Article

Human Comfort-Based-Home Energy Management for Demand Response Participation

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Abstract: The residential building sector is encouraged to participate in demand response (DR) programs owing to its flexible and effective energy resources during peak hours with the help of a home energy management system (HEMS). Although the HEMS contributes to reducing energy consumption of the building and the participation of occupants in energy saving programs, unwanted interruptions and strict guidance from the system cause inconvenience to the occupants further leading to their limited participation in the DR programs. This paper presents a human comfort-based control approach for home energy management to promote the DR participation of households. Heating and lighting systems were chosen to be controlled by human comfort factors such as thermal comfort and visual comfort. Case studies were conducted to validate the proposed approach. The results showed that the proposed approach could effectively reduce the energy consumption during the DR period and improve the occupants’ comfort.

Keywords: home energy management system; human comfort factor; thermal comfort; visual comfort; demand response

1. Introduction

A building energy management system (BEMS) measures, analyzes, reports, and optimizes the demand and supply of energy in a building for saving its energy and cost, and for realizing the occupant’s comfort [1]. As the BEMS can globally control the demand and supply of energy inside a building, it should be installed in green energy buildings to balance their energy generation and consumption. The BEMS can be integrated into both residential and non-residential buildings by focusing on the energy-saving potentials of these buildings [2].

Moreover, the BEMS can generate the profile of demand resources of the buildings for realizing their participation in demand response (DR) programs. The demand resources in DR programs are proactive resources that are assured by modifying the energy consumption pattern of occupants in the buildings. The energy saving accomplished by the occupants is considered as a form of energy resource and is traded in power markets by load aggregators. The load aggregators need to collect a quantity of demand resources from individual DR participants and provide the individuals with benefits of energy savings and economic profits from power markets [3]. The power markets and utilities take advantage of demand resources by reducing energy production and operational costs of the grid, and by improving the reliability of power systems through demand resources [4].

In industrial and commercial buildings, several electricity customers have participated in the DR programs with the help of BEMS, and they followed fixed building control strategies. Most of the occupants of these buildings were the general public, and therefore, services were provided to them via BEMS operation. In other words, the occupants did not have any authority to control the building, and they generally accepted the hierarchical control schedule of the buildings via energy management systems. Therefore, the energy management of these buildings was relatively simple and effective.
for participating in DR programs. However, the fast cut-off in these buildings can cause malfunction, failure, or life-shortening of mechanical and electrical equipment and their installations [5,6].

In contrast, household-level occupants found it difficult to participate in DR programs due to several barriers such as lack of individual smart infrastructures, home energy management systems (HEMS) and smart meters to monitor and control their appliances, technical mismatches among systems, and their small energy resource quantity [3]. However, aggregated demand resources of households are still attractive to utility operators and load aggregators, as these resources are flexible and effective during peak hours [7,8]. Several researchers have investigated HEMS algorithm for DR participation [9–13]. They formulated optimization problems to minimize the electricity cost of the households [9–11], physical and operational constraints of appliances [12], and the cost of energy and thermal discomfort [13]. These investigations focused on the generation of appropriate input scenarios for the households and their load scheduling.

Even though these algorithms allow the household occupants to participate in DR programs owing to the advanced logic and reasonable scheduling of households, it is not easy for them to allow unidirectional and formulated energy management. For example, a unidirectional HEMS oriented to the reduction of energy consumption causes inconvenience to occupants via unwanted interruptions or strict guidelines on the usage of building sub-systems such as washing machines, refrigerators, computers, rice cookers, electrical ovens, televisions, lighting fixtures, and other home appliances. Further, the occupants at home tend to actively interact with their energy management system and with its connected systems. Therefore, it is important to develop a bi-directional HEMS which follows the occupants’ behavioural patterns and their preferences for the usage of appliances and equipment to reduce their fatigue [13,14]. As one of the methods to preserve the user’s comfort and to reduce the peak load and electricity bill at smart homes, control algorithms of home appliances, renewables, electric vehicles, and energy storage system based on the quality of experience (QoE) were presented for the HEMS [15,16]. Even though these investigations did not consider the DR programs, the proposed algorithms may further cover the DR programs.

More specifically, building environmental conditions such as indoor/outdoor temperature, meteorological and thermal response characteristics of the building, as well as the occupants’ preferences should be considered to control a heating, ventilation, and air-conditioning (HVAC) system. While the operational response characteristic of the HVAC system is faster, the thermal response of the building is slower due to its slower thermal dynamics. It is considered to be one of the advantages of using the HVAC system as an important demand resource. This means that switching on/off the HVAC system does not directly influence the thermal satisfaction of occupants and thus, they have a relatively smaller amount of risks to participate in DR programs and to reply to DR events by using HVAC loads. In addition, the acceptable operating range of HVAC systems contributes to large energy savings owing to their relatively larger power capacity than that of small appliances in buildings. However, despite its potentials as a demand resource, there are few studies on the HVAC system for DR programs in residential buildings, whereas considerable effort has been devoted to this system in industrial and commercial buildings [14,17,18].

Apart from the occupant’s thermal comfort, visual comfort was also considered as an important environmental issue in buildings. For achieving low energy consumption and high thermal and visual comforts, natural lighting by using large glazing windows was investigated in different buildings [19–22]. The illuminance level, luminance, and glare indices affecting the visual comfort in these buildings were used as a control input of these buildings [22,23]. However, although much research on natural lighting in the analysis of building energy performance and visual comfort were conducted, there is still less study to apply the natural lighting to HEMS algorithms. As a related study by Li et al. [24] suggested a smart lighting control methodology integrated in a smart home control system to save energy consumption at home with respect to the design of lighting systems for buildings. They confirmed in detail the feasibility and the performance of the lighting control algorithm in the smart home control system. Owing to the effectiveness of the lighting system and the HVAC system
for both energy management and user’s comfort, these systems should be prior-candidates integrated in the HEMS.

To maintain the satisfaction of occupants, HEMS implementing technologies are required to sense, monitor the environmental conditions and occupants’ individual data, store and reproduce the data as knowledge and information of the overall building system. As such, home appliances and equipment should finely be controlled by HEMS by considering the influence of the occupants’ preference and fatigue. They should be also considered as demand resources for the purpose of energy savings of the household during DR events. The contributions of this paper are highlighted as follows.

- The human comfort factors including both thermal and visual comforts were integrated into the HEMS algorithm in this study. As mentioned above, the effectiveness of the lighting system and the HVAC system in terms of energy savings and user’s comfort have been confirmed in several investigations. However, there has rarely been the investigations dealing with both systems in different perspectives of energy savings and human thermal and visual comfort integrated into the HEMS.
- To reduce the response fatigue of occupants and to slow down the negative effect of curtailment of appliances during DR events, an HVAC system was proposed as a prior demand resource in the household due to its slower thermal dynamics and higher power capacity than those of other appliances. The HVAC system was controlled to follow the DR events as well as the occupant’s thermal comfort in the household.
- In addition to the occupants’ thermal comfort, a visual comfort-based-control algorithm for a dimming artificial lighting system using natural lighting was integrated into HEMS to improve the visual comfort and energy savings of the household.
- Simulation case studies were performed using Matrix Laboratory (MATLAB)/Simulink® to verify the effectiveness of the proposed approach.

The rest of this paper is organized as follows. Section 2 suggests the comfort-based HEMS and the human comfort factors considered in the proposed algorithm. Section 3 describes a building integrated HEMS to present the thermal and visual dynamics of the building and its HVAC and lighting systems controlled by HEMS. Section 4 elaborates on case studies to test and validate the proposed approach. Finally, Section 5 draws the conclusions of this study.

2. Comfort-Based Home Energy Management System

2.1. Main Features of the Comfort-Based HEMS

The HEMS accomplishes the sensing, processing, monitoring, and reproducing of information to control the electric and thermal energy fluxes of the building by appropriately combining the operations of electrical and thermal appliances. In this study, human comfort factors such as the thermal and visual comforts were integrated into the HEMS algorithm. The thermal condition of the indoor environment was controlled by the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) values. The PMV-based control strategy of a heating system as an HVAC system was integrated into the proposed HEMS. Even though several metrics of user comfort were defined and proposed in the literature [15,16,25], this study only considered the PMV and PPD as the evaluation index of user’s thermal comfort in order to present that the suggested HEMS algorithm could be useful to control an HVAC system to participate in DR programs preserving user’s thermal comfort. Then, a dimmable light-emitting diode (LED) lighting system was applied to the proposed HEMS to efficiently use the daylight as a natural lighting and to satisfy the visual comfort of occupants. Illuminance inside a building was the factor that assessed the visual comfort of the occupants in this study.

The comfort-based control algorithm comprises the following sequences. At first, the presence of occupants was detected to assess the necessity of operation of heating/cooling and lighting systems. If any occupant was detected inside the target space, the PMV values were calculated. The thermal
condition of the household was then controlled by the predefined ranges of the PMV values. Because
the main idea of this study was the availability of the proposed HEMS algorithm during the occurrence
of DR events, the acceptable ranges of the PMV values was adjusted and the control command signals
of the heating/cooling system depended on these values. At the same time, the lighting system was
controlled for the purpose of visual comfort and energy savings.

2.2. Thermal Comfort

Thermal comfort is defined as ‘the expression of mind that expresses satisfaction with the
thermal environment’, according to the American society of heating, refrigerating, and air-conditioning
(ASHRAE) [26]. It is a personally determined sensation that has a large discrepancy among different
people. It is also difficult to quantify the value and analyze it. Several researchers have investigated
the parameters influencing thermal comfort and have developed models to express a common range
of thermal comfort among people. Among the models, the PMV model introduced by Fanger is the
most used model to assess thermal sensation of the human body with respect to the environment [25].
The thermal comfort was assessed by considering six parameters including the indoor air temperature,
mean radiant temperature, relative humidity, air velocity, clothing, and metabolic rate of the occupant.
As a result of the evaluation, PMV was obtained and PPD was expressed as a function of the PMV
value as follows [27]:

$$PMV = [0.303 \cdot \exp(-0.036 \cdot M) + 0.028] \cdot L$$  

$$PPD = 100 - 95.0 \cdot \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2 - 0.028)$$

where $M$ is the metabolic rate ($W/m^2$) and $L$ is the thermal load of the human body ($W/m^2$). The PPD
value is symmetric with respect to thermal neutrality, whereas the PMV value is zero. However,
as shown in Equation (2), a minimum rate of dissatisfaction of 5% always exists. The index of the PMV
is listed in Table 1. The PPD as a function of the PMV is depicted in Figure 1.

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

Table 1. Index of predicted mean vote (PMV).

![Figure 1. Percentage of dissatisfied (PPD) as a function of PMV.](image)

Acceptable ranges of PMV and PPD variations were defined by the ASHRAE, the European
Committee for Standardization (CEN), and the International Organization for Standardization
(ISO) [26,28–31]. ASHRAE Standard 55-2013 [26] indicates an acceptable thermal environment for general comfort. It recommends that the PPD is inferior by 10% and the PMV is between −0.5 and +0.5. This indicated that 10% of the people were dissatisfied [26,28]. The CEN Standard EN 15251 and ISO EN 7730 recommend four categories by prescribing a maximum PPD value for the body and the corresponding PMV range [29–31]. Category I commonly describes a high level of expectation for spaces occupied by very sensitive and fragile persons. Categories II and III explain a normal and moderate expectation, respectively. Category IV is applicable only for a limited period of the year. The first three recommended PPD and PMV ranges are listed in Table 2.

Based on the above recommended thermal comfort values in the standards, appropriate values of PMV and PPD could be selected to control the heating/cooling system of the building.

| Category | PPD   | PMV Range                |
|----------|-------|--------------------------|
| I        | < 6   | −0.2 < PMV < +0.2        |
| II       | < 10  | −0.5 < PMV < +0.5        |
| III      | < 15  | −0.7 < PMV < +0.7        |

2.3. Visual Comfort

The European standard EN 12665 [32] defines the visual comfort as ‘the subjective condition of visual well-being induced by the visual environment’. The visual environment inside a building is formed by both natural and artificial lighting. To immediately respond to an occupant’s visual demand, the visual comfort index should be easily measured for on-demand services. The quantity, quality, uniformity, and glare of light are the four main factors that evaluate the visual environment.

Among them, the value of the illuminance, which was found to be independent of the light source, was easily and immediately measured. The illuminance is a physical quantity, and is measured in lux (lx) at a point on a given surface by an illuminometer, an illuminance sensor, or by a smartphone that has an illuminance measurement application and its calibration algorithm. It is defined as the ratio between the luminous flux incident on an infinitesimal surface and the area of that surface. It has threshold values for each task or space inside a building. The illuminating engineering society (IES), the commission Internationale de l’Éclairage (CIE), the U.S. general services administration (GSA), the chartered institution of building services engineers (CIBSE), and most countries have their own recommended lighting levels [32,33]. An example of the recommended illuminance levels indicated in the illuminance recommendations [34] is listed in Table 3.

| Visual Tasks                                      | Illuminance (lx) |
|--------------------------------------------------|------------------|
| Resting, causal visual tasks                     | 10–50            |
| Simple activities, ordinary visual tasks         | 100              |
| Visual tasks of high contrast and large size     | 300              |
| Visual tasks of high contrast and small size     | 500              |
| Visual tasks of low contrast and large size      | 1000             |
| Severe visual tasks                              | Above 3000       |

3. Building Integrated HEMS

3.1. Thermal Dynamics of the Building

Based on the first principle of thermodynamics, a heat balance of a building with a HVAC system could be developed based on the first principle of thermodynamics as follows [35]:
where \( U_{\text{stored}} \) is the stored heat energy inside the building (J), \( Q_{\text{HVAC}} \) is the heat flow (W) through the HVAC system including heating flow \( Q_{\text{heating}} \) (W), ventilation flow \( Q_{\text{ventilation}} \) (W), and cooling flow \( Q_{\text{cooling}} \) (W). However, in heating mode of the HVAC system, the cooling flow \( Q_{\text{cooling}} \) (W) is zero, while the heating flow \( Q_{\text{heating}} \) is zero in cooling mode of the system. \( Q_{\text{envelope}} \) is the heat loss (W) through the building envelope, \( C_{\text{building}} \) is the thermal capacitance (J/kg·°C) of the building, \( R_{\text{building}} \) is the thermal resistance (°C/W) of the building, \( T_{\text{building}} \) and \( T_{\text{outside}} \) are the indoor temperature and outdoor temperature (°C) of the building, respectively. Focusing on the control command of the HVAC system, the thermal dynamics of the building could be established as follows:

\[
C_{\text{building}} \frac{dT_{\text{building}}}{dt} = \delta(t) Q_{\text{HVAC}} - \frac{1}{R_{\text{building}}} (T_{\text{building}} - T_{\text{outside}})
\]  

where \( \delta(t) \) is the binary control command of the HVAC system. The conventional control strategy of the HVAC system is to follow the acceptable temperature range of the building. The control command of the system follows the temperature of the building, as depicted in Figure 2.

![Control command of the heating, ventilation, and air-conditioning (HVAC) system based on acceptable temperature range: (a) cooling process and (b) heating process.](image)

**Figure 2.** Control command of the heating, ventilation, and air-conditioning (HVAC) system based on acceptable temperature range: (a) cooling process and (b) heating process.

When the temperature was at the desired temperature, the system turned off. When the difference between the present temperature and the desired temperature was beyond a specified threshold, the system turned on. However, the proposed control strategy of this study focused on human comfort. The control command based on the thermal comfort index PMV is depicted in Figure 3. The control command was determined by the acceptable range of the PMV. When the PMV value reached the desired PMV, the system turned off. When the difference between the values of the present PMV and the desired PMV was beyond a specified threshold, the system turned on.
Artificial lighting systems are designed based on their power consumption, illumination, working area, and functionality. In this study, a dimmable LED lighting fixture was selected for both visual comfort of the occupants and low energy consumption of the building. The required illumination of the artificial lighting, $E_{art, total}$ is expressed as follows:

$$E_{art, total} = \eta(t)\kappa(t)E_{art} + E_{aux}$$  \hfill (8)

$$\eta(t) = 0(E_{nat} \geq E_{ref})$$  \hfill (9)

$$\eta(t) = \frac{E_{ref} - E_{nat}}{E_{art}}(E_{nat} < E_{ref})$$  \hfill (10)

where $\eta(t)$ is the lighting control command, $E_{nat}$ and $E_{art}$ are the illumination (lx) by natural lighting and artificial lighting, respectively. $E_{aux}$ is the auxiliary illumination (lx) for night time or for emergency. $E_{ref}$ is the illumination reference (lx) of the building. $\kappa(t)$ is the binary switch following the time schedule of the lighting system. $\kappa(t)$ was 1 when the occupants were present, whereas, it was 0 during both night time as well as when the occupants were absent. However, during night time or in emergency, occupants may use the auxiliary illumination as indicated in Equation (8). The required artificial illumination of the building and its operating time schedule is depicted in Figure 4.

![Figure 3](image-url)  
**Figure 3.** Control command of the HVAC system based on acceptable PMV range: (a) cooling process and (b) heating process.  

**3.2. Visual Comfort-Based Control of Artificial Lighting Systems**

![Figure 4](image-url)  
**Figure 4.** The required artificial illumination of the building. (a) Artificial lighting versus natural lighting and (b) control command based on a time schedule.
4. Case Study

4.1. Simulation Conditions

To investigate the effect of human comfort-based algorithm-integrated HEMS, a numerical study on building energy performance was conducted using MATLAB/Simulink®. A simple RC-lumped building model for a house was developed based on the first principle of thermodynamics. Three cases were selected to investigate the HEMS function for DR participation and human comfort. Each scenario of the cases is listed in Table 4. The simulation of each scenario was conducted assuming that the house was occupied during the simulation and that the DR command was provided from 9 to 12 h and 18 to 22 h for a week during winter to avoid peak loads and peak electricity pricing. The meteorological data provided by the French Technical Research Center for Building (CSTB) were used [36,37]. The time step of the simulation was in a minute. A heating system was used for heating the space and was considered as a demand resource for replying to the DR commands. If the simulation is conducted during summer, a cooling system may be preferred. In addition, a lighting system is operated for the occupants’ visual comfort during the day and night time. To ensure the occupants’ visual comfort, the lighting system inside the house was controlled to keep the illuminance above 300 lx from 7 to 22 h [34]. The illuminance data was calculated by using a simple window model and a lighting system model integrated in a building simulation tool developed by the CSTB [36].

| Table 4. Scenario description of case studies. |
|-----------------|-----------------|-----------------|-----------------|
| Case | Scenario | Regulation Method | Regulation Range | Metabolic Heat |
| 1   | Scenario 1 | Temperature | Without DR: 19–21 °C | 115 W |
|     |           |             | With DR: 19–21 °C   |               |
| 2   | Scenario 2 A | Temperature | Without DR: 19–21 °C | 100 W |
|     |           |             | With DR: 18–20 °C   |               |
|     | Scenario 2 B | Temperature | Without DR: 19–21 °C | 115 W |
|     |           |             | With DR: 18–20 °C   |               |
| 3   | Scenario 3 A | PMV        | Without DR: −0.2—0   | 100 W |
|     |           |             | With DR: −0.5—0.2   |               |
|     | Scenario 3 B | PMV        | Without DR: −0.2—0   | 115 W |
|     |           |             | With DR: −0.5—0.2   |               |
|     | Scenario 3 C | PMV        | Without DR: −0.2—0   | 130 W |
|     |           |             | With DR: −0.5—0.2   |               |

Case 1 represents a basic case followed a predefined temperature range without any additional adjustment of a heating system for responding to DR. The temperature-based control strategy was applied to case 1, as depicted in Figure 2. The temperature ranges of the heating system in case 1 was fixed from 19 to 21 °C. There was only one scenario with a metabolic heat of 115 W in case 1.

Meanwhile, cases 2 and 3 followed the DR commands by controlling the heating systems. In case 2, a heating system was controlled by a temperature range similar to that of case 1 without the DR command. However, the heating system was controlled in the temperature range of 18–20 °C with the DR command. To reduce the power consumption of the heating system during the DR period, the indoor temperature remained relatively lower than that in the normal conditions without DR events. The heating system in case 3 was regulated by PMV ranges as depicted in Figure 3. The PMV ranged from 0 to −0.2 without DR events, and from −0.2 to −0.5 with DR events. The range of PMV was first set from 0 to −0.2 to ensure the occupants’ thermal comfort when there was no DR command. When a DR command was provided during a certain period, the PMV value within the range of −0.2 to −0.5 was applied as acceptable ranges at normal expectation. There were three types of scenarios in each of cases 2 and 3. However, they differed from the aspect of metabolic heat quantity. Scenario A
represented a low metabolic heat of 100 W. Scenario B showed a moderate metabolic heat of 115 W. Scenario C indicated a high metabolic heat of 130 W.

4.2. Simulation Results

The indoor and outdoor temperatures of the house in scenario 1 of case 1 is depicted in Figure 5. The outdoor temperature varied from −2 °C to 6 °C during the simulation, and this was applied to all the scenarios of this study. In scenario 1 of case 1, the heating system of the house was always set from 19 to 21 °C, although there were DR commands from 9 to 12 h and from 18 to 22 h. In scenario 1, the amount of heat energy consumed during a week was 1166 kWh.

Figure 5. Indoor (—) and outdoor (- -) temperatures in scenario 1.

The zoomed indoor temperature of scenario 1 for reference and that of scenario 2 B for comparing the DR participation with and without a heating system as demand resources is depicted in Figure 6a. In these scenarios, a metabolic heat of 115 W was applied. In scenario 2 B, the temperature ranges of the house were modified when DR commands arrived during a DR period. As stated above, the DR events were sent to the house for 9–12 h and 18–22 h. During this period, the temperature was set from 18 to 20 °C.

Figure 6. Comparison of indoor temperature and heater signal: (a) temperature and (b) heater command (—: scenario 1 and - -: scenario 2 B).

The heater command of scenarios 1 and 2 B based on the temperature-based control strategy is depicted in Figure 6b. The indoor temperature varied (increased and decreased) with respect to the thermal dynamics of the building once the power was on and off, respectively. The indoor temperature
was set below 19 °C during the DR period in scenario 2 B and therefore, the heater command was not rapidly reversed compared to the heater command of scenario 1. It permitted the curtailing of the heater’s power consumption during DR periods and reduced the energy consumption of the house while there were DR commands. The amount of heat energy consumed during a week in scenario 2 B was 1136.6 kWh. In this scenario, less amount of heat energy was required compared to that of the heat energy in scenario 1.

This result showed that lower temperature ranges for a heating system reduced the energy consumption of the house and realized its participation in DR programs with a heating system as the demand resource. However, this did not mean that the temperature ranges ensured the thermal comfort of the occupants. The occupants dissipated different amounts of metabolic heat according to their physical properties, physical activities, and conditions. The indoor temperature of the house in scenarios 2 A, B, and C distinguished by different quantity of the metabolic heat of occupants is depicted in Figure 7. As the heating system of the house operated in fixed temperature ranges in these scenarios, all the evolutions of indoor temperatures for the three scenarios were in the range of 19–21 °C in a non-DR period and 18–20 °C in a DR period.

![Figure 7. Comparison of indoor temperature (—: scenario 2 A, - -: scenario 2 B, and —-: scenario 2 C).](image)

Therefore, the problem of thermal comfort increased as depicted in Figure 8. Under the same indoor temperature conditions, occupants dissipated different metabolic heat with different thermal comfort values. Although the occupants could successfully participate in the DR programs by controlling the temperature ranges of heating systems, it had a negative effect on personal satisfaction. This may induce a short continuity of DR participation in households. Therefore, during a DR period, a simple curtailment of power cannot be recommended as a single solution for all the occupants. To satisfy the thermal comfort of occupants as well as to participate in DR programs with an HVAC system, a PMV-based-control strategy has to be proposed as stated in the previous section. From the perspective of energy saving, the quantities of energy consumption in scenarios 2 A, B, and C were 1138.6, 1136.6, and 1133.1 kWh, respectively, during the given period. As higher metabolic heat contributed in heating the space, the energy consumption of the house was more in scenario 2 C than those in 2 A and B.

The evolution of the indoor temperature of the house in scenarios 3 A, B, and C is depicted in Figure 9. Although the difference in temperature was more than 3 °C among the three scenarios of the same case, the thermal comfort of occupants in each scenario was ensured at the expected PMV ranges between −0.2 and 0 during the non-DR period and between −0.5 and −0.2 during the DR period as depicted in Figure 10. In scenario 3 A, the indoor temperature was higher than those in other scenarios. It explains that the lowest metabolic heat requires the more quantity of heat in the house for improving occupant’ thermal comfort. In other words, the occupant dissipated lower heat feels colder than the occupants dissipating higher metabolic heat. Therefore, in a house where an occupant dissipating lower metabolic heat, more heat should be supplied to this house for thermal satisfaction of
the occupant. In contrast, the indoor temperature was lower in scenario 3 C as the occupant dissipated more heat and thus feels warmer or hotter than others. This led to a higher PMV value of the occupant even at a lower temperature. This indicated that the occupants dissipating different quantities of heat have a significant gap with the satisfaction on the indoor thermal condition. This result supported the previously obtained results depicted in Figures 7 and 8. Moreover, the highest metabolic heat required less heating energy in the house. The quantities of energy consumption during the given period in scenarios 3 A, B, and C were 1263, 1094, and 920 kWh, respectively. This showed that thermal comfort could be obtained by controlling a heating system based on the expected PMV values of the occupants. As the curtailment of heating power depended on the thermal comfort of the occupants, their satisfaction in DR programs could be ensured by maintaining their thermal comfort.

To achieve the visual comfort of occupants and energy savings of the building, a dimming artificial lighting system was integrated into the building model. The illuminance level of the house and natural illuminance are depicted in Figure 11. When the occupant was awake from 7 to 22 h, the minimum artificial illuminance was maintained at 300 lx. Therefore, the artificial illuminance was controlled by dimming the artificial lighting with respect to the recommended illumination level of 300 lx, a lighting system operated for the occupants’ visual comfort during the day and night time. The dimming level of the lighting system is depicted in Figure 12. Compared to the system without dimming control, this system reduced 27% of the lighting energy. However, in this study, glare occurrence was not considered. In further studies, a blind system for avoiding glares would be investigated.

![Figure 8](image_url) Comparison of PMV (—: scenario 2 A, - -: scenario 2 B, and —- -: scenario 2 C).

![Figure 9](image_url) Comparison of indoor temperature (—: scenario 2 A, - -: scenario 2 B, and —- -: scenario 2 C).
5. Conclusions

Home appliances and equipment should be finely controlled by HEMS by considering the influence of occupant’s preferences and behaviour patterns. To promote the occupant’s participation in DR programs, this paper has presented an algorithm based on human comfort factors that can be integrated into the HEMS. The proposed algorithm included PMV and PPD values for the thermal comfort of the
occupants, and illuminance level for their visual comfort. To reduce response fatigue of occupants and the curtailment of small appliances, the HVAC system with a relatively larger power capacity and faster dynamics was preliminarily selected to be used as the demand resource of a household. The HVAC system could be controlled to follow the DR events and to reduce the energy consumption of the household. To perform the proposed approach, the thermal comfort-based-control algorithm for a heating system in HEMS was proposed to improve the occupants' thermal comfort. At the same time, a dimming artificial lighting system (LED) was integrated into the visual comfort-based-control algorithm of the lighting system in HEMS to improve the visual comfort and energy savings of the household. Simulation studies were carried out using MATLAB/Simulink® to verify the effectiveness of the proposed approach. Because the simulation was conducted during winter, the heating process of the HVAC system was controlled. The results showed that the heating system with PMV-based control significantly improved the thermal comfort of the occupants during both the DR and non-DR periods compared to the temperature-based control in scenarios with different metabolic heat dissipation of occupants. In addition, visual comfort based on illuminance and energy savings of a lighting system controlled by the proposed approach in HEMS was also validated. Further study includes advanced control strategies of the HVAC system by using thermal inertia of the households before and after DR events and a blind system control for avoiding glare occurrences.

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