charge, customer charge, and taxes. Similarly, the average natural gas cost ($/MMBtu) is used for determining the cost of natural gas. Moreover, the total cost for electricity and natural gas is determined for each month, and the percentage of electricity and the natural gas cost is calculated for respective months.

Furthermore, a continuous scale of 1 to 5 is used to determine the effectiveness of BEMS, where a rating of 1 represents poor, and 5 represents excellent energy management system, respectively. The rating of BEMS starts with 1, and the remaining 4 scores are assigned to the electrical and natural gas energy based on the percentage of their energy cost for each month. Once the energy consumption data for the Base Case and TEE Case has been determined, the percentage difference of the TEE Case from the Base Case is calculated for both electricity and natural gas. Moreover, the total scale assigned for electricity and natural gas is multiplied with the remaining percentage value than what was obtained from the TEE Case and Base Case difference for electricity and natural gas.

The overall effectiveness of the BEMS is determined in similar way by taking energy consumption data. A rating Table 1 is given below for guiding users regarding the meaning of the rating value.

Table 1: User guidance for representation of rating value

Range of rating value	Effectiveness of BEMS
1–2	Poor
2–2.75	Not good
2.75–3.5	Not satisfactory
3.5–4	Satisfactory
4–4.75	Good
4.75–5	Excellent

Note: The range of rating starts from the left-hand side value.

3.6.4 Reduction of GHG Emissions for Site Energy and Source Energy

In this research, the reduction of CO_2 emission was calculated based on annual energy savings by adding BEMS controls and/or improvement in the building envelope. The site energy usage obtained from the first simulation (i.e., Base Case) and second simulation (i.e., TEE Case) and reduction of energy between the two cases are converted to source energy by multiplying with 2.8 for electrical energy source and 1.05 for natural gas. Furthermore, the reduction of CO_2 emission was calculated by multiplying the CO_2 emission rate of 2.19 lbs/kWh for electrical energy and 113 lbs/MMBtu of natural gas for both site and source energy. Finally, the total reduction of CO_2 emission was obtained by summing the each of energy source for site energy and source energy.

3.7 Simulation Excel Input Tabs Details

This excel-based effectiveness of energy management system determination of buildings contains five worksheets named User Manual, Reference, Inputs, Occupancy, and Climatic Data.

3.7.1 "Occupancy" Worksheet

This worksheet includes all the different types of rooms where occupancy can impact air supply. The occupancy level, i.e., percentage of total allowable occupants as shown in Fig. 1, is considered during the calculation of ventilation requirements.

3.7.2 "Reference" Worksheet

The objective of the "Reference" worksheet is to save all the required information to run the simulation. It contains data such as people's outdoor air rate (cfm/person), area outdoor air rate (cfm/ft^2), Occupant density (#/1000 ft^2), and ACH for 16 different types of rooms.

3.7.3 "Climatic Data" Worksheet

This worksheet contains information regarding climatic data for nine regions. For simplification, only two states from each region and only two weather stations from each state are considered for the simulation. For each of the weather stations, further data such as elevation (ft), heating DBT ($^\circ$F), cooling DBT ($^\circ$F), and humidity ratio (grains of moisture/grains of dry air) is provided in the sheet. The worksheet "Climatic Data" is shown in Fig. 2.

Gymnasium					
				Weekdays	**Weekends**
Time Interval		**Random number range**		**Percentage of Total Allowable Occupants**	**Percentage of Total Allowable Occupants**
12:00 AM	8:00 AM	0	0.99	0%	0%
		0.991	1	5%	2%
8:01 AM	9:00 AM	0	0.75	80%	0%
		0.751	1	25%	5%
9:01 AM	10:00 AM	0	0.8	80%	0%
		0.81	1	30%	10%
10:01 AM	12:00 PM	0	0.98	20%	0%
		0.981	1	75%	20%
12:01 PM	1:00 PM	0	0.3	55%	5%
		0.31	1	15%	0%
1:01 PM	4:00 PM	0	0.98	60%	0%
		0.981	1	95%	10%
4:01 PM	5:00 PM	0	0.8	40%	0%
		0.81	1	90%	5%
5:01 PM	6:00 PM	0	0.75	0%	0%
		0.751	1	35%	5%
6:01 PM	8:00 PM	0	0.35	35%	5%
		0.351	1	0%	0%
8:01 PM	12:00 AM	0	0.99	0%	0%
		0.991	1	5%	2%

Figure 1: Occupancy chart

	Climatic Region		State		Weather Station	Elevation (ft)	Heating DBT (oF) (99.6%)	Cooling DBT (oF) (0.4%)	HR (g/lbs) (0.4%)	HR (g/g)
1	Pacific	1	WA	1	Olympia Regional	188	20.4	87.3	82.7	0.0118
				2	Fairchild AFB	2,461	5.2	91.8	81.7	0.0117
		2	CA	3	Southern California Logistics	2,885	27.6	100.7	101.2	0.0145
				4	Monterey Regional	165	36.6	78.7	76.1	0.0109
2	Mountain	3	MT	5	Missoula Intl	3,192	-3.5	93.1	81.8	0.0117
				6	Bert Mooney AP	5,506	-17.3	87.9	77.8	0.0111
		4	AZ	7	Luke AFB	1,085	34.8	110.9	125.6	0.0179
				8	Window Rock AP	6,739	0.1	89.8	92.2	0.0132
3	West North Central	5	ND	9	Hector Intl	900	-18.7	90	123.7	0.0177
				10	Minot Intl	1,665	-18.1	90.5	118.4	0.0169
		6	KS	11	Lawrence Municipal	832	3.4	99.2	141.4	0.0202
				12	Mcconnell AFB	1,371	8.3	100.2	137.4	0.0196
4	West South Central	7	AR	13	Texarkana regional	361	23.8	99.3	139.5	0.0199
				14	Bentonville Municipal	1,296	10.1	96.6	130.1	0.0186
		8	TX	15	Victoria regional	115	31.4	97.9	78.7	0.0112
				16	San angelo regional	1,916	22.2	101.7	125.7	0.0180
5	East North Central	9	WI	17	Sheboygan	577	-1.8	83	136.3	0.0195
				18	Appleton Intl	917	-6	88.4	136.7	0.0195
		10	OH	19	JMCOX dayton Intl	1,000	2.3	90.3	128.8	0.0184
				20	Toledo Express AP	669	1.5	91.2	129.7	0.0185
6	East South Central	11	KY	21	Henderson City-County AP	387	8.8	93.4	135.1	0.0193
				22	Cincinnati Northern Ky Intl	869	5.9	91.6	133.8	0.0191
		12	AL	23	Montgomery regional	202	24.3	96.8	139.9	0.0200
				24	Birmingham Shuttlesworth Intl	615	20.8	95.6	138.7	0.0198
7	Middle Atlantic	13	NY	25	Plattsburgh Intl	234	-8.7	86.6	71.2	0.0102
				26	Elmira Corning regional	955	-0.1	89.6	120.3	0.0172
		14	PA	27	Erie Intl	730	6.1	86.7	125	0.0179
				28	Washington County AP	1,185	2.7	88.3	122.5	0.0175
8	South Atlantic	15	WV	29	Mid-Ohio Valley Regional	831	8.6	90.6	130	0.0186
				30	Yeager AP	910	10.7	91.2	130.8	0.0187
		16	FL	31	Orlando Intl	90	38.3	93.8	144.6	0.0207
				32	Jacksonville Intl	26	29.5	94.5	142.7	0.0204
9	New England	17	ME	33	Brunswick NAS	70	-2.2	86.2	112.1	0.0160
				34	Sanford seacost regional	244	-6.1	89.7	117.9	0.0168
		18	CT	35	Hartford-brainard AP	19	8.2	90.9	125.7	0.0180
				36	Waterbury-oxford AP	726	3.2	87.6	125.4	0.0179

Figure 2: Climatic data from 2017 ASHRAE handbook [32]

3.7.4 "Inputs" Worksheet

Once the information is provided on the "User Manual" worksheet, the model directs the user to the sheet "Inputs." The user must select all the rooms from the given list and level for the building envelope from the drop-down menu for each room. The model explains to the user to decide on what level of building envelope to select. Further, the user must enter the room's dimensions (area and height), thermostat settings for setpoint, and setback temperature for summer and winter. The screenshot of the sheet "Inputs" is shown in Fig. 3.
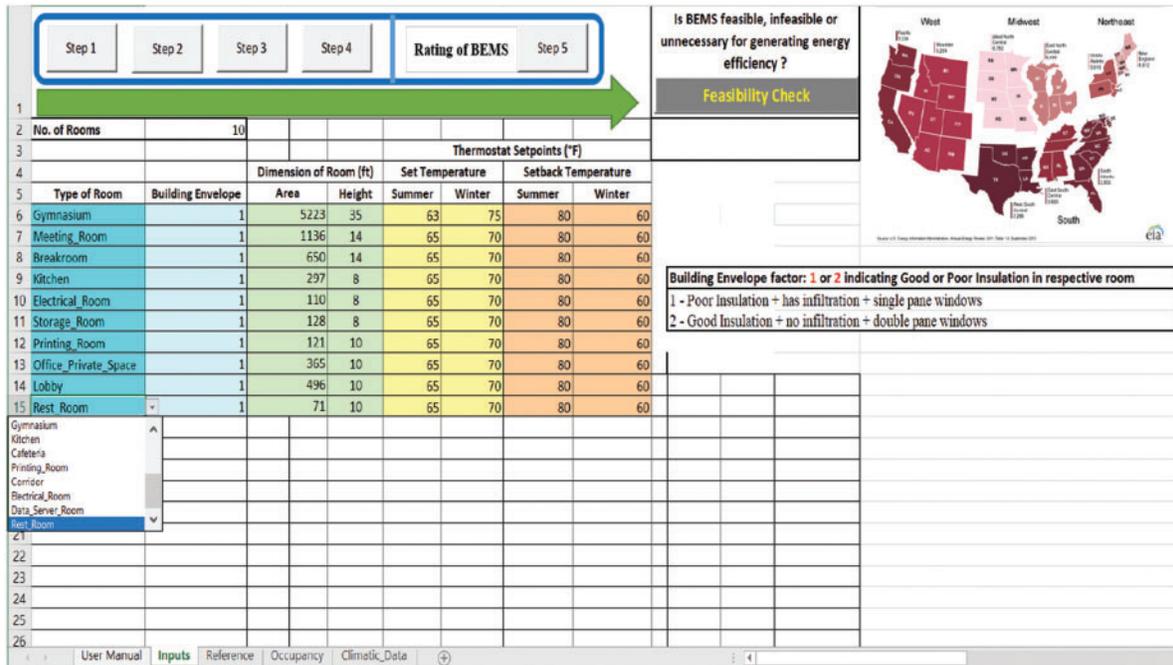
Figure 3: "Inputs" worksheet

4 Simulation System Execution, Results and Discussion

4.1 Building Description

For the demonstration of the simulation tool, a community center in Huntington, West Virginia, has been selected. The reason for choosing this community center is that it has multiple types of zones such as Gymnasium, Breakroom, Meeting Room, and Office spaces with different occupancy levels at different periods throughout the day. Hence, this building is considered an ideal building to determine the effectiveness of the energy management system. The floorplan of the community center is shown in Fig. 4.

Considering all the current operating characteristics of the building, the annual energy required for the HVAC system of the building is determined by using the simulation tool.
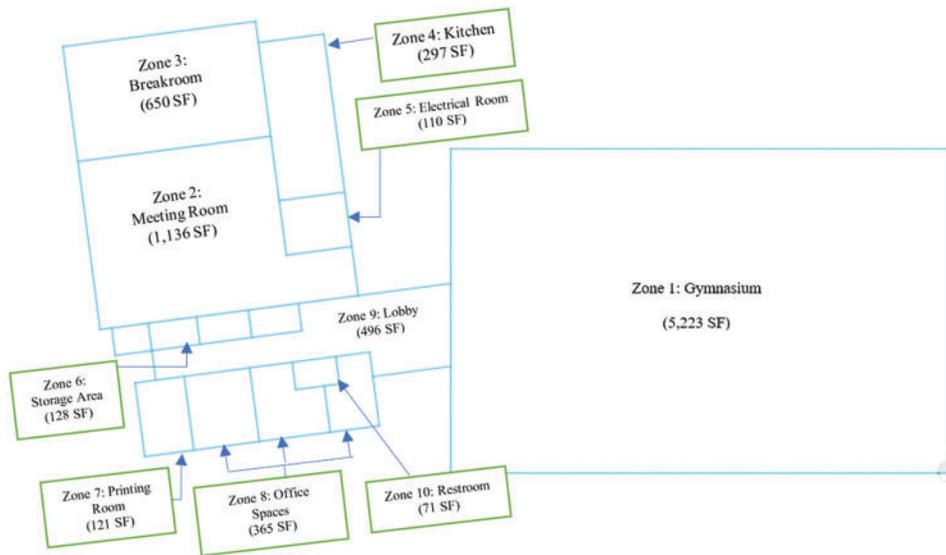
Figure 4: Floorplan of the community center

4.2 Simulation Demonstration with Community Center Building

The simulation is performed in two runs. For the first run (Base Case), the current operating characteristics of the building with current BEMS controls are input into the model.

4.2.1 Simulation with User-Defined/Base Case

The user is asked to select the BEMS controls used in the building. The user is asked to input the approximate percentage of outdoor air intake inside the building for ventilation. The user has to manually input the thermostat setting, area, and height of the individual room. The simulation will summarize the total energy required for space heating and cooling for all twelve months, as shown in Table 2.

Table 2: Monthly energy consumption for the Base Case

Year	Month	Energy usage, (kWh)	Natural gas usage, (MMBtu)
	January	3,360	64.71
	February	3,028	58.32
	March	2,254	43.29
	April	1,865	33.93
	May	3,559	0
2020	June	6,269	0
	July	7,850	0
	August	7,342	0
	September	4,205	0
	October	2,819	0
	November	1,892	36.27

(Continued)

Table 2 (continued)

Year	Month	Energy usage, (kWh)	Natural gas usage, (MMBtu)
	December	3,425	65.99
Total	-	**47,868**	**303**

4.2.2 Simulation with all BEMS Controls and Improved Building Envelope

Table 3 summarizes the total energy needed for space heating and cooling for all twelve months during the TEE Case.

The simulation determined that the total annual electrical energy (kWh) and natural gas (MMBtu) required for the Base Case was 47,868 kWh and 303 MMBtu, respectively. While, for the TEE Case considering all the BEMS controls and improved building envelope insulation, the total annual electrical energy (kWh) and natural gas (MMBtu) required is 21,034 kWh and 115 MMBtu, respectively. The electrical energy consumption was reduced by approximately 56%, and the natural gas consumption was reduced by about 62%.

Table 3: Monthly energy consumption for TEE Case

Year	Month	Energy usage, (kWh)	Natural gas usage, (MMBtu)
	January	1,410	23.88
	February	1,297	21
	March	1,063	17.19
	April	968	14.89
	May	1,546	0
	June	2,345	0
2020	July	3,562	0
	August	2,982	0
	September	1,853	0
	October	1,515	0
	November	964	15.65
	December	1,529	21.97
Total	-	**21,034**	**115**

4.3 Result Analysis

Table 4 compares the difference in energy consumption for electricity (kWh) and natural gas (MMBtu) monthly. Further, the effectiveness of BEMS is also determined every month.

Table 5 shows the summary of the reduction of CO_2 emission for the TEE Case. By upgrading the building to TEE Case from Base Case, the reduction of CO_2 for site energy is 80,010 lbs/yr, and for source, energy is 186,852 lbs/yr.

Table 4: Comparison of energy consumption between Base Case and TEE Case

Year	Month	Energy usage, (kWh)		Natural gas usage, (MMBtu)		Percentage reduction from Base Case		Effectiveness of BEMS (1–5)
		Base Case	TEE Case	Base Case	TEE Case	kWh	MMBtu	
	January	3,360	1,410	64.71	23.88	58%	63%	2.55
	February	3,028	1,297	58.32	21	57%	64%	2.54
	March	2,254	1,063	43.29	17.19	53%	60%	2.7
	April	1,865	968	33.93	14.89	48%	56%	2.88
	May	3,559	1,546	0	0	57%	0%	2.74
	June	6,269	2,345	0	0	63%	0%	2.5
2020	July	7,850	3,562	0	0	55%	0%	2.82
	August	7,342	2,982	0	0	59%	0%	2.63
	September	4,205	1,853	0	0	56%	0%	2.77
	October	2,819	1,515	0	0	46%	0%	3.15
	November	1,892	964	36.27	15.65	49%	57%	2.84
	December	3,425	1,529	65.99	21.97	55%	67%	2.5
Total	-	**47,868**	**21,034**	**303**	**115**	**56%**	**62%**	**2.67**

Table 5: Summary of reduction of CO_2 emission for TEE Case

Energy source	Site energy		Source energy	
	Electricity, (kWh/yr)	Natural gas, (MMBtu/yr)	Electricity, (kWh/yr)	Natural gas, (MMBtu/yr)
Base Case energy usage	47,868	303	134,030	318
TEE Case energy usage	21,034	115	58,895	121
Annual energy savings	26,834	188	75,135	197
CO_2 emission saved based on energy source (lbs/yr)	58,766	21,244	164,546	22,306
Total CO_2 emission saved (lbs/yr)	80,010		186,852	

Figs. 5 and 6 show that the highest electricity demand for space cooling during July has reduced from 7,850 to 3,562 kWh. This reduces the energy cost of the building and reduces the overall demand cost for electricity. Further, the highest demand for natural gas during December of 66 MMBtu declined to 23.88 MMBtu in January in the TEE Case. Hence, by adding the BEMS controls, the overall need for space cooling and heating can be reduced. This reduces the cost associated with energy consumption and opens areas for downsizing the HVAC components while upgrading the system. Downsizing the HVAC equipment can further help to minimize the excess waste of energy.
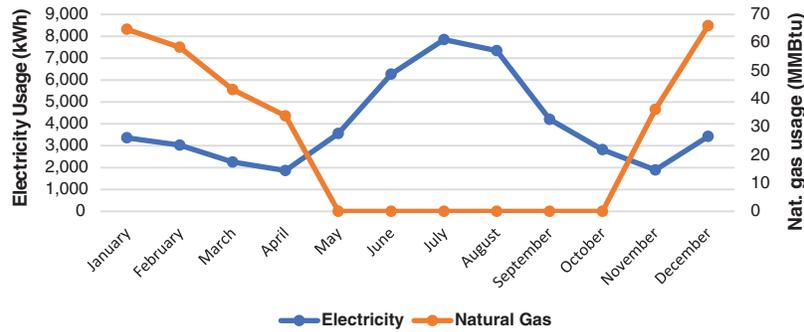
**Figure 5:** Energy consumption pattern for the Base Case
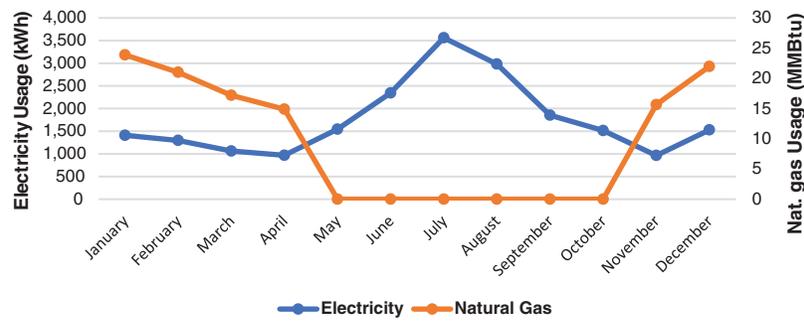
Figure 6: Energy consumption pattern for TEE Case

The following Figs. 7 and 8 compare the electric energy consumption and natural gas consumption for the Base Case and TEE Case.
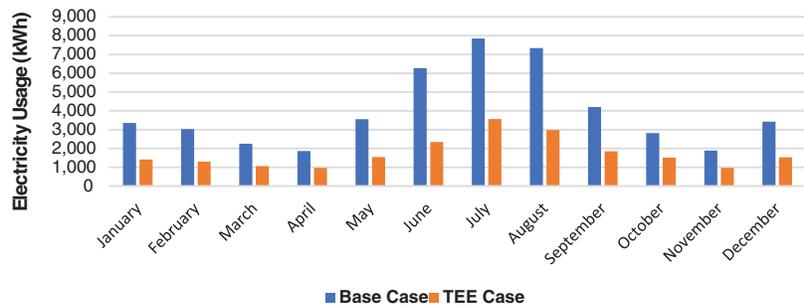

Figure 7: Comparison of electrical energy consumption between Base Case and TEE Case

From Fig. 9, it can be seen that the efficacy of BEMS ranges from 2.5 to 3.15. The overall usefulness of BEMS is determined to be 2.67. According to the rating chart, as shown in Table 1, the effectiveness of BEMS is considered "Not Good".
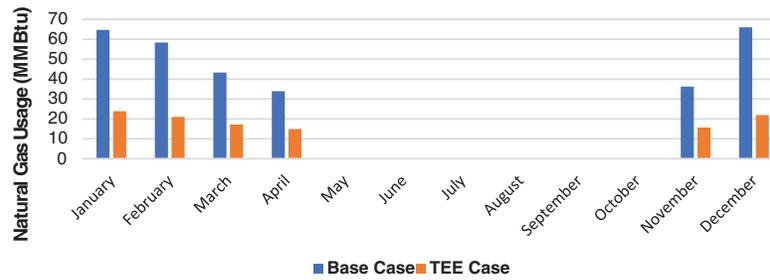
Figure 8: Comparison of natural gas consumption between Base Case and TEE Case
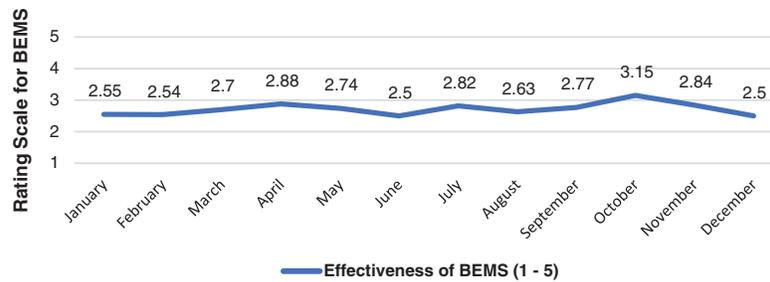
Figure 9: Effectiveness of BEMS for Base Case

5 Conclusion and Future Work

5.1 Conclusion

The simulation tool is designed to handle any number of rooms; however, the constraint would be the time required for the simulation run, available BEMS controls, and building parameters to input in the model. Only four BEMS controls are considered in this study, and limited building parameters can be input into the model. Furthermore, multiple tests were performed to determine the time required for a various number of rooms, and it was found that the total time needed to simulate three rooms was 15–20 min, five rooms were 25–30 min, ten rooms were 35–45 min, and 15 rooms were 50–60 min. A default time of 10 min is included in above mentioned time duration for the input of the values from the user. The simulation was run on a computer with Intel Core i7-8550U CPU @ 1.80 GHz (8 CPUs) and 8,192 MB RAM. The simulation would take less time if run on a computer with better computing capabilities.

Further, with advanced computing computers, the simulation tool can perform faster even with a more significant number of rooms. This simulation tool would be a helpful tool to get a quick estimate of the energy required for space heating and cooling of the building. Further, it would also help in understanding the requirement of outside air for maintaining the IAQ. Moreover, it can act as a bridge between building owner/energy managers and advanced energy modeling tools to benchmark the effectiveness of their BEMS. Since energy modeling of a building is cumbersome work and would require professional help to model the building in the software. By using this simulation tool, building owners can easily understand the energy required for space heating and cooling the building and the effectiveness of their BEMS.

In this study, the effect of building operating characteristics and BEMS controls on energy consumption for heating and cooling the building is studied. The study was carried out by developing an MS Excel-based decision support system where users can enter the input parameters related to

their building operating characteristics and BEMS controls. A rating of the BEMS is calculated on a continuous scale of 1–5 based on the estimated annual energy consumption. These data could benefit energy managers or building owners to design the HVAC system and add control systems based on their necessity. Further, this rating could also help benchmark the energy consumption of the building against their past energy consumption data.

5.2 Limitations

The limitations are described below:

– Only electricity and natural gas are accounted as a source of energy for cooling and heating the building.
– The model uses many input boxes, and none of them take any character (alphabet/words) or 0 or anything out of the range.
– The model is capable of handling only 16 different types of rooms/spaces. If a building has a different kind of room than available in the model, then the analysis of the building cannot be performed.
– The thermostat settings are set constant throughout the year. Hence, the actual variation in the settings of a thermostat is not accounted for in the model.
– Nine climatic regions, two states from each climatic region, and two weather stations from each state only have been considered for this study.
– Only dehumidification is accounted for energy calculation and not the humidification process for simplicity in calculations.
– The seasonal factor is generated for zone 1 and will remain constant for all the other zones for particular hours.

5.3 Future Work

Future work on this research study involves increasing the number of operating parameters of BEMS controls to determine the effectiveness of a much complex building energy management system. A summary of possible forthcoming work related to this study are listed below:

1. Inclusion of more BEMS controls/operating parameters such as advanced metering infrastructure to analyze electric demand and consumption patterns for a building, automated demand response controls, and benchmarking of energy consumptions.
2. Accounting for more energy sources other than electricity and natural gas. Many commercial buildings also use district steam and fuel #2 oil.
3. Including all of the states of the United States for the study. This will help analyze the effectiveness of BEMS of commercial buildings from any part of the U.S.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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