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Home energy management of thermostatically controlled loads and photovoltaic-battery systems

Mohammed Jasim M. Al Essa

Faculty of Engineering, University of Kufa, P.O. Box (21), Najaf Governorate, Iraq

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ABSTRACT

Energy management systems modify typical electricity consumption of some appliances to enhance energy efficiency, while considering operational characteristics of such devices. This paper proposes a scheme of home energy management (HEM) to adapt power consumption and generation of thermostatically controlled loads (TCLs) and photovoltaic-battery systems based on their operating conditions. TCLs of air conditioning systems are initially evaluated considering variable in-home temperatures, whereas their energy consumption is estimated using degree-days. Meanwhile, power generation of the photovoltaic-battery system is calculated according to technical parameters, solar irradiances and ambient temperatures. The proposed scheme of HEM system optimizes power consumption of TCLs using linear programming, sustaining the in-house temperature within its threshold. Charging and discharging power of the photovoltaic-battery system is accordingly re-scheduled while monitoring its battery state of charge. Simulation results of different case studies show that the proposed HEM scheme reduces energy consumption of the TCLs and photovoltaic-battery systems by 30%, while maintaining customer's quality of experience. Moreover, the proposed strategy prevents batteries from being intensely charged and dis-charged to improve their performance and to expand their lifecycle. Consequently, the proposed HEM plan is able to decrease operational and maintenance costs of such systems.

1. Introduction

An energy management system optimizes power consumption based on an implementation of demand side management (DSM) using different approaches such as flexible loads with variable tariffs to enhance energy efficiency [1]. It shifts or curtails electric loads to improve energy generation and consumption profiles of a building considering several objectives (operational costs, environmental aspects, consumer satisfaction, etc.) [2]. Such scheme modernizes central energy management systems towards an autonomous regional system with the aid of information and communication technologies (ICTs), smart meters, and renewable energy sources [3,4].

Energy efficiency of residential and commercial premises plays an essential role in energy policy at local and nation-wide levels [5]. Thermostatically controlled loads (e.g. heating, ventilation and air conditioning) are able to improve the performance of domestic energy consumption using home energy management (HEM) systems. Several energy management schemes were discussed in the literature [6–9] to enhance the use of thermostatically controlled loads (TCLs) considering photovoltaic energy. For example, a decentralized control strategy of active power management was proposed in Ref. [6] to coordinate TCLs (i.e. residential air conditioning systems) in electricity grids considering photovoltaic energy generation. Heating, ventilation and air conditioning loads were controlled in Ref. [7] to achieve energy matching with photovoltaic and wind generation using a stochastic energy management of genetic algorithm optimization. An energy management scheme was proposed in Ref. [8] to reduce operational costs of heating systems, while predicting their energy consumption considering different case studies of simulation for residential applications. A probabilistic scheme of energy management was proposed in Ref. [9] to re-schedule the operation of combined air conditioning and power, photovoltaic array, battery storage, and other distributed resources using mixed-integer nonlinear programming to minimize total emissions and electricity costs.

An energy management algorithm was presented in Ref. [10] to supply dynamic loads using photovoltaic-storage system based on experimental results of smart grid applications. A project-based

E-mail address: mohammedj.alisa@uokufa.edu.iq.

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system of energy management was proposed in Ref. [11] to increase the revenue of residential photovoltaic generation using mixed-integer linear optimization while supplying ancillary services of active power delivery. A smart home energy management system was developed in Ref. [12] to reduce operational costs of re-charging batteries of electric vehicles using intermittent solar generation, considering dynamic programming with time-of—use tariffs. An optimal energy management scheme of a hybrid grid-integrated photovoltaic-battery system was presented in Ref. [13] to re-schedule power flows, while minimizing electricity costs. Demand side management programs and battery energy storage systems were suggested in Refs. [14,15] to accomplish a self-consumption of photovoltaic energy generation inside residential premises. The photovoltaic self-consumption was defined in Ref. [16] as a direct distribution of solar generation across in-home appliances without reverse power flows using demand side management and battery energy storage. An energy management system was proposed in Ref. [17] to coordinate the power of photovoltaic-battery system according to signals of electricity price and predictions of average solar generation, responding to variable loads in a smart grid. A domestic energy-box management system of photovoltaic power and residential load was designed and implemented in smart grids [18], while considering a multi-objective function of minimizing cost and maximizing satisfaction based on actual signals of electricity price. Another energy management system was presented in Ref. [19] for re-scheduling residential loads in smart grids using a modified multi-objective genetic algorithm. Moreover, energy management systems were addressed in Ref. [20] to improve energy efficiency of emerging mixed-energy structures by proposing an optimal planning configuration of cost minimization. Table 1 shows a summary of energy management schemes of either TCLs or photovoltaic-battery systems considering different objectives, constraints and programming techniques.

Energy consumption of air conditioning TCLs fluctuates based on some factors such as building structure, outside temperature, set-point temperature, inside temperature, etc. The accuracy of modelling the TCLs increases when more factors that are relevant are considered. However, there are disadvantages while dealing with enormous information and extensive simulation (e.g. an increased likelihood of errors). Therefore, a simplified model is developed in this paper to represent power consumption of the studied type of air conditioning TCLs based on ambient temperature, thermal resistivity, thermal capacity and other influences. Meanwhile, degree-days method is used to estimate the energy consumption of the TCLs.

Weather datasets (solar irradiance and ambient temperature) and technical parameters (e.g. module area and generation efficiency) were studied to calculate photovoltaic power generation, whereas battery state of charge and depth of discharge were monitored to develop the complete model of the photovoltaic-battery system considered in this paper.

The HEM scheme proposed in this paper is demonstrated as follows. A linear optimization problem was formulated to minimize the operational costs of the TCLs while considering the in-house temperature based on an energy estimate, which was calculated using the degree-days method. Afterwards, charging and discharging power of the photovoltaic-battery system was accordingly scheduled based on optimization results of the TCLs.

This paper contributes to existing literature by highlighting the following points.

- A simplified mathematical model is developed to evaluate power consumption of air conditioning units considering variable in-house temperatures.
- Energy consumption of a part of residential building is estimated using degree-days technique.
- Energy generation and consumption profiles of photovoltaic-battery systems are determined using technical parameters, weather datasets and its battery state of charge.
- Linear programming is used to minimize the operational costs of air conditioning TCLs while maintaining the in-house temperature within its threshold.
- Power profiles of the photovoltaic-battery system are cooperatively re-scheduled in line with the optimized TCLs considering the battery state of charge.

The remainder of this paper is arranged as follows. Section 2 presents mathematical models of air conditioning TCLs and degree-days. Section 3 develops the equations that have been used to model the photovoltaic-battery system. Section 4 formulates the main objective function along with indicating simulation parameters, electricity prices and weather datasets. Section 5 demonstrates the schematic diagram of the proposed HEM scheme considering the algorithmic steps to activate such strategy in residential premises. Section 6 shows the case studies considered in this paper besides simulation results. Section 7 highlights some corollaries and provides recommendations for future work.

2. Thermostatically controlled loads and degree-days

Energy consumption of air conditioning TCLs was mainly driven by temperature difference between inside and outside environment of a building. A certain level of details was studied in this paper to represent the rate of heat exchange while modelling power profiles of TCLs. In the meantime, degree-days was employed to acquire an estimate of energy consumption of TCLs over a pre-specified timescale. The following sub-sections demonstrate equations that have been considered while modelling energy consumption of the studied category of thermostatically controlled systems.

2.1. Thermostatically controlled systems

The thermostatically controlled system considered in this paper performs space heating or cooling functions while extracting

Table 1
A brief review of energy management schemes of thermostatically controlled loads (TCLs) or photovoltaic-battery systems in terms of objectives, constraints and programming techniques.

Studies	Management of	Objectives	Constraints	Techniques
[6]	Air conditioning TCLs	Maximizing active power	In-home temperatures	Heuristic algorithm
[7]	Air conditioning TCLs	Minimizing energy costs	Power balance equations	Genetic algorithm
[8]	Combined heat and power systems	Minimizing energy costs	Power balance equations	Mixed integer linear programming
[11]	Photovoltaic-battery systems	Maximizing revenues	Battery state of charge	Two-level mixed integer programming
[13]	Photovoltaic-battery systems	Minimizing electricity costs	Battery state of charge	Linear programming
[17]	Photovoltaic-battery systems	Maximizing revenues	Power balance equations	Dynamic programming

additional energy from the ambient air. Therefore, electricity consumption of TCLs is calculated based on its coefficient of performance (*COP*). The *COP* represents a measure of heat transfer in a thermostatically controlled unit depending on output and input power considering the energy added from renewable resources (e.g. the ambient air).

$$COP(t) = \frac{p_{out}(t)}{p_{in}(t)} \tag{1}$$

where $p_{in}(t)$ and $p_{out}(t)$ indicate the input and output power of the thermostatically controlled unit for each time step in W. The TCLs of air conditioning systems are then estimated based on the air flow rate (φ) in m^3/s and the air density (ϕ) in kg/m^3 considering the specific heat of air (α) in kJ/kg.°C, as follows [21–23].

$$p_{in}(t) = \begin{cases} \dfrac{\phi \times \varphi \times \alpha \times \Delta\theta_{sur}}{COP(t)}, & \exists \;\; \theta_{in}(t) < \left(\theta_{thresh} - \theta_{hys}\right) \\ p_{fan,} & \nexists \;\; \theta_{in}(t) < \left(\theta_{thresh} - \theta_{hys}\right) \end{cases} \tag{2}$$

where $\Delta\theta_{sur}$ indicates the absolute value of the difference between supply and return temperatures of the thermostatically controlled unit in °C. $\theta_{in}(t)$ is the inside temperature of the building in °C. θ_{thresh} refers to the threshold temperature (i.e. the set-point temperature) of the building that has to be maintained in °C. θ_{hys} represents the value of temperature regarding to thermostatic-hysteria effect in °C (i.e. ±1 °C) [21]. p_{fan} is a constant value of power representing electricity drawn by the fan of the thermostatically controlled air-conditioning unit.

By using Carnot's cycle, Eq. (2) is re-written as follows [21,24].

$$p_{in}(t) = \begin{cases} \dfrac{\phi \times \varphi \times \alpha \times \Delta\theta_{sur} \times \left[\theta_{sup} - \theta'_{amb}(t)\right]}{FAC \times \theta_{sup}}, & \exists \;\; \theta_{in}(t) < \left(\theta_{thresh} - \theta_{hys}\right) \\ p_{fan}, & \nexists \;\; \theta_{in}(t) < \left(\theta_{thresh} - \theta_{hys}\right) \end{cases} \tag{3}$$

where θ_{sup} is the supply temperature of the thermostatically controlled unit in Kelvin. θ'_{amb} is the ambient temperature of the outside environment in Kelvin. *FAC* is an empirical parameter that was adjusted to acquire a reasonable value of rated *COP* for the thermostatically controlled system. Thermal resistivity and thermal capacity of fenestrations and walls are used to determine the inside temperature of the building, as follows.

$$\theta_{in}(t) = \theta_{thresh} + \Delta\left[\frac{r_{eq} \times COP(t) \times p_{in}(t) - \theta_{ret} + \theta_{amb}(t)}{m_{air} \times \alpha \times \left({}^{1}/_{c_{eq}}\right)}\right] \tag{4}$$

where θ_{ret} represents the return temperature of the thermostatically controlled unit in °C. θ_{amb} is the ambient temperature of the outside environment in °C. r_{eq} indicates the equivalent thermal resistivity of fenestrations and walls in °C/kW. c_{eq} refers to the mean value of thermal capacity of the building in kWh/°C [25]. m_{air} is the air mass flow in kg/s.

Eq. (3) calculates power consumption of air-conditioning TCLs considering operational parameters such as airflow rates, supply temperatures, and outside temperatures. Moreover, it considers inside temperatures based on thermal capacity and thermal resistivity of fenestrations and walls as assessed in Eq. (4). These equations were used to evaluate air-conditioning TCLs corresponding to variations of inside temperatures, while considering the operational and structural characteristics of residential buildings modelled with pre-indicated simulation parameters. Such parameters are eventually identified in this study as demonstrated in sub-section 4.2.

2.2. Degree-days

Degree-days have been used in monitoring energy consumption of space heating and cooling systems based on historical data. Degree-days offer a simple technique to estimate energy consumption of heating and cooling units using minimal input data. Although such methods are less accurate, it is more beneficial to discuss their results in terms of uncertainty despite of accuracy to reach a reasonable conclusion [23]. The accuracy of such method increases with the increase of the timescale considered in the simulation (e.g. daily degree-days results are less accurate as compared to monthly degree-days calculations) [23]. Therefore, monthly degree-days were used in this paper to guide the proposed HEM scheme of thermostatically controlled systems by calculating the average energy of heating, which is required to maintain in-house temperature within its threshold. An estimate of energy consumption of space heating systems of a building over a given timescale was calculated using the following equation [23].

$$E = \mathrm{U} \times \mathrm{D} \tag{5}$$

where E is the estimated energy consumption in kWh using degree-days method to maintain the building within comfortable conditions. U is the overall heat-loss coefficient of the building in kW/°C. D represents the value of degree-days in °C/day. If the value of base temperature is adjusted to be θ_{BASE} in °C, degree-days are calculated using the following equation [23].

$$D = \begin{cases} \dfrac{\sum_{k=1}^{24}\left[\theta_{BASE} - \theta_{amb}(t)_k\right]}{24}, & \exists \;\; \left(\theta_{BASE} > \theta_{amb}(t)_k\right) \\ 0, & \nexists \;\; \left(\theta_{BASE} > \theta_{amb}(t)_k\right) \end{cases} \tag{6}$$

3. Photovoltaic-battery systems

Photovoltaic systems are installed in residential premises using either on-grid or off-grid configuration. In this paper, a grid-integrated photovoltaic-battery system is considered to implement the proposed HEM scheme. Relevant equations were presented in the following sub-sections to explain the model of the photovoltaic-battery system considered in this paper.

3.1. Photovoltaic system

Simplified equations were used to evaluate the maximum power generated from the studied photovoltaic system based on the number of its photovoltaic modules, the area of each photovoltaic module and the amount of incident solar irradiance as presented below [22,26].

$$p_{max}(t) = n_{module} \times a_{module} \times irr(t) \tag{7}$$

where $p_{max}(t)$ represents the maximum power generated from the photovoltaic system in W for each time step. n_{module} is the total number of photovoltaic modules used in the system, considering the rated power of each solar module as p_{rated} in W. a_{module} is the area of each photovoltaic module in m^2 and $irr(t)$ is the global solar irradiance in W/m^2 for each time step. The net output power of photovoltaic generation is calculated using the following equation [26].

$$p_{pvs}(t) = p_{max}(t) \times \eta_{stc} \times \mathscr{C}_{L\&T} \times \{1 - [\mathscr{C}_T \times (\theta_{cel}(t) - \theta_{stc})]\} \tag{8}$$

where $p_{pvs}(t)$ refers to the net output power of the photovoltaic system in W for each time step. η_{stc} denotes the efficiency of the photovoltaic module at standard testing conditions. θ_{stc} represents the temperature of standard testing conditions in °C, while considering a pre-indicated value of solar irradiance [27]. η_{stc} and θ_{stc} are usually given by the manufacturer of photovoltaic modules regarding standard testing conditions. $\mathscr{C}_{L\&T}$ refers to the parameter of less than unity considering energy reduction due to inverter and maximum power point tracking controller together. $\mathscr{C}_T$ refers to the parameter of temperature coefficient fluctuating between 4×10^{-3} and 6×10^{-3} per °C [26]. $\theta_{cel}(t)$ refers to the temperature of photovoltaic cells in °C for each time step. The temperature of photovoltaic cell is determined using energy balance equation as expressed below [26].

$$\theta_{cel}(t) = \theta_{amb}(t) + [\mathrm{H} \times \mathrm{A} \times \mathrm{T}] \times irr(t) \tag{9}$$

where H indicates the reciprocal of overall heat losses coefficient in °C.m^{-2}/W. A and T indicate the absorbing coefficient in cm^{-1} [28] and transmitting coefficient of photovoltaic cells, respectively. The coefficients of heat losses of H, A and T are evaluated considering the nominal operating cell temperature ($noct$) in °C using the following equation [26,29].

$$\mathrm{H} \times \mathrm{A} \times \mathrm{T} = \frac{noct - 20}{800} \tag{10}$$

Therefore, the temperature of photovoltaic cell is estimated based on the energy balance equation, which is re-written as follows [26,29].

$$\theta_{cel}(t) = \theta_{amb}(t) + \left[\frac{noct - 20}{800}\right] \times irr(t) \tag{11}$$

Thus, the net output power of the photovoltaic system is calculated using the following equation.

$$p_{pvs}(t) = n_{module} \times a_{module} \times \eta_{stc} \times \mathscr{C}_{L\&T} \times irr(t) \times \left\{1 - \left[\mathscr{C}_T \times \left(\theta_{amb}(t) + \left[\frac{noct - 20}{800}\right] \times irr(t) - \theta_{stc}\right)\right]\right\} \tag{12}$$

where $noct$ indicates the nominal operating cell temperature, fluctuating between 40 and 70 °C [26,29]. It can be seen that the equations of calculating photovoltaic power generation developed in this study considers explicit factors such as manufacturing specifications of solar cells (η_{stc} and θ_{stc}), while regarding general physical parameters (e.g. the area of photovoltaic module) and weather datasets (e.g. solar irradiance). Such consideration improves the precision of the photovoltaic power computed with the equations presented in this study.

3.2. Battery system

It is assumed that the storage system of lead-acid batteries is recharged by using a hybrid-charging controller with charging capacity of $p_{chc}(t)$ in kW/h. Therefore, the state of charge of the battery system is determined as follows [30].

$$SOC(t) = \left(SOC_0 + \eta_{charger} \times \sum_{l=1}^{L} p_{chc}(t)_l\right) \Big/ SOC_r \tag{13}$$

where $SOC(t)$ denotes the battery state of charge (SOC) in percentage with respect to an initial values of SOC. $\eta_{charger}$ denotes the efficiency of the charging controller, L denotes the number of time slices bounded by initial and final time of charging considering the resolution of the whole simulation time steps. SOC_r indicates the rated capacity of batteries in kWh. Meanwhile, the value of depth of discharge (DOD) in percentage for each time step is calculated using the following equation.

$$DOD(t) = SOC(t) - \frac{\eta_{inverter} \times \sum_{x=1}^{X} p_{inv}(t)_x}{SOC_r} \tag{14}$$

where $\eta_{inverter}$ indicates the efficiency of the inverter of the photovoltaic-battery system. p_{inv} denotes the supply capacity of the photovoltaic inverter system in kW/h. X refers to the number of time slices over the interval of using battery storage to supply energy consumption. Power equations of the grid-connected models of thermostatically controlled loads and photovoltaic-battery systems were presented as follows.

$$P_{grid}(t) = \begin{cases} P_{load}(t) + p_{in}(t) + p_{chc}(t) - p_{pvs}(t), \ \exists \ (p_{inv}(t) = 0) \\ P_{load}(t) + p_{in}(t) - p_{inv}(t) - p_{pvs}(t), \ \exists \ (p_{chc}(t) = 0) \end{cases} \tag{15}$$

where $P_{grid}(t)$ indicates the net power of the grid at each time step in kW. $P_{load}(t)$ denotes the mean power consumed by other residential appliances at each time step in kW. Therefore, power profiles of battery system (i.e. $p_b(t)$ in kW) is expressed as follows, considering the previous operating conditions of system components.

$$p_b(t) = \begin{cases} -p_{inv}(t), \ \exists \ \left(p_{pvs}(t) = 0 \vee p_{in}(t) \neq 0\right) \\ p_{chc}(t), \ \exists \ \left(p_{pvs}(t) \neq 0 \vee p_{in}(t) = 0\right) \\ 0, \quad \exists \ \left(p_{pvs}(t) = 0 \wedge p_{in}(t) = 0\right) \end{cases} \tag{16}$$

where $p_{in}(t)$ denotes the input power of the thermostatically controlled unit for each time step in W.

4. Problem formulation

The mathematical models of thermostatically controlled loads and photovoltaic-battery systems, which were previously presented in this paper, have been used to formulate the main objective of the proposed HEM scheme as shown in the following sub-section.

4.1. Objective function

Linear programming was employed to direct the scheduling algorithm of the proposed HEM scheme by considering the following equation of TCLs.

$$Minimize\ CF = \sum_{i=1}^{M} Tar(t)_i \times p_{in}(t)_i \forall\ i \in \{1,\ 2,\ 3,\ \ldots,\ M\} \tag{17}$$

Subject to the following constraint conditions.

$$CF > E \vdash \theta_{in}(t) > \left(\theta_{thresh} - \theta_{hys}\right) \tag{18}$$

$$0 \leq p'_{in}(t)_i \leq p_{in}(t)_i \tag{19}$$

where CF denotes the objective function that was used to minimize the operational costs of TCLs over a pre-specified timescale. $Tar(t)$ indicates the variable tariffs in $/kWh. $p'_{in}(t)_i$ refers to the values of optimized power consumption of TCLs while applying linear programming. M represents the number of time slices over the timescale of optimizing energy consumption of TCLs. Meanwhile, the value of E is calculated using Eq. (5). A built-in function of "*linprog*" in MATLAB [31] was used to obtain the solution of the problem formulated in this paper.

Power profiles of the photovoltaic-battery system are rescheduled based on the optimized energy consumption of TCLs by considering the following operational conditions.

$$p'_b(t) = \begin{cases} -p_{inv}(t),\ \exists\ \left(p'_{in}(t) \neq 0 \wedge SOC(t) \geq SOC_{min}\right) \\ p_{chc}(t),\ \exists\ \left(p_{pvs}(t) \neq 0\ \wedge\ SOC(t) \leq SOC_{max}\right) \\ 0, \quad \nexists\ (SOC_{min} \leq SOC(t) \leq SOC_{max}) \end{cases} \tag{20}$$

where p'_b indicates the re-scheduled power profiles of the photovoltaic-battery system based on the optimized power of TCLs (i.e. p'_{in}) using Eq. (17). SOC_{min} and SOC_{max} are the minimum and maximum values of battery state-of-charge [30], avoiding deep discharge and over-charge levels.

4.2. Simulation parameters

In this section, the technical parameters that have been used in the simulation are presented. Table 2 shows the parameters that was adopted while simulating thermostatically controlled air-conditioning systems and degree-days considering the literature [23,25,32,33]. Meanwhile, simulation parameters of the photovoltaic-battery system is illustrated in Table 3 by studying the systems presented in Refs. [22,26,29,30].

Table 2
Simulation parameters of degree-days and thermostatically controlled systems.

Parameters	Values	Units
θ_{BASE}	18.3	°C
θ_{thresh}	22	°C
θ_{sup}	300	Kelvin
θ_{ret}	24	°C
U	0.64	kW/°C
r_{eq}	1.56	°C/kW
c_{eq}	10	kWh/°C
α	1.02	kJ/kg.°C
m_{air}	1	kg/s
ϕ	1.28	kg/m^3
φ	0.6	m^3/s
COP_r	3	–
FAC	0.3	–
p_{fan}	0.1	kW

Table 3
Simulation parameters of photovoltaic-battery system.

Parameters	Values	Units
p_{rated}	130	W
n_{module}	6	–
θ_{stc}	25	°C
$noct$	50	°C
a_{module}	1.2	m^2
η_{stc}	18	%
$\mathscr{C}_{L\&T}$	0.9	–
$\mathscr{C}_T$	0.005	per °C
$\eta_{charger}$	93	%
p_{chc}	1	kW
$\eta_{inverter}$	85	%
p_{inv}	1	kW
SOC_r	8	kWh
SOC_{min}	10	%
SOC_{max}	90	%

4.3. Electricity prices and weather data

Variable electricity prices fluctuate over time to describe some of system conditions (e.g. marginal costs), whereas fixed electricity rates ignore such system importance. Time-variant electricity rates (e.g. time-of-use tariffs) cannot necessarily capture the full details of actual real-time prices [34]. Therefore, the model of time-variant tariff, which was presented in Ref. [35], was utilized in this paper by considering real supply rates [36]. Such model uses actual electricity prices to synthesize time-variant tariffs, while confirming that electricity consumers cannot be overpriced with the tariffs produced for an equivalent amount of energy consumption. In other words, the calculation of electricity bills must be identical using either the real supply rates or the synthesized time-variant tariffs for the similar amount of energy consumption.

Weather data of ambient temperature and solar irradiance were gathered from the typical metrological datasets that have been produced in Ref. [37] on an hourly basis considering the instructions presented in Ref. [38].

A 5-min time step resolution was adopted in this paper to construct power profiles of TCLs and photovoltaic-battery systems. Consequently, weather data were interpolated into a 5-min resolution based on hourly metrological datasets.

5. Description of the proposed scheme of home energy management

The proposed HEM scheme improves energy efficiency of residential premises by considering the interaction of the system components modelled in this paper. The configuration presented in Fig. 1 is used to enable power management of the proposed HEM system and to export the surplus of photovoltaic generation toward electricity grid. More details on the control strategy of this hybrid solar-storage system are presented in Ref. [39], considering photovoltaic power tracking controller. The additional power exported to the grid will be further investigated and optimized in the future work of this study using feed-in tariffs and smart meters. A hybrid-charging controller is used to provide a reliable constant rate of charging power to the storage system of lead-acid batteries. It is assumed that the proposed HEM scheme has access to coordinate thermostatically controlled units and photovoltaic-battery

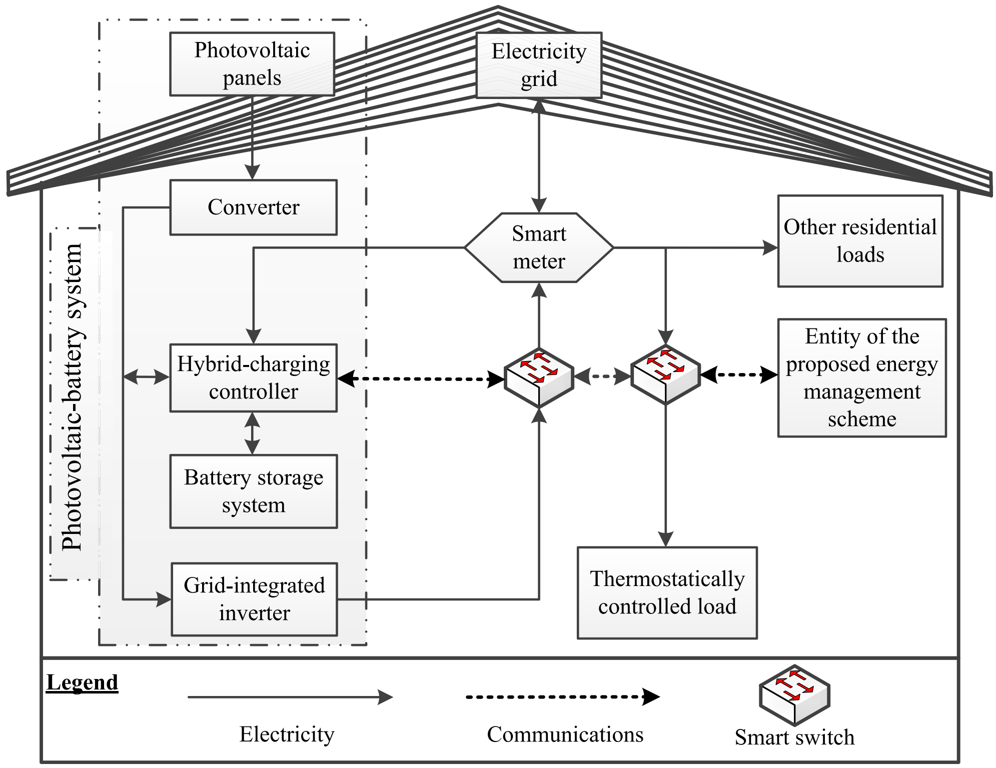

Fig. 1. Schematic diagram of the proposed home energy management in residential sector.

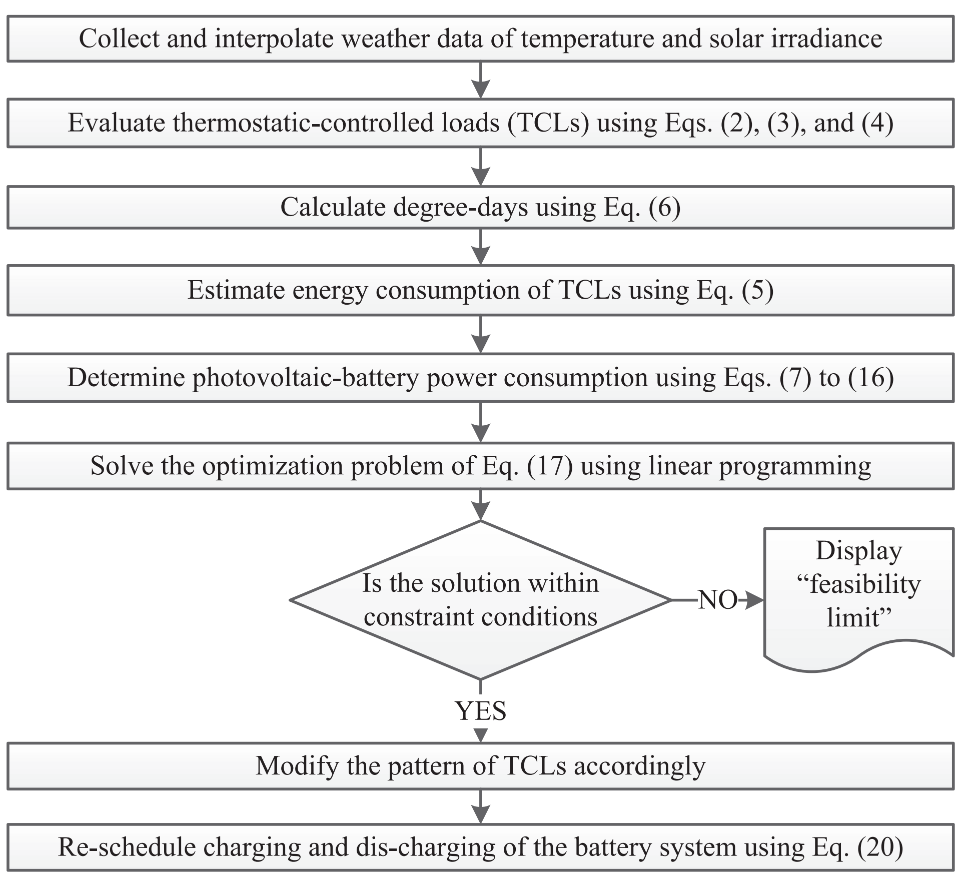

Fig. 2. Algorithmic steps of the proposed scheme of home energy management.

systems using communication signals and smart switches. A home area network provides a protocol to send control signals to the smart systems. The proposed algorithm of home energy management generates scheduling messages, which are then transmitted to smart switches in order to coordinate thermostatically controlled units and photovoltaic-battery systems accordingly. The proposed algorithm of home energy management is demonstrated in Fig. 2.

The proposed algorithm compiles weather datasets from an external source (e.g. weather station), considering their compatibility with a pre-specified time resolution. The weather datasets are then used for TCLs to estimate energy consumption required for maintaining the considered part of the building within comfortable conditions using degree-days, as illustrated in Eq. (5) and Eq. (6). Power evaluation is prepared for thermostatically controlled units using Eq. (2) to Eq. (4). Correspondingly, power is determined for photovoltaic-battery systems using Eq. (7) to Eq. (16). Afterwards, a linear programming technique is employed to solve the optimization problem described in Eq. (17) based on the time-variant tariff considered in this study. Thereafter, the optimal solution is arranged to adjust typical patterns of TCLs. Accordingly, charging and dis-charging power profiles of lead-acid batteries are re-scheduled, using Eq. (20) based on the TCLs optimized in preceding steps, as shown in Fig. 2.

6. Case studies and simulation results

The performance of the proposed HEM scheme is verified in this paper using two case studies. The first case study is presented by monitoring power profiles of the modelled TCLs and photovoltaic-battery systems over two days on a 5-minite basis. In other words, a business as usual scenario of modelling the TCL and photovoltaic-battery system was firstly implemented without employing the optimization of the proposed HEM scheme. Meanwhile, the second case study is shown considering the proposed HEM scheme to modify energy consumption of the TCL and photovoltaic-battery system while maintaining the constraint conditions of the optimization.

Fig. 3 shows the estimate of heating energy consumption, which was calculated using degree-days method considering the simulation parameters of Table 2, over a month (commencing from the end of January until the end of February) based on weather data in Ref. [37]. In addition, values of degree-days were indicated in Fig. 3 over that month based on the base temperature considered in this paper (see Table 2).

Fig. 4 shows TCL power profiles and *COP* values that were modelled over two days on a 5-min basis while considering the technical parameters of Table 2. Weather temperatures, which were collected from Ref. [37] on an hourly basis, were interpolated into a 5-min time resolution to calculate air conditioning TCLs, as shown in Eq. (3). Moreover, the inside temperature of the part of the building considered in this paper was monitored using Eq. (4) over these two days as presented in Fig. 4. It can be noticed that the inside temperatures vary around the threshold value considering the thermostatic-hysteria impact on TCLs model developed in this paper. The average value of estimated heating energy calculated in degree-days method is embedded in the constraint conditions of the objective function to optimize TCLs accordingly using linear programming, maintaining the inside temperature within its threshold.

Fig. 5 illustrates the modification of energy consumption of TCLs while applying the proposed HEM scheme over two days on a 5-min basis. The constraint conditions were effectively adjusted to maintain the inside temperature within its threshold, considering the energy that was estimated using the degree-days technique.

Fig. 6 exhibits power profiles of the photovoltaic-battery system modelled in this paper considering the technical parameters of Table 3. In Fig. 6, negative values of power were used to indicate the energy generation produced by solar cells and inverters of the photovoltaic-battery system. The constant rate of charging power was achieved based on a complementary power delivery from both electricity grid and photovoltaic module, as illustrated in Fig. (1). The SOC values of the photovoltaic-battery system are clearly demonstrated in Fig. 6. The battery is re-charged over the period of photovoltaic power generation awaiting 100% SOC (see Fig. 6), whilst it is deeply dis-charged until 0% SOC without using the proposed HEM scheme, as shown in Fig. 6. Such overcharging and deep dis-charging cycles of batteries shorten their lifespan.

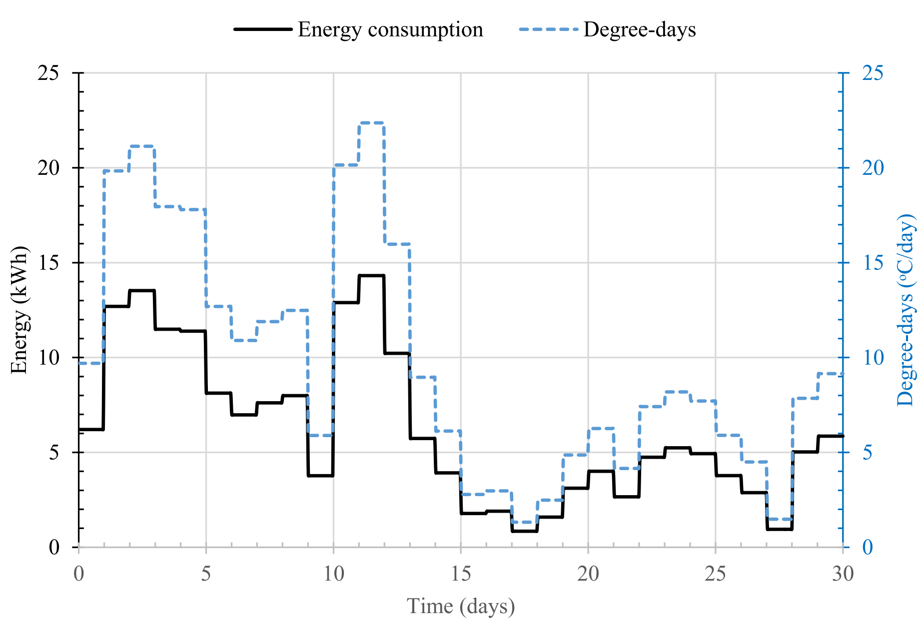

Fig. 3. An estimate of energy consumption of space heating over a month for the part of the building considered in this paper using degree-days method.

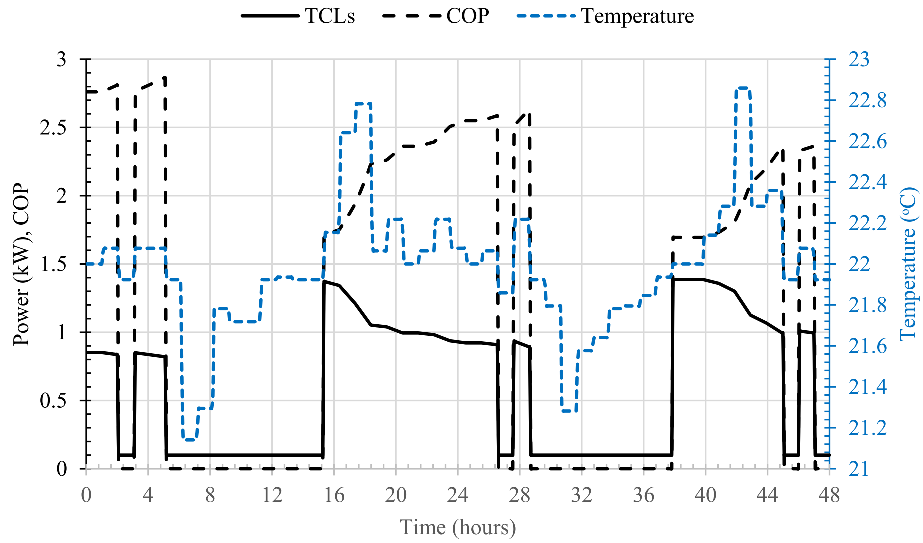

Fig. 4. Power consumption, coefficient of performance and inside temperature considering the model of air conditioning TCLs developed in this paper over two days.

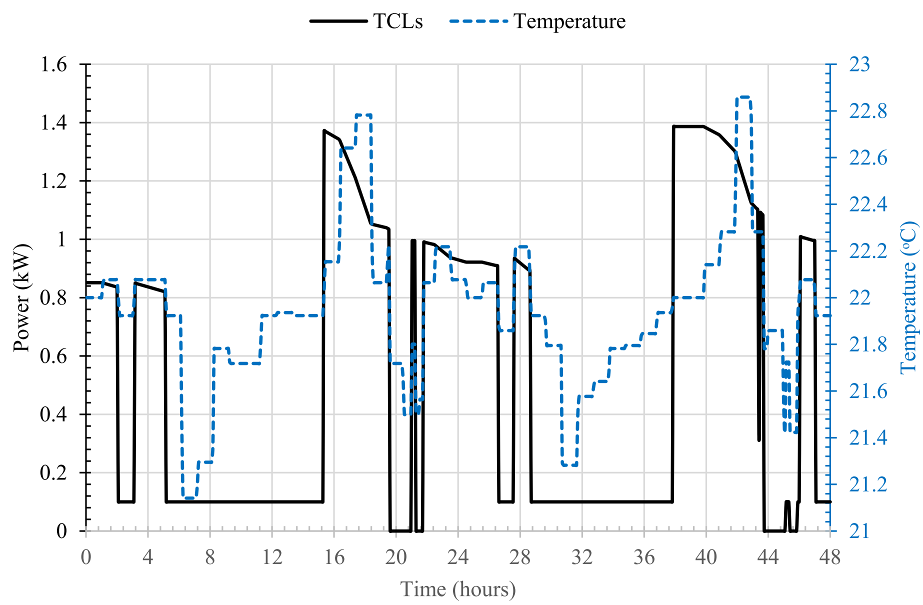

Fig. 5. The impact of the proposed scheme of home energy management on energy consumption of air conditioning TCLs and the inside temperature of the part of the building considered in this paper over two days.

Although another objective function was not considered with the proposed HEM system to minimize the operational cost of photovoltaic-battery system, such cost was minimized by re-scheduling the charge and dis-charge of the battery using Eq. (20). The battery is cooperatively dis-charged based on optimization results of TCLs, while maintaining the minimal limit of SOC_{min}. The battery is therefore charged considering the generation of photovoltaic panels until achieving the maximum value of SOC_{max}.

Fig. 7 shows the impact of re-scheduling method discussed earlier on the photovoltaic-battery power profile and the SOC value. The proposed algorithm adapts charging power of batteries to track photovoltaic generation without exceeding SOC_{max}, whereas it adjusts their dis-charging power consistent with the optimized TCLs keeping the SOC values within the pre-identified margins, as shown in Table 3 and Fig. 7. Therefore, the proposed HEM strategy prevents over-charging and deep dis-charging of batteries to increase their lifespan.

Fig. 8 compares the cumulative energy consumption of both thermostatically controlled loads and photovoltaic-battery systems over two days on a 5-minute basis while considering their operation with and without the proposed HEM scheme. It can be seen that the proposed HEM scheme reduces energy consumption and subsequently decreases electricity bill, while maintaining user's quality of experience [40].

A reasonable correlation is remarked between the cumulative energy consumption of the system (see Fig. 8) and the average value of energy estimated in degree-days method, as shown in Fig. 3. To illustrate this point further, if corresponding photovoltaic energy is deducted from the value of energy appointed at the completion of the solid line (i.e. without management) in Fig. 8, the result will be comparable to the average value of energy assessed in Fig. 3 using degree-days technique. The corresponding photovoltaic

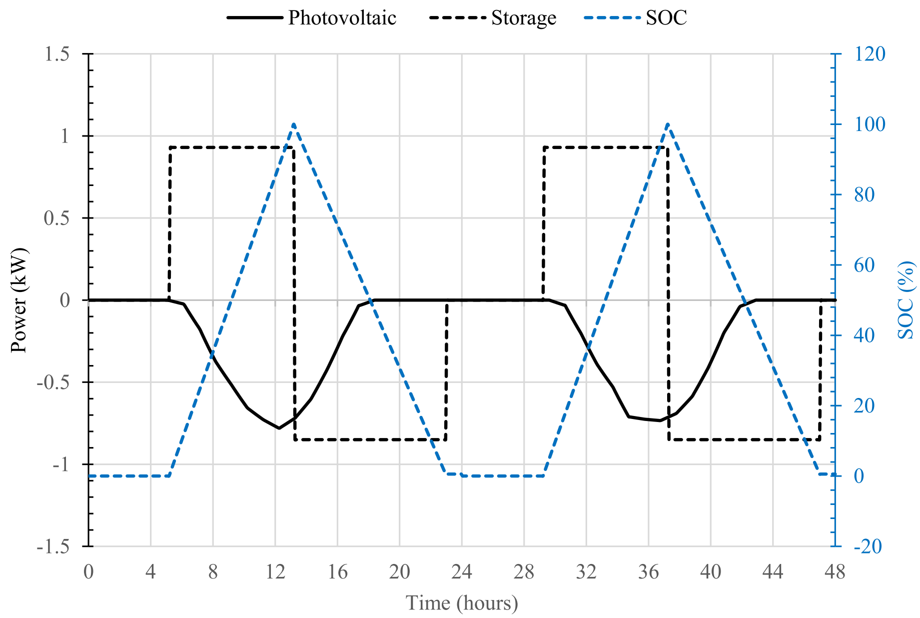

Fig. 6. Power profile and battery state of charge of the photovoltaic-battery system modelled in this paper over two days.

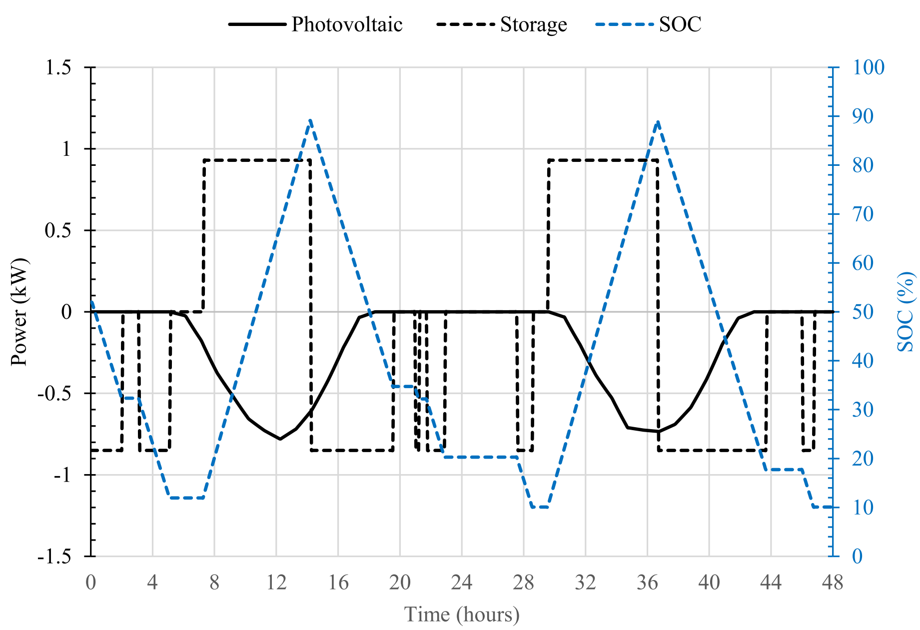

Fig. 7. The impact of the proposed scheme of home energy management on power profile and battery state of charge of the photovoltaic-battery system over two days.

energy is calculated by adding the photovoltaic power presented in Fig. 6.

Mathematically, Eq. (3) evaluates power consumption of air conditioning TCLs over two days. An integration of this power calculates diurnal energy consumption of TCLs. Eq. (5) estimates the energy consumption required to maintain the considered part of the building within comfortable condition over a month, whereas its diurnal average value is calculated over that month to indicate an amount of energy. This amount has the reasonable correlation with the energy calculated by the integration of the power determined using Eq. (3) on a daily basis. Such connection validates the model of air conditioning TCLs developed in this paper.

7. Conclusion and future work

A scheme of home energy management (HEM) requires a sensible level of modelling details to achieve practical changes on regular electricity consumption. In this paper, the operational characteristics of the thermostatically controlled system were modelled in Eq. (3) and Eq. (4) in terms of power consumption and in-house temperature. Meanwhile, power generation and consumption profiles of the photovoltaic-battery system were studied in Eq. (12) and Eq. (16) while modelling its battery state of charge (SOC) and its depth of discharge (DOD) in Eq. (13) and Eq. (14), respectively. Linear programming was used to solve the optimization problem of the proposed HEM scheme to modify thermostatically controlled loads (TCLs) of air conditioning systems,

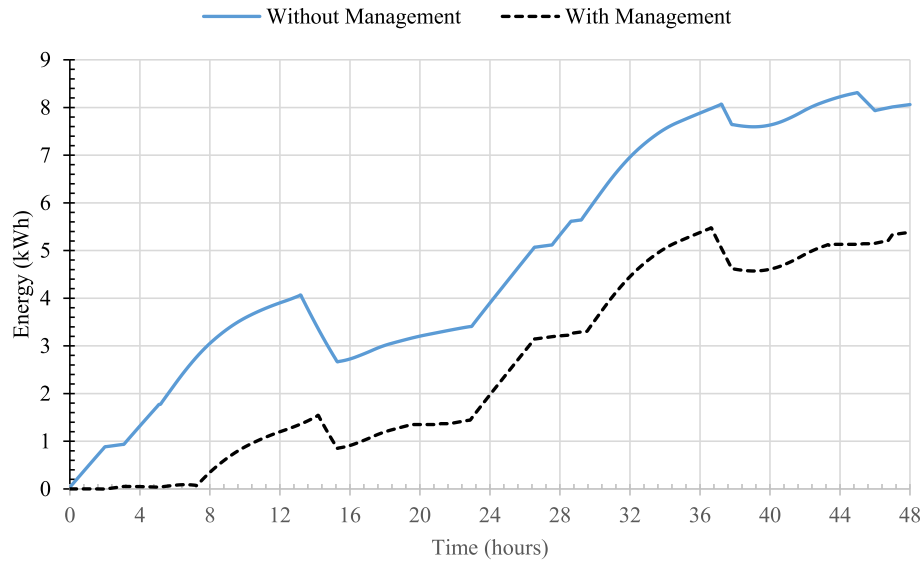

Fig. 8. A comparison of cumulative energy consumption with and without the proposed scheme of home energy management for the thermostatically controlled loads and photovoltaic-battery systems together.

minimizing the cost of their energy consumption based on variable electricity tariffs. Degree-days were observed in Eq. (6) to evaluate the required energy, which was embedded in Eq. (18) (i.e. the constraint conditions of the optimization), maintaining the in-house temperature within its threshold. The battery of the photovoltaic-battery system was simultaneously charged and discharged with the optimized air conditioning TCLs, keeping SOC limited by pre-identified margins, as indicated in Eq. (20). The proposed HEM scheme reduces energy consumption of the thermostatically controlled loads and photovoltaic-battery systems together by 30% (see Fig. 8), while maintaining the quality of experience of such systems.

Utility companies can adopt the proposed HEM scheme to incentivise consumers to enhance their electricity consumption profiles while reducing electricity bills. Residential customers can use the proposed HEM scheme (see Fig. 1) to accomplish energy savings and bill reductions if they install thermostatically controlled units and photovoltaic-battery systems in their premises.

The future work of this study will employ the proposed HEM scheme to control thermostatically controlled units and photovoltaic-battery systems in real-time applications. Smart switches will be experimentally programmed based on the algorithmic steps presented in Fig. 2 to control such systems as demonstrated in Fig. 1. Smart meters and feed-in tariffs will be used to optimize the excess of photovoltaic power exported to the grid (see Fig. 1). Moreover, a comparative study will be accomplished by solving the optimization problem using another programming technique (e.g. mixed integer linear programming) to reach the optimal solution.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2019.04.041.

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