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QoE-Aware Smart Home Energy Management Considering Renewables and Electric Vehicles

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Abstract: To reduce the peak load and electricity bill while preserving the user comfort, a quality of experience (QoE)-aware smart appliance control algorithm for the smart home energy management system (sHEMS) with renewable energy sources (RES) and electric vehicles (EV) was proposed. The proposed algorithm decreases the peak load and electricity bill by deferring starting times of delay-tolerant appliances from peak to off-peak hours, controlling the temperature setting of heating, ventilation, and air conditioning (HVAC), and properly scheduling the discharging and charging periods of an EV. In this paper, the user comfort is evaluated by means of QoE functions. To preserve the user's QoE, the delay of the starting time of a home appliance and the temperature setting of HVAC are constrained by a QoE threshold. Additionally, to solve the trade-off problem between the peak load/electricity bill reduction and user's QoE, a fuzzy logic controller for dynamically adjusting the QoE threshold to optimize the user's QoE was also designed. Simulation results demonstrate that the proposed smart appliance control algorithm with a fuzzy-controlled QoE threshold significantly reduces the peak load and electricity bill while optimally preserving the user's QoE. Compared with the baseline case, the proposed scheme reduces the electricity bill by 65% under the scenario with RES and EV. Additionally, compared with the method of optimal scheduling of appliances in the literature, the proposed scheme achieves much better peak load reduction performance and user's QoE.

Keywords: dynamic electricity prices; electric vehicles (EV); fuzzy control; home energy management system (HEMS); peak load; quality of experience (QoE); renewable energy

1. Introduction

To reduce energy consumption and carbon emission, several works had proposed various energy management systems [1,2] for smart grids [3] or smart homes [4]. The main purposes of original energy management systems are to reduce the energy consumption, peak load, and electricity cost. One popular method for reducing the peak load and electricity cost is shifting the power demand from peak to off-peak hours. For example, the results in [5] revealed that 37.9% of refrigerator's demand in peak period can be shifted to other periods and annual electricity bills for customers can be reduced by 11.4%. In [6], the authors investigated the cost minimization problem in which the electrical appliances allow different levels of delay tolerance. The work [7] evaluated the performance of a wireless sensor network (WSN)-based in-home energy management (iHEM) application whose objective is to minimize the energy expenses of the consumers and reduce the peak load of the household by scheduling the appliances. Additionally, Collotta et al. [8,9] proposed a bluetooth low energy (BLE) and fuzzy-based solution for the smart energy management system, in which the consumer is involved in the choice of switching on/off of home appliances, to reduce peak load and electricity bill by shifting the appliance's operation. However, shifting the power demand may degrade the user comfort. For instance, delaying the starting time of an electric oven or a microwave oven to shift the power demand, the user may become hungry because of deferring his mealtime, resulting in user comfort degradation. On the contrary, delaying the starting time of an automatic washing machine, the user comfort may be rarely degraded. Hence, related problems such as the user comfort, reduction in electricity bill, electrical appliance scheduling, and required addition of renewable energy sources (RES) had been surveyed in [3]. Undoubtedly, a modern home energy management system (HEMS) must not only decrease the power consumption and electricity bill, but also preserve the user comfort.

To resolve the defects of conventional HEMSs, Floris et al. [10] presented a quality of experience (QoE)-aware HEMS. The degree of satisfaction perceived, in terms of the mean opinion score (MOS) [11], when the starting times of appliances are delayed was investigated using subjective tests which are time-consuming and costly. To evaluate the user comfort under power demand shifting, Chen et al. [12] introduced the concept of operational comfort level (OCL) and proposed the OCL models for several smart appliances. Additionally, the authors in [12] proposed a min-max load scheduling (MMLS) algorithm in order to minimize the peak-to-average ratio (PAR) while optimizing the OCL of users. The inconvenience experienced by users when decreasing the power consumption is necessary under the control of an HEMS was also studied in [13]. Another study [14] proposed an intelligent HEMS algorithm for residential demand response applications and investigated the impact of the HEMS operation on the user comfort. However, there is still no cost-efficient QoE evaluation method proposed in the literature for an HEMS. Thus, in order to efficiently evaluate the user's QoE, several QoE mapping functions for delay-tolerant appliances and the heating, ventilation, and air conditioning (HVAC) were introduced in [15]. Additionally, a QoE-aware smart appliance control algorithm was designed in [15] to effectively reduce the peak load and electricity bill while guaranteeing the user's QoE never less than a given threshold.

In the work [15], a fixed QoE threshold was used so that the setting of the QoE threshold becomes an annoying problem. For example, in a season of high power demand, lowering the QoE threshold significantly reduces the peak load and electricity bill. However, in a season of low power demand, lowering the QoE threshold has a little effect on the reduction of peak load and electricity bill while significantly degrading the user's QoE. Therefore, how to determine a proper QoE threshold for the smart appliance control algorithm to perform well under various scenarios of different power demands becomes a challenging issue. It is well known that fuzzy logics have been popularly used in an HEMS [16–18]. Thus, one aim of this paper is to design a fuzzy logic controller to dynamically adjust the QoE threshold for the proposed smart appliance control algorithm performing well under different profiles of power demands.

Recently, the development and deployment of microgrids with RES have been rapidly increasing all over the world. The contribution of renewable energy to the energy supply has also been increasing. However, to ensure the operation of microgrids, microgrids are always connected to the main grid [19,20]. Therefore, it is necessary to take RES into consideration in designing a smart home energy management system (sHEMS). On the other hand, electric vehicles (EV) have been regarded as an effective way to reduce carbon emissions. Additionally, EV batteries can be used for regulating the grid demand by properly scheduling EV charging and discharging to decrease the user's electricity bill [21–23]. Thus, designing a QoE-aware smart appliance control algorithm for the sHEMS considering RES and EV is mandatory.

To summarize, the main contributions of this work are fourfold. First, several QoE mapping functions for delay-tolerant appliances and HVAC are derived to efficiently evaluate the user comfort. Second, a QoE-aware smart appliance control algorithm is proposed to reduce the peak load and electricity bill while preserving the user's QoE. Thirdly, a fuzzy logic controller for dynamically setting the QoE threshold is designed to resolve the trade-off problem between the user's QoE and reduction performance of peak load and electricity bill. Finally, the effects of power allocation of RES and EV batteries on the peak load, electricity bill, and user's QoE are evaluated as well.

The rest of this paper is organized as follows. Section 2 describes the architecture of a smart microgrid system. Section 3 introduces the classification of home appliances, defines the QoE functions of home appliances, and describes the designed QoE-aware smart appliance control algorithm for the sHEMS with RES and EV. Section 4 presents the fuzzy logics and inference rules to dynamically adjust the QoE threshold. Section 5 evaluates and compares the performance of the proposed QoE-aware smart appliance control algorithm and other existing schemes. Finally, the concluding remarks are made in Section 6.

2. Smart Microgrid System

In this paper, the smart microgrid system that consists of home appliances, EV, RES, energy storage system, smart meter, smart home network, and sHEMS, as shown in Figure 1, is considered. RES such as photovoltaics (PV) and wind turbines can generate the power that is temporarily stored in the storage system for later use. The smart meter records and monitors the power consumption of home appliances. The smart home network may include the TCP/IP network, WSN, and power line communication network [24]. The sHEMS collects (1) the environmental data such as temperature and illuminance sensed by sensors, (2) statuses of home appliances, storage system, and EV, and (3) power consumption information from the smart meter via the smart home network. In Figure 1, the red lines indicate the power lines while the green lines indicate the network path to the Internet. As to the dashed lines, they represent logical communication connections. However, practical communications must be accomplished using physical communication links and diverse communication protocols such as the wired Ethernet, Wi-Fi, power line communication, and ZigBee protocols can be used. The purpose of the sHEMS is to properly control the operations of home appliances to optimize the energy usage and electricity bill subject to the user comfort constraint. To optimize the energy usage and electricity bill, a smart appliance control algorithm must be designed for the sHEMS.

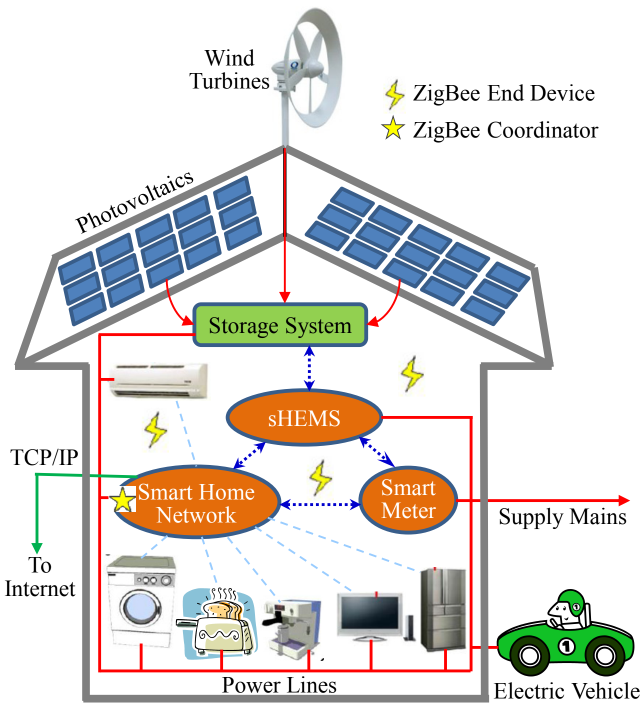


Figure 1. Architecture of the smart microgrid system.

As mentioned above, the goal of the sHEMS is to minimize the energy usage and electricity bill while preserving the user comfort. It is well known that shifting the starting times of electrical appliances from peak to off-peak hours can reduce the peak load. However, deferring the starting times of home appliances may degrade the user's QoE. While the impact of deferring the starting times of home appliances on the user's QoE is rarely studied in the literature. Hence, this paper proposes several QoE functions for efficiently evaluating the user comfort and a QoE-aware smart appliance control algorithm for the sHEMS with RES and EV to reduce the peak load and electricity bill while preserving the user's QoE. Additionally, a fuzzy logic controller for dynamically adjusting the QoE threshold to improve the user's QoE is designed.

3. QoE-Aware Smart Appliance Control Algorithm for sHEMS

In this section, the classification of home appliances is first introduced. Next, the QoE mapping functions are designed to evaluate the user comfort. Finally, a QoE-aware smart appliance control algorithm is proposed for the sHEMS with RES and EV.

3.1. Classification of Home Appliances

Similarly to our previous work [15], home appliances are categorized into three types: delay-tolerant, delay-intolerant with essential load, and delay-intolerant with flexible load [6,12,13]. For delay-tolerant appliances, their starting times can be shifted from peak to off-peak hours to decrease the peak load. Such delay-tolerant appliances consist of the electric oven, microwave oven, water heater, dishwasher, washing machine, clothes dryer, and so on. For appliances of delay-intolerant with essential load, shifting their starting times is not allowed and the variation of their working loads among various states is usually negligible. The LED bulbs, fans, TV, and computers are this type of delay-intolerant with essential load. As for the appliances of delay-intolerant with flexible load, users may change their working states to save energy consumption and shave peak load. This type of appliances consists of the water dispenser, refrigerator, and HVAC. The classification of home appliances is listed in Table 1.

Table 1. Classification of home appliances.

Type	Home Appliances
Delay-Tolerant	Dishwasher, Washing Machine, Clothes Dryer, Water Heater, Electric Oven, Microwave Oven
Delay-Intolerant with Essential Load	TV, LED Bulb, Fan, Computer
Delay-Intolerant with Flexible Load	Refrigerator, Water Dispenser, HVAC

3.2. Evaluation of the User Comfort

Although shifting the starting times of electrical appliances from peak hours to off-peak hours can reduce the peak load, the user comfort may be degraded. To study the impact of deferring the starting time of a home appliance on the user comfort, Floris et al. [10] conducted subjective tests on users' satisfactions about deferring starting times of home appliances. The degree of the user comfort is evaluated by means of mean opinion score (MOS) [11]. MOS is a measure used in the domain of QoE and telecommunications engineering, representing overall quality of a stimulus or system. It is usually expressed as a rational number, typically in the range of 1 to 5, which maps ratings between *Bad* and *Excellent* to numbers between 1 and 5, as shown in Table 2. In [10], time-consuming and costly subjective tests were used and only some discrete data points (*delay*, *MOS*) were investigated so that the applications of their results are limited. Hence, in this paper, cost-efficient QoE mapping functions are proposed to evaluate the user comfort. According to the findings in [25], most of the QoE functions behave like an exponential function. Hence, the following piecewise exponential function

$$\mathrm{QoE}(d) = \begin{cases} 5, & d \leq b, \\ 5e^{-a(d-b)}, & d > b, \end{cases} \tag{1}$$

is adopted to be the QoE mapping function of delay d (in hours) for most electrical appliances. Given the piecewise exponential QoE mapping function in Equation (1) and the data points (d, MOS) obtained in [10] using questionnaires of subjective tests, the decaying exponent parameter a and the offset parameter b can be easily obtained using the nonlinear regression approach. The derived parameters a and b for various electrical appliances in weekdays and days off are listed in Table 3. The derived QoE mapping functions for the dishwasher and washing machine are plotted in Figure 2a,b.

Table 2. Definitions of MOS [11].

MOS	Quality	Impairment
5	Excellent	Imperceptible
4	Good	Perceptible but not annoying
3	Fair	Slight annoying
2	Poor	Annoying
1	Bad	Very annoying

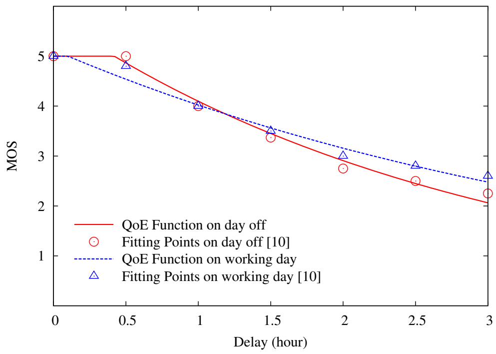
Table 3. Parameters a and b of QoE mapping functions for delay-tolerant appliances [15].

Appliances	Weekdays		Days Off	
	a	b	a	b
Dishwasher (DW)	0.242	0.100	0.343	0.420
Water heater (WH)	0.677	0.392	0.018	0
Electric oven (EO)	0.694	0	0.676	0.405
Microwave oven (MO)	0.910	0.470	0	0
Washing machine (WM)	0.495	0.491	0	0
Clothes dryer (CD)	0.356	0.906	0.601	0.933

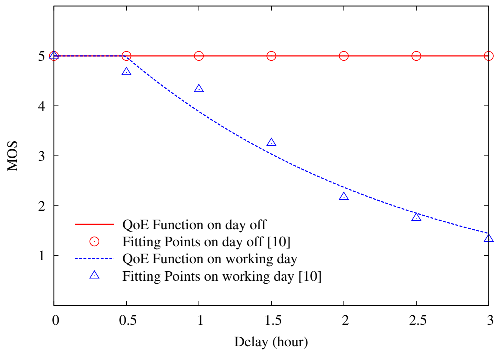
As to the setting of target temperature of HVAC, it is determined by the QoE mapping function of temperature for HVAC. In this work, the Gaussian-like function

$$\mathrm{QoE}(T) = 5e^{-0.0568(T-27)^2} \tag{2}$$

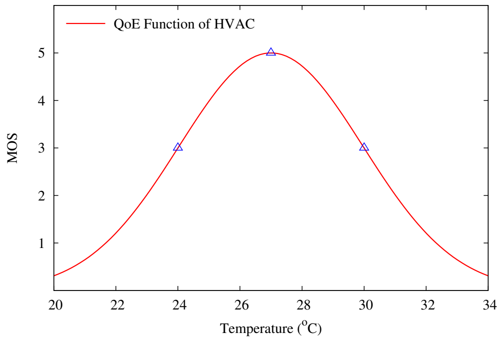
is employed to represent the QoE function of the target temperature T (°C) for HVAC [15]. Notably, in this paper, the most comfortable temperature is assumed to be 27 °C. Additionally, the QoE is assumed to be 3 when T is 24 or 30 °C. The designed QoE mapping function for the HVAC is plotted in Figure 2c. Notably, users may change the most comfortable temperature 27 °C to any other values they prefer, but the corresponding parameters in Equation (2) must be refitted.



(**a**) Dishwasher



(**b**) Washing machine



(**c**) HVAC

Figure 2. QoE mapping functions of dishwasher, washing machine, and HVAC.

3.3. Proposed QoE-Aware Smart Appliance Control Algorithm

Figure 3 plots the flowchart of the proposed QoE-aware smart appliance control algorithm for the sHEMS with RES and EV. $P^L(t)$ represents the total load of currently working appliances in the considered microgrid system at time t. $P^G(t)$ is the power supplied by the main grid at time t. $P^R(t)$ is the generating power of the RES at time t. $P^B(t)$ and $P^E(t)$ are the available output powers of the RES storage system and EV battery, respectively, at time t. P_i indicates the working power of Appliance i. According to Figure 3, if the generating power $P^R(t)$ of RES is enough for supporting the requested appliance and all working appliances, the requested Appliance i starts immediately and no battery and grid power is required; otherwise, the energy stored in the storage system of RES may be required. If the generating power $P^R(t)$ plus the available output power $P^B(t)$ of the RES storage system is not less than $P^L(t) + P_i$, the requested appliance starts immediately; otherwise, the state of the EV battery is checked. If the generating power $P^R(t)$ plus the available output power $P^B(t) + P^E(t)$ of the RES storage system and EV battery is not less than $P^L(t) + P_i$, the requested appliance also starts immediately; otherwise, the grid power is required. That is, the RES generating power has the highest use priority while the grid power has the lowest use priority. Such a strategy is to minimize the electricity bill resulting from the energy consumption supplied by the grid. Notably, the state of the EV battery depends on the schedule of charging and discharging, and state of charge (SOC) of the battery.

Subsequently, the starting time of the requested appliance is determined according to the type of the requested appliance and the present time slot. If the requested appliance belongs to the type of delay-intolerant with essential load or the power consumption $P^G(t) + P_i$ supplied by the main grid is less than the power constraint P_0, the requested appliance starts immediately. When a request for starting a delay-tolerant appliance arrives at peak hours and the power consumption $P^G(t) + P_i$ is larger than the power constraint P_0, the starting of the appliance may be deferred if the resulting

QoE is not below the threshold value. When a request for starting a delay-tolerant appliance arrives at off-peak hours and the power consumption $P^G(t) + P_i$ is larger than P_0, the starting of the requested appliance is shifted to the time slot with the lowest price if the resulted QoE is not below the threshold value. The allowable delay time d of the starting of an electrical appliance relies on the QoE mapping function, QoE threshold, power consumption supplied by the grid, and power constraint. Notably, the longer the delay time is, the worse the user's QoE is.

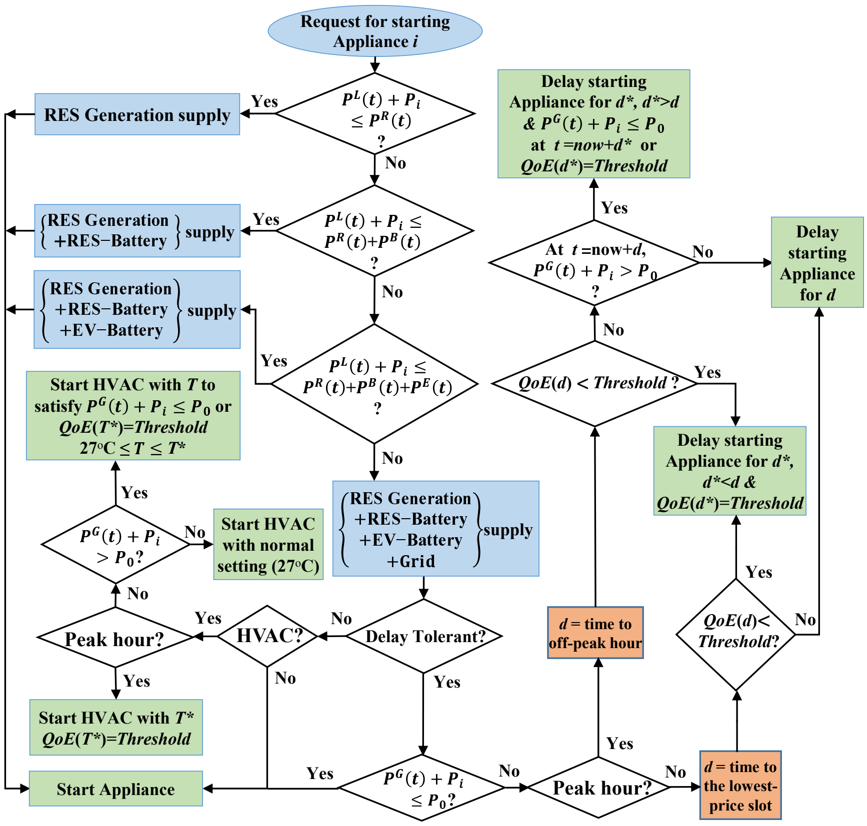


Figure 3. QoE-aware smart appliance control algorithm for sHEMS.

When a request for turning on the HVAC arrives, the HVAC is turned on immediately. At peak hours, the HVAC is set to the highest target temperature T^*, where $\text{QoE}(T^*) = \textit{Threshold}$, in order to reduce the working load. During the off-peak hours, if the power consumption $P^G(t) + P_i$ exceeds the power constraint P_0, the HVAC is set to a higher target temperature T, where 27 °C < $T \le T^*$, in order to meet the power constraint; otherwise, the HVAC is set to the normal target temperature 27 °C to achieve the most comfortable environment for users.

4. Fuzzy-Controlled QoE Threshold

According to the experiments, a higher QoE threshold used in the proposed QoE-aware smart appliance control algorithm usually results in a better user's QoE, but a worse reduction in peak load and electricity bill. However, in the case of low power demand, increasing the QoE threshold barely degrades the reduction performance in the peak load and electricity bill while significantly enhancing the user's QoE. Therefore, the QoE threshold must adapt to different power demands. For example, the QoE threshold decreases as the power demand grows while it increases as the power demand decreases. Hence, in this paper, both the instantaneous power consumption and the power deviation are used to determine a proper QoE threshold. Since the fuzzy theory has been well applied to several different applications [16–18], this paper proposes a fuzzy logic control method to determine a proper QoE threshold for the proposed smart appliance control algorithm in Figure 3.

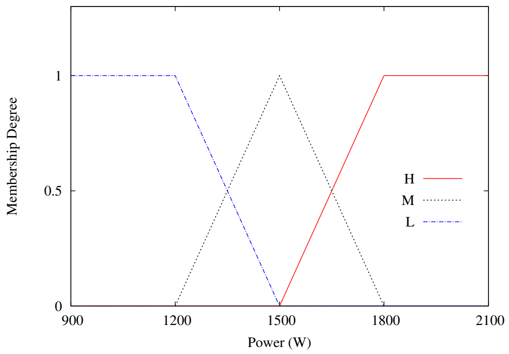
First, the instantaneous power consumption $P(t)$ supplied by the main grid at time slot t and the power deviation $P_D(t)$ between $P(t)$ and $P_{ave}(t)$ are used to decide the optimal QoE threshold $Threshold(t)$. Notably, in this paper, the power consumption is observed at the beginning of each time slot of equal length. The average power consumption $P_{ave}(t)$ is computed based on the power consumption of the M most recent time slots using the moving average. That is,

$$P_{ave}(t) = \frac{1}{M} \sum_{k=t-M+1}^{t} P(k). \tag{3}$$

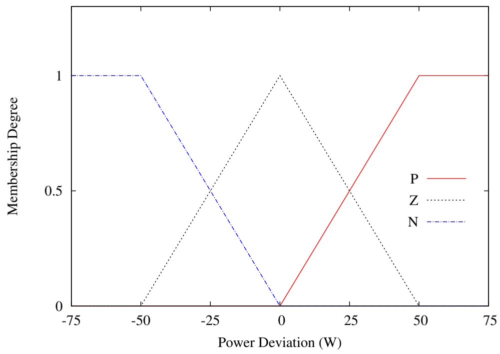
The power deviation $P_D(t)$ is defined by

$$P_D(t) = P(t) - P_{ave}(t). \tag{4}$$

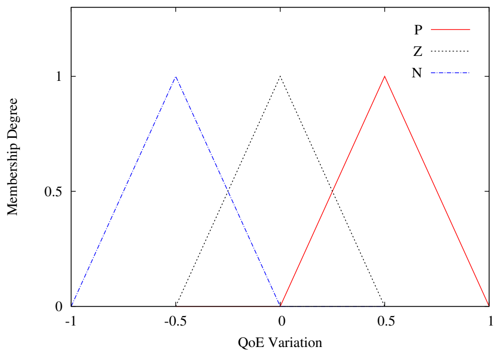
According to the fuzzy logic theory, the membership functions of $P(t)$, $P_D(t)$, and the variation ΔQ of QoE threshold must be first defined. This paper categorizes the instantaneous power consumption $P(t)$ into three levels: H (High), M (Medium), and L (Low). The membership function of $P(t)$ is given by Figure 4a. The power deviation $P_D(t)$ is categorized into P (Positive), Z (Zero), and N (Negative), and its membership function is given by Figure 4b. Similarly, ΔQ is categorized into P (Positive), Z (Zero), and N (Negative), and its membership function is plotted in Figure 4c.



(**a**) Power consumption $P(t)$.



(**b**) Power deviation $P_D(t)$.



(**c**) QoE variation ΔQ.

Figure 4. Membership functions of the proposed fuzzy logic controller.

Second, the Mamdani-type inference rules [26] to determine the variation ΔQ of QoE threshold based on $P(t)$ and $P_D(t)$ are listed in Table 4. The AND operation in the fuzzy logic rule A AND B is defined to be the minimum value of two operands $\mu_1(x_1)$ and $\mu_2(x_2)$, where $\mu_i(x_i)$ is a membership function and $x_1 \in A$ and $x_2 \in B$. In the aggregation process, the max rule is used in deriving the overall output. After the aggregation process, the centroid of area is computed in the defuzzification process to find a crisp value ΔQ. Finally, the QoE threshold $Threshold(t)$ at time slot t is determined as follows:

$$Threshold(t) = Threshold(t-1) + \Delta Q. \tag{5}$$

The block diagram of the proposed fuzzy logic controller is plotted in Figure 5.

Table 4. Inference rules of proposed fuzzy logic.

Rule	$P(t)$	AND	$P_D(t)$	ΔQ
1	H	AND	P	N
2	H	AND	Z	N
3	H	AND	N	Z
4	M	AND	P	N
5	M	AND	Z	Z
6	M	AND	N	P
7	L	AND	P	Z
8	L	AND	Z	P
9	L	AND	N	P

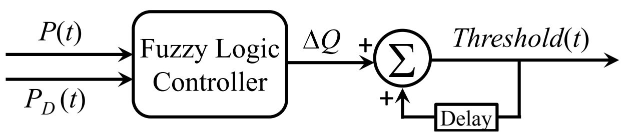


Figure 5. Block diagram of the proposed fuzzy logic controller.

5. Numerical Results

In this paper, C++ simulation programs are created to evaluate the performance of the proposed QoE-aware smart appliance control algorithm with a fuzzy-controlled QoE threshold. The considered delay-tolerant appliances consist of the electric oven, microwave oven, dishwasher, and washing machine. The appliances of delay-intolerant with essential load consist of the TV, fan, computer, and LED bulb. The appliances of delay-intolerant with flexible load consist of the refrigerator, water dispenser, and HVAC. However, in simulations, the refrigerator and water dispenser are treated as the background appliances that are always ON (switching randomly between working and standby states) and no control on them. The mean working powers of the refrigerator and water dispenser are 70 W and 660 W, respectively. The reasons for treating the refrigerator and water dispenser as always ON are explained as follows. First, the refrigerator must always keep its inside temperature within a predefined range such as 3 to 7 °C to keep the food, fruits, and vegetables fresh. If the refrigerator is turned OFF, its inside temperature may increase over the predefined range, maybe resulting in corruption of food, fruits, and vegetables. Second, users may need to have warm or hot water for drink or making tea at any time. If the water dispenser is turned OFF, users may not have warm or hot water for use at their request instant. Therefore, almost all the households keep the refrigerators and water dispensers always ON.

As to the operation of HVAC, it is governed by the following Equation [27]:

$$T_{in}(t) = T_{in}(t-1) + \tau\{E[T_{out}(t) - T_{in}(t)] - \phi S_{HVAC}(t)\}, \tag{6}$$

where $T_{in}(t)$ and $T_{out}(t)$ are the indoor and outdoor temperatures, respectively, at time t. The curve of outdoor temperature $T_{out}(t)$ used in simulations is given in Figure 6 [28]. The parameter τ is the sampling interval of temperature. E is an increasing factor of temperature per unit time and is set to 0.0408 [27] in simulations. The parameter ϕ is the cooling efficiency of HVAC in working state and is set to 3.8 in simulations. Finally, $S_{HVAC}(t)$ is the status of HVAC at time t. Whenever the indoor temperature $T_{in}(t)$ is higher than the target temperature of the HVAC by 1 °C, the HVAC starts working, i.e., $S_{HVAC}(t) = 1$, to cool down until $T_{in}(t)$ is less than the target temperature. Whenever $T_{in}(t)$ is less than the target temperature, the HVAC stays at the standby state of $S_{HVAC}(t) = 0$ until $T_{in}(t)$ exceeds the target temperature by 1° C again. Under the QoE-aware smart control, the target temperature of the HVAC is automatically controlled by Equation (2) and the power constraint $P_0 = 2200$ W. The moving average parameter M for calculating the average power consumption $P_{ave}(t)$ in Equation (3) is set to 5. In simulations, the length of each time slot is set to 15 min. Other simulation parameters of home appliances in summer and winter are given in Table 5, where the request arrival time during a given interval follows the uniform distribution. The simulation parameters of home appliances in summer and winter are almost similar except that fans and HVAC are always OFF in winter. The duration of 100 days is simulated both in summer and winter, and the average of the measured parameter is taken over 100 days. According to the dynamic electricity prices [29] given by Figure 7, the peak period ranges from 12:00 p.m. to 7:00 p.m.

Table 5. Simulation parameters of home appliances used in simulations.

Appliances	Power (W)	Summer		Winter	
		Request Arrival Time	Working Time (h)	Request Arrival Time	Working Time (h)
TV	150	7:00–8:00 13:00–14:00 18:00–20:00	4	7:00–8:00 13:00–14:00 18:00–20:00	4
Fan	80	7:00–8:00 13:00–14:00	3	- -	- -
Computer	450	11:00–13:00	12	11:00–13:00	12
LED bulbs	200	6:30–7:00	18	6:30–7:00	18
LED bulbs	50	Poisson: rate 0.2/h	4	Poisson: rate 0.2/h	4
Dishwasher	1300	9:00–10:00 15:00–16:00 19:00–19:30	1	9:00–10:00 15:00–16:00 19:00–20:30	1
Electric oven	1500	7:00–9:00 14:00–16:00 17:00–18:00	0.5	7:00–9:00 14:00–16:00 17:00–18:00	0.5
Microwave oven	1000	7:00–9:00 12:00–14:00 18:00–19:00	0.2	7:00–9:00 12:00–14:00 18:00–19:00	0.2
Washing machine	500	20:30–21:30	2	20:30–21:30	2
HVAC/Bedroom	1380	21:00–22:00	11	-	-
HVAC/Living Room	1380	10:30–11:00	10	-	-

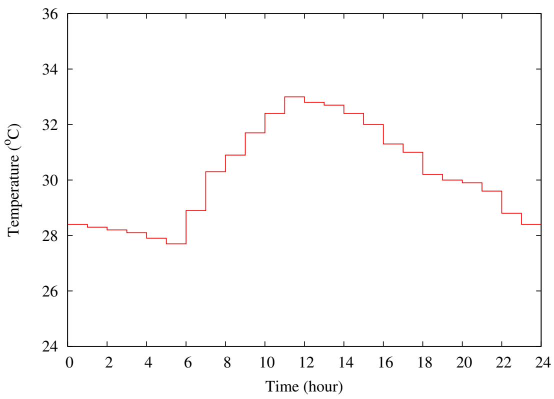


Figure 6. Outdoor temperature [28].

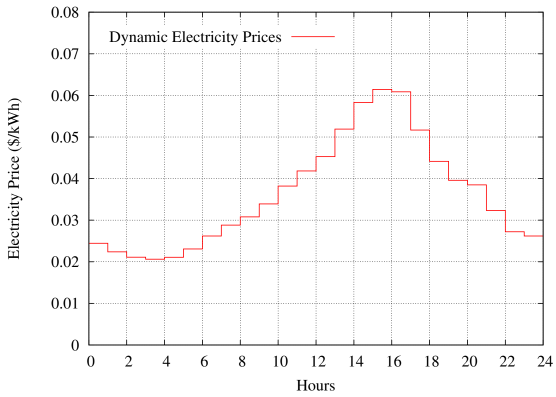


Figure 7. Dynamic electricity prices [29].

To investigate the performance of the proposed QoE-aware smart appliance control algorithm, the scenario without RES nor EV is first considered. Figure 8 shows the average power consumption in a day. The baseline in Figure 8 represents the scheme without any control on home appliances or HVAC, i.e., a home appliance is turned on immediately at its request arrival instant and the HVAC always has the setting of normal target temperature (27 °C). The optimal scheduling of appliances presented in [30] is also simulated for comparison. In the optimal scheduling scheme, the HVAC always has the setting of normal target temperature (27 °C) and the starting times of delay-tolerant appliances are determined by solving the optimization problem of minimizing the electricity bill, subject to the constraint that the starting time of an appliance must fall within the interval between the request arrival instant t and $t + d^*$, where $\text{QoE}(d^*) = 3$. In the proposed with fixed QoE TH scheme, the proposed QoE-aware smart appliance control algorithm is simulated and the QoE threshold is fixed at 3. As to the proposed with fuzzy-controlled QoE TH scheme, the proposed QoE-aware smart appliance control algorithm and the fuzzy-controlled QoE threshold are used. In Figure 8, whether using a fixed or fuzzy-controlled QoE threshold, the peak load significantly decreases under the proposed QoE-aware smart appliance control algorithm, relative to the baseline case. As to the optimal scheduling scheme, it is worse than the proposed QoE-aware smart appliance control algorithm in terms of the peak load reduction performance.

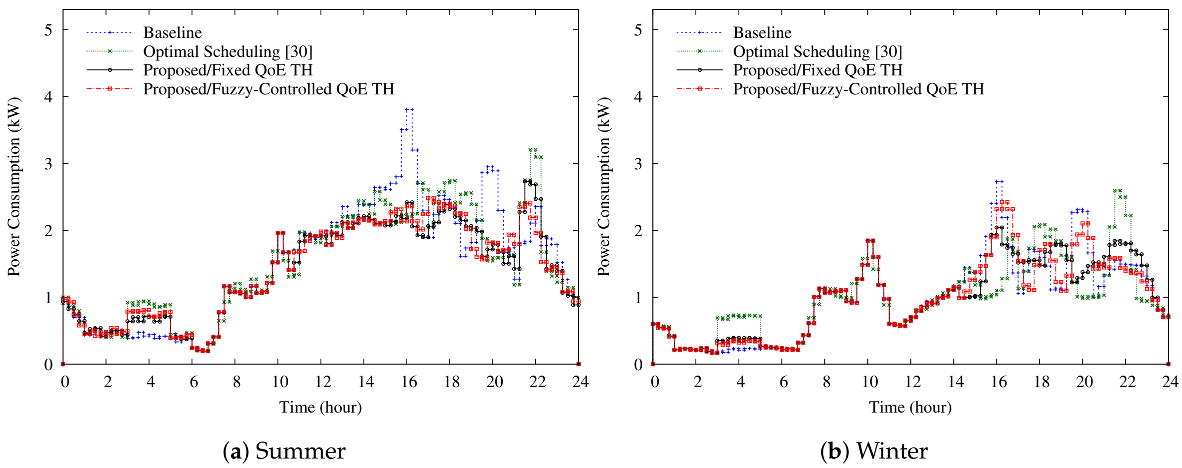
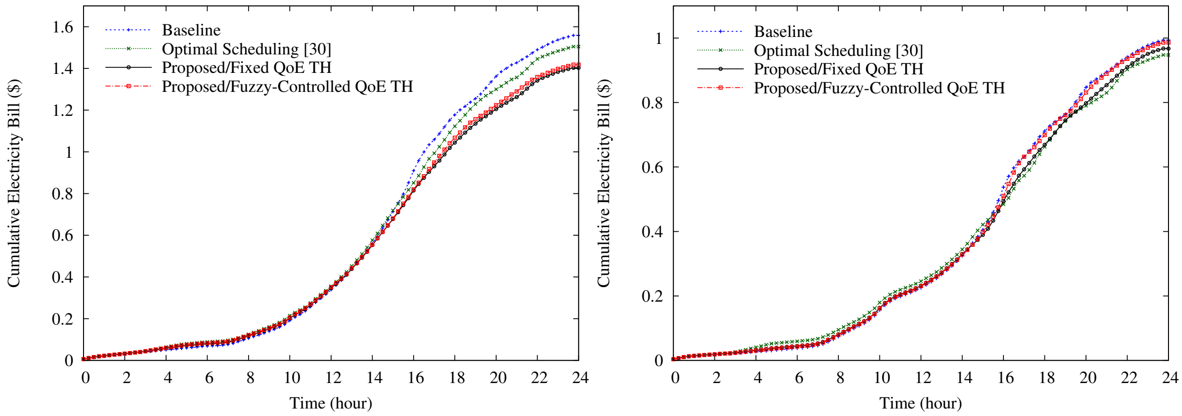


Figure 8. Comparison of power consumption.

The cumulative electricity bill per day is plotted in Figure 9. In summer days, the proposed QoE-aware smart appliance control algorithm achieves a lower electricity bill, compared with the baseline and optimal scheduling schemes. In winter days, the optimal scheduling scheme achieves the lowest electricity bill. However, the difference among various schemes is very minor because the power consumption in winter days is lower. Thus, sacrificing a user's QoE may not significantly reduce the electricity bill in winter days. To further evaluate the performance of different schemes, the user's QoE under different schemes must be compared.



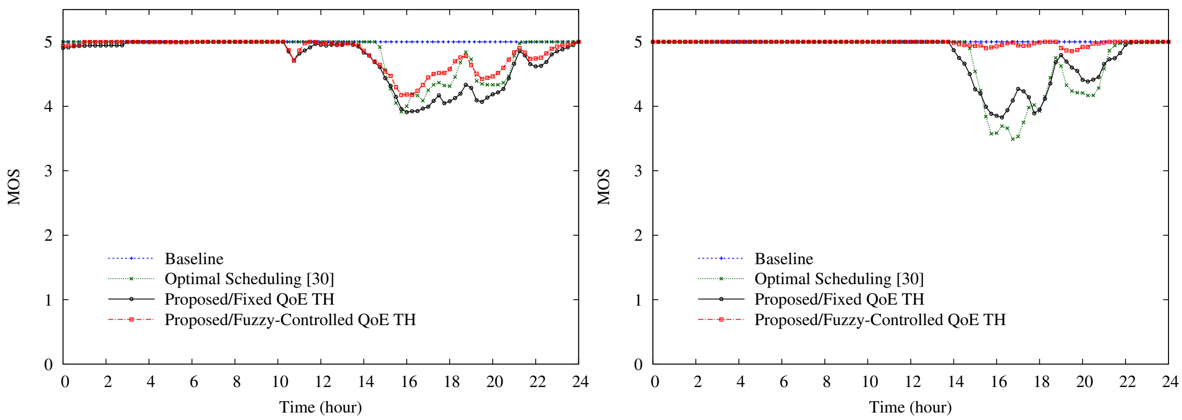
(**a**) Summer (**b**) Winter

Figure 9. Comparison of the electricity bill.

Figure 10 shows the user's average QoE under different schemes. The average QoE $QoE_{ave}(t)$ at time slot t is computed according to the following equation:

$$\text{QoE}_{ave}(t) = \frac{1}{N(t)} \sum_{i=1}^{N(t)} \text{QoE}_i(t), \tag{7}$$

where $N(t)$ is the number of requested appliances (delay-tolerant appliances or HVAC) waiting to start or in ON at time slot t. For a delay-tolerant appliance, $\text{QoE}_i(t)$ equals 5 if the appliance has been ON and is computed according to Equation (1) if the appliance is waiting to start. For the HVAC, $\text{QoE}_i(t)$ is computed according to Equation (2). According to Figure 10, the proposed QoE-aware smart appliance control algorithm with a fuzzy-controlled QoE threshold significantly outperforms the other schemes in terms of the user's QoE, especially in winter days. Although the optimal scheduling scheme achieves the lowest electricity bill in winter days, compared with other schemes, it results in the worst user's QoE.



(**a**) Summer (**b**) Winter

Figure 10. Comparison of user's QoE.

According to the results in Figures 8–10, the following conclusions are made. First, compared with the baseline and optimal scheduling schemes, the proposed QoE-aware smart appliance control algorithm effectively shaves the peak load, demonstrating that the proposed control algorithm with a power constraint P_0 is outstanding. Second, compared to the QoE-aware smart appliance control algorithm with a fixed QoE threshold scheme, the one with a fuzzy-controlled QoE threshold can achieve similar reduction performance in the peak load and electricity bill while significantly improving the user's QoE, demonstrating the superiority of the proposed fuzzy logic controller for setting the QoE threshold. Finally, compared with the baseline and optimal scheduling schemes, the proposed control algorithm for the HVAC can further decrease the electricity bill in summer days.

Next, the scenario of the sHEMS with RES and EV in summer days is simulated. In this section, the renewable energy sources only include the PV. Twelve solar panels of CS6P-255P of 255 W are assumed in simulations. The generating power profile of these 12 solar panels is shown in Figure 11 [31]. The schedule of EV charging and discharging is given in Table 6, where the SOC constraint of the EV battery is set to the range of 60% to 100%. Since the lowest electricity price is at 3:00 according to Figure 7, the charging of EV battery starts randomly between 2:00 to 3:00. The discharging of EV battery to the load starts at the time of the highest electricity price, i.e., 15:00. The capacity of the EV battery is assumed to be 16 kWh and the charging power rate is set to 1.92 kW/hr [32]. The setting of other simulation parameters is similar to the first scenario without RES nor EV. The baseline in Figure 12 is the case that does not consider PV or EV and does not have any appliance control. The proposed QoE-aware smart appliance control algorithm with a fuzzy-controlled QoE threshold is considered in Figure 12.

Table 6. Schedule of EV charging and discharging.

Battery Status	Start Time	SOC Constraint of Battery
Charging	Random over (2:00, 3:00)	≤100%
Discharging	15:00	≥60%

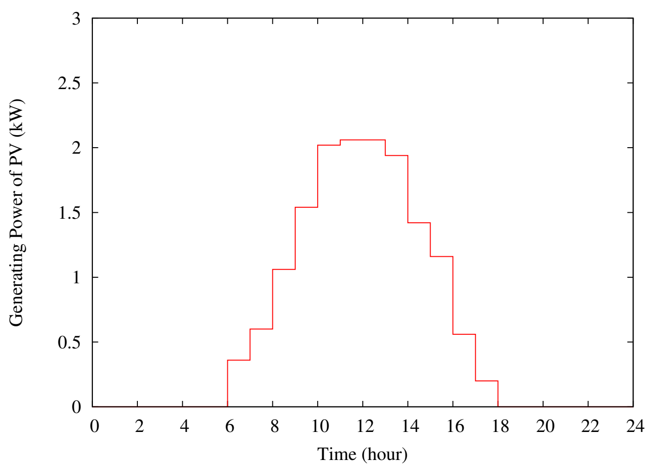
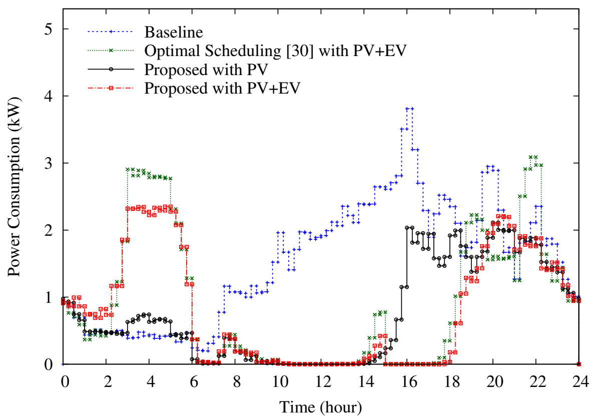
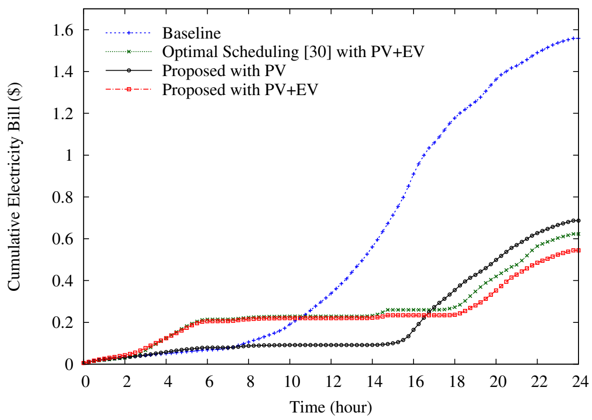


Figure 11. Generating power of 12 solar panels [31].

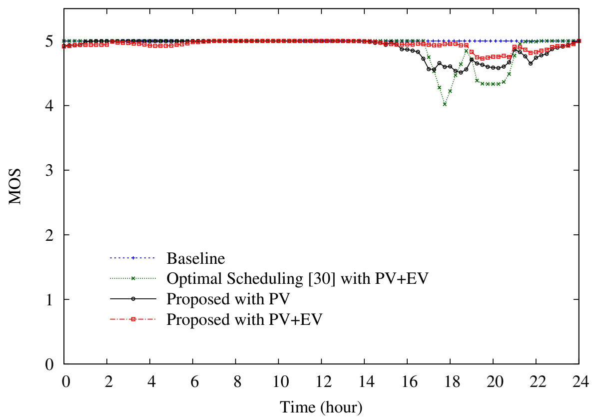
Figure 12a shows the power consumption supplied by the grid under different schemes. Obviously, PV significantly reduces the power consumption supplied by the grid during the periods with high electricity prices, yielding a significant reduction in the electricity bill, as shown in Figure 12b. Additionally, observing the difference between the proposed scheme with PV and the proposed scheme with PV+EV in Figure 12b,c, one can conclude that a proper scheduling for EV battery charging and discharging results in a further reduction in the electricity bill and an increase in the user's QoE. Compared with the baseline case, the proposed scheme reduces the electricity bill by 65% under the scenario with RES and EV. Compared with the optimal scheduling scheme, the proposed scheme achieves better reduction performance in the peak load and electricity bill, and has a better user's QoE, as shown in Figure 12. Finally, compared with Figures 8–10, the electricity bill and power consumption supplied by the grid significantly decrease while the user's QoE substantially increases under the scenario with PV or EV, as shown in Figure 12. All these results validate the superiorities of the proposed QoE-aware smart appliance control algorithm with a fuzzy-controlled QoE threshold and the power allocation strategy for RES and EV batteries.



(**a**) Power consumption.



(**b**) Electricity bill.



(**c**) User's QoE.

Figure 12. Performance comparison of various schemes under the scenario with PV and EV.

6. Conclusions

In this work, a QoE-aware smart appliance control algorithm with a fuzzy-controlled QoE threshold for the sHEMS with RES and EV to shave the peak load, reduce the electricity bill, and optimize the user's QoE is proposed. According to the simulation results, the proposed QoE-aware smart appliance control algorithm significantly decreases the peak load and electricity bill. Additionally, the designed fuzzy logic controller for dynamically adjusting the QoE threshold can optimize the user's QoE while preserving the reduction performance in the peak load and electricity bill. Moreover, under the case of high power demand, the proposed QoE-aware smart appliance control algorithm with a fuzzy-controlled QoE threshold significantly outperforms the optimal scheduling scheme [30] in terms of the peak load, electricity bill, and user's QoE. Finally, numerical results show that integrating RES and EV into the sHEMS and properly scheduling the EV charging and discharging can further decrease the peak load and electricity bill, and improve the user's QoE. Compared with the baseline case, the proposed scheme reduces the electricity bill by 65% under the scenario with RES and EV, demonstrating that the proposed scheme is outstanding.

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Author Contributions: M.L. designed the QoE functions, QoE-aware smart appliance control algorithm, and wrote the paper; G.-Y.L. designed the QoE-aware smart appliance control algorithm and experiments, and analyzed data; H.-R.C. designed the fuzzy logics of QoE threshold and experiments, and analyzed data; C.-W.J. designed the QoE-aware smart appliance control algorithm and did the curve fittings of QoE functions.

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