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Smart Home Energy Management Optimization Method Considering Energy Storage and Electric Vehicle

XUAN HOU[1,2], JUN WANG[1,2], TAO HUANG[1,3], (Member, IEEE), TAO WANG[1,2], (Member, IEEE), AND PENG WANG[4], (Fellow, IEEE)

[1]School of Electrical Engineering and Electronic Information, Xihua University, Chengdu 610039, China
[2]Key Laboratory of Fluid and Power Machinery, Ministry of Education, Xihua University, Chengdu 610039, China
[3]Department of Energy, Politecnico di Torino, 10129 Turin, Italy
[4]School of Electrical and Electronic Engineering, College of Engineering, Nanyang Technological University, Singapore 639798

Corresponding authors: Jun Wang (wj.xhu@foxmail.com) and Tao Huang (tao.huang@polito.it)

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ABSTRACT As the last link of an integrated future energy system, the smart home energy management system (HEMS) is critical for a prosumer to intelligently and conveniently manage the use of their domestic appliances, renewable energies (RES) generation, energy storage system (ESS), and electric vehicle (EV). In this paper, we propose a holistic model to center the preference of users when scheduling the involved physical equipment of different natures. Further, a dedicatedly designed charging and discharging strategy for both the ESS and EV considering their capital cost is proposed to integrate them into the HEMS for providing a better flexibility and economic advantages as well as to prolong the life of the batteries. Based on the mixed integer linear programming (MILP) and the proposed model, the energy schedule of the smart home can be derived to guarantee both the lowest cost and the comfort for the users. An illustrative case study is employed to demonstrate the effectiveness of the proposed method.

INDEX TERMS Smart home, energy management, MILP, smart grid.

NOMENCLATURE

CA	Constrained appliances
EA	Entertainment appliances
ESS	Energy storage system
ESS2H	ESS-to-Home
EV	Electric vehicle
HEMS	Home energy management system
MILP	Mixed integer linear programming
PEV	Plug-in electric vehicle
PV	Photovoltaic
RES	Renewable energies
RTP	Real-time pricing
SA	Schedulable appliances
V2H	Vehicle-to-Home

INDICES

$d \in \{1, 2, \cdots, D\}$	Index of SA loads
$t \in \{1, 2, \cdots, T\}$	Index of time slots

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PARAMETERS

α	Thermal characteristic of air conditioning
β	Work mode of air conditioning. $\beta > 0$ corresponds to the heating mode; $\beta < 0$ corresponds to the cooling mode
η_{ESS}^{ch}	ESS charging efficiency
η_{ESS}^{dis}	ESS discharging efficiency
η_{PEV}^{ch}	PEV charging efficiency
η_{PEV}^{dis}	PEV discharging efficiency
C_{ESS}^{int}	ESS initial capacity (kWh)
C_{ESS}^{max}	ESS maximum capacity (kWh)
C_{PEV}^{int}	PEV initial capacity (kWh)
C_{PEV}^{max}	PEV maximum capacity (kWh)
N_d	Length of time for the dth SA to complete all tasks
P_{AC}^{max}	Air conditioning rated power (kW)
P_{DG}	RES generation (kW)
P_{DR}	Power limit drawn from the utility (kW)
P_d	Power consumption of the dth SA (kW)
P_{ESS}^{chmax}	Maximum charging power of ESS (kW)

P_{ESS}^{dismax}	Maximum discharging power of ESS (kW), $P_{ESS}^{dismax} < 0$
P_{EWH}^{max}	Electric water heater rated power (kW)
P_E	EA power consumption (kW)
P_{PEV}^{chmax}	Maximum charging power of PEV (kW)
P_{PEV}^{dismax}	Maximum discharging power of PEV (kW), $P_{PEV}^{dismax} < 0$
RTP	Electricity price ($/kWh)
RTP_{AVG}	Average electricity price ($)
$RTP_{ESS_{dis}}$	ESS discharging price threshold ($)
$RTP_{PEV_{ch}}$	Average electricity price during PEV access to the home ($)
$RTP_{PEV_{dis}}$	PEV discharging price threshold ($)
T	Set of time slots
T^{cw}	Incoming cold water temperature (°F)
T^{en}	Ambient temperature (°F)
T^{out}	Outdoor temperature (°F)
T_{AC}^{max}	Upper limit of user acceptable indoor temperature (°F)
T_{AC}^{min}	Lower limit of user acceptable indoor temperature (°F)
t_a	PEV arrival time
t_d	PEV departure time
t_d^{begin}	Start time of the allowable operation range of the dth SA
t_d^{end}	End time of the allowable operation range of the dth SA
T_{EWH}^{max}	Upper limit of user acceptable hot water temperature (°F)
T_{EWH}^{min}	Lower limit of user acceptable hot water temperature (°F)
T_{hw}^{int}	Initial water temperature in the tank (°F)
T_{in}^{int}	Initial indoor temperature (°F)

VARIABLES

C_{ESS}	ESS capacity (kWh)
C_{PEV}	PEV capacity (kWh)
P_{AC}	Air conditioning power consumption (kW)
P_{ESS}^{chable}	Maximum allowable charging power of ESS under its capacity constraint (kW)
P_{ESS}^{ch}	ESS charging power (kW)
$P_{ESS}^{disable}$	Maximum allowable discharging power of ESS under its capacity constraint (kW)
P_{ESS}^{dis}	ESS discharging power (kW), $P_{ESS}^{dis} < 0$
P_{EWH}	Electric water heater power consumption (kW)
P_G	Interaction power between the utility and HEMS (kW). $P_G > 0$ indicates the power drawn form the utility; $P_G < 0$ indicates the power injected to the utility
P_{PEV}^{chable}	Maximum allowable charging power of PEV under its capacity constraint (kW)
P_{PEV}^{ch}	PEV charging power (kW)
$P_{PEV}^{disable}$	Maximum allowable discharging power of PEV under its capacity constraint (kW)
P_{PEV}^{dis}	PEV discharging power (kW), $P_{PEV}^{dis} < 0$
T^{hw}	Hot water temperature (°F)
T^{in}	Indoor temperature (°F)
u_d	Binary variable, the startup/shutdown state of dth SA, 1 if dth SA operating, else 0
u_{ESS}	Binary variable, the charging/discharging state of ESS, 1 if ESS charging, else 0
u_{PEV}	Binary variable, the charging/discharging state of PEV, 1 if PEV charging, else 0

I. INTRODUCTION

Smart home energy management is an indispensable part of the smart grid environment, which allows load management to be implemented among residents for reducing electricity bills [1], flexibly accommodating high penetrated renewable energies (RES), both at remote and local [2]. An efficient and economical home energy management system (HEMS) must consider not only the traditional domestic appliances but also emerging ones, such as energy storage system (ESS), electrical vehicle (EV), etc. The emerging appliances provide an opportunity for the HEMS to further lessen costs, mitigate peak pressures and overcome the uncertainty of RES generation [3], [4]. Yet, they are also accompanied by challenges. For instance, the random charging and discharging of unmanaged EVs can exacerbate peak demand, cause potential overload and damage local distribution lines [5], [6]. Therefore, a reasonable charging and discharging control strategy of ESS and EV, which is intelligently regulated by HEMS, will play an important role in the smart home operation.

As the main trend of intelligent scheduling domestic appliances, HEMS has attracted a lot of studies [7]–[10]. In [11], a low complexity HEMS model equipping with real time appliances and schedulable appliances is proposed to minimize operational cost. In [12], a convex programming home energy optimization framework including schedule-based appliances, battery-assisted appliances and model-based appliances is introduced to minimize the user's electricity bill and dissatisfaction. Similarly, on the basis of reducing cost and discomfort, RES and storage models are further developed to lower the power purchased from the utility [13], avoid peak demand [14] and fossil fuel consumption. Both environmental pollution and the cost of gasoline promote the use of EVs. However, neither [13] nor [14] discusses the opportunities and challenges that EV brings to the HEMS. The HEMS model with RES, energy storage and plug-in electric vehicle (PEV) is established in [15] to achieve the cost saving for the residential consumer and the full utilization of RES. However, the EV discharging mode for further reducing cost and peak load is not included in this model. In [16]–[18], ESS and EV with bidirectional energy flow are used to help schedule the operation of domestic appliances, aiming to provide more economic benefits for the smart home.

The smart home energy management is an optimization problem with multidimensional variables and multiple constraints, where the variables include discrete and continuous ones. In general, heuristic algorithms are often used to solve the above problem, such as genetic algorithms [15], [19], [20], particle swarm optimization algorithms [21]–[23], the cuckoo search algorithm and strawberry algorithm [24], and the ant colony algorithm [25]. When faced with multivariate problems, due to the poor efficiency, high complexity and inaccuracy of heuristic algorithms, the mixed integer linear programming (MILP) as an alternative method, can obtain the unique optimal solution quickly and accurately. The modular structure of MILP model also makes it easy to modify to adapt the various preferences of users [17]. In [26], a MILP model is designed for smart homes to optimize the environment and cost. In order to minimize the operating costs, a residential microgrid model based on the MILP is proposed in [27].

However, the above works fail to deeply study the combined charging and discharging strategy of ESS and EV in a comprehensive HEMS model, which can save more costs, reduce battery degradation and meet the travel needs of residents. Therefore, in this paper, a MILP-based model including HEMS, RES, ESS, PEV and various domestic appliances is formulated. Then, an exact solution method based on the bidirectional energy control strategy of ESS and PEV is adopted to achieve the lowest cost control target for a smart home. The main contributions of this study are listed as follows:

1) We classified common domestic appliances into 3 catalogues and modelled by various dimensions, i.e. the operating nature (e.g. consumption limits, time limits, relativity to temperature, etc.), controllability. Based on that, user' satisfaction as to how to engage them is employed together to form relevant analytic models. By considering with the RES generation, real-time pricing (RTP), batteries energy storage, the minimal total cost of a smart home can be achieved with a guaranteed user satisfaction.
2) A combined charging and discharging strategy for the ESS and PEV considering their technical constraints and the RTP is proposed to rationally manage the energy transaction between the residence and utility. Due to the restrictions of both the discharging price thresholds on the ESS and PEV and the duration of PEV V2H mode, this strategy not only brings a better economic revenue to the user, but also prolongs the life of batteries and meets the PEV capacity requirement when traveling.

The rest of this paper is organized as follows: in Section II, we introduce the energy flow structure and the scheduling objective for the smart home. Then, Section III proposes a method to solve the smart home energy optimization problem. Simulations are carried out in Section IV and conclusions are given in Section V.

II. PROBLEM FORMATION

In this paper, the designed energy flow structure for a smart home is shown in Fig. 1. The structure integrates the smart meter including bidirectional metering and bidirectional communication, HEMS, utility, RES (the rooftop photovoltaic generation), ESS, PEV and domestic appliances. Among them, ESS and PEV have ESS-to-Home (ESS2H) and Vehicle-to-Home (V2H) modes, respectively. Furthermore, in order to more efficiently schedule various domestic appliances, appliances are classified into three categories. The first is entertainment appliances (EA), such as smartphone, television and computer. EA loads can obtain sufficient energy in each time slot because of user's entertainment needs. The second is constrained appliances (CA), which can be scheduled under the premise of satisfying comfort requirements of user, such as air conditioning and electric water heater. The third is schedulable appliances (SA), such as washing machine and dishwasher. Based on the electricity price and necessary constraints, HEMS will find the optimal operating plan for SA loads.

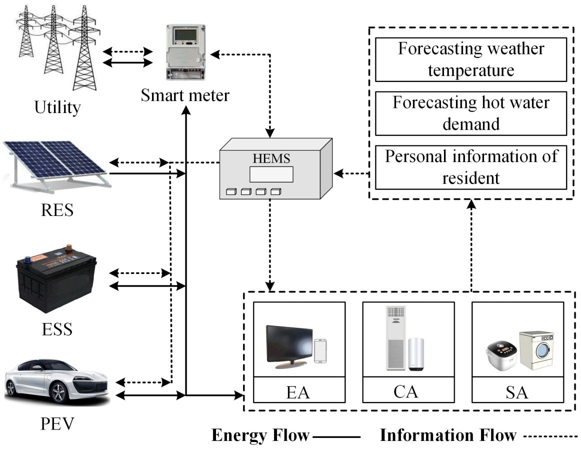

FIGURE 1. The energy flow structure of a smart home.

In the presented structure, RTP, photovoltaic (PV) generation, outdoor temperature, hot water demand, domestic appliance parameters and user personal information are transmitted to HEMS before scheduling. As part of the needed data are based on forecast, which can be either from public available sources, such as the weather stations for temperature, or the in-house forecast, such as the hot water demand. Therefore, dedicated modules for communicating with public information platform and in-house forecast are required in the HEMS. Due to the focus of this paper, such module will not be discussed and we assume the needed forecast data are available. In addition, we assume that the smart meter receives RTP from the utility over power line carrier [11]. The HEMS communicates with each device in the structure through a wireless ZigBee network to achieve automatic control of the smart home [15].

A. SYSTEM MODEL

In what follows, devices in the energy flow structure of the smart home are formulated respectively.

1) CA LOADS

CA loads are closely related to the temperature comfort requirements of the resident. The temperatures considered in this paper are the indoor temperature and the hot water temperature. Thus, in order to ensure resident's comfort, we use the temperature deadband constraints according to (3) and (7).

The indoor temperature is calculated by (1) [28].

$$\begin{aligned} T^{in}(t) &= T^{in}(t-1) + \alpha\left(T^{out}(t) - T^{in}(t-1)\right) \\ &\quad + \beta P_{AC}(t)\,\Delta t && (1) \\ T^{in}(t-1) &= T_{in}^{int},\ t=1 && (2) \\ T_{AC}^{min} &\leqslant T^{in}(t) \leqslant T_{AC}^{max} && (3) \\ P_{AC}(t) &\leqslant P_{AC}^{max} && (4) \end{aligned}$$

The hot water temperature is calculated by (5).

$$\begin{aligned} T^{hw}(t) &= T^{hw}(t-1)\cdot e^{-\left(\frac{1}{R'\cdot C}\right)\Delta t} \\ &\quad + \left\{G\cdot R'\cdot T^{en} + B\cdot R'\cdot T^{cw} + Q(t)\cdot R'\right\} \\ &\quad \cdot\left[1 - e^{-\left(\frac{1}{R'\cdot C}\right)\Delta t}\right] && (5) \\ T^{hw}(t-1) &= T_{hw}^{int},\ t=1 && (6) \\ T_{EWH}^{min} &\leqslant T^{hw}(t) \leqslant T_{EWH}^{max} && (7) \\ P_{EWH}(t) &\leqslant P_{EWH}^{max} && (8) \end{aligned}$$

where $Q(t) = 3.4121 \times 10^3 \times P_{EWH}(t)$, $Q(t)$ is the energy input rate. More detailed explanations for the hot water temperature calculation can be found in [29].

2) SA LOADS

For all SA loads, the constraint (9) needs to be added to guarantee their running length. The constraint (10) is set for a portion of SA loads, such as washing machine and dishwasher, to maintain their running continuity.

$$\sum_{t=t_d^{begin}}^{t_d^{end}} u_d(t) = N_d \tag{9}$$

$$\begin{cases} \sum_{t=2}^{T} |u_d(t) - u_d(t-1)| = c1, & u_d(1) = 1\ \&\ u_d(T) = 1 \\ c1 < \sum_{t=2}^{T} |u_d(t) - u_d(t-1)| \leqslant c2, & Otherwise \end{cases} \tag{10}$$

where $c1 = (num_d - 1) \times 2$, $c2 = num_d \times 2$, num_d is the number of times that dth SA needs to fulfill established tasks in the calculated horizon. If $num_d = 1$, then $c1 = 0$, $c2 = 2$, indicating that the total number of times for dth SA from 0 to 1 (startup) and from 1 to 0 (shutdown) is greater than or equal to 0 and less than or equal to 2.

3) ESS

Since the charging and discharging power of ESS can be dynamically adjusted according to energy surplus or insufficient, the flexibility of HEMS can be enhanced by using the ESS. The operating constraints of ESS are the upper and lower limits of capacity and maximum charging and discharging power defined by (14), (15), and (16), respectively.

$$\begin{aligned} P_{ESS}(t) &= P_{ESS}^{ch}(t)\,u_{ESS}(t) + P_{ESS}^{dis}(t) \\ &\quad (1 - u_{ESS}(t)) && (11) \\ C_{ESS}(t) &= C_{ESS}(t-1) + P_{ESS}^{ch}(t)\,u_{ESS}(t)\,\Delta t\,\eta_{ESS}^{ch} \\ &\quad + P_{ESS}^{dis}(t)\,(1 - u_{ESS}(t))\,\Delta t/\eta_{ESS}^{dis} && (12) \\ C_{ESS}(t-1) &= C_{ESS}^{int},\ t=1 && (13) \\ 0.2C_{ESS}^{max} &\leqslant C_{ESS}(t) \leqslant 0.8C_{ESS}^{max} && (14) \\ 0 &\leqslant P_{ESS}^{ch}(t)\,\eta_{ESS}^{ch} \leqslant P_{ESS}^{chmax} && (15) \\ P_{ESS}^{dismax} &\leqslant P_{ESS}^{dis}(t)/\eta_{ESS}^{dis} \leqslant 0 && (16) \end{aligned}$$

4) PEV

Compared with energy storage that requires high installation, operation and maintenance costs, PEV can be used as a relatively inexpensive way to store and transfer energy [30]. Similar to ESS, the capacity constraint and the maximum charging and discharging power constraints of PEV are represented in (20), (21) and (22).

$$\begin{aligned} P_{PEV}(t) &= P_{PEV}^{ch}(t)\,u_{PEV}(t) + P_{PEV}^{dis}(t) \\ &\quad (1 - u_{PEV}(t)),\ t \in [t_a,\ \ t_d) && (17) \\ C_{PEV}(t) &= C_{PEV}(t-1) + P_{PEV}^{ch}(t)\,u_{PEV}(t)\,\Delta t\,\eta_{PEV}^{ch} \\ &\quad + P_{PEV}^{dis}(t)\,(1 - u_{PEV}(t))\,\Delta t/\eta_{PEV}^{dis}, \\ &\quad t \in [t_a, t_d) && (18) \\ C_{PEV}(t-1) &= C_{PEV}^{int},\ t \leqslant t_a && (19) \\ &\begin{cases} 0.3C_{PEV}^{max} \leqslant C_{PEV}(t) \leqslant 0.8C_{PEV}^{max}, \\ \qquad t \in [t_a, t_d - 1) \\ C_{PEV}(t) \geqslant 0.8C_{PEV}^{max}, \\ \qquad t = t_d - 1 \end{cases} && (20) \\ 0 &\leqslant P_{PEV}^{ch}(t)\,\eta_{PEV}^{ch} \leqslant P_{PEV}^{chmax},\ t \in [t_a, t_d) && (21) \\ P_{PEV}^{dismax} &\leqslant P_{PEV}^{dis}(t)/\eta_{PEV}^{dis} \leqslant 0,\ t \in [t_a, n] && (22) \end{aligned}$$

The time period for PEV to participate in scheduling as energy storage is $[t_a, n]$. In $[n+1, t_d)$, PEV is used only as a household load. The calculation of n will be discussed in detail in the next section.

5) UTILITY

The HEMS should also manage the energy exchange with outside, either with utility companies [17] or local energy community [31]. HEMS has the ability to shift domestic loads from peak period to valley period to avoid exacerbating peak demand which usually resulting in potential overload and damage to local distribution lines. Therefore, even if the user's electricity cost reduction brings some economic losses to utility in terms of the electricity selling business, the HEMS can ultimately benefit the utility by reducing the investment and operation and maintenance costs due to the flattening of the peak loads. In addition, as the HEMS uses the RTP, the utility can also find new business models based on the RTP, e.g. using RTP to encourage the customers to participate the demand response or lower the total cost for purchasing electricity in the day-ahead wholesale market etc.

The interaction power between utility and HEMS is calculated by (23). The peak power constraint is expressed by (24) to avoid the formation of new peaks during low price periods.

$$P_G(t) = P_E(t) + P_{AC}(t) + P_{EWH}(t) + \sum_{d=1}^{D} P_d(t)\, u_d(t) + P_{ESS}(t) + P_{PEV}(t) - P_{DG}(t) \tag{23}$$

$$P_G(t) \leqslant P_{DR} \tag{24}$$

B. OBJECTIVE FUNCTION

The control objective of this paper is to minimize the cost of the user, which can be calculated in (25).

$$minCost\,(P_G) = \sum_{t=1}^{T} P_G(t) \times RTP(t) \times \Delta t \tag{25}$$

III. SMART HOME ENERGY MANAGEMENT METHOD

Based on the combined charging and discharging strategy of ESS and PEV, an energy management method is proposed in this section, which can provide the optimal scheduling scheme for the smart home.

A. COMBINED CHARGING AND DISCHARGING STRATEGY OF ESS AND PEV

In order to maximize the economic benefits and reduce the charging and discharging cycles, the combined charging and discharging strategy is proposed to optimize the charging and discharging time and power for ESS and PEV. In this strategy, when PEV is connected to the home, the operating time of the V2H mode of PEV is limited to $[t_a, n]$. Algorithm 1 is used to calculate the value of n, and its execution steps are as follows:

Step.1 Calculate $RTP_{PEV_{ch}}$. $RTP_{PEV_{ch}}$ is the average electricity price during PEV access to the home;

Step.2 Filter the time slots that can be used to charge PEV. Only when the current price is lower than $RTP_{PEV_{ch}}$, the current time slot is considered to be available for charging;

Step.3 Set the capacity of PEV in the last charging time slot to the maximum capacity;

Step.4 Calculate P_{PEV} in each charging time slot by choosing a smaller value between P_{temp} and the maximum charging power of PEV;

Step.5 Calculate C_{PEV} from the last charging time slot until C_{PEV} is less than or equal to the minimum capacity, then stop the calculation and obtain n.

There are some additional explanations for Algorithm 1. 1) The reason for the calculation from back to front is to extend the discharging time of PEV; 2) since PEV charging is usually concentrated in the early morning and there is almost no SA loads operation at that time, the calculation of P_{PEV} is implemented by utilizing P_{DR}, P_E, P_{AC}, P_{EWH} and P_{PEV}^{chmax}; 3) in order to reserve sufficient energy for PEV to meet the user's travel, Algorithm 1 stops the calculation when the PEV capacity drops to a minimum.

Algorithm 1 The Calculation of n.

```
Input: $C_{PEV}^{max}$, $P_{PEV}^{chmax}$, $\eta_{PEV}^{ch}$, $t_a$, $t_d$, $T$, $RTP$, $P_{DR}$, $P_E$, $P_{AC}$, $P_{EWH}$
Output: $n$
Compute $RTP_{PEV_{ch}}$
for $t \leftarrow 1$ to $T$ do
    $P_{PEV}(t) \leftarrow 0$
    $C_{PEV}(t) \leftarrow 0$
    $P_{temp}(t) \leftarrow P_{DR} - P_E(t) - P_{AC}(t) - P_{EWH}(t)$
end for
$Index \leftarrow$ Find time slots with $RTP(t_a : t_d - 1)$ less than $RTP_{PEV_{ch}}$
for $i \leftarrow$ length($Index$): -1: 2 do
    if $i \leftarrow$ length($Index$) then
        $C_{PEV}(Index(i)) \leftarrow 0.8 \times C_{PEV}^{max}$
    end if
    $P_{PEV}(Index(i)) \leftarrow min\left(P_{temp}(Index(i)), P_{PEV}^{chmax}/\eta_{PEV}^{ch}\right)$
    $C_{PEV}(Index(i-1)) \leftarrow C_{PEV}(Index(i)) - P_{PEV}(Index(i)) \times \eta_{PEV}^{ch} \times \Delta t$
    if $C_{PEV}(Index(i-1)) \leqslant 0.3 \times C_{PEV}^{max}$ then
        $n \leftarrow i - 1$
        Exit
    end if
end for
Return $n$
```

Based on the value of n, the proposed charging and discharging strategy for ESS and PEV is shown in Fig. 2. This strategy will first calculate the maximum allowable charging and discharging power of ESS and PEV under battery capacity constraints according to (26)-(29).

$$P_{ESS}^{chable}(t) = \left(0.8C_{ESS}^{max} - C_{ESS}(t-1)\right) / \left(\eta_{ESS}^{ch}\Delta t\right) \tag{26}$$

$$P_{ESS}^{disable}(t) = \left(C_{ESS}(t-1) - 0.2C_{ESS}^{max}\right)\eta_{ESS}^{dis} / \Delta t \tag{27}$$

$$P_{PEV}^{chable}(t) = \left(0.8C_{PEV}^{max} - C_{PEV}(t-1)\right) / \left(\eta_{PEV}^{ch}\Delta t\right) \tag{28}$$

$$P_{PEV}^{disable}(t) = \left(C_{PEV}(t-1) - 0.3C_{PEV}^{max}\right)\eta_{PEV}^{dis} / \Delta t \tag{29}$$

Then, the specific execution process of this strategy is elaborated through the following two situations.

Situation 1: in $[t_a, n]$, PEV will be used as an energy storage device to further improve the flexibility and economy of HEMS scheduling. The steps in situation 1 are as follows:

Step.1 Calculate $P1$. $P1$ is the insufficient or surplus energy of the smart home system without considering the charging and discharging power of ESS and PEV;

Step.2 If $P1(t) > 0$ (system energy is insufficient) and $RTP(t) > RTP_{ESS_{dis}}$, ESS will discharge. The discharging power and capacity of ESS will be calculated by (30) and (31). Then, whether PEV is used to meet the still insufficient energy is determined by

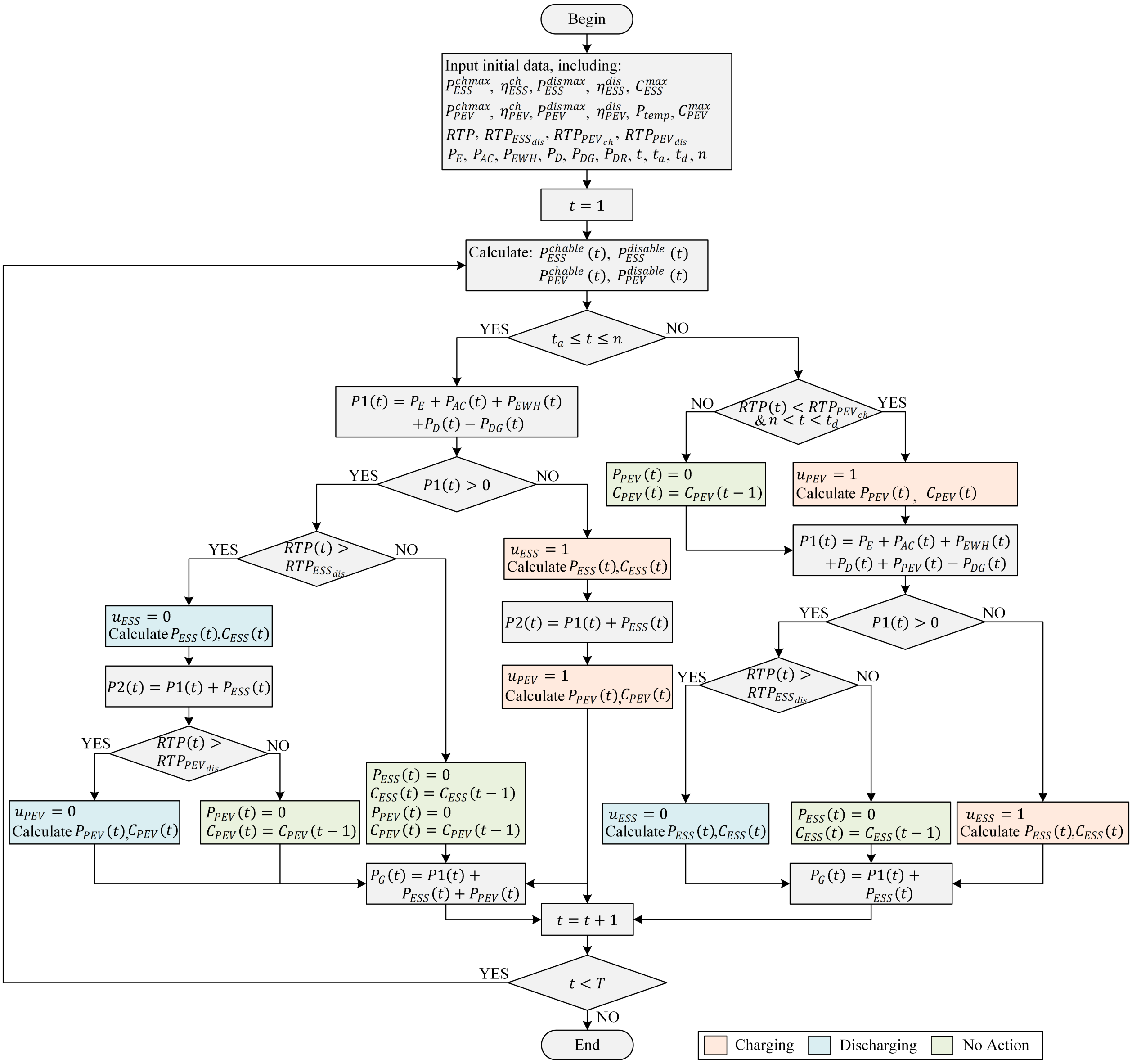

FIGURE 2. The flow chart of combined charging and discharging strategy of ESS and PEV.

the current price. If $RTP(t) > RTP_{PEV_{dis}}$, PEV will discharge, and the discharging power and capacity of PEV will be calculated by (32) and (33); otherwise, PEV will take no action;

$$P_{ESS}(t) = -min\left(P1(t), P_{ESS}^{disable}(t), \left|P_{ESS}^{dismax}\right|\eta_{ESS}^{dis}\right) \tag{30}$$

$$C_{ESS}(t) = C_{ESS}(t-1) + P_{ESS}(t)\,\Delta t/\eta_{ESS}^{dis} \tag{31}$$

$$P_{PEV}(t) = -min\left(P2(t), P_{PEV}^{disable}(t), \left|P_{PEV}^{dismax}\right|\eta_{PEV}^{dis}\right) \tag{32}$$

$$C_{PEV}(t) = C_{PEV}(t-1) + P_{PEV}(t)\,\Delta t/\eta_{PEV}^{dis} \tag{33}$$

Step.3 If $P1(t) > 0$ and $RTP(t) \leqslant RTP_{ESS_{dis}}$, neither ESS nor PEV will discharge;

Step.4 If $P1(t) < 0$ (system energy is surplus), ESS and PEV will be charged, and the charging power and capacity of ESS and PEV will be calculated by (34), (35), (36) and (37);

$$P_{ESS}(t) = min\left(-P1(t), P_{ESS}^{chable}(t), P_{ESS}^{chmax}/\eta_{ESS}^{ch}\right) \tag{34}$$

$$C_{ESS}(t) = C_{ESS}(t-1) + P_{ESS}(t)\,\eta_{ESS}^{ch}\Delta t \tag{35}$$

$$P_{PEV}(t) = min\left(-P2(t), P_{PEV}^{chable}(t), P_{PEV}^{chmax}/\eta_{PEV}^{ch}\right) \tag{36}$$

$$C_{PEV}(t) = C_{PEV}(t-1) + P_{PEV}(t)\,\eta_{PEV}^{ch}\Delta t \tag{37}$$

Step.5 Calculate the interaction power between utility and HEMS.

Situation 2: in $[1, t_a)$ and $(n, T]$, the PEV is not connected to the home or only acts as a load. The calculation steps of situation 2 can be explained as follows:

Step.1 If $n < t < t_d$ (PEV acts as a load) and $RTP(t) < RTP_{PEV_{ch}}$, PEV will be charged, and the charging power and capacity of PEV will be calculated according to (38) and (37); otherwise, PEV will take no action;

$$P_{PEV}(t) = \min\left(P_{temp}(t), P_{PEV}^{chable}(t), P_{PEV}^{chmax}/\eta_{PEV}^{ch}\right) \tag{38}$$

Step.2 Calculate $P1$. $P1$ is the insufficient or surplus energy without considering the charging and discharging power of ESS;

Step.3 If $P1(t) > 0$ and $RTP(t) > RTP_{ESS_{dis}}$, ESS will discharge; otherwise, ESS will take no action;

Step.4 If $P1(t) < 0$, ESS will be charged;

Step.5 Calculate the interaction power between utility and HEMS.

As the capital cost of the battery is currently not negligible; therefore, the PEV will only discharge when the electricity price is above a certain threshold and the ESS cannot meet the household energy consumption.

B. OPTIMIZATION METHODOLOGY

Combining the control objective with the control strategy of ESS and PEV, a smart home energy management optimization method is proposed, as shown in Fig. 3. First, the HEMS receives initial data, such as calculated horizon, time granularity, RTP and domestic appliance parameters, etc., and then optimizes the consumption of CA loads based on the acceptable temperature range set by user. Finally, according to the control target of cost minimization, practical constraints and the combined charging and discharging strategy of ESS and PEV, the optimal solution is obtained.

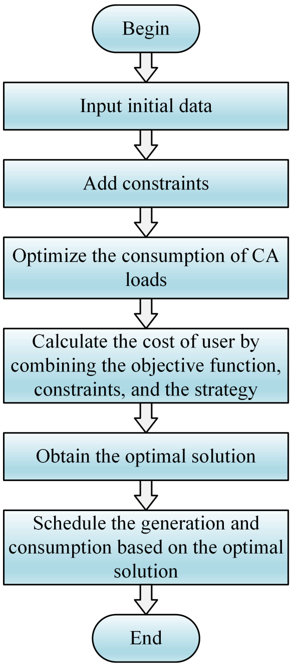

FIGURE 3. The flow chart of smart home energy management optimization method.

IV. SIMULATION AND RESULTS DISCUSSION

The simulation will be carried out to verify the effectiveness and economy of the proposed method.

A. SIMULATION PARAMETERS

In this paper, we set the calculated horizon to 24 hours and the time granularity to 15 minutes. Fig. 4 shows PV generation data from the European Network of Transmission System Operators (ENTSOE) [32]. Because the simulation objective of this paper is a single residence, the output of PV is generally small, but the data obtained from ENTSOE is MW-class, so we convert the original generation data to kW-class. Fig. 5, Table 1 and Table 2 depict the RTP [33], domestic appliance parameters and other related parameters. The price sold to the utility is considered to be 50% of the RTP, and the power purchased from the utility is limited to 5 kW. Suppose the PEV arrives home at 18:30 and leaves home at 7:30. Besides, the outdoor temperature information in the summer of 2018 is taken from [34], and the hot water demand information is taken from [35].

The simulation is conducted on a personal computer with Intel® Core™ i5-4200U CPU @ 1.60GHz and 4 GB of RAM, running on Windows 10 64bit home system. Matlab R2015a with CPLEX and YALMIP is used as the programming and solving platform.

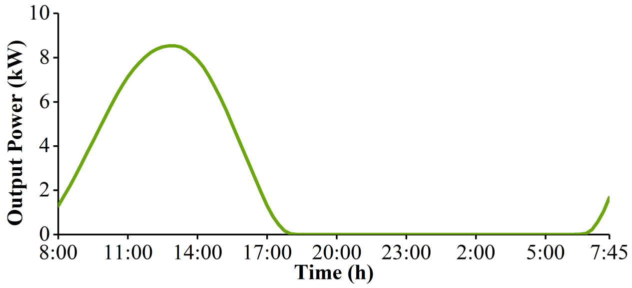

FIGURE 4. PV generation in summer.

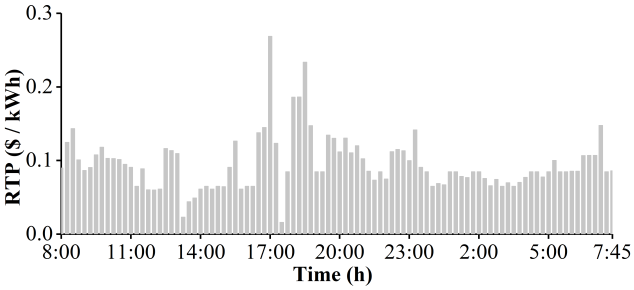

FIGURE 5. Real-time pricing.

TABLE 1. Domestic appliance parameters.

Category	Appliances	Max power (kW)	Min power (kW)	Start time	End time	Run time (h)
EA	Light Phone Computer	1	1	8:00	8:00	24
CA	Air conditioning	3	0	8:00	8:00	24
	Electric water heater	3.5	0			
SA	Washing machine	1.5	1.5	9:00 10:00	22:00 24:00	1(wash) 2(dry)
	Dishwasher	1.2	1.2	10:00 18:00	15:00 22:00	2
	Hairdryer	1.8	1.8	8:00	23:00	0.25
	Vacuum cleaner	1.2	1.2	14:00	18:00	0.5
	Rice cooker	0.8	0.8	10:00 16:00	12:00 19:00	0.75
	Oven	2	2	10:00	19:00	2
	Humidifier	0.15	0.15	8:00	24:00	4
	Robot Vacuum cleaner	0.7	0.7	8:00	24:00	5

TABLE 2. Other related parameters.

ESS parameters		PEV parameters	
C_{ESS}^{max} (kWh)	8	C_{PEV}^{max} (kWh)	30
C_{ESS}^{int} (kWh)	3.5	C_{PEV}^{int} (kWh)	12
P_{ESS}^{chmax} (kW)	3	P_{PEV}^{chmax} (kW)	4
P_{ESS}^{dismax} (kW)	-3	P_{PEV}^{dismax} (kW)	-4
$\eta_{ESS}^{ch}/\eta_{ESS}^{dis}$	0.92	$\eta_{PEV}^{ch}/\eta_{PEV}^{dis}$	0.92
$RTP_{ESS_{dis}}$	$1.1RTP_{AVG}$	$RTP_{PEV_{dis}}$	$1.18RTP_{AVG}$
Parameters for indoor temperature calculation		**Parameters for hot water temperature calculation**	
T_{AC}^{max} (°F)	80	T_{EWH}^{max} (°F)	130
T_{AC}^{min} (°F)	73	T_{EWH}^{min} (°F)	120
T_{in}^{int} (°F)	77	T_{hw}^{int} (°F)	70
α	0.9	T^{cw} (°F)	70
β	-11	T^{en} (°F)	80

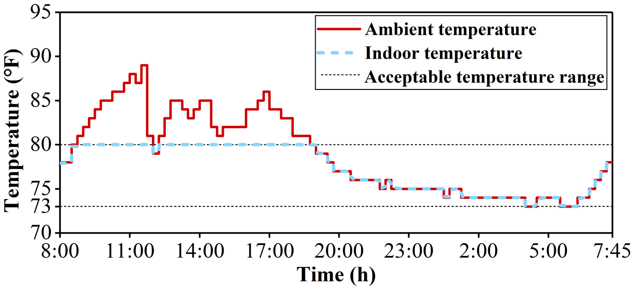

FIGURE 6. The indoor temperature result under optimal scheduling.

B. SCHEDULING RESULTS

The solution results of the proposed method are shown in Fig. 6 to Fig. 11. In this study, the indoor temperature is allowed to vary between 73°F and 80°F, and the hot water temperature is allowed to vary between 120°F and 130°F. Fig. 6 and Fig. 7 show that both the indoor temperature result and the hot water temperature result do not violate the acceptable temperature limits. Therefore, the smart home energy management method can improve the enthusiasm of users to join the intelligent scheduling.

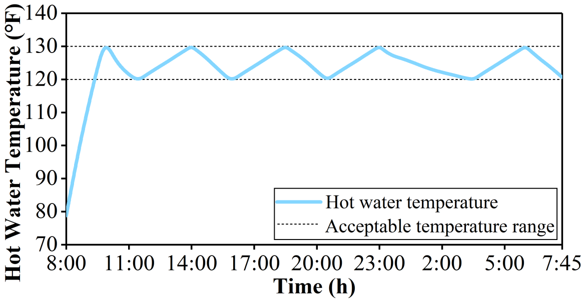

FIGURE 7. The hot water temperature result under optimal scheduling.

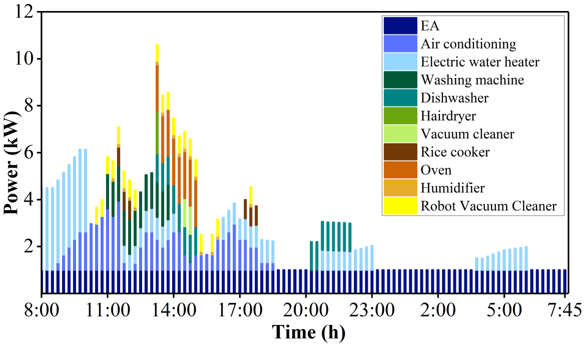

FIGURE 8. The scheduling plan for domestic appliances.

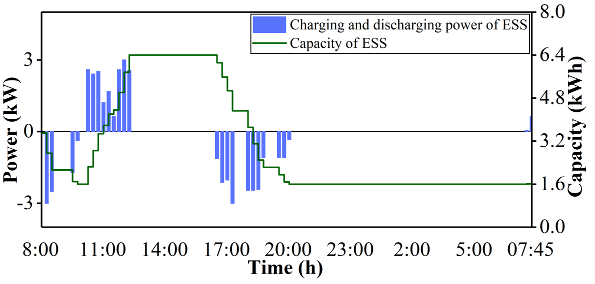

FIGURE 9. Charging and discharging power and capacity of ESS under optimal scheduling.

Fig. 8 depicts the optimized scheduling plan of domestic appliances. It can be found that these domestic appliances complete their tasks in the corresponding operation time slots, and non-interruptible appliances also guarantee the operation continuity. Most appliances operate when the PV output is high (see Fig.4) or the price is low (see Fig.5). In addition, PV generation is first used to meet the consumption of appliances, and then to provide charging energy for ESS (see Fig. 9). If the PV generation is still excessive, all remaining energy will be sold to the utility (see Fig. 11). Since PV generation is almost zero after the PEV arrives at home, the energy used for PEV charging mainly comes from the utility. So this method not only provides a reasonable and economical work plan for domestic appliances, but also maximizes RES utilization.

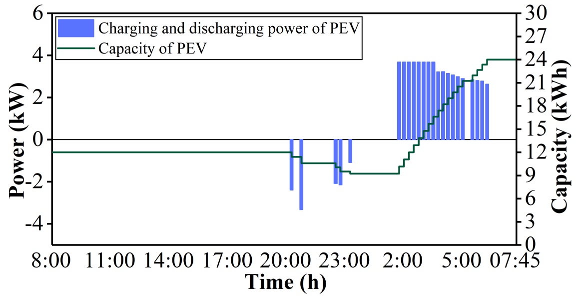

FIGURE 10. Charging and discharging power and capacity of PEV under optimal scheduling.

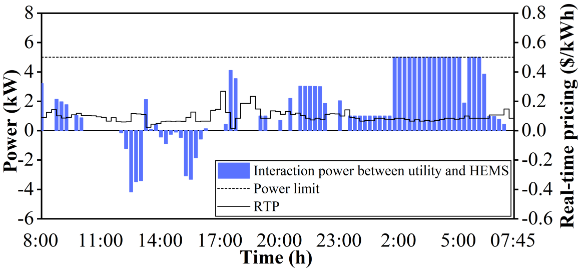

FIGURE 11. Interaction power between utility and HEMS.

Fig.9 shows that the ESS releases energy at high price time slots (e.g. 8:30, 9:45, 17:00, 18:30, 20:00) to meet all or part of the insufficient energy. Although there are also high price periods around 12:30 and 15:30, the PV output can fully meet the consumption during these periods, so no additional energy is required. Limited by ESS capacity and PV generation, the ESS discharges to the minimum capacity around 20:00, and there is no excess energy to charge the ESS before 7:30 the next morning. When PEV arrives at home, PEV can assist ESS to discharge (e.g. 20:00) or independent discharge (e.g. 23:00) to reduce the power drawn from the utility during peak periods, as shown in Fig. 10. It can also be noted from Fig.10 that the low price slots are selected to charge the PEV to reduce the charging cost. The PEV can be charged to the maximum capacity before departure to satisfy the driving needs of the user. Moreover, the charging and discharging power and capacity of both ESS and PEV are within the limits. The discharging price threshold set in this paper also reduces the charging and discharging cycles of ESS and PEV, which helps to prolong the life of batteries.

The power transmitted between the HEMS and the utility is shown in Fig. 11. In the high price periods, the surplus electricity will be sold to the utility for profit (e.g. 12:00-13:00). In the low price periods, the HEMS will first purchase the insufficient energies from the utility (e.g. 21:00-22:00). Besides, the power purchased from the utility in each time slot is below the maximum power limit, avoiding new peak phenomena.

In order to improve the convenience for smart home users, artificial intelligence can also be considered in the future, which can systematically establish users' habits of using domestic appliances by learning from their behaviors, and then readjust the scope of constraints to minimize the participation degree of users. Depends on the communication protocols (such as Wifi, Bluetooth, ZigBee, etc.) of the smart appliances, the scheduling results can also be automatically and silently sent to relevant equipment; yet, if the user does not want to accept the schedule, users' interference has always the highest priority.

TABLE 3. Case comparison results.

Case	ESS	The V2H mode of PEV	Charging and discharging strategy	Cost (cents)
Case1	No	No	No	374.1072
Case2	Yes	No	No	317.051
Case3	Yes	Yes	No	294.3198
Case4	Yes	Yes	Yes	267.6973

TABLE 4. Algorithm comparison results.

Solving method	Iteration time	Population size	Cost (cents)	Time (seconds)
GA	1000	500	290.9602	54.7875
PSO&BPSO	1000	500	279.1575	99.0335
DE&BLDE	500	200	273.9225	70.3362
CPLEX			267.6973	11.0669

1) COMPARATIVE CASES

We design four different cases to verify the economy of the proposed method, and the comparison results are shown in Table 3. It can be seen that when there is no ESS and the PEV has no V2H mode, the cost is the highest (Case 1). Case 2 reduces the cost by 15.25% on the basis of Case 1, Case 3 reduces the cost by 7.17% on the basis of Case 2, and Case 4 reduces the cost by 9.05% on the basis of Case 3. Therefore, the inclusion of both ESS and the V2H mode of PEV can decrease the cost for the smart home, but the combined charging and discharging strategy of ESS and PEV presented in this paper can maximize users' benefits.

2) COMPUTATIONAL EFFICIENCY

As the smart home energy management problem involves both continuous and discrete binary variables, the mixed integer linear program can be solved by heuristic algorithms, such as genetic algorithm (GA), particle swarm optimization algorithm (PSO) combined with binary particle swarm optimization algorithm (BPSO) and differential evolution algorithm (DE) combined with binary learning differential evolution algorithm (BLDE) [36]. However, the above mentioned algorithms are often know as computationally demanding and non-stable from the convergence of the final results point of view; therefore, we adopt the solver of the CPLEX as another alternative. To compare the efficiency of different solving techniques, we implement all the mentioned methods and the results are reported in Table 4. The cost and calculation time of heuristic algorithms are the average values

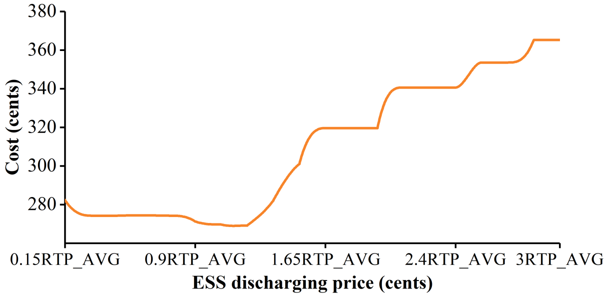

FIGURE 12. **The impact of ESS discharging price threshold on the total cost.**

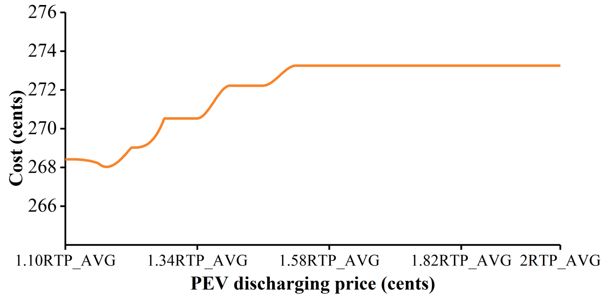

FIGURE 13. **The impact of PEV discharging price threshold on the total cost.**

obtained after 20 optimizations. As can be seen from Table 4, the CPLEX optimization solver adopted in this paper obtains the best result with the shortest time.

It should be noted that as a single home, the user will not have a very large number of domestic appliances that could possibly cause computational problems, even considering newly included equipment in the future.

3) SENSITIVITY ANALYSIS

In order to further discuss the influence of different factors on the electricity cost, this paper makes sensitivity analysis on the ESS discharging price and the PEV discharging price. The analysis results are shown in Fig. 12 and Fig. 13. We set the discharging price of ESS to increase from 0.15 times RTP_{AVG} to 3 times RTP_{AVG}, and the step length defaults to 0.05 times RTP_{AVG}. Fig. 12 shows that when ESS discharging price is less than 1.1 times RTP_{AVG}, the cost is gradually decreasing. This is because with the increase of discharging price, ESS can avoid releasing all stored energy in the low price periods. However, as the discharging price continues to increase, the discharging time and energy of ESS will decrease, and if the discharging price is higher than the highest RTP, ESS will not be able to discharge at any time slot. Therefore, when ESS discharging price is higher than 1.1 times RTP_{AVG}, the cost is gradually increasing. Due to the performance of PEV battery is worse than ESS, PEV discharging price is defaulted to be higher than ESS. So the discharging price of PEV is increased from 1.1 times RTP_{AVG} to 2 times RTP_{AVG} to analyze its impact on the total cost. Similar to ESS, Fig. 13 shows that when PEV discharging price is equal to 1.18 times RTP_{AVG}, the benefit to the user is greatest.

V. CONCLUSION

The emergence of the HEMS in smart homes will benefit both the user and utility by automatically optimize the use of electricity. In this paper, we universally classified domestic appliances and modelled each type of them considering their physical features as well as satisfactory constraints from the users. A comprehensive MILP-based framework is then proposed to intelligently schedule the operation of domestic appliances, RES, ESS, PEV for a minimum cost of electricity with guaranteed user satisfaction. To further make a better use of the ESS and PEV and prolong their battery lives, a specifically designed strategy for charging and discharging power and time period according to the RTP and energy surplus has been integrated into the scheduling problem, which enables an optimal trading plan between home and utility. The simulation results show that the proposed method obtains better performances in terms of economy and computational efficiency as well as efficiently guarantees user's comfort and the completion of the tasks of domestic appliances, maximizes the RES utilization and flattens the peak load. The comparative study shows that with the EES and PEV control strategy, the total cost can further be reduced by 28%.

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XUAN HOU is currently pursuing the M.S. degree in electrical engineering with Xihua University, Chengdu, China. Her research interests include the smart home and electric vehicle energy management.

JUN WANG received the Ph.D. degree in electrical engineering from Southwest Jiaotong University, China, in 2006. She was a Lecturer with the Sichuan College of Science and Technology, China, from 1991 to 2003, and an Associate Professor with Xihua University, China, from 1998 to 2003. She has been a Professor with the School of Electrical and Information Engineering, Xihua University, China, since 2004. Her research interests include electrical automation, intelligent control, and membrane computing.

TAO HUANG (M'18) received the Ph.D. degree from the Politecnico di Torino, Italy, in 2011. He is currently a Researcher and a Professor with the Department of Energy, Politecnico di Torino and the School of Electrical Engineering and Electronic Information, Xihua University, China. His research interests include critical infrastructure protection, power system modeling and analysis, electricity markets, and smart grids.

TAO WANG (M'18) received the Ph.D. degree in electrical engineering from Southwest Jiaotong University, Chengdu, China, in 2016. She was a Visiting Student in computer science and artificial intelligence with the University of Seville, Seville, Spain, from November 2013 to November 2014. She has been a Lecturer with the School of Electrical Engineering and Electronic Information, Xihua University, since 2016. Her research interests include microgrid energy management, fault diagnosis, membrane computing, and bioinspired model theory and its application in electrical power systems.

PENG WANG (M'00–SM'11–F'18) received the B.Sc. degree from Xi'an Jiaotong University, Xian, China, in 1978, the M.Sc. degree from the Taiyuan University of Technology, Taiyuan, China, in 1978, and the M.Sc. and Ph.D. degrees in power engineering from the University of Saskatchewan, Saskatoon, SK, Canada, in 1995 and 1998, respectively. He is currently a Professor with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore.

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