IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 8, 2021, accepted July 5, 2021, date of publication July 12, 2021, date of current version February 2, 2022.

Digital Object Identifier 10.1109/ACCESS.2021.3096208

Improving Quality of Experience Using Fuzzy Controller for Smart Homes

QURAT-UL AIN[1], **SOHAIL IQBAL**[1], **AND HAMID MUKHTAR**[2]
[1]School of Electrical Engineering and Computer Science (SEECS), National University of Sciences and Technology (NUST), Islamabad 44000, Pakistan
[2]Department of Computer Science, College of CIT, Taif University, Taif 21944, Saudi Arabia

Corresponding author: Sohail Iqbal (sohail.iqbal@seecs.edu.pk)

ABSTRACT Internet of things is providing us numerous ways to improve our quality of experience by using smart cyber-physical infrastructure systems. Also, due to arrival of LED lighting systems, there is the possibility to improve user's visual comfort at less cost. In our proposed model, by using a fuzzy inference system, used in cyber-physical infrastructure system, we save energy from the heating, ventilation and air conditioning system. This saved energy is used to improve the visual comfort of the user. Simulation results show that considering the visual comfort standard of 500 lux instead of 250 lux results in energy savings and ensures visual comfort. Together with the preservation of thermal comfort increases the overall users' comfort. Since research confirms that users' improved comfort results in up to 14% of increased productivity. Our model is unique in the sense that using fuzzy logic, indirectly improved the users' productivity. By using our fuzzy logic controller on electric equipment, we can achieve improved users' performance without paying any extra cost.

INDEX TERMS Home energy management system, cyber-physical infrastructure system, visual comfort, thermal comfort, Internet-of-Things, energy savings, fuzzy logic controller.

I. INTRODUCTION

The residential sector is the third-highest energy-consuming sector, and the residential load is estimated to increase by 24% in 2035 [1], [2]. The residential load consists of the energy consumed by homes that have usually a number of occupants utilizing a range of small or large electrical appliances such as refrigerators, air conditioners, televisions, computers, microwave oves, washing machines, heaters, and lighting devices, etc. Due to advancements in Internet of Things (IoT), simple homes are evolving into smart homes. A smart home is equipped with intelligent devices that can communicate with one another through the Internet or local area network (LAN). This feature allows the remote monitoring and control of the system and appliances, such as lighting and heating. The cyber-physical infrastructure systems (CPIS) of smart homes is a system that combines sensing, monitoring and control of intelligent devices using controllers that are connected through IoT. In CPIS of smart home, physical components (sensors, appliances, and controllers) are intertwined with software components (algorithms) which will help in efficient utilization of energy. To manage the energy flow of the smart home, different techniques have been proposed in the literature for the smart home energy management system (SHEMS). The key functions of a SHEMS are to monitor, control, and optimize energy consumption. The objectives of SHEMS are energy efficiency, cost reduction, and users' comfort improvement. Furthermore, SHEMS supports utility demand response (DR) programs which encourage consumers to change the electricity demand in response to the change in the electricity price [3], [4].

The energy consumption pattern of a smart home is changed by scheduling and controlling the home appliances. According to the energy consumption pattern, home appliances lie in three major categories: delay-tolerant, delay-intolerant with essential load, and delay-intolerant with flexible load [5], [6]. Delay-tolerant appliances are also known as shiftable appliances because their starting time can be shifted from high-peak hours to off-peak hours to save energy costs resulting from lower tariffs in off-peak hours. The category of delay-tolerant appliances includes oven, water heater, washing machine, and dishwasher to name a few. The independence of varying the starting time of delay-tolerant appliances makes them suitable

The associate editor coordinating the review of this manuscript and approving it for publication was Vahid Vahidinasab.

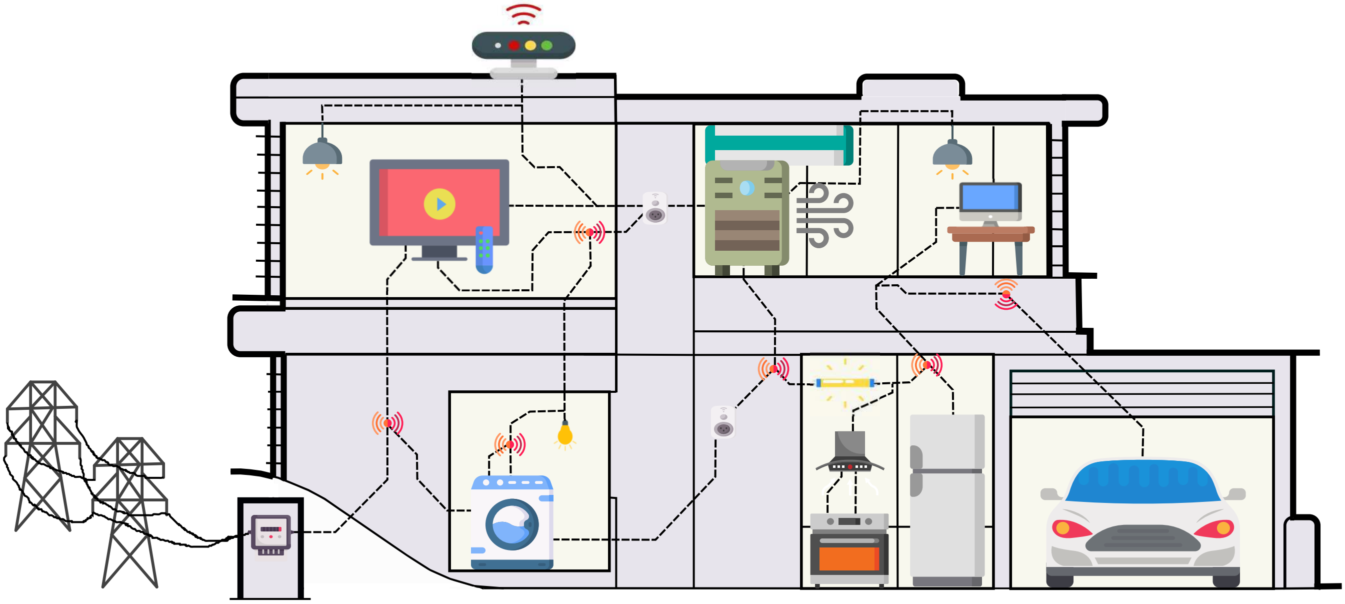


FIGURE 1. **Smart home consists of electric appliances, sensors, smart meter, and electric vehicles. All these intelligent devices communicate with the home energy management controller to achieve the objectives of energy efficiency and QoE.**

for scheduling. The second category is delay-intolerant appliances with essential load, e.g., TV, bulb, computer, etc. Because these appliances are classified as essential load, shifting their starting time is not allowed, rather controllers are used for the efficient usage and controlling of these appliances. Heating, ventilation, and air conditioning (HVAC) along with refrigerators are categorized under the delay-intolerant with flexible load category. These appliances are also known as thermostatically controlled appliances because the consumers can change their working state according to the thermal constraints. Figure 1 shows the general view of a smart home with different residential appliances working in coordination with the energy management controller (EMC).

To implement DR effectively, researchers have been working in the domain of SHEMS. Different scheduling algorithms for the delay-tolerant home appliances to reduce peak- load have been proposed. Hussain *et al.* proposed an efficient home energy management system based on a hybrid approach named genetic harmony search algorithm (GHSA) in [7]. Their proposed system reduces energy consumption and peak-to-average ratio (PAR). It increases user comfort by reducing the delay time i.e., the difference between the start time of the appliances after being scheduled and the user's preferred start time. Similarly, a priority-based hybrid approach in [8] was proposed by combining the best feature of meta-heuristic algorithms named: optimal stopping rule (OSR) theory, genetic algorithm (GA), teaching learning-based optimization (TLBO), and firefly algorithm (FA). Another hybrid technique by combining state-of-the-art algorithms like enhanced differential evolution (EDE) and teaching learning-based optimization (TLBO) was proposed in [9]. Simulation results validate that the hybrid technique performs better when compared to the performance of EDE and TLBO individually.

The lighting system (delay-intolerant with essential load) and HVAC (delay-intolerant with flexible load) are the major contributors to energy consumption in a smart home. These appliances are also directly related to user comfort [10]. The user comfort or quality perceived by the user when controller commands are in action is important for user experience and comes under the umbrella term of Quality of Experience (QoE). QoE is a subjective measure of user's satisfaction with the surrounding which in our case is determined in visual and thermal comfort. Visual comfort is the subjective condition of visual well-being influenced by the visual environment, whereas thermal comfort is the human expression of satisfaction with the thermal environment. Maintaining the physical working environment according to the user comfort standard will result in improvement in QoE. Furthermore, a research study shows that improvement in user comfort or QoE will result in an increase of 14% in people productivity [11].

Different closed control loop strategies have been used in literature for joint demand response management and thermal comfort optimization by considering occupancy schedules [12] weather information, smart zoning [13], and by integrating renewable energy resources [14]. In recent studies, fuzzy logic is used to control the HVAC and lighting system [15], [16]. Fuzzy logic is used to adjust the setpoint of the thermostat for the HVAC system in response to variations in electricity price and energy demand of smart homes [15]. Likewise, a fuzzy logic-based illuminance controller was proposed to control the illuminance setpoints in response to variation in price, outdoor and indoor illuminance [16]. However, these proposed controllers are designed to save energy and cost without paying much attention to the comfort evaluation. These control techniques often fix the thermostat setpoint and illuminance setpoint to a single value, consequently, jeopardizing the users' comfort [15], [16]. Therefore, designing control techniques to minimize the tradeoff between energy consumption and user comfort is required. This will not only improve the overall QoE but also increase the productivity of a user in a working environment. We propose two controllers: fuzzy logic controller for HVAC and fuzzy logic controller for the lighting system to maintain thermal and visual comfort of users for improved QoE along with achieving energy efficiency.

Our proposed fuzzy logic controller for HVAC, denoted as (FLC_{h1}), helps in the optimal energy consumption by setting the thermostat setpoints that lie within the thermal comfort zone. Our system utilizes the relationship of humidity and temperature along with other environmental factors for the initialization of setpoints. Energy saved using our HVAC controller, can be used by the proposed light controller (FLC_{l1}) that is designed to initialize high illuminance setpoint for achieving enhanced visual comfort. For the initialization of illuminance setpoints, we have used users' preference and daylight to manage the tradeoff between user's comfort and energy consumption. Furthermore, our proposed light and HVAC controllers automatically initialize the setpoints for every time interval without users' intervention which maximizes the benefits of DR. The main contributions of our work are highlighted as follows:

- Improved QoE by preserving thermal and visual comfort by using fuzzy controller
- Increase in productivity because of comfortable environment
- Optimal initialization of thermal and illuminance setpoints for DR participation
- Evaluation of the proposed controller using Fuzzy Synthesis to validate our approach
- Reduction in energy consumption, cost, and PAR

The remaining paper is organized as follows. Section II describes the previously proposed approaches along with their limitations. Section III provides the details of the proposed energy controllers whereas the analysis of the fuzzy synthetic evaluation is presented in Section IV. Analysis of the simulation results with the proposed LED lighting controller and the overall performance of the proposed controllers is presented in Section V. This paper is summarized and concluded with future recommendations in Section VI.

II. RELATED WORK

Several fuzzy logic controllers (FLC) for smart home energy management system are available in the literature. In this section, we discuss the controllers proposed recently to manage the energy consumption of lighting devices and HVAC system. Although, these controllers show improvement in energy efficiency but the user comfort is often sacrificed.

A. FUZZY LOGIC CONTROLLERS FOR LIGHTING SYSTEM

A fuzzy logic controller for a commercial building to achieve energy consumption minimization and visual comfort was proposed in [16]. Experiments were performed on the building equipped with LED luminaries, motion sensors, light sensors, and digital addressable lighting interface (DALI) control. Their proposed fuzzy logic controller consists of daylight and room lighting as input parameters to produce the required dimming lighting output based on user preferences. Furthermore, a proportional-integral (PI) controller was used to maintain the output around the desired illumination level. Different experimental scenarios were considered e.g., without any control, occupancy considered, optimal visual comfort setpoints, and user-preferred setpoints validating that the proposed methodology has the potential for energy savings. However, this work does not consider the electricity price which when integrated can result in better decision making.

To achieve the objective of a comfortable and healthy indoor environment for a smart home, a fuzzy-based intelligent windowsill system (IWS) was proposed in [17]. Environmental factors like indoor-luminance, temperature, humidity, carbon dioxide concentration, outdoor rain, and wind direction were used for the control of the electric windowsill system. A smart hand-held device was used for the manual and automatic working of the IWS. The proposed prototype was tested in different environmental conditions which shows the prospective environment comfort however, this work would be more substantial if the authors had provided any performance comparison with the existing techniques.

For energy saving, several proposed methodologies also integrate renewable energy resources (RESs) besides utilizing the local energy sources. In [18], authors have proposed a fuzzy expert system for efficient working of dimmable LED luminaires along with wind and solar power sources. Using light and motion sensor data, decision-making is performed using FLC where the input is the lighting average values and output is the control power command for the LEDs. The performance of the proposed methodology was compared with fluorescent and LED lighting without control which shows a 23% reduction in energy consumption. Although the proposed methodology shows the energy efficiency, it does not consider the user's visual comfort and external environmental factors. Furthermore, the proposed controller maintains the illumination level around a fixed value of 300 lux which makes the approach less adaptive.

Fayaz and Kim used fuzzy logic and bat algorithm to optimize the user comfort and energy savings in a building environment [19]. Another technique combining fuzzy logic, IoT, and RESs was proposed in [20]. The designed fuzzy controller consists of the light level of the environment and the battery level of the RESs as input and optimal light intensity level as output. This work was simulated using the predefined user schedule that is subject to change in real-time. Also, more details on simulations were not provided by the authors missing its mark to make an impact.

The meta-heuristic technique for global optimization named bat algorithm was used to set the optimized comfort parameters. Error difference between an optimized parameter and the real-time environment was computed and fed to the proposed fuzzy controller for the appropriate control command for energy consumption. Additionally, a method for comfort index calculation was also proposed to evaluate the user's comfort basis of comfort criteria. Even though their proposed methodology improved user comfort and energy efficiency, adding the parameters of occupancy, electricity price, etc. to the controller can help in better decision making.

Khalid *et al.* proposed a home energy management system that schedules and manages different classes of home appliances and load [21]. Flexible load like HVAC is controlled using the fuzzy logic methodology along with the hybrid optimization technique of bat and pollination algorithms used to schedule the shiftable appliances. The fuzzy illumination controller takes the input of electricity price, occupancy, indoor light, and outdoor light parameter to decide the setpoints for the illuminance. Their proposed technique is adaptive and learns the occupant's preference for comfort. Simulation results validate the claim of energy consumption minimization, but it does not account for how the user comfort is measured to support the user comfort maintenance claim. In addition to this, the relationship between the increase in light and loss in thermal comfort is a concept that has not been explored.

It has been observed that daylight or natural lighting is an important factor considered to minimize the tradeoff between visual comfort and energy consumption. A lot of research has been found on daylight in the energy performance and visual comfort of buildings [22], however, a smaller number of studies have explored the impact of daylight in HEMS algorithms. Daylight needs to be considered to reduce the energy consumption, by designing the controller in such a way to intelligently decides when to benefit from daylight rather than using the artificial lighting system for users' visual comfort. For better comparison, the input parameters considered in the literature and input parameters of the proposed methodology are listed in Table 1.

B. FUZZY LOGIC CONTROLLERS FOR HVAC SYSTEM

To reduce the energy consumption of HVAC, a fuzzy logic rule-based system is proposed in [23] by simulating the wireless programmable thermostat. Real-time data of outdoor temperature, load demand, electricity tariff, and user presence is fed to the fuzzy logic system. The output of the system decides how much load reduction should be applied by changing the initialized setpoints. The proposed system focuses on energy consumption minimization and demand response maximization, but user comfort is not considered. Autonomous thermostat working in the two modes of economy and comfort is proposed in [24]. Their proposed supervised fuzzy logic learning method utilizes outdoor temperature, occupancy, electricity prices, and demand to change the thermostat setpoint.

With technological and communication advancement, a programmable communicating thermostat (PCT) is recommended to use [4]. PCTs can communicate with advanced metering infrastructure (AMI) to change the setpoints base on electricity rates without user interaction. A combination of the PCT with the fuzzy logic approach is proposed in [25] that works on real-time pricing and time-of-use pricing. Their proposed combination shows promising results when compared to other thermostats though lacks adaptiveness. Kesktkar *et al.* enhanced the proposed approach in [15] using the Adaptive Fuzzy Logic Model (AFLM) which learns and adapts the thermostat setpoint according to user priorities.

A world-wide adaptive thermostat controller using fuzzy logic is presented in [26]. The proposed controller is evaluated using two types of fuzzy inference system (FIS) named Mamdani and Sugeno using input data of outdoor temperature, initialized setpoints, utility price, and resident's presence to compute the energy consumption. The proposed system results in cost reduction and avoidance of peak formation but user comfort is neglected.

To summarize, controllers designed for HVAC systems in literature often overlook the users' thermal comfort. Energy consumed by HVAC is dependent on the thermostat setpoints initialized. Relative humidity is one of the important factors that impact user thermal comfort. Thermostat's setpoints initialized considering the thermal comfort zone defined using the relationship between temperature and relative humidity can result in energy consumption reduction as well.

III. SYSTEM MODEL

In this paper, two FLCs are proposed to achieve the users' comfort leading to increase productivity and energy consumption minimization which results in cost savings. This section will discuss the details of FLC for HVAC (FLC_{h1}) and FLC for lighting system (FLC_{l1}). The formulation of the energy consumption, cost, user comfort, PAR, and efficiency gain is also discribed in this section.

A. FUZZY LOGIC

As mentioned earlier, DR programs (e.g., Time of Use (ToU) pricing) suffer to achieve the objectives of energy efficiency and comfort preservation due to lack of user's time or training for participation in the DR program. This emphasizes on the need of an automated controller which optimizes the usage of HVAC and lighting systems based on different environmental factors and electricity price imposed by the electric utility. Different conventional controllers for smart homes e.g., ON-OFF controller and PID controller [27] etc. were designed in the literature to achieve the objective of energy savings. However, fuzzy logic control has a major advantage over ON-OFF control as the controlled variables considered in our study vary continuously with time. FLC responds very well to these changes. Besides, conventional techniques lack in handling the non-linear features of a complex system like HVAC [28]. The fuzzy logic controller is classified as a non-linear controller that works according to

TABLE 1. Comparison of fuzzy inference systems proposed for lighting system.

Reference	Outdoor Illumiance	Indoor Illumiance	Occupancy	Price	Priority	Renewable Energy
Liu *et al.* [16]	✓	✓	✗	✗	✗	✗
Kiyak *et al.* [18]	✓	✗	✗	✗	✗	✓
Fayaz and Kim [19]	✓	✗	✗	✗	✗	✗
Khalid *et al.* [21]	✓	✓	✓	✓	✗	✗
Our proposed FIS	✓	✓	✓	✓	✓	✗

human thinking. As compared to classical control theory, an intelligent fuzzy logic controller does not require the specific mathematical formula for design, rather a practical understanding of the system under consideration is required. Fuzzy controllers have been considered the most suitable choice among researchers for systems where analysis is very complex with existing linear controllers. Deployment of the fuzzy controller has been found in various domains, such as aerospace, medical imaging, data mining, classification, etc. [29] to name a few.

Designing a fuzzy logic system consists of four major components: 1) fuzzification 2) rule-base 3) inference engine and 4) defuzzification [28]. The input and output of FLC are real variables that are connected through IF-THEN rules to achieve the desired output. The major advantage of FLC as compared to other controllers is its requirement of little mathematical modeling. Another reason for using the FLC is that the rules defined are purely on human intuition which is effective and more expressive. Mamdani FIS is the most used type of fuzzy inference system for evaluation because of its simple nature [28].

The input parameters used in this study are directly related to energy management and user comfort in residential buildings. Optimized setpoints based on environmental conditions are decided with the help of fuzzy rules. In this paper, energy consumption is computed while considering the daylight luminance within the comfortable range of visual comfort.

Mamdani FIS takes crisp input, fuzzify these values, run the inference engine and produces a fuzzified output that is converted back to crisp value using centroid defuzzification method which is as follows:

$$z = \frac{\int \mu_C(z).zdz}{\int \mu_C(z)dz}. \tag{1}$$

Rule base of Mamdani FIS takes antecedent and consequent part as linguistic variables taken from human experts. For example: *IF* Outdoor-Illuminance is "Low Light" *AND* Indoor-Illuminance is "Medium" *AND* Electricity-Tariff is "Off Peak" *AND* Occupant is "Absent" *AND* Priority is "Low" *THEN* Illuminance-Setpoint is "Very Low".

B. FUZZY LOGIC CONTROLLER FOR THE LIGHTING SYSTEM

Approximately 20% to 40% of the total energy is consumed using lighting devices [16]. Therefore, optimizing the energy consumption of lighting systems along with preserving the users' visual comfort is very important. A fuzzy logic controller for lighting system (FLC_{l1}) is proposed to control the illumination to achieve the objective of visual comfort and energy savings. The block diagram of the proposed FLC for the lighting system inside the smart home is shown in Figure 2.

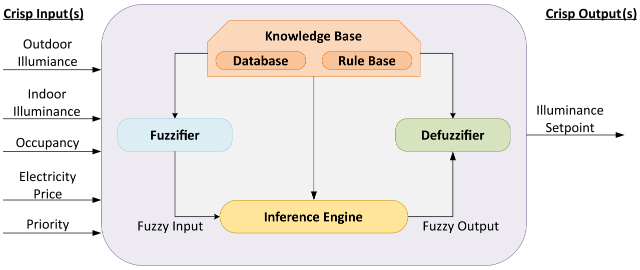
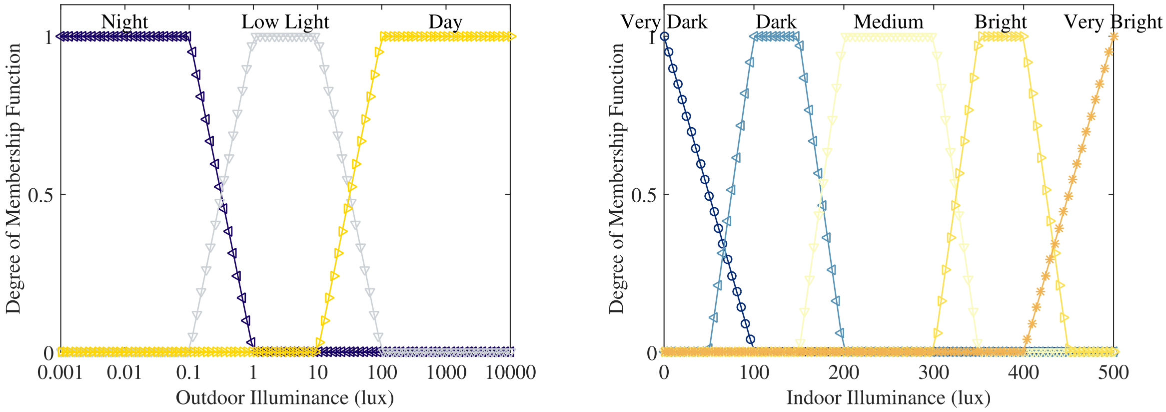


FIGURE 2. Block diagram of the proposed fuzzy inference system.

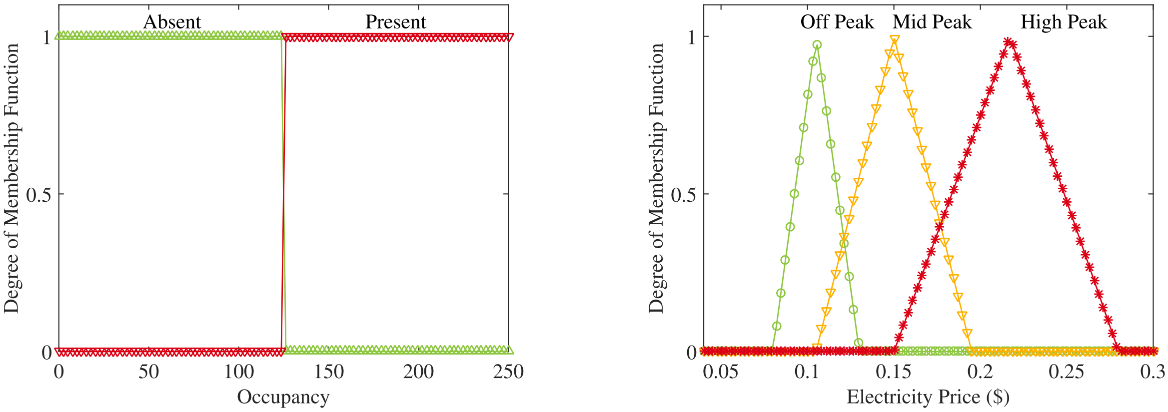
The proposed FLC for the lighting system takes the input parameters of outdoor illuminance, indoor illuminance, ToU electricity tariff, occupancy status, and users' priority whereas the output parameter is the adjusted illuminance setpoint. Trapezoidal and triangular membership functions are used to represent the linguistic variables of the input parameter as they are simple in use. These membership functions are also more capable of mapping the crisp data of input parameters with the desired degree of memberships. Details of the input and output parameters of our proposed controller are as follows:

1) Outdoor Illuminance: Illuminance or light level is a measure of the total amount of luminous flux incident on a plane surface and is measured in lux. The plane surface is defined as the area where residents are performing their tasks. Luxmeter is often used to measure illuminance levels. Daylighting can be used in the residential building using windows, etc. as the main lighting source which helps in reduce the illuminance setpoints for artificial lights. The more daylight available e.g., on a bright sunny day, the more it will be available in the room as compared to the overcast day. Membership functions of the input parameter named outdoor illuminance ($Light_{out}$) are 1) Night, 2) Low Light, and 3) Day as shown in Figure 3. The trapezoidal membership function is used to define the linguistic



(a) Membership Functions of Outdoor Light **(b)** Membership Functions of Indoor Light

FIGURE 3. **Membership functions for illuminance.**

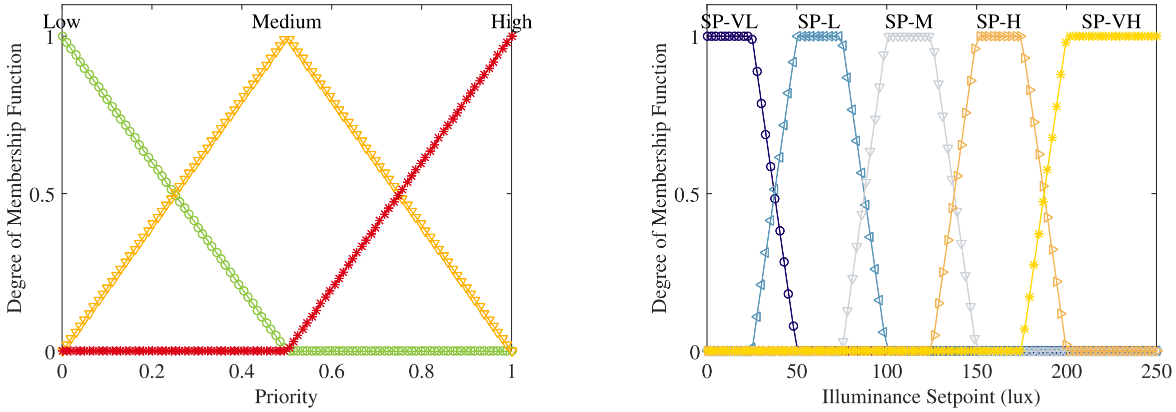


(a) Categories of User Occupancy **(b)** Categories of Electricity Tariff

FIGURE 4. **Membership functions for occupancy and utility's electricity tariff.**

variable of "Night", "Low Light" and "Day" as the values within a certain range can be categorized in a single group without sudden change as shown in Figure 6. Membership function of "Night" ranges from 0.001 lux to 1 lux considering different night light illuminance from starry night to full moonlight. The "Low Light" membership function represents the range of the light illuminance that occurs at the time of dawn and dusk. Membership function named "Day" shows the illumination range from very dark day to direct sunlight illuminance.

2) Indoor Illuminance: Indoor illuminance, measured using light sensors, consists of artificial light sources, e.g., bulb and natural illumination capturing daylight. Indoor illuminance ($Light_{in}$) are 1) Very Dark, 2) Dark, 3) Medium, 4) Bright, and 5) Very Bright as shown in Figure 3b. The trapezoidal membership function is used to map the range of the values considered for linguistic variables of indoor illuminance.
3) Occupancy: The demand response programs are heavily dependent on the occupancy status. Occupancy variation inside a smart home is one of the major parameters that contribute to the change in energy consumption behavior. The membership function of occupancy ($User_{Occ}$) is divided into two categories of 1) Absent and 2) Present measured using occupancy sensor as shown in Figure 4a.
4) Electricity Tariff: Different DR programs have been implemented to persuade users to change their energy consumption patterns. ToU is a tariff structure to incentivize consumers to use electricity when generation cost is low by reducing the electricity cost and disincentivize when the electricity generation cost is high by increasing the price of electricity consumed per kilowatt-hour. Figure 4b represents the three membership functions for input parameter electricity tariff ($Price_{ToU}$) named as 1) High Peak, 2) Mid Peak, and 3) Low Peak. Electricity tariff for simulation and result evaluation is taken from a Canadian utility Hydro One [30].
5) Occupants' Priority: Participation in DR often results in user discomfort because occupants are often required to



(a) Categories of Priority

(b) Illuminance Setpoint Range

FIGURE 5. Membership functions for user's priority and illuminance setpoint.

turn off the appliances when electricity prices are high. Proposed FLC integrates occupants' priority based on the nature of the activities and time of the day. Priority ($User_{Pr}$) defined by occupants is categorized into three membership functions 1) Low, 2) Medium and 3) High as shown in Figure 5a. Membership function "Low" means occupants' are not performing visually intensive tasks consequently resulting in maximum participation in DR by lowering the illuminance setpoint. Contrary to membership function "High" which represents that consumer is performing visually extensive task e.g., office work or study that requires the preservation of visual comfort to increase productivity.

6) Illuminance Setpoints: The universe of discourse for the illuminance setpoint (I_{sp}) covers the comfortable visual range of luminance and has five membership functions of 1) Very Low, 2) Low, 3) Medium, 4) High, and 5) Very High. From Figure 5b, it can be observed that the universe of discourse for output variable ranges from 0–250 lux for the case when the standard value for visual comfort is 250 lux. For the second scenario when the visual comfort standard value is raised to 500 lux, the universe of discourse for illuminance setpoints ranges from 0–500 lux.

The rule base of the FLC for the lighting system is defined using the combinations of the membership functions from input parameters in the antecedent of the rules. A specific weight value is assigned to every membership function of an input parameter. The output parameter is specified in the consequent of the rule based on the aggregated weight value of the membership functions for input. Let us take the example of the input parameter "Outdoor Illuminance", if the value of illuminance lies within "Night" membership function the weight assigned is large. This weight will directly impact on the output parameter "Illuminance Setpoint" by setting it to higher lux value to ensure the visual comfort. Similarly, if the value of input parameter "Outdoor Illuminance", lies within "Day" membership function the weight assigned is small so that the output parameter "Illuminance Setpoint" is initialized on the lower lux values taking advantage of the daylight. In the similar way, the weights of the rest of the input parameters are assigned to efficiently determine the value of "Illuminance Setpoint" for visual comfort. There are three input variables (outdoor illuminance, price, priority) with three membership functions and two variables (indoor illuminance, occupancy) with five and two membership functions. This results in a total of 270 combinations of the membership functions in the antecedent of fuzzy rules. Two hundred and seventy rules are defined in the rule-base of Mamdani FIS and some of the added rules are shown in Table 2. After the illuminance setpoint has been initialized, the total number of bulbs that are required to maintain that illuminance and the subsequent energy consumption is calculated [31]. According to lumen method, illuminance level (I_l) is calculated using Equation 2 [32].

$$I_l = \frac{\Phi \times C_U \times L_{LF}}{A}, \tag{2}$$

where:

I_l = illuminance level (lux);
Φ = illumination flux ($lumen$);
C_U = coefficient of utility;
L_{LF} = light loss factor;
A = area per bulb (m^2).

When illumination level is defined according to the variation in the value of lumen or lighting flux at time interval t, Equation 2 can be modified as follows:

$$I_l(t) = \frac{\Phi(t) \times C_U \times L_{LF}}{A}. \tag{3}$$

As the illuminance setpoints (I_{sp}) for time interval t are already being initialized with the help of our FLC_{l1}, illumination flux (Φ) required to maintain the visual comfort is calculated as follows:

$$\Phi(t) = I_l(t) \times \frac{A}{C_U \times L_{LF}}. \tag{4}$$

TABLE 2. Sample of rules defined in the proposed fuzzy inference system rule base.

#Rule	Outdoor Illuminance	Indoor Illuminance	Electricity Tariff	Occupant	Priority	Illuminance Setpoint
1	Day	Very Bright	High-Peak	Absent	Low	Very Low
2	Day	Very Bright	Off-Peak	Present	Low	Low
3	Low Light	Medium	Off-Peak	Present	Low	Medium
4	Low Light	Dark	High-Peak	Absent	Low	Low
5	Night	Dark	Mid-Peak	Present	Medium	High
6	Night	Very Dark	Off-Peak	Present	High	Very High

The total value of lighting flux or lumens is defined as the number of bulbs turned ON times the lighting emitted by a single bulb as follows:

$$\Phi(t) = \aleph(t) \times L_{EB}, \tag{5}$$

where:

$\Phi(t)$ = illumination flux at time t;
$\aleph(t)$ = number of bulbs turned ON at time t;
L_{EB} = light emitted by a single bulb.

From Equation 5 number of bulbs ($\aleph$) that needs to be turned ON at time interval t to achieve visual comfort can be calculated as shown in Equation 6.

$$\aleph(t) = \frac{\Phi(t)}{L_{EB}}. \tag{6}$$

Energy consumed by turning ON the number of the bulb at a specific time interval t is calculated using Equation 7 where P_l represents the power rating of the lighting bulb. Total energy consumed by the lighting system E_l over 24 hours is computed using Equation 8.

$$e_l(t) = \aleph(t) \times P_l. \tag{7}$$

$$E_l = \sum_{t=1}^{24} e_l(t). \tag{8}$$

At a time interval t, the cost of the energy consumed to turn ON a specific number of bulbs ($cost_l$) is calculated with the help of ToU electricity tariff ($Price_{ToU}$) as shown in Equation 9. The total cost incurred using the lighting system ($Cost_l$) when energy consumed in a day is computed using Equation 10.

$$cost_l(t) = e_l(t) \times Price_{ToU}(t). \tag{9}$$

$$cost_L = \sum_{t=1}^{24} cost_l(t). \tag{10}$$

C. FUZZY LOGIC CONTROLLER FOR THE HVAC SYSTEM

In residential buildings, HVAC systems are directly related to residents' thermal comfort. The operating time of HVAC systems cannot be altered however, their energy consumption can be controlled within a certain range. In this paper, we have taken our fuzzy logic controller for the HVAC system (FLC_{h1}) which was previously proposed in [33]. In this study, simulations are performed considering a 10kW HVAC system based with thermostat as control unit. Proposed (FLC_{h1}) considers the relation between humidity and temperature to initialize thermostat setpoints (T_{sp}). Ain *et al.* [33] proposed the FLC which guarantees the user thermal comfort along with energy consumption minimization however, their study does not consider the visual comfort and productivity. It takes input parameters of outdoor temperature ($Temp_{out}$), indoor temperature ($Temp_{in}$), Time-of-Use electricity pricing ($Price_{ToU}$), user's occupancy ($User_{Occ}$), thermostat setpoints (T_{sp}), and relative humidity ($Humidity_{rel}$). It can be observed that the input parameters of our proposed FLC_{h1} have a direct influence on thermal comfort and energy consumption. In general, when the outdoor temperature very hot or cold, maintaining the indoor temperature according to thermal comfort becomes very difficult. These variations impact the thermostat setpoints (T_{sp}) initialization in addition to the occupants' presence and electricity price imposed by the electric utility.

Real-time variation in environmental variables like temperature, humidity, and status of occupancy is measure using sensors installed in the building. In this paper, HVAC simulations were performed considering sunny days where outdoor temperature ranges from 25–50°C. Similarly, variation in the electricity tariff and thermostat setpoint (T_{sp}) is communicated to FLC via the smart meter and thermostat, respectively. The output of the FLC_{h1} controls the amount of energy consumed using the HVAC system (EC_{HVAC}). In this paper, the input parameters of the outdoor temperature, indoor temperature, relative humidity, and thermostat setpoints are defined as trapezoidal membership functions as their linguistic variables cover a range of universe discourse [33]. The input parameters of occupancy and electricity tariff are defined as shown in Figure 5.

The total number of rules defined in the rule base of FIS is based on the combinatorics method. The antecedent pairs of the first IF-THEN rule comprise the first combination of the linguistic variables from input parameters. Similarly, the antecedent pair of the last IF-THEN rule is defined using the last combination of linguistic variables of the input parameters of the fuzzy logic system. The consequent pair of the IF-THEN rule is decided intelligently by considering the specific combination of antecedent pairs as discussed in [33]. Following the number of linguistic variables for every input parameter results in 486 combinations, hence resulting in a total of 486 fuzzy rules being defined in the rule base.

The defuzzified value of the energy consumed controlled using the FLC_h is used to control the energy consumed by HVAC (e_h) at the time any time interval t. The total energy consumed by the HVAC system (E_h) while using our proposed FLC_{h1} for 24 hours is calculated using Equation 11.

$$E_h = \sum_{t=1}^{24} e_h(t). \tag{11}$$

Amount of the electricity charges $cost_h$ to pay corresponding to energy consumed by HVAC at time interval t is computed as follows:

$$cost_h(t) = e_h(t) \times Price_{ToU}(t). \tag{12}$$

The total cost incurred ($cost_H$) over the span of 24 hours while using the HVAC system is calculated as follows:

$$cost_H = \sum_{t=1}^{24} cost_h(t). \tag{13}$$

D. EVALUATION OF QUALITY OF EXPERIENCE

Different environmental and physiological factors impacting visual and thermal comfort are monitored to evaluate the QoE inside smart home. Due to the complex nature of comfort indexes, comfort standards are used to assess the users' visual and thermal comfort. In this paper, we have used EN-12665 [34] and ASHRAE - 55 [35] standards to evaluate the QoE which are described below.

1) Users' Visual Comfort

   Visual comfort is the individual-based condition of visual well-being mainly because of darkness that creates discomfort. Visual comfort is mainly dependent on the following factors: glare, amount of light, quality of light in rendering, uniformity of light, and visual comfort indices. A systematic review of the long-term indices is done in [36] to characterize the relationship between the user and visual environment. It is however, observed that the factors considered while evaluating the occupants' visual comfort are very difficult to monitor. To evaluate the users' comfort on time, there is a need for a visual comfort index that can be measured easily. The value of the illuminance is a quantity that can be measured easily using a light sensor or by a smartphone with an illuminance measurement application. The illuminance is a physical quantity measured in *lux* that represents the ratio between the illumination flux incident to the surface and the area of that surface. The variation in the outside illumination is shown in Figure 6 where the illuminance value is divided into day time and night time [37].

   Initially, the visual comfort of the occupants is considered as 250 lux [32], however, nowadays European standard EN-12665 [34] is used by most countries. According to the recent visual standards, 500 lux is recommended for the activities like study, office work, PC work, and kitchen work inside a building [38]. In this paper, we have proposed the FLC for the lighting system considering both old and new standards, however, the emphasis is placed on the setting of illuminance setpoints (I_{sp}) considering 500 lux as a comfort standard to increase productivity. If the lighting level is below the recommended illuminance value it can result in eyestrain which will affect the well-being of the occupants. Living in this less comfortable environment will eventually leads to the decrease in productivity.

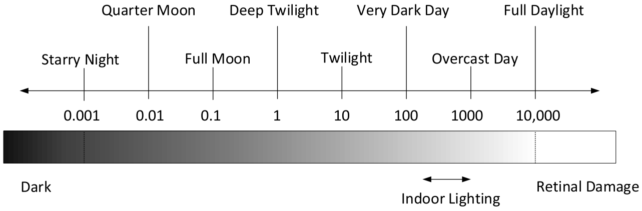


FIGURE 6. Variation in outdoor illuminance.

2) Users' Thermal Comfort

   Thermal comfort is the human expression of satisfaction with the thermal environment. Human thermal comfort is dependent on various environmental factors and physiological factors. Environmental factors include 1) air temperature, 2) air motion, 3) relative humidity, 4) mean radiant temperature, while physiological factors consist of 5) clothing and 6) the metabolic rate of the people. Rational thermal methods, like predicted mean vote (PMV) and predicted percentage of dissatisfied (PDD), are the thermal comfort models used for the evaluation of the HVAC system. The calculation of PMV and PDD consists of several equations and factors required to predict the percentage of users that will show dissatisfaction with thermal conditions. The equations used for PMV and PDD are complex and require the computer to process. Furthermore, a large-scale setup is required to monitor the factors like metabolic rate which not only hinders but also lengthen the process of the thermal comfort calculation.

   In this paper, we have used the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard - 55 [35] for the evaluation of the user's thermal comfort. According to the ASHRAE standard, there is exists a thermal comfort zone defined with the help of temperature and relative humidity. Generally, it can be observed that the variations in the combination of both temperature and humidity can lead to the difference in thermal sensations. Exploiting the relationship of temperature and relative allows flexibility in the initialization of the thermostat setpoint (T_{sp}) that not only ensures thermal comfort but also results in energy savings.

E. PERFORMANCE PARAMETERS FOR MODEL EVALUATION

In addition to the users' comfort, energy consumption, and cost incurred, our proposed FLC for HVAC and lighting system is also evaluated in terms of PAR and efficiency gain. Formulation of these performance parameters is discussed as follows:

1) Peak-to-Average Ratio (PAR) The peak-to-average ratio is defined as the load value of the highest instantaneous load ($Peak_{load}$) compared to the average load value ($Average_{load}$). PAR is used to examine the even distribution of load over time as a large value of PAR represents fluctuations to a very large value. PAR is calculated using the formula below:

$$PAR(load_t) = \frac{Peak_{load}}{Average_{load}}. \tag{14}$$

2) Efficiency Gain The efficiency gain (η) of our proposed EMC ($e_{proposed}$) as compared to the previously proposed EMC ($e_{earlier}$) is calculated using Equation 15 shown below. The positive value of η shows an increase in efficiency and improved performance of the proposed EMC when compared with earlier EMCs in the literature. On the other hand, the negative value of η shows less efficiency and a decline in performance.

$$\eta = \frac{e_{earlier} - e_{proposed}}{e_{earlier}} \times 100. \tag{15}$$

IV. THEORETICAL EVALUATION USING FUZZY SYNTHESIS

In most of the recent studies, performance evaluation of the proposed system is conducted quantitatively. However, it becomes difficult with the performance parameters that are based on the subjective evaluation like user comfort and productivity of occupants. Users' comfort and productivity is a non-numeric element where fuzziness arises because of the linguistic variables without clear boundaries. The fuzzy synthesis is performed to aggregate the numeric or non-numeric terms for evaluation. Fuzzy synthetic evaluation uses terms in natural languages as compared to numerical evaluation. In order to formalize the fuzzy synthetic evaluation, consider X be a universe of performance parameters or factors defined as follows: $X = \{x_1,x_2,\ldots,x_n\}$ Furthermore, take Y be the universe of evaluations performed corresponding to factors where $Y = \{y_1,y_2,\ldots,y_m\}$. Let $\underset{\sim}{R} = [r_ij]$ be the fuzzy relationship between pairs of factors and evaluations, where $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$. For the evaluation of a particular technique, a set of "scores" (w_i) for each of the n performance parameters arranged as a fuzzy vector $\mathbf{w}$ is defined for each factor x_i.

$$\underset{\sim}{\mathbf{w}} = \{w_1, w_2, \ldots, w_n\}, \quad where \sum_i w_i = 1. \tag{16}$$

The process of evaluation for the performance parameters is implemented through the composition operation as follows:

$$\underset{\sim}{\mathbf{e}} = \underset{\sim}{\mathbf{w}} \circ \underset{\sim}{R}, \tag{17}$$

where $\underset{\sim}{\mathbf{e}}$ is a fuzzy vector containing the membership values for each of the performance evaluation categories. In our case, performance evaluation of the two cases considering 250 lux and 500 lux as the standard is based on user comfort (UC), increase in productivity (PD), energy consumption (EC) and cost reduction ($). After defining the criteria for performance, evaluations are categorized as Excellent (e), Best (b), Adequate (a) and Worst (w). "Excellent" represents the category where a certain EMC is the best based on criteria used for evaluation. "Best" means the EMC can be categorized among the best concerning the criterion. "Adequate" shows that although the EMC is not the best, however, it meets the minimum acceptable criteria. In the last, "Worst" means that the EMC considered for comparison is unable to meet minimum acceptable criteria. In our case, the following relation has been assigned between performance factors and their corresponding criteria:

$$R = \begin{array}{cc} & \begin{array}{cccc} e & b & a & w \end{array} \\ & \begin{bmatrix} 0.2 & 0.6 & 0.2 & 0.0 \\ 0.4 & 0.3 & 0.2 & 0.1 \\ 0.0 & 0.5 & 0.4 & 0.1 \\ 0.0 & 0.4 & 0.6 & 0.2 \end{bmatrix} & \begin{array}{c} UC \\ PD \\ EC \\ \$ \end{array} \end{array}.$$

While evaluating the proposed lighting control methodologies, scoring factor for controller with 250 lux standard and 500 lux defined is as follows:

$$\underset{\sim 250}{\mathbf{w}} = \begin{bmatrix} 0.2 & 0.4 & 0.3 & 0.1 \end{bmatrix},$$
$$\underset{\sim 500}{\mathbf{w}} = \begin{bmatrix} 0.4 & 0.2 & 0.1 & 0.3 \end{bmatrix}.$$

Following the max-min composition method for evaluation results in $\underset{\sim 250}{\mathbf{e}} = \begin{bmatrix} 0.2\ 0.4\ 0.6\ 0.2 \end{bmatrix}$, having highest membership in the "Adequate" category. This describes the energy management controller proposed for HVAC and lighting system with 250 lux as visual comfort standard can meet the minimum requirements of comfort maintenance and energy consumption minimization. However, the composition $\underset{\sim 500}{\mathbf{e}} = \begin{bmatrix} 0.3\ 0.4\ 0.2\ 0.2 \end{bmatrix}$ shows that energy management controller while considering 500 lux as visual comfort standard lies in "Best" category. Hence it can be said that for current situation, it is advisable to use fuzzy logic controller with 500 lux as optimal illuminance setpoint making it one of the best methodologies available for user comfort maintenance and energy consumption reduction.

V. SIMULATION RESULTS

In this section, simulation results of the proposed fuzzy controller for the residential lighting system are discussed. All the implementation and simulations of this study were carried out on an Intel(R) Core(TM) i7-6500U CPU @2.50GHz with MATLAB R2015a installed on it. MATLAB simulations using 13-Watt LED bulbs installed in a medium-size family room with size 14' × 20' of a smart home are performed. Energy consumption is computed by dividing simulations

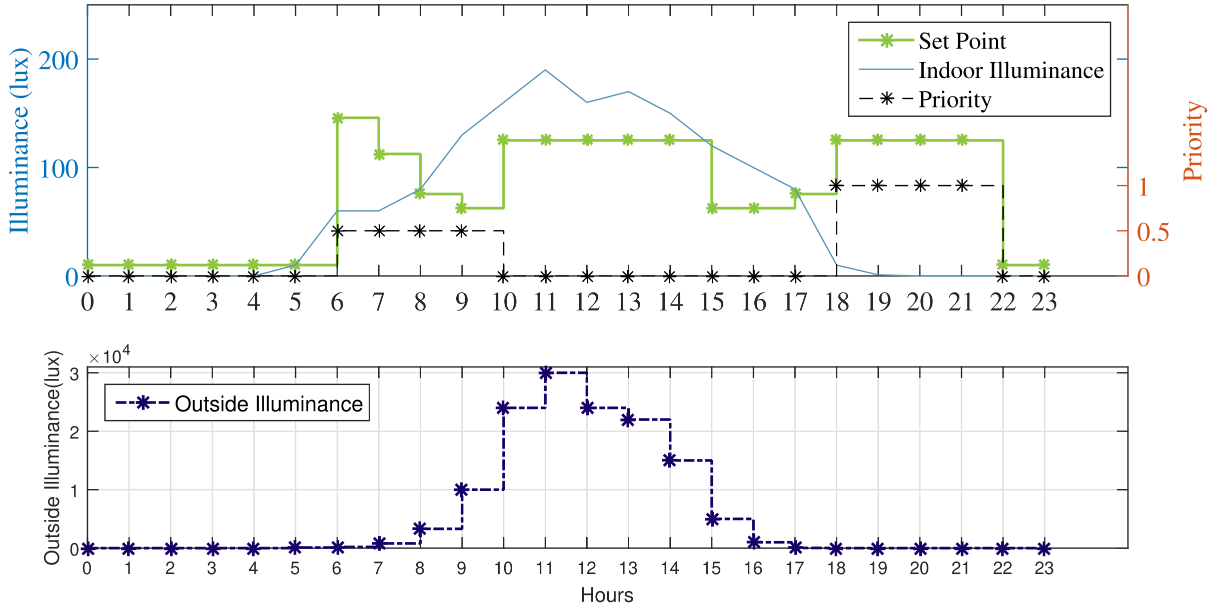


FIGURE 7. Variation of outdoor illuminance, indoor illuminance, priority and illuminance setpoints.

into two cases: Case I shows the simulations when the illuminance setpoint range for visual comfort is considered from 0 lux to 250 lux for optimal value selection. Case II is considered to incorporate the change in visual standards recently, where 500 lux is recommended for the office work, study, and kitchen activities.

The proposed technique is compared with the three energy management techniques. The first method considered is without controller i.e., a fixed setpoint of 250 lux is maintained using the LED lighting system installed in the family room. In this method, the illuminance setpoint of 250 lux will be maintained 24 hours except when the residents of the home are sleeping. The second method considered is a fuzzy logic controller that considers the real-time variation in outdoor and indoor light using sensors and output of the controller is required illumination of the lighting system [32]. For the rest of the text, this method will be referred to as "Model A". The third method used for the evaluation and comparison of the proposed fuzzy logic controller considers occupancy and electricity prices in addition to outdoor and indoor lighting for the selection of the illuminance setpoint in autonomous mode [21]. In this article, "Model B" will be used when discussing the simulation results using fuzzy controller proposed in [21]. Simulation results are numerically evaluated based on total energy consumed, cost incurred, PAR, and efficiency achieved by these energy management controllers.

A. SIMULATIONS FOR CASE I: LIGHTING CONTROLLER WITH 250 LUX STANDARD

Performance of purposed fuzzy logic controller in Case I is evaluated considering the visual comfort standard up to 250 lux of illuminance [21]. As shown in Figure 7, starting from midnight 00:00 hrs. till 05:00 hrs., the outdoor illumination is below 100 lux. Furthermore, the status of the occupants is "Sleep" due to which the minimum value of illuminance is decided by the controller.

After 05:00 hrs. residents of the home wake up and start doing morning activities. Outdoor illuminance is increasing, and the user-defined priority is now set to "Medium". At 06:00 hrs. electricity price is charged according to the off-peak hours' tariff. Taking this information into consideration controller decides to set the initialized setpoint highest around 145 lux according to user activity. From 07:00 hrs. onward high-peak hours start, where the proposed fuzzy logic controller decides the optimal value of required illuminance around 112 lux so that it does increase the electricity consumption cost. From 09:00 hrs. onwards the user-defined priority reaches "Low", considering the real-time information proposed fuzzy logic controller maintains the illuminance setpoint around 125 lux. After 17:00 hrs., most of the residents are present inside the residential building and are performing activities requiring high illuminance. However, these are the hours when the electric utility charges the electricity consumed according to the high-peak tariff. In this case, our proposed fuzzy logic controller considers both user's priority and electricity tariff to decide the targeted value of illuminance which will not increase the energy consumption and hence resulting in electricity bill reduction without disturbing the visual comfort of occupants.

1) Energy Consumption in a Day
   Considering the scenario and input values of the fuzzy logic controller, energy consumed in a day by the proposed technique is compared with three other methods. As Figure 8 shows, energy consumed with a fixed setpoint is more as compared to the rest of the methods considered. The maximum amount of energy

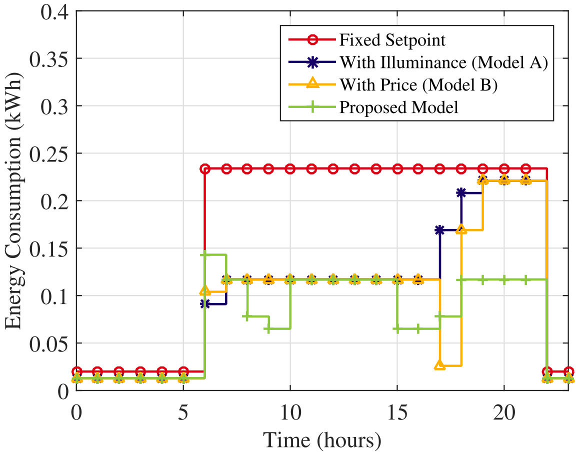


FIGURE 8. **Amount of energy consumed in a day.**

consumed using the fixed setpoint method in a day is 0.23 kWh. In the case of maintaining a fixed setpoint, the total energy consumed in a day is 3.90 kWh. Model A and Model B considered for the comparison almost perform similarly where the maximum amount of energy being consumed by both is 0.22 kWh. However, the total energy consumed in a day by Model A and Model B is 2.40 kWh and 2.23 kWh, respectively. Simulation results also show the effect of electricity price on energy consumption. The difference in energy consumption arises as the fuzzy logic controllers considered for comparison take electricity tariff as a deciding parameter for setting the illuminance setpoints.

As shown in Figure 8, energy consumed by Model B is less at time 17:00 hrs. and 18:00 hrs. which are the peak hours. Model B starts considering the electricity price when deciding the illuminance setpoints autonomously, which results in less energy consumption as compared to Model A which is only considering outdoor and indoor illuminance. An additional parameter of the user's priority is added in the proposed fuzzy logic controller. Simulation results presented in Figure 8, show the variation in energy consumption by the addition of the user's priority. The timestamp of 06:00 hrs. is classified as off-peak hours and the priority is set to "Medium" by the electricity consumers for instance. The proposed controller initializes the setpoint to 145 lux which is much higher as compared to the Model A and Model B where the illuminance setpoint is initialized as 96 lux and 98 lux, respectively. Hence shows that the proposed controller has more potential of maintaining the users' visual comfort when compared to the rest of the techniques. Another effect of user priority combined with electricity tariff is shown at the time 17:00 hrs. when the priority is "Low", and the price is charged according to the high-peak tariff. The illuminance setpoint initialized by the proposed model is 75 lux which is higher than Model B i.e., 21 lux, and lower than Model A i.e., 168 lux. Simulation details show that the proposed fuzzy logic controller maintains an intricate balance between the user's priority and electricity tariff when deciding the illuminance setpoints. The maximum amount of energy consumed using the proposed lighting control system is 0.14 kWh and the total energy consumed in a day is 1.76 kWh.

2) Energy Consumption in a Month

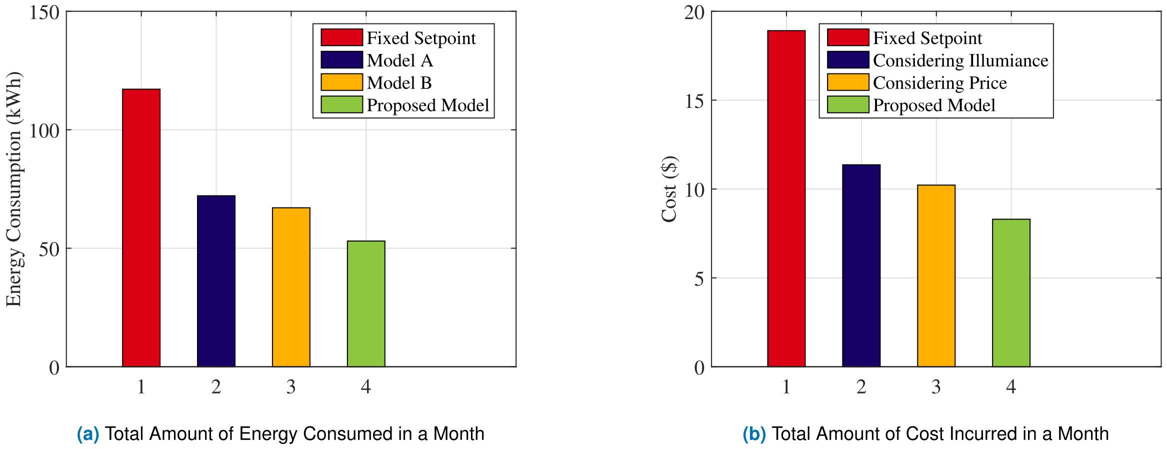
Total energy consumed in a month using the proposed fuzzy logic controller and the other techniques for comparison is shown in Figure 9a. The total energy consumed using the fixed setpoint approach is 117 kWh. Energy consumed using a fixed setpoint is highest because light illuminance is set to 250 lux all the time regardless of user priority, electricity price, and daylight effect. Model A ranks second in terms of energy consumption by consuming 72 kWh of the energy as it considers both indoor and outdoor illuminance while deciding the illuminance setpoint in real-time. Model B shows the variation in energy consumption when input parameters of outdoor light, indoor lighting, user occupancy, and electricity prices combined are considered. Results show that Model B performs better in achieving the objective of demand response by reducing the total amount of energy consumed to 67 kWh. However, this energy minimization is achieved at the cost of sacrificing the users' visual comfort. Our proposed method of fuzzy logic controller considers the user's priority as an addition to maintaining visual comfort and reduces the total energy consumed in a month to 53 kWh. Result analysis of the energy consumption shows that the proposed fuzzy logic controller is 26% more efficient as compared to Model A which considers only outdoor and indoor light. Similarly, it can be observed that the proposed model by considering the user's priority as an input parameter is 20% more efficient in energy consumption reduction as compared to Model B. The values of energy consumed using proposed FLC are shown in Table 3.

TABLE 3. **Comparison of energy consumption for Case I.**

	Per Day (kWh)	Per Month (kWh)
Fixed Setpoint	3.90	117
Model A [32]	2.40	72
Model B [21]	2.23	67
Proposed Model	1.76	53

3) Analysis of Electricity Cost Incurred

One of the incentives of the demand response program that persuade energy consumers to change the electricity consumption pattern is the reduction in the total cost of electricity being used. The total amount of cost incurred in a day is compared using above mentioned methodologies for comparison. The total



(a) Total Amount of Energy Consumed in a Month

(b) Total Amount of Cost Incurred in a Month

FIGURE 9. **Simulation result over the span of one month for Case I.**

TABLE 4. **Comparison of cost incurred for Case I.**

	Per Day ($)	Per Month ($)
Fixed Setpoint	0.63	18
Model A [32]	0.37	11
Model B [21]	0.34	10
Proposed Model	0.27	08

TABLE 5. **Comparison of energy consumption & cost incurred using LEDs in a month.**

	Energy Consumption (kWh)	Cost ($)
Fixed Setpoint	229	37
Model A [32]	136	22
Model B [21]	130	20
Proposed Model	100	15

amount of cost is calculated by multiplying the amount of energy consumed in a particular hour by the rate specific to those hours. The cost incurred using fixed point of illuminance for the whole day is $0.63 whereas the total cost of electricity consumed in a day for Model A, Model B, and the proposed fuzzy controller is $0.37, $0.34, and $0.27, respectively. Simulation results clearly show that the amount of bill for a month using the proposed fuzzy controller is less as compared to the other techniques considered for comparison. The monthly cost incurred using the proposed fuzzy logic controller, Model B, Model A, and fixed setpoint method is $08, $10, $11, and $18, respectively. The proposed fuzzy logic controller considering outdoor illuminance, indoor illuminance, occupancy, electricity price, and priority helps in demand response by initializing the maximum illuminance setpoints during off-peak hours when electricity charges are low and reduce the illuminance setpoint to optimal value when operating during high-peak hours. Hence, reducing the total cost of electricity consumption. Summary of the electricity bill for one day and one month using fixed setpoint control, Model A, Model B, and our proposed controller is summarized in Table 4.

4) Comparison of PAR

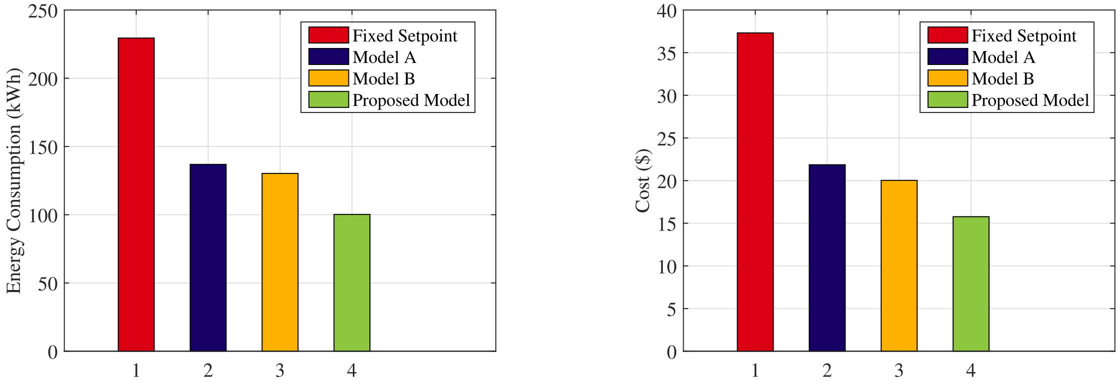
The process of shifting most of the home appliances to off-peak hours to avoid load peak during high-peak hours often leads to system instability and an increase in peak-to-average ratio. As the proposed method often utilizes the off-peak hours for maximum energy consumption by setting the highest possible illuminance setpoint, it is evaluated and compared with other methods in terms of PAR as well. Values of PAR computed for Model A, Model B, and the proposed model is 2.2, 2.4, 1.9, respectively. The proposed fuzzy logic controller for the lighting system outperforms in terms of PAR and is 14%, and 20% more efficient than Model A and Model B, respectively. Values of PAR show that our proposed fuzzy logic controller can balance the load distribution without drastically disturbing the visual comfort along with energy efficiency.

B. SIMULATIONS FOR CASE II: LIGHTING CONTROLLER WITH 500 LUX STANDARD

According to earlier standards, for normal activities, the lighting illumination range was recommended between 100–300 lux. Due to COVID-19 situations mostly educational institutes have shifted to distance learning mode and organizations are emphasizing their employees to work from home which leads to additional electricity usage. Nowadays, the illuminance level of up to 500 lux is recommended to perform the normal PC work, office work, for the kitchen and study area. In this section, the simulations of our proposed FLC when initialization of setpoints is between 0–500 lux are discussed.

1) Analysis of Energy Consumption

Simulation for one month is studied to compare the energy consumption between the proposed model when the LED lighting system is installed in the room. The total amount of energy consumed in a day using a



(a) Amount of Energy Consumption in a Month

(b) Amount of Cost Incurred in a Month

FIGURE 10. Simulation result over the span of one month for Case I.

fixed setpoint setting is 7.64 kWh. Similarly, daily energy consumed using Model A, Model B is 4.63 kWh and 4.34 kWh, respectively. In a day, a total amount of 3.34 kWh energy is consumed using the proposed fuzzy logic controller for the LED lighting system. Figure 10a shows the amount of energy for one month. Total energy consumed using fixed setpoint, Model A, Model B, and proposed controller in a month is calculated as 229 kWh, 136 kWh, 130 kWh, and 100 kWh, respectively. The efficiency gain of the proposed model when compared with fixed setpoint, Model A and Model B is computed as 56%, 27%, and 23%, respectively. In addition to this, when the performance of the proposed system is compared between the fluorescent bulb and LED bulb results in around 35% of efficiency.

2) Analysis of Electricity Cost Incurred
The total amount of bill incurred corresponding to the energy consumed in a month is shown in Figure 10b. Amount of bill charged when fixed illuminance setpoint of 500 lux is maintained regardless of the outdoor illuminance variation is $37. When outdoor illuminance variation is considered in Model A, total electricity charges in a month are $22. Similarly, when the fuzzy logic controller decides the illuminance setpoint while participating in demand response results in $20 of monthly electricity bill. Our proposed model FLC_{h1} considers the user's priority as one of the input parameters for decision making which results in $15 of the total monthly cost. Simulation results show an increase in efficiency by 58%, 28%, 21% when the proposed energy management controller is compared with the fixed setpoint, Model A and Model B, respectively. Cost of the system installation is not considered in this paper.

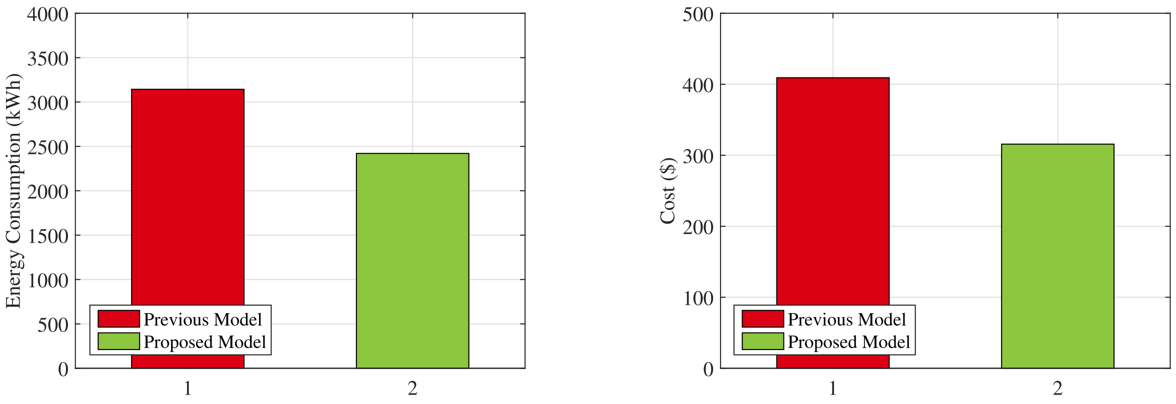
C. PERFORMANCE ANALYSIS OF LIGHTING PLUS HVAC CONTROLLERS

In this section, the combined performance of lighting and HVAC controllers by considering EN-12665 [34] and ASHRAE - 55 [35] standards is examined. The performance of our proposed controllers (FLC_{S1}) is compared with combined performance of controllers proposed in literature. The simulation results show that our proposed system improves the QoE in smart home which eventually increases users' productivity. without paying an extra cost.

1) Analysis of Energy Consumption
To evaluate the combined performance of our proposed fuzzy logic controller for HVAC (FLC_{h1}) and LED lighting (FLC_{l1}) taking 0–500 lux as visual comfort standard, it is compared with previous EMCs. The FLC of the HVAC system considered for comparison referred to as FLC_{h0}, consists of input parameters outdoor temperature, indoor temperature, occupancy, temperature setpoints, electricity prices. The lighting FLC which was previously proposed in [21] with input parameters of outdoor illuminance, indoor illuminance, occupancy, and electricity prices is selected for comparison. The lighting FLC proposed in [21] is denoted by FLC_{l0} for the rest of the text in this paper. Combined working of the previous EMCs for HVAC FLC_{h0} and lighting FLC_{l0} is denoted by (FLC_{S0}). The total amount of energy consumed (EC_{total}) using both controllers is calculated by adding the total energy consumed using HVAC (E_h) and lighting (E_l) controller which is as follows:

$$EC_{total} \approx E_h + E_l. \tag{18}$$

The maximum amount of energy consumed at one point of the day is 6.12 kWh by using the previously proposed fuzzy logic controllers working with the objective of energy consumption minimization. When compared to the proposed fuzzy controller, the highest amount of energy consumed at one hour of a day equal to 4.73 kWh. The cumulative amount of energy consumed in a day using previous fuzzy logic models is 105 kWh which is much higher as compared to our proposed fuzzy logic controller calculated as 81 kWh. Analysis of monthly energy consumption



(a) Monthly Energy Consumption

(b) Monthly Cost Incurred

FIGURE 11. Results for one month simulation of lighting plus HVAC controllers.

TABLE 6. Comparison of energy consumption.

	HVAC System	Lighting System
Previous Model	3000	129
Proposed Model	2310	99

shows a similar pattern where values calculated are 3143 kWh and 2420 kWh for the previous model and proposed model, respectively. Simulation results show that with the help of the proposed energy management controller, residential consumers can reduce 23% of total energy consumption as compared to the previous fuzzy logic controller. Analysis of PAR is performed which shows 0.7% improvement in the proposed fuzzy logic-based energy controller as compared to the previous controllers considered.

2) Analysis of Cost Incurred

Analysis of results for the cost incurred to the residential consumers shows improvement with the help of the proposed fuzzy logic controller. Setpoints for lighting and HVAC systems are intelligently initialized by the proposed controller that helps in cost reduction considering the TOU electricity tariff. The total cost incurred ($Cost_{total}$) over a particular time duration using both HVAC and lighting controllers is calculated using following Equation 19. The total cost incurred by the energy consumed under controllers consists of the total electricity charges of using HVAC ($Cost_h$) and lighting ($Cost_l$) system and miscellaneous charges (ϵ). However, it is to be noted that the total cost is calculated using HVAC and lighting system without considering the expenditures from miscellaneous sources.

$$Cost_{total} = Cost_h + Cost_l + \epsilon. \tag{19}$$

The total amount of the price calculated for the energy usage in a day is \$14 and \$11 for previous techniques and proposed model, respectively. The total amount of electricity bill calculated at the end of the month using the previous fuzzy logic controller is \$409 whereas the total cost computed using the proposed fuzzy logic controller at the end of the month is \$315. Analysis of the simulations in terms of monthly cost incurred shows 23% of improvement that helps in achieving the objective of cost reduction without jeopardizing the user comfort.

D. DISCUSSION

Analysis of the energy consumption by varying the visual comfort standard from 250 lux to 500 lux for LED lighting system in combination with the HVAC system is also performed. Simulation results show the interesting observation of a slight difference in the aggregated energy consumption by varying the visual comfort standard. In the case of energy consumed in a day, the maximum value recorded for the proposed HVAC plus lighting controller considering 250 lux as standard is 4.61 kWh. The maximum value of energy consumed using the HVAC along with the light controller by considering 500 lux as standard is 4.73 kWh. Total energy consumed in a day using a combination of HVAC controller proposed in [33] and LED lighting controller with 250 lux and 500 lux is 79 kWh and 80 kWh, respectively. Similarly, monthly consumption calculated by controlling the energy using 250 lux and 500 lux is 2373 kWh and 2420 kWh, respectively. The total amount of the bill corresponding to energy consumption in a month using an HVAC controller considering the humidity parameter and proposed lighting energy controller with 250 lux as standard for visual comfort is \$308. Similarly, the monthly cost using the HVAC controller in combination with our proposed lighting energy management system considering the 500 lux as user visual comfort standard is calculated as \$315. Results of the simulations show that considering the nowadays COVID-19 situation, an increase in the visual comfort can be achieved using our proposed lighting controller in combination with

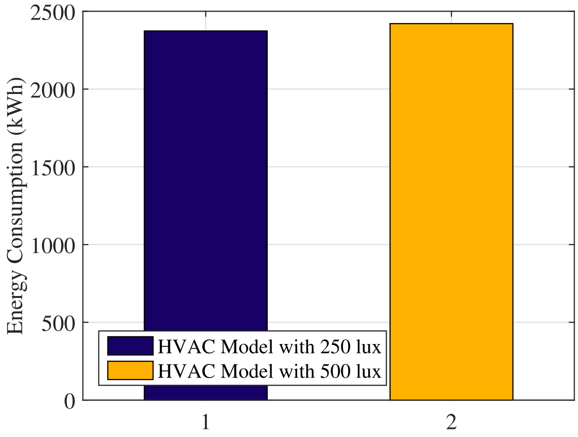


FIGURE 12. Comparison of HVAC energy management controller with lighting controller by varying the visual comfort standard.

the HVAC controller proposed in [33]. A comparison of both simulations shows a very little increase in the total energy consumption and cost incurred. Overall, the total energy consumption when using 500 lux as visual comfort standard is only 2% greater than the energy consumed using the combination of the HVAC controller with the fuzzy logic controller proposed for the lighting system where the output ranges to set the illuminance setpoints up to 500 lux. Hence proposed approach of energy management helps residential energy consumers to set the illuminance setpoints according to the new standard of visual comfort i.e., 500 lux with having much increase in energy consumption, cost incurred, and PAR.

Simulation results of energy consumption show a minute increase when FLC_{S1} considering the range of 0–500 lux as compared to the FLC_{S0} model with 0–250 lux as illuminance range. This minute difference in energy consumption can easily be overcome using glazing. In glazing, the glass component of the building can be tinted to increase energy efficiency.

VI. CONCLUSION

The integration of IoT in CPIS such as smart home shows great benefits of effective decision making and increase in efficiency of the infrastructure. In this paper, we proposed a fuzzy logic-based lighting controller working inside a smart home for the optimal setting of the illuminance set points. One of the novelties of this paper is to utilize the energy saved from the HVAC, without compromising the user comfort, for improved illuminance. This increase in visual comfort helps to improve the productivity of the residents. Based on the idea proposed in this paper, future researchers may focus on the improvement of the workplace environment, instead of merely saving the money. Benefits of this research is to achieve better working conditions without spending extra money and consuming extra energy. Limitation is not considering the very small amount of extra heat produced by the LED bulbs. In the future, the proposed system can also be made adaptive which learns from the user's preferences. More parameters that affect the users' decision of the set point initialization can be considered for future research in improving the smart homes.

REFERENCES

[1] *Energy Efficiency Trends in Canada*, Office Energy Efficiency, Natural Resour. Canada, Calgary, AB, Canada, 2012.

[2] J. Conti, P. Holtberg, J. Beamon, A. Schaal, G. Sweetnam, and A. Kydes, "Annual energy outlook with projections to 2035," U.S. Energy Inf. Admin., Washington, DC, USA, Tech. Rep. DOE/EIA-0383(2010), Apr. 2010.

[3] *Household Energy Consumption and Expenditures, Consumption By End Use*, Energy Inf. Admin., Washington, DC, USA, 2010.

[4] M. H. Albadi and E. F. El-Saadany, "A summary of demand response in electricity markets," *Electr. Power Syst. Res.*, vol. 78, no. 11, pp. 1989–1996, 2008.

[5] M. Rasheed, N. Javaid, M. Awais, Z. Khan, U. Qasim, N. Alrajeh, Z. Iqbal, and Q. Javaid, "Real time information based energy management using customer preferences and dynamic pricing in smart homes," *Energies*, vol. 9, no. 7, p. 542, Jul. 2016.

[6] M. Li, G.-Y. Li, H.-R. Chen, and C.-W. Jiang, "QoE-aware smart home energy management considering renewables and electric vehicles," *Energies*, vol. 11, no. 9, p. 2304, Sep. 2018.

[7] H. M. Hussain, N. Javaid, S. Iqbal, Q. U. Hasan, K. Aurangzeb, and M. Alhussein, "An efficient demand side management system with a new optimized home energy management controller in smart grid," *Energies*, vol. 11, no. 1, p. 190, Jan. 2018.

[8] Z. Nadeem, N. Javaid, A. Malik, and S. Iqbal, "Scheduling appliances with GA, TLBO, FA, OSR and their hybrids using chance constrained optimization for smart homes," *Energies*, vol. 11, no. 4, p. 888, Apr. 2018.

[9] N. Javaid, A. Ahmed, S. Iqbal, and M. Ashraf, "Day ahead real time pricing and critical peak pricing based power scheduling for smart homes with different duty cycles," *Energies*, vol. 11, no. 6, p. 1464, Jun. 2018.

[10] N. H. Motlagh, M. Mohammadrezaei, J. Hunt, and B. Zakeri, "Internet of Things (IoT) and the energy sector," *Energies*, vol. 13, no. 2, p. 494, Jan. 2020.

[11] H. Soewardi, A. Dila, and P. Rizkiningtias, "Development of working environment comfort to improve productivity," in *Proc. IEEE Int. Conf. Knowl. Eng. Appl. (ICKEA)*, Sep. 2016, pp. 177–180.

[12] C. D. Korkas, S. Baldi, I. Michailidis, and E. B. Kosmatopoulos, "Occupancy-based demand response and thermal comfort optimization in microgrids with renewable energy sources and energy storage," *Appl. Energy*, vol. 163, pp. 93–104, Feb. 2016.

[13] S. Baldi, C. D. Korkas, M. Lv, and E. B. Kosmatopoulos, "Automating occupant-building interaction via smart zoning of thermostatic loads: A switched self-tuning approach," *Appl. Energy*, vol. 231, pp. 1246–1258, Dec. 2018.

[14] C. D. Korkas, S. Baldi, and E. B. Kosmatopoulos, "Grid-connected microgrids: Demand management via distributed control and human-in-the-loop optimization," in *Advances in Renewable Energies and Power Technologies*, vol. 2. Amsterdam, The Netherlands: Elsevier, 2018, pp. 315–344.

[15] A. Keshtkar and S. Arzanpour, "An adaptive fuzzy logic system for residential energy management in smart grid environments," *Appl. Energy*, vol. 186, pp. 68–81, Jan. 2017.

[16] J. Liu, W. Zhang, X. Chu, and Y. Liu, "Fuzzy logic controller for energy savings in a smart LED lighting system considering lighting comfort and daylight," *Energy Buildings*, vol. 127, pp. 95–104, Sep. 2016.

[17] J.-M. Wang, M.-T. Yang, and P.-L. Chen, "Design and implementation of an intelligent windowsill system using smart handheld device and fuzzy microcontroller," *Sensors*, vol. 17, no. 4, p. 830, Apr. 2017.

[18] İ. Kıyak, B. Oral, and V. Topuz, "Smart indoor LED lighting design powered by hybrid renewable energy systems," *Energy Buildings*, vol. 148, pp. 342–347, Aug. 2017.

[19] M. Fayaz and D. H. Kim, "Energy consumption optimization and user comfort management in residential buildings using a bat algorithm and fuzzy logic," *Energies*, vol. 11, no. 1, p. 161, 2018.

[20] S. N. Altun, M. Dörterler, and I. A. Dogru, "Fuzzy logic based lighting system supported with IoT for renewable energy resources," in *Proc. Innov. Intell. Syst. Appl. Conf. (ASYU)*, Oct. 2018, pp. 1–4.

[21] R. Khalid, N. Javaid, M. H. Rahim, S. Aslam, and A. Sher, "Fuzzy energy management controller and scheduler for smart homes," *Sustain. Comput., Inform. Syst.*, vol. 21, pp. 103–118, Mar. 2019.
[22] X. Huang, S. Wei, and S. Zhu, "Study on daylighting optimization in the exhibition Halls of museums for Chinese calligraphy and painting works," *Energies*, vol. 13, no. 1, p. 240, 2020.
[23] A. Keshtkar and S. Arzanpour, "A fuzzy logic system for demand-side load management in residential buildings," in *Proc. IEEE 27th Can. Conf. Electr. Comput. Eng. (CCECE)*, Toronto, ON, Canada, May 2014, pp. 1–5.
[24] A. Keshtkar, S. Arzanpour, and F. Keshtkar, "An autonomous system via fuzzy logic for residential peak load management in smart grids," in *Proc. North Amer. Power Symp. (NAPS)*, Charlotte, NC, USA, Oct. 2015, pp. 1–6.
[25] A. Keshtkar, S. Arzanpour, F. Keshtkar, and P. Ahmadi, "Smart residential load reduction via fuzzy logic, wireless sensors, and smart grid incentives," *Energy Buildings*, vol. 104, pp. 165–180, Oct. 2015.
[26] S. Javaid, N. Javaid, S. Iqbal, and M. J. Mughal, "Controlling energy consumption with the world-wide adaptive thermostat using fuzzy inference system in smart grid," in *Proc. Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Oct. 2017, pp. 66–71.
[27] D. Kolokotsa, D. Tsiavos, G. Stavrakakis, K. Kalaitzakis, and E. Antonidakis, "Advanced fuzzy logic controllers design and evaluation for buildings' occupants thermal-visual comfort and indoor air quality satisfaction," *Energy Buildings*, vol. 33, no. 6, pp. 531–543, Jul. 2001.
[28] T. J. Ross, *Fuzzy Logic With Engineering Applications*, 3rd ed. Hoboken, NJ, USA: Wiley, 2009.
[29] S. Iqbal and N. Boumela, *Fuzzy Controllers: Recent Advances in Theory and Applications*. Norderstedt, Germany: BoD-Books on Demand, 2012.
[30] Hydro One Limited. *Rates & Charges*. Accessed: Jan. 31, 2021. [Online]. Available: https://www.hydroone.com/rates-and-billing/rates-and-charges/customer-choice
[31] A. Hartoyo and S. D. Panjaitan, "Development of automation system for room lighting based on fuzzy logic controller," *Int. J. Inf. Electron. Eng.*, vol. 2, no. 6, pp. 1–5, 2012.
[32] S. D. Panjaitan and A. Hartoyo, "A lighting control system in buildings based on fuzzy logic," *Telkmnika*, vol. 9, no. 3, pp. 423–432, 2013.
[33] Q.-U. Ain, S. Iqbal, S. A. Khan, A. W. Malik, I. Ahmad, and N. Javaid, "IoT operating system based fuzzy inference system for home energy management system in smart buildings," *Sensors*, vol. 18, no. 9, p. 2802, 2018.
[34] *EN 12665, Lihgt and Lighting—Basic Terms and Crieria for Specifying Lighting Requirements*, Eur. Committee Standardization, Brussels, Belgium, 2011.
[35] *Thermal Environmental Conditions for Human Occupancy*, Standard 55, American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, NY, USA, 2013.
[36] S. Carlucci, F. Causone, F. De Rosa, and L. Pagliano, "A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design," *Renew. Sustain. Energy Rev.*, vol. 47, pp. 1016–1033, Jul. 2015.
[37] 2M CCTV LUX. *LUX Light Ratings*. Accessed: Jan. 31, 2021. [Online]. Available: https://www.2mcctv.com/blog/2011_09_15-cctv-lux-light-ratings/
[38] The Engineering Toolbox. *Illuminance—Recommended Light Level*. Accessed: Jan. 31, 2021. [Online]. Available: https://www.engineeringtoolbox.com/light-level-rooms-d_708.html

QURAT-UL AIN received the M.S. degree in computer science from the National University of Sciences and Technology (NUST), Islamabad, Pakistan, where she is currently pursuing the Ph.D. degree in computer science under the supervision of Dr. S. Iqbal. Her research interests include smart grid, energy management, fuzzy controller, and data analytics.

SOHAIL IQBAL received the M.Sc. and M.Phil. degrees in mathematics from Quaid-i-Azam University, Pakistan, in 2002 and 2004, respectively, and the Ph.D. degree in surgical robotics from the University of Paris-Est, France, in 2010. He was a Scientific Advisor with the French Ministry of Higher Education, from 2008 to 2010. He is currently an Associate Professor with the National University of Sciences and Technology, Islamabad. His main research interests include apply mathematical techniques to different areas of computer science and engineering with special focus on robot modeling, energy management, and fuzzy controllers.

HAMID MUKHTAR received the Ph.D. degree in computer science from Telecom SudParis, France, in 2009. He was a Visiting Scientist with Telecom SubParis, in 2013. He is currently an Associate Professor with Taif University, Saudi Arabia. His research interests include ubiquitous computing, user modeling, and machine learning.

• • •