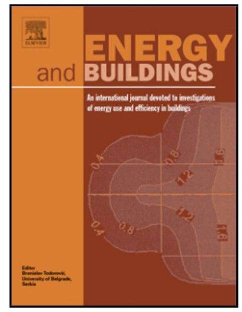
Accepted Manuscript



Title: An Intelligent System Architecture in Home Energy Management Systems (HEMS) for Efficient Demand Response in Smart Grid

Author: Mohammad Shakeri Mohsen Shayestegan Hamza Abunima S.M. Salim Reza M. Akhtaruzzaman A.R.M. Alamoud Kamaruzzaman Sopian Nowshad Amin

PII: S0378-7788(16)31836-9
DOI: http://dx.doi.org/doi:10.1016/j.enbuild.2016.12.026
Reference: ENB 7205

To appear in: *ENB*

Received date: 6-9-2016
Revised date: 13-11-2016
Accepted date: 9-12-2016

Please cite this article as: Mohammad Shakeri, Mohsen Shayestegan, Hamza Abunima, S.M.Salim Reza, M.Akhtaruzzaman, A.R.M.Alamoud, Kamaruzzaman Sopian, Nowshad Amin, An Intelligent System Architecture in Home Energy Management Systems (HEMS) for Efficient Demand Response in Smart Grid, Energy and Buildings http://dx.doi.org/10.1016/j.enbuild.2016.12.026

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

ACCEPTED MANUSCRIPT

An Intelligent System Architecture in Home Energy Management Systems (HEMS) for Efficient Demand Response in Smart Grid

Mohammad Shakeri[1], Mohsen Shayestegan[1], Hamza Abunima[1], S. M. Salim Reza[1], M. Akhtaruzzaman[2], A. R. M. Alamoud[3], Kamaruzzaman Sopian[2] and Nowshad Amin[1,2,3*]

[1] Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering and Built Environment, The National University of Malaysia, 43600 Bangi, Selangor, Malaysia
[2]Solar Energy Research Institute, The National University of Malaysia, 43600 Bangi, Selangor, Malaysia
[3]Department of Electrical Engineering, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia

*Corresponding author: nowshad@ukm.edu.my

Phone: +60193296750, Fax: +60389118359

ACCEPTED MANUSCRIPT

Research Highlights:

1. We present a novel Home Energy Management System (HEMS) system architecture and control algorithm that that enables the residential customers to execute demand response programs autonomously.
2. The proposed algorithm assures that the power consumption of the electrical appliances is always less than certain level.
3. The proposed house is supported by the battery system and Photovoltaic system as to increase the green index by utilizing alternative energy resource.

ACCEPTED MANUSCRIPT

Abstract

The Home Energy Management System (HEMS) is an important part of the smart grid that enables the residential customers to execute demand response programs autonomously. This study presents the outcome of a new system architecture and control algorithm that can use both battery storage and manage the temperature of thermal appliances. The proposed algorithm receives the price information from the utility company in advance and purchases the electricity at off-peak hours and utilizes the battery as well as manages the temperature of the thermal appliances during peak hours. The proposed algorithm assures that the power consumption of the electrical appliances is always less than certain level. The proposed house is supported by the battery system and Photovoltaic system as to increase the green index by utilizing alternative energy resource. The amount of the power that can be drained from the battery is limited by the algorithm to remain more during a day. The simulation results indicate that the proposed system is able to reduce the electricity price up to 20% a day without sacrificing the user's comfort.

Keywords: Power Distribution; Smart Grid; Demand Response; Home Energy Management Systems (HEMS); Smart Appliance.

1. Introduction

Emission of greenhouse gasses and their effects on climate changes have become a matter of serious concern around the world. In addition, the ever growing demand for increasing the supply and expanding the infrastructure of the power plants, the costs of energy will increase consequently. Moreover, it is extremely hard to add new electrical generator units, as thermal generators are still producing CO_2, whereas nuclear power plants are not free of radiation concerns and have issues with nuclear proliferation, and it is difficult to find a place for new hydro-based generators due to environmental issues. Therefore, demand response programs are considered as a new element that can help the countries to control their electricity consumption [1]. According to some previous studies [2, 3], demand response is a modification in normal

ACCEPTED MANUSCRIPT

consumption of demand by decreasing or increasing the loads when there is shortage or excess of power, in response to the condition of suppliers. Demand response programs appeared since 1970 to control peak hours in the United States. In those days, time of use pricing (TOU) and incentive programs were used in order to control the demand [4]. Gradually more strategies have been used for demand response programs such as critical pick pricing (CPP), real-time pricing, a day ahead pricing and incremental block rate pricing. Needless to mention, demand response programs cannot singly control the electricity consumption or influence the rate of participants to reduce the demand. In most of the cases, consumers do not like or cannot spend their time to calculate and analysis their power consumption and schedule the run time of their appliances in order to save their money [3]. Thus, smart technologies in grid infrastructure and appliances are required to be responsive to residential electricity consumption scenario. Smart controllers or home energy management systems (HEMS) are the technologies that can respond to the altered conditions independently and without human intervention. HEMS can shift or curtail the demand in response to electricity price and according to the human comfort to optimize the electricity consumption at peak or jeopardize hours. The main objective of HEMS is to reduce the electricity price with the minimum sacrifice in the dwelling comforts. Over the last decade many researchers worked on HEMS, these researchers are divided into two main categories, such as predictive energy management and consumption and real time management. The former category uses the prediction models and data to forecast the consumption and available supply in order to find the optimum strategy to control the electrical devices.

In some related literatures [5-8], researchers tried to use forecasting in their energy management systems. These algorithms are usually none-linear and somewhat difficult to implement as the forecasting is not so accurate and optimization algorithms are often very complex. The second category uses the real-time algorithms to control the thermal devices or shift the controllable devices to get to two important aims, i.e. reduce the peak to average ratio in load demand and reduce the electricity bills. Some researchers used real-time algorithm to optimize the electricity consumption [9-12]. These algorithms are usually linear and easy to implement, however, human comfort should be sacrificed more in order to get better results. In this research work, we propose additional local battery storage as the supplementary source that helps the grid to supply the electrical appliances with a careful eye on overall cost of energy minimization. There is also a real-time algorithm to find the suitable source for each electrical

ACCEPTED MANUSCRIPT

appliances to operate on grid or battery based on the electricity price, the amount of state of charge of battery, a power required to operate the electrical appliance and maximum limitation power of draining the battery. The study also includes description about the proposed structure of the standard domestic house/premise (i.e. smart house) with implementation of the electrical appliances as well as comparative results of the proposed algorithm with other methods and final recommendation.

2. The Proposed Smart House Architecture

The proposed smart home is a typical premise located in any Southeast Asian cities, which consists of smart plugs and local controller to monitor and control the consumption of electrical appliances, based on the condition of the electricity price as well as condition of the battery. Smart plugs are able to measure the power of the appliances and send the data to the local controller. They are also able to receive a signal from the local controller to start, stop and switch between the battery and the grid the operation of the electrical appliances. The local controller in HEMS aims to determine the best operation for electrical appliances by switching them between battery and grid to optimize the electricity price during a day considering the price information from grid and user comfort. Eq. (1) represents the cost function of electricity, where E_P is electricity price at the time of h, K is the normalized price of installation and maintenance fees of the PV system and P_G represents the purchasing electricity amount from the grid at the time h.

$$\text{Electricity cost} = \sum_{h=1}^{24} (E_P(h) * P_G(h)) + K(h)) \tag{1}$$

Fig. 1 represents the layout of the proposed smart house or apartment. This premise has all appliances required for any standard household and is equipped with the grid connected PV system with storage battery that the designed controller is able to make a decision to operate each appliance either on battery or grid at any time. Eq. (2) shows the power consumption of the house, where, $P_{Grid}(h)$ indicates the power used from grid, $P_{et}(h)$ represents the total power of electrical appliances. Negative value for the $P_{Battery}$ represents the situation where the appliances are operating on battery and positive value for $P_{Battery}$ represents the charging the battery through the grid.

ACCEPTED MANUSCRIPT

$$P_{Grid}(h) = P_{et}(h) - P_{PV\ panel}(h) \pm P_{Battery}(h) \quad (2)$$

According to equation (1), it is required to reduce the P_{Grid} as minimum as possible in order to optimize the electricity consumption cost. Hence, the proposed algorithm limits the maximum power we can drain from the grid as shown in Eq. (3) as the grid limitation/constraint.

$$\text{gbm}\ (h) \geq \sum P_e\ (h) \quad (3)$$

Where, gbm is the maximum power that is allowed to drain from the grid and P_e represents the operational power of electrical appliances on grid at each slot of time. In addition, a battery storage is used as the supplemental source besides the grid. Therefore, the total consumption from the grid is limited by the algorithm and kept under certain (threshold) value that is measured based on the capacity of the battery as well as consumption of the premise/house. If the certain (threshold) level is crossed the new appliance is shifted to battery instead of shifting to another time slot and therefore human comfort is violated less rather than curtail or shifting the appliance usage to other time.

Fig.1 Layout of the proposed smart home

It is also required to model and implement the pilot electrical appliances to prove its implementation potential. In the following sections, detailed implementation of the smart home appliances in MATLAB/ SIMULINK software is described.

2.1.Configuration of the thermal model of the building

According to model of the power Flex-House in literature [13-15], the inside ambient temperature of the house at each time is equal to:

$$C\frac{dT_{in}}{dt} = \frac{1}{R_t}(T_{out} - T_{in}) + \frac{1}{R_{iw}}(T_{iw} - T_{in}) + \frac{1}{R_{ow}}(T_{ow} - T_{in}) + \emptyset_{H/A} + A(1-p)\emptyset_{ir} + T_{rand} \quad (4)$$

Where, C is the capacity of the total indoor air's heat, R_t indicates the total resistance against heat flow to the outside of the room or thermal energy from heater/air-conditioner, T_{in} is the room temperature, T_{out} is the outside temperature, R_{iw} is the total resistance between inner layers of the room's walls and indoor air temperature, R_{ow} indicates the thermal resistance

ACCEPTED MANUSCRIPT

between the wall and outside air temperature, $\emptyset_{H/A}$ is the thermal energy flow of the heater/air-conditioner, A is the area of the window of the room, p is the part of the irradiation of sun which is directly observed by inner layer of indoor walls, $\emptyset_{ir}$ is the thermal energy from sun, T_{rand} is the random temperature due to changing the air of the room with outside and T_{iw} represents the temperature of the inner layer of the room's walls and obtained by:

$$C_{iw}\frac{dT_{iw}}{dt} = \frac{1}{R_{iw}}(T - T_{iw}) + Ap\emptyset_{ir} \quad (5)$$

Where, C_{iw} is the heat capacity of inner walls and T_{ow} is the temperature of the outer layer of the room's walls and outside temperature and obtained by:

$$C_{ow}\frac{dT_{ow}}{dt} = \frac{1}{R_{ow}}(T - T_{ow}) + \frac{1}{R_w}(T_{out} - T_{ow}) \quad (6)$$

Where, C_{ow} is the heat capacity of inner walls and $R_w$is the thermal resistance between the outside air temperature and outer layer of walls. The parameters of the thermal model are estimated with Continuous Time Stochastic Modelling (CTSM), and the parameters are shown in Table 2.

Table 2 The parameters of the proposed thermal model of the house

According to Rupp at el. [16], human comfort level is between 18℃ to 24℃ and optimum temperature is 21℃. The local controller is able to change the set point temperature of the house to make sure that the total power consumption of the electrical appliances does not cross the limit.

2.2. Refrigerator

Previously, electrical performance and modeling of a refrigerator were addressed by approaches such as dynamic simulation tool [17], steady state simulation [18], or CFD models [19]. In this work, a grey-box model of refrigerator [20] is used to provide an ordinary, ready-to-use tool for simulation and control the refrigerator. As the temperature of the room influences the operation of the refrigerator, the aim is to consider the refrigerator as a shift-able appliance with a flexible

ACCEPTED MANUSCRIPT

consumption unit according to the temperature and operational power. Therefore, according to grey-box model of refrigerator, temperature of inside the chamber of refrigerator is obtained by:

$$\frac{dT_{in}}{dt} = \frac{1}{R_i C_i}(T_{room} - T_{in}) + \frac{1}{R_o C_i}(T_c - T_{in}) + t_{rand} \quad (7)$$

Where, R_i is the thermal resistance of inside the refrigerator envelope, C_i is the thermal mass of the refrigerator, T_{room} is the room temperature, T_{in} is the refrigerator temperature, R_o is the thermal resistance of outside the refrigerator envelope and T_c is the temperature of the chamber and t_{rand} is the random variation of the temperature of the refrigerator by opening the door of the refrigerator. Chamber temperature is measured by:

$$\frac{dT_c}{dt} = \frac{1}{R_i C_c}(T_{in} - T_c) + \frac{1}{C_i}(cop * \emptyset_e) + t_{rand2} \quad (8)$$

Where, C_c is the thermal mass of the chamber, cop is Refrigeration cycle and $\emptyset_e$ is the electrical power consumed by the compressor. Temperature of the refrigerator is fixed at 5°C. The parameters of the grey-box model of the refrigerator are estimated with CTSM, and the parameters are shown in Table 3.

Table 3 The parameters of the grey-box model of the refrigerator

2.3. Washing machine

Washing machine is sift-able and uninterruptable appliance. Power consumption of this appliance is recorded by data logger and will be used in this research. Figure 2 represents the operational characteristics and cycle time of the proposed washing machine. Based on the condition of the grid and battery, the algorithm can make a decision about the operation of the washing machine to be either on grid or battery. In the same way, the data of microwave, toaster and coffee maker is collected by data logger and used in the simulation software.

ACCEPTED MANUSCRIPT

Fig. 2 Operational characteristics of the washing machine

2.4. Configuration of uncontrollable appliances

According to a study [21], operation of electrical appliances is related to the number of residents and the size of the house as well as the human activities . Figure 3 shows the probability of operation of electrical consumption among 24 hours of a young couple in the apartment as an example. Therefore, it has tried to model the operation of electrical appliances such as TV, lamps, water heater, and so on. Time of start and duration of operation of these appliances are totally random and based on the pattern of the human behavior in figure 3. These appliances are also able to operate either on grid or battery based on the decision of the algorithm.

Fig. 3 Pattern of consumption of electrical appliances by 2 persons in the apartment [21]

2.5. Configuration of the Supply System

Supply part consists of grid, battery, solar panel and the supply controller. The battery can use as a supplier or consumer based on the state of charge (SOC) of the battery. Supply controller is responsible to manage between the solar panel and grid to charge a battery in the different situations and send the information about the status of battery to local controller. It is assumed that electricity price is fixed in the utility company and is conveyed to the local controller in advance. An exemplary model on TOU price is shown in Figure 4, referring to Huang et al. [12]

Fig. 4 The price of electricity based on time of use (TOU) model

2.6. Configuration of Solar panel

ACCEPTED MANUSCRIPT

Equation 9 represents the output current of solar cell [22]. Where I is the output current, I_{Ph} is the solar-induced current, I_d is the saturation current of diode, V is the output voltage, R_s is series resistance, R_P is parallel resistance, V_T is the thermal voltage and N indicates the quality factor of the diode. Equation 10 represents the thermal voltage, where k is the Boltzmann constant, T is temperature, n is the number of series cells, and q is the electronic charge.

$$I = I_{Ph} - I_d * \left(e^{(V+I*R_S)/(N*V_T)} - 1\right) - (\frac{V+I*R_S}{R_P}) \tag{9}$$

$$V_T = \frac{n*k*T}{q} \tag{10}$$

Based on these equations, the solar panel is modeled by one diode equivalent circuit in Simulink. A Mitsubishi PV-UD190MF5 solar photovoltaic module is chosen for modeling the proposed PV power source. This panel consists of 50 series connected crystalline silicon solar cells that generates the maximum of 190 W. The detail parameters of Mitsubishi PV-UD190MF5 are indicated in Table 4.

Table 4 Characteristics of MSX-60 PV panel

2.7. Configuration of the battery

The battery can charge or discharge in different situations to avoid peak hours, reduce the cost and increase the efficiency of overall electricity consumption. According to [23] the lifetime of the battery is indicated by a state of charge (SOC) of the battery. Equation 11 represents the SOC of battery that are limited by the range of SOC_{max} and SOC_{min}.

$$SOC(t) = SOC_{Initial} + \frac{1}{SOC_{max}} + \int \left[\frac{E_{ch}V_C I_b - DSOC(t-\Delta t)SOC_{max}}{3600}\right], \forall\, SOC_{min} \leq SOC \leq SOC_{max} \tag{11}$$

Where, E_{ch} is the charge efficiency of battery and D is the self-discharging rate. Here, SOC_{max} is equal 90% and SOC_{min} is equal to 30%. In addition, discharging of the battery is defined in Equation 12.

$$V_{Battery} = V_{dch} + I_{dch} * R_{dch} \tag{12}$$

ACCEPTED MANUSCRIPT

$$V_{dch} = (1.926 + 0.124\alpha) * N_S \quad (13)$$

Where $\alpha = \frac{soc_{initial}}{soc_{max}}$ and N_S is the number of cells inside the battery. Since the efficiency of charging of most of the lead-acid batteries are more than 85% [24, 25] and the efficiency of most inverters are greater than 96% [26], the energy conversion efficiency of the battery is greater than $85\% \times 96\% = 81.6\%$. On the other hand, the ratio of the lowest rate ($0.05\, USD/kWh$) and the average rate ($0.09\, USD/kWh$) is equal to 55% as shown in Fig. 4. Therefore, the conversion efficiency of the battery is greater than the ratio of the lowest and the average rate. So, both the highest rate and average rate incentivize the battery storage.

Since the capacity of the battery is unable to run the appliances with high consumption, let $So_B\,(h)$ denotes the current energy is exist in the battery at time interval h, $P_{pv}\,(h)$ is the solar energy is stored in the battery, and $P_b(h) = \sum P_e\,(h)$ is the total power of the electrical appliances are currently operating on the battery, therefore, the stored energy in the battery at each time interval is given by:

$$So_B\,(h) = P_{pv}\,(\delta) + So_B\,(\delta) + P_b(\delta), \forall \delta < h \quad (14)$$

The power generated by the solar panel is charging the battery system during daytime and its excessive power can be sold to the grid. Battery system is supported by photovoltaic (PV) panel. However for simplicity it is assumed that the energy produced by solar panel is equal to sum of energy is used by electrical appliances and battery. As mentioned earlier, supply controller is responsible for managing the supply system as well as sending the information to the local controller upon checking the status of the battery. Based on Eq. (11), status of the battery (S) is equal to zero when the $SOC \leq SOC_{min}$ and it is equal to one when the $SOC \leq SOC_{max}$.

3. Load Management Algorithm

In each time interval, the proposed algorithm aggregates the information of the electrical appliances such as the status of electrical appliances, the power consumption of electrical appliances, room temperature as well as the status of the battery and electricity price. When a

ACCEPTED MANUSCRIPT

user tries to turn on the appliance, the smart controller receives the request from the electrical appliance. At each time interval the algorithm checks the electricity price at the beginning. If the electricity price is cheaper (Figure 4), algorithm sends a signal to the smart plug to connect the electrical appliance to the grid. If it finds the status of the battery at zero, then the battery starts to recharge. Otherwise, the proposed algorithm enables the power consumption of appliances via smart plug (P_e) from battery. The algorithm sends a signal to smart plug to connect the appliance to the battery only when the appliances can meet the limitation of the battery according to equation 14.

If the power consumption of the appliance doesn't meet the required condition of the battery or the status of battery is zero, control algorithm ensures the total household power consumption to run on the grid (gbm). If the power consumption of the appliances can meet the limitation of the grid according to equation 3, algorithm sends a signal to the smart plug to run it on the grid. Otherwise, algorithm tries to increase the set temperature of the thermal appliances until the room temperature reaches $24℃$. If the room temperature exceeds $24℃$ and still the total power consumption of electrical appliances are more than the set value of (gbm), control algorithm checks the electricity price again. If the electricity price is equal to the average ratio, electrical appliances are connected to the grid. Otherwise, local controller warn the user to purchase electricity from grid or terminate the operation of the appliance.

Fig. 5 Flowchart of the smart controller algorithm

4. Case Study Formulation

This section represents the applicability of the implemented simulation model and algorithm in managing the electricity consumption. The layout of the proposed virtual house is shown in Figure 6, where one typical residential dwelling for two persons is equipped with 26 electrical appliances.

Fig. 6 Layout of the virtual residential dwelling

ACCEPTED MANUSCRIPT

A typical hot day of any city of Southeast Asian countries is opted as the case study that ambient temperature is varying in between 23℃ and 34℃ during 24 hours throughout the year. Table 4 shows the rated power consumption of all electrical appliances obtained by either measuring their power by data logger or their manufacturer catalogues. House is equipped with a smart controller to control and optimize the electricity price based on the condition of the suppliers and price information from utility grid. The electricity price is known and is received automatically a day ahead through internet communication between smart controller and utility company. The electricity price used in this study refers to the TOU charge as shown in Figure 4 [12]. According to [27] the total price of the opted system is around 1500$, therefore after normalized the prices for 25 years the price of the Solar panel is $K(h) = 0.03\ \$/kWh$.

Table 4 Rated power of electrical appliances

Now, several case studies will be discussed aligned with the objectives of this study. In order to understand the performance of the optimization algorithm and structure, three different scenarios are studied and compared as shown below.

1. Scenario 1 operates the electrical appliances without any optimization. Occupants need not care about the price of the electricity and their comfort is the utmost priority.
2. Scenario 2 operates the electrical appliances with optimization of the thermal appliances and shift-able appliances. Comfort of occupants is not important and it tries to reduce the electricity consumption as minimum as possible.
3. Scenario 3 operates the electrical appliances with optimization algorithm. Comfort of the consumers is on priority as well as occupants need not care about the price of the electricity.

4.1. Results and Discussion

The operation of the electrical appliances without optimization algorithm is represented in Figure 7. In the basic scenario, it is assumed that occupants are using a normal power supply and the electrical appliances operate by the grid. It is also assumed that occupants want to satisfy their

ACCEPTED MANUSCRIPT

comfort without considering the electricity price. Occupants set the room temperature at 18 ℃ and the temperature of the refrigerator is set to 3℃. Other home appliances are working as usual and there is no scheduling for the appliances. The results find that there are some peak power situations between 6 AM and 8 AM as well as 12 PM and 2 PM as shown in Fig. 7(A).

Fig. 7.(A)Total power consumption by the electrical appliances,(B) outdoor temperature, (C) indoor temperature, (D) refrigerator temperature

As shown in figure 7A, the electricity consumption of this permits has some fluctuation during a day and in some hours a day its reach to 7kW. The electricity price for this house is around 3,15 $\$/Day$.

In the second scenario, the temperature of the room is set to the optimized temperature (21℃ to 24℃), shift-able electrical appliances such as washing mashing are operated when the electricity is cheap (between 10 PM and 12 PM) and other electrical appliances are working as usual.

Fig. 8. (A) Total power of electrical appliances, (B) The room temperature and (C) The refrigerator temperature.

Fig 8A shows that controlling the set point of the thermal appliances as well as shifting the operation of the shift-able appliances are not successful as still there are some peak hours between 6 AM and 8 AM as well as 12 PM and 20 PM. The electricity price of the building with this strategy is reduced to 2.87 $\$/Day$ while due to reach this goal, the human comforts sacrificed a lot as the operation of some appliances are shifted to the cheap hours.

In the third scenario, the battery system charges at off-peak hours and discharges at peak hours. Fig. 9 shows power consumption of the proposed house on both grid and battery, state of charge of the battery and solar panel production during 24 hours as the execution of the algorithm. During a day, 600 Wp PV panel supports the battery system and charges the battery when the electrical appliances need not use the power produced by solar panel. In this case, the comfort of the occupants is on priority and gbm is set to 3.1kW.

ACCEPTED MANUSCRIPT

Fig. 9 (A) State of charge (SOC) of the battery, (B) Total power of electrical appliances operating on grid, (C) Total power of electrical appliances operating on Battery. (D) Power generated by solar panel, (E) Room temperature fluctuation in 24 hours (F) refrigerator temperature.

Fig. 9 summarized the results of the third scenario. During any nighttime when the electricity price is cheaper, battery is being charged though the grid. As the electricity price becomes expensive after 5AM, local controller tries to switch some electrical appliances on the battery to reduce the overall consumption from the grid, as shown in Fig.9 A and Fig.9 B. Again, when the solar panel production is sufficiently enough in between 9 AM and 3 PM, battery is charged by PV panel as shown in Fig.9 D. And, between 3 PM and 10 PM, local controller again tries to operate some of electrical appliances on battery. During the duration between 6 AM and 8 AM as well as between 12 PM and 9 PM, when the consumption of electrical appliances exceed more than 3000 W the set point of the air conditioner is increased to shave the peaks and reduce the consumption as shown in Figure 9E. Around 10 PM the state of charge of the battery is less than SOC_{min} , so the supply controller set the status of the battery to zero, hence, appliances are operating on grid directly and as the electricity price is cheap according the price signal from Fig.4, in order to avoid the residence wellbeing violence there is no any interruption in electrical appliances. In this scenario total price of operated electrical appliances on grid is equal to 2.4 $\$/Day$ and total price of the operated appliances on PV system is equal to $6.5kWh \times 0.03\$/kWh = 0.195\$$. Therefore the total price of the proposed system per day is $2.4\$ + 0.195\$ = 2.595\$$ with a minimum human comfort violation.

Table 5 shows the comparison among four different scenarios executed in terms of total power consumption of the electrical appliances from the combination of grid and battery during 24 hours for the proposed smart house.

Table 5 Comparison among the scenarios

Fig. 10 shows the total saving of the proposed house by deploying HEMS algorithms in different situations, besides the total electricity (in case of purchase from grid) need for the house in a day.

ACCEPTED MANUSCRIPT

Fig.10 Comparison of total cost-savings by HEMS at different scenarios

As found here, the proposed algorithm i.e. scenarios 3 can save the electricity cost of around 8%, comparing with the one by shifting the deferrable appliances from peak-hours to off-peak hours in conjunction with the increasing set point temperature of the thermal appliances (scenarios 2). It is also found that 20% cost saving can be achieved comparing to scenarios 1, where any control algorithm is deployed. This savings are generated by switching the appliances on battery during peak-hours as well as controlling the thermal appliances too. However, we need to pay grid for recharging the batteries, which could be totally eliminated if optimized solar system is installed to do the task. By comparing the cases 2 and 3, it is obvious that the proposed algorithm is able to reduce the cost with a minimum restriction to human comfort, while in the 2nd scenarios the human comfort should be sacrificed more to reach the optimum cost minimization.

Results show that human activity and variation of irradiance are two external parameters that can influence the output of the algorithm. While in Southeast Asian countries, ambient temperature does not change significantly and therefore should not have any sharp influence on the output of the algorithm. However, by optimizing the solar system and battery capacity we can easily eliminate the influence of irradiance on output.

Obviously, human activity can influence the power consumption on the grid. For example, the algorithm tries to manage and schedule the electrical appliances when the consumption from the grid is restrictive and electrical appliances can operate on grid when the consumption is relaxed. Moreover, we can use feed-in-tariff or any other option to sell off the excess of the electrical energy in this kind of situations.

By using battery as a storage device, the proposed smart house requests less energy from electrical grid during most of the high rated period. The results show that not only does the proposed smart controller have the potential to lower the electricity price, but it also has the potential to lower the production cost across the entire grid by reducing the consumption during peak hours. By comparing the second and third scenarios, it is obvious that using the battery system with solar PV system has huge impact on the saving the electricity cost rather than

ACCEPTED MANUSCRIPT

shifting and changing the set point of thermal appliances. Therefore, it is found that the storage device as battery plays an important role in the future of the demand response programs, of course at the lowest possible capital or installation cost. This model is suitable for typical premises in south-Asian countries and the calculation of 20% saving is valid for this specific case. However, the model is applicable for other regions such as other Asian or European countries with some modifications.

5. Conclusion

In this study, a novel system architecture and control algorithm has been proposed for demand response of electricity of any smart house. This algorithm is able to manage the operation of electrical appliances to work on battery or grid based on the electricity price in hourly basis. The battery is charged during any night time, when the electricity price is lower and then is utilized or discharged during peak hours. The algorithm is also able to adjust the temperature of the room to optimize the electricity consumption when the total power consumption of the house is more than a certain level which is adjusted in advanced. The model of the building including 26 electrical appliances are designed and implemented in MATLAB/Simulink software. Simulation results show that the proposed algorithm is able to reduce the electricity price significantly up to 20% per day by managing the operational power of electrical appliances. Results also find that total power consumption of the proposed house has significantly reduced by the deployment of the storage device i.e. battery equipped with small scale solar PV system. This will encourage the consumers to participate in demand response programs. This study can be extended to usage forecasting in load and output power of solar panel to enable user to use feed-in-tariff (FIT) to further reduce electricity cost in smart homes.

ACCEPTED MANUSCRIPT

Reference

[1] P. Stoll, N. Brandt, L. Nordström, Including dynamic CO 2 intensity with demand response, Energy Policy, 65 (2014) 490-500.
[2] M. Beaudin, H. Zareipour, Home energy management systems: A review of modelling and complexity, Renewable and Sustainable Energy Reviews, 45 (2015) 318-335.
[3] A. Faruqui, S. Sergici, Household response to dynamic pricing of electricity: a survey of 15 experiments, Journal of Regulatory Economics, 38 (2010) 193-225.
[4] D. Hurley, P. Peterson, M. Whited, Demand Response as a Power System Resource, (2013).
[5] A. Agnetis, G. de Pascale, P. Detti, A. Vicino, Load Scheduling for Household Energy Consumption Optimization, Smart Grid, IEEE Transactions on, 4 (2013) 2364-2373.
[6] P. Samadi, H. Mohsenian-Rad, V.W.S. Wong, R. Schober, Tackling the Load Uncertainty Challenges for Energy Consumption Scheduling in Smart Grid, Smart Grid, IEEE Transactions on, 4 (2013) 1007-1016.
[7] O.A. Sianaki, M.A. Masoum, A multi-agent intelligent decision making support system for home energy management in smart grid: A fuzzy TOPSIS approach, Multiagent and Grid Systems, 9 (2013) 181-195.
[8] S. Salinas, L. Ming, L. Pan, Multi-Objective Optimal Energy Consumption Scheduling in Smart Grids, Smart Grid, IEEE Transactions on, 4 (2013) 341-348.
[9] Q. Li Ping, Y.J.A. Zhang, H. Jianwei, W. Yuan, Demand Response Management via Real-Time Electricity Price Control in Smart Grids, Selected Areas in Communications, IEEE Journal on, 31 (2013) 1268-1280.
[10] S. Koch, M. Zima, G. Andersson, Potentials and applications of coordinated groups of thermal household appliances for power system control purposes, Sustainable Alternative Energy (SAE), 2009 IEEE PES/IAS Conference on, 2009, pp. 1-8.
[11] R. Missaoui, H. Joumaa, S. Ploix, S. Bacha, Managing energy smart homes according to energy prices: analysis of a building energy management system, Energy and Buildings, 71 (2014) 155-167.
[12] Y.T. Huang, H.J. Tian, L. Wang, Demand response for home energy management system, International Journal of Electrical Power & Energy Systems, 73 (2015) 448-455.
[13] A. Thavlov, Dynamic optimization of power consumption, Technical University of Denmark, DTU, DK-2800 Kgs. Lyngby, Denmark, 2008.
[14] A. Staino, H. Nagpal, B. Basu, Cooperative optimization of building energy systems in an economic model predictive control framework, Energy and Buildings, 128 (2016) 713-722.
[15] K.K. Andersen, H. Madsen, L.H. Hansen, Modelling the heat dynamics of a building using stochastic differential equations, Energy and Buildings, 31 (2000) 13-24.
[16] R.F. Rupp, N.G. Vásquez, R. Lamberts, A review of human thermal comfort in the built environment, Energy and Buildings, 105 (2015) 178-205.
[17] C.J. Hermes, C. Melo, Assessment of the energy performance of household refrigerators via dynamic simulation, Applied Thermal Engineering, 29 (2009) 1153-1165.
[18] C.J. Hermes, C. Melo, F.T. Knabben, J.M. Gonçalves, Prediction of the energy consumption of household refrigerators and freezers via steady-state simulation, Applied Energy, 86 (2009) 1311-1319.
[19] J. Gupta, M.R. Gopal, S. Chakraborty, Modeling of a domestic frost-free refrigerator, International Journal of refrigeration, 30 (2007) 311-322.
[20] G.T. Costanzo, F. Sossan, M. Marinelli, P. Bacher, H. Madsen, Grey-box modeling for system identification of household refrigerators: A step toward smart appliances, Energy (IYCE), 2013 4th International Youth Conference on, IEEE, 2013, pp. 1-5.
[21] J.P. Zimmerman, End-use metering campaign in 400 households in Sweden, Assessment of the potential electricity savings. Enertech & Energimyndigheten, (2009).

ACCEPTED MANUSCRIPT

[22] S. Sumathi, L.A. Kumar, P. Surekha, Solar PV and Wind Energy Conversion Systems: An Introduction to Theory, Modeling with MATLAB/SIMULINK, and the Role of Soft Computing Techniques, Springer2015.
[23] D. Iero, R. Carbone, R. Carotenuto, C. Felini, M. Merenda, G. Pangallo, F.G. Della Corte, SPICE modelling and experiments on a complete photovoltaic system including cells, storage elements, inverter and load, 2016 IEEE International Energy Conference (ENERGYCON), IEEE, 2016, pp. 1-5.
[24] G. Lorenzi, C.A. Santos Silva, Techno-economic comparison of storage vs. demand response strategies in distributed generation systems, European Energy Market (EEM), 2015 12th International Conference on the, IEEE, 2015, pp. 1-5.
[25] J.W. Stevens, G.P. Corey, A study of lead-acid battery efficiency near top-of-charge and the impact on PV system design, Photovoltaic Specialists Conference, 1996., Conference Record of the Twenty Fifth IEEE, IEEE, 1996, pp. 1485-1488.
[26] G. Bin, J. Dominic, L. Jih-Sheng, C. Chien-Liang, T. LaBella, C. Baifeng, High Reliability and Efficiency Single-Phase Transformerless Inverter for Grid-Connected Photovoltaic Systems, Power Electronics, IEEE Transactions on, 28 (2013) 2235-2245.
[27] S. Electronics, Sun Electronics, http://sunelec.com/, 2016.

ACCEPTED MANUSCRIPT

Fig.1 Layout of the proposed smart home

Fig. 2 Operational characteristics of the washing machine

Fig. 3 Pattern of consumption of electrical appliances by 2 persons in the apartment [21]

Fig. 4 The price of electricity based on time of use (TOU) model

Fig. 5 Flowchart of the smart controller algorithm

Fig. 6 Layout of the virtual residential dwelling

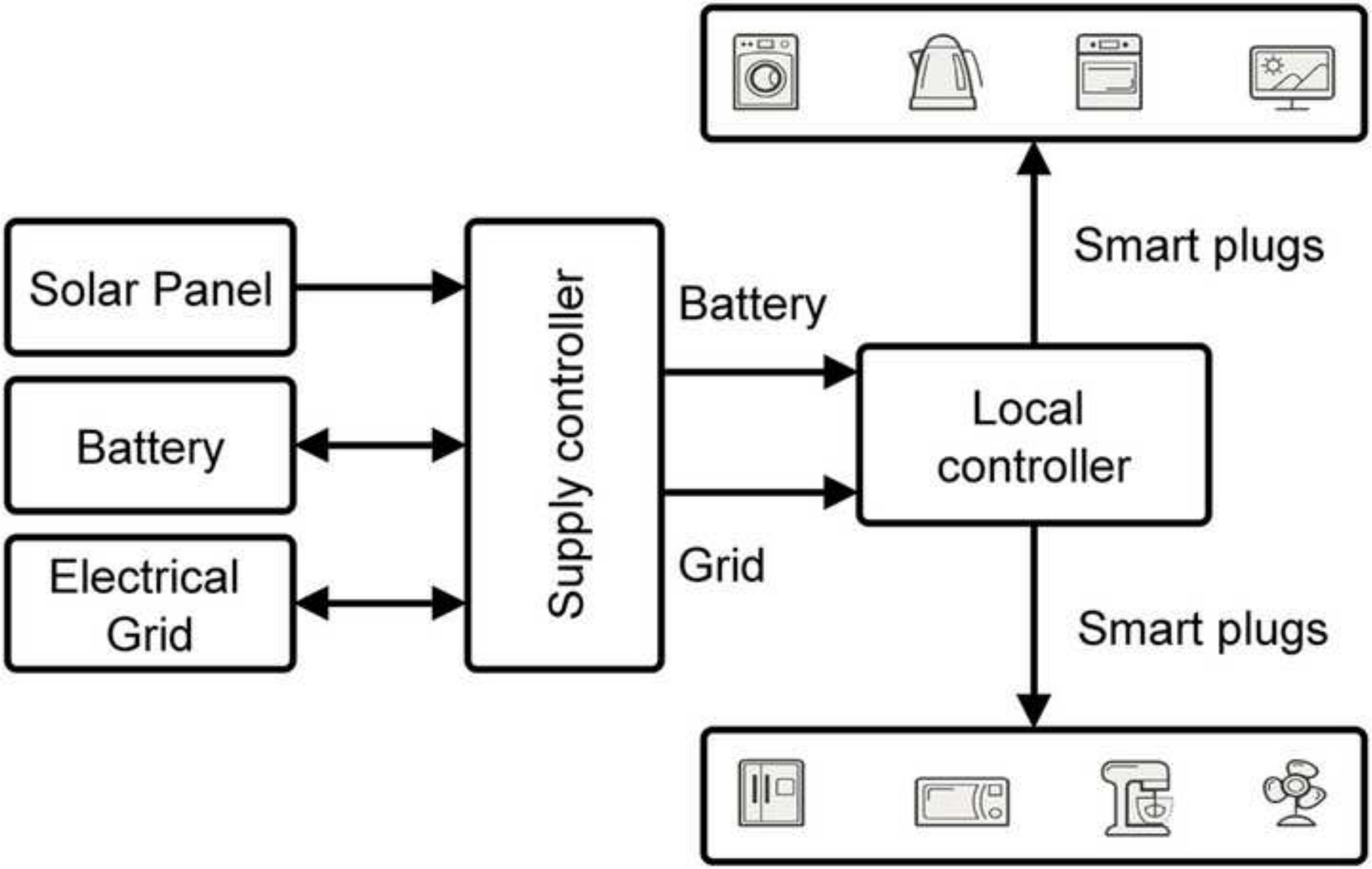
Fig. 7.(A)Total power consumption by the electrical appliances,(B) outdoor temperature, (C) indoor temperature, (D) refrigerator temperature

Fig. 8. (A) Total power of electrical appliances, (B) The room temperature and (C) The refrigerator temperature.

Fig. 9 (A) State of charge (SOC) of the battery, (B) Total power of electrical appliances operating on grid, (C) Total power of electrical appliances operating on Battery. (D) Power generated by solar panel, (E) Room temperature fluctuation in 24 hours (F) refrigerator temperature.

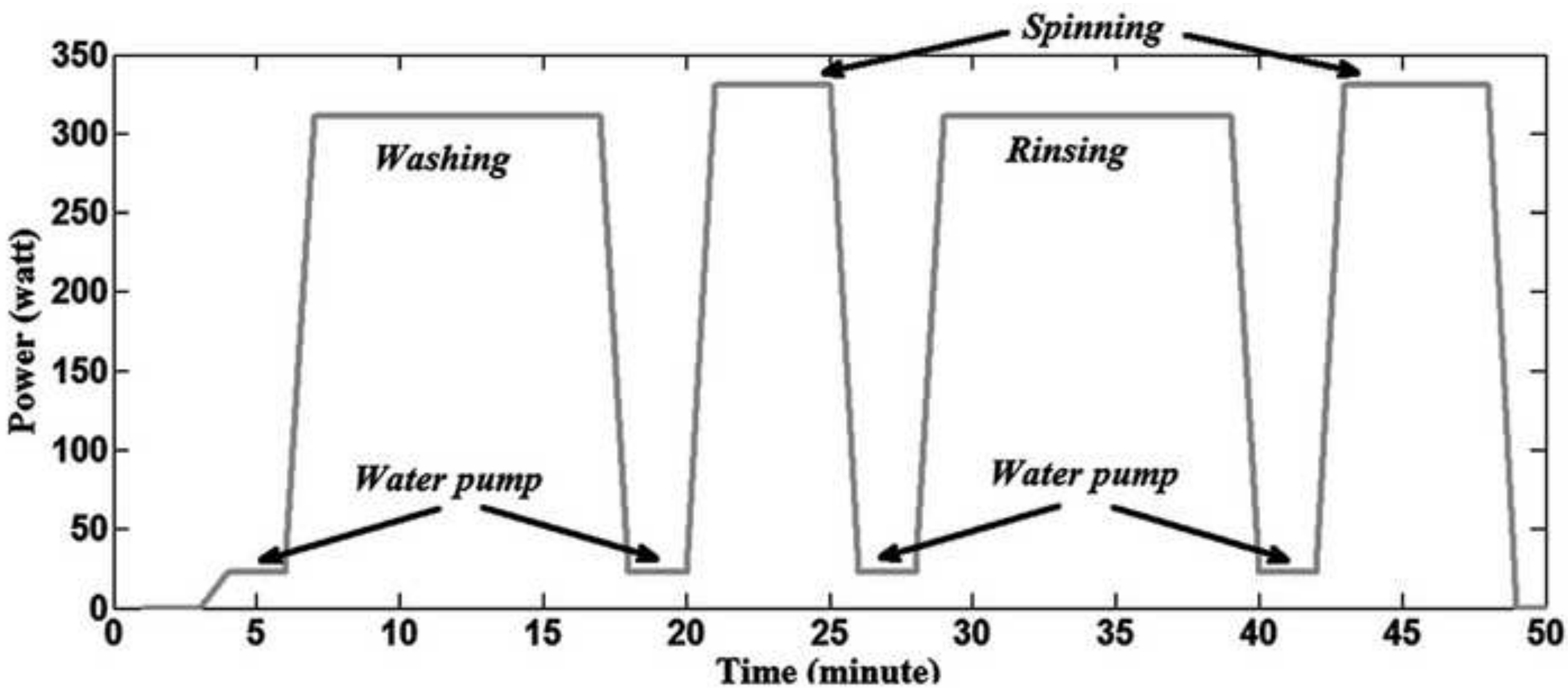
Fig.10 Comparison of total cost-savings by HEMS at different scenarios

Figure 1



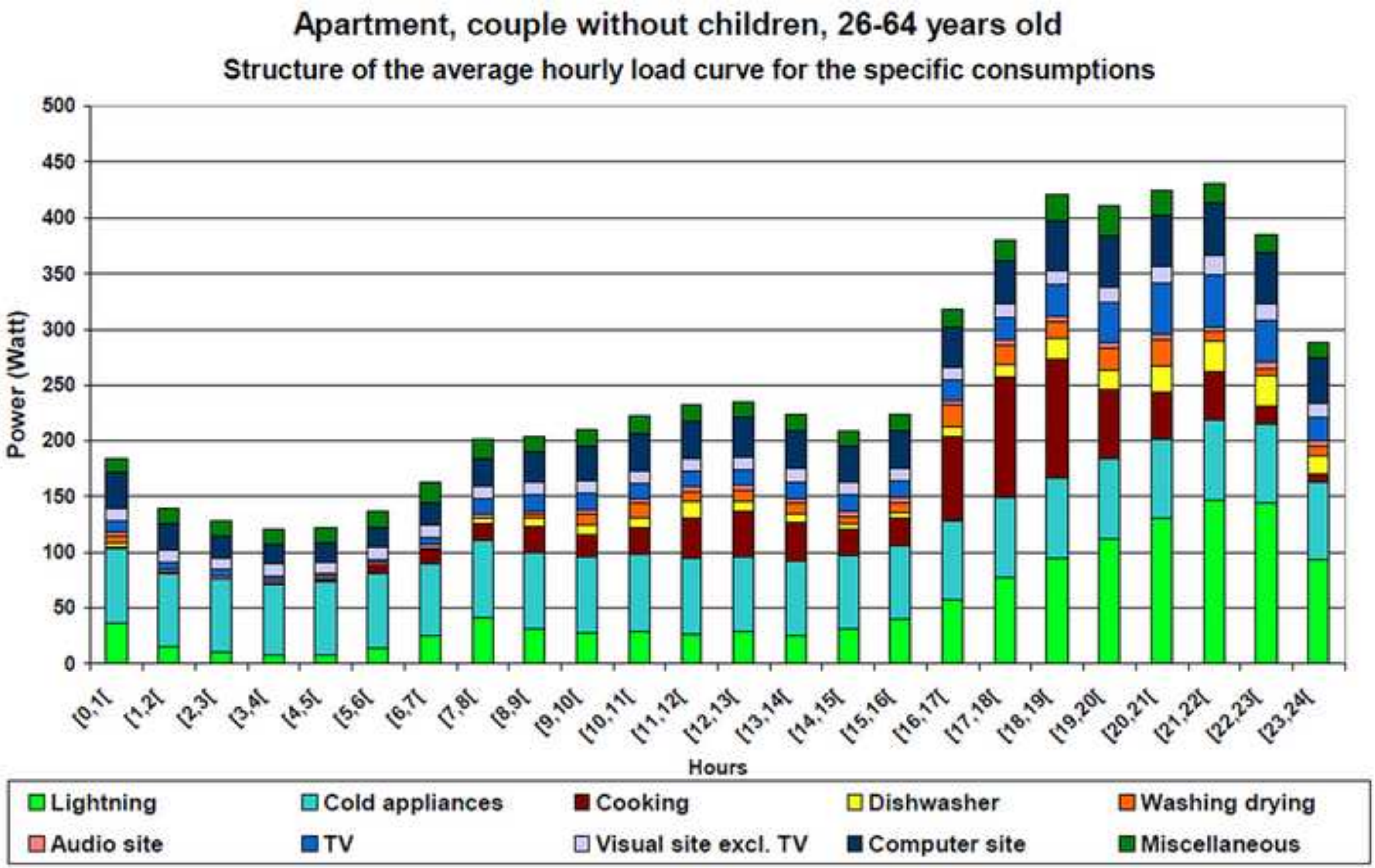
Solar Panel
Battery
Electrical Grid
Supply controller
Battery
Grid
Local controller
Smart plugs
Smart plugs

Figure 2



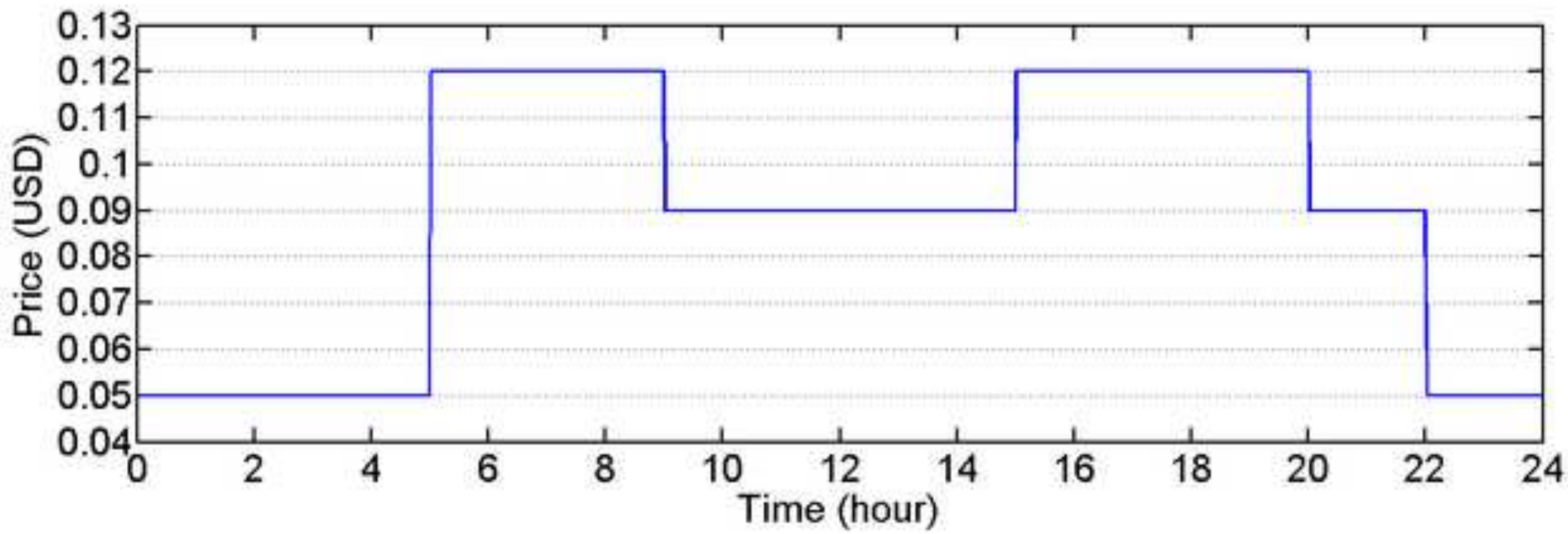
Samsung (WA88V4)	Power (w)	Cycle time (m)
Washing/rinsing	311	20
Water pump	25	12
Spinning	331	15

Figure 3



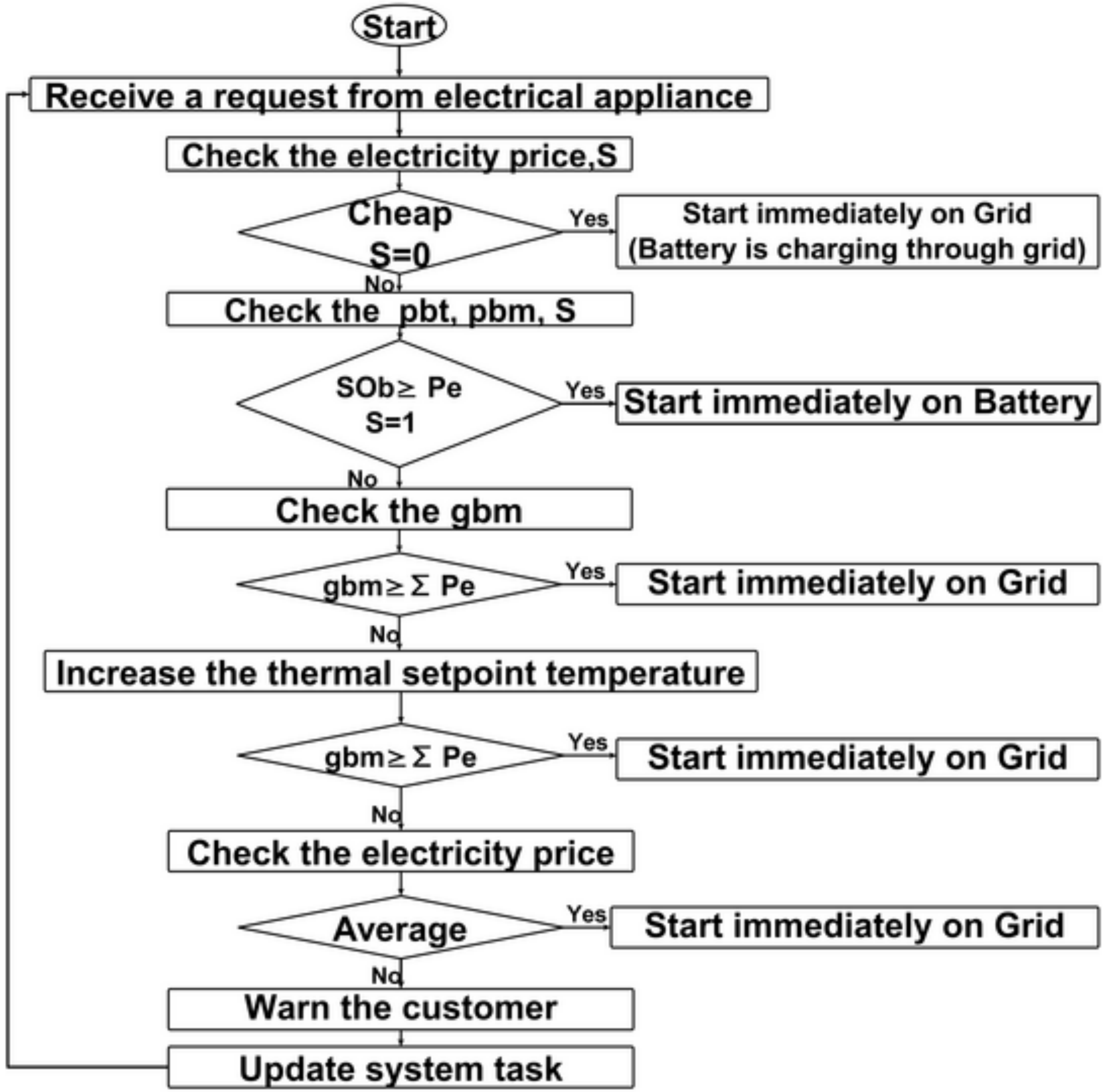
Apartment, couple without children, 26-64 years old
Structure of the average hourly load curve for the specific consumptions
Power (Watt)
500
450
400
350
300
250
200
150
100
50
0
[0,1[
[1,2[
[2,3[
[3,4[
[4,5[
[5,6[
[6,7[
[7,8[
[8,9[
[9,10[
[10,11[
[11,12[
[12,13[
[13,14[
[14,15[
[15,16[
[16,17[
[17,18[
[18,19[
[19,20[
[20,21[
[21,22[
[22,23[
[23,24[
Hours
Lightning
Cold appliances
Cooking
Dishwasher
Washing drying
Audio site
TV
Visual site excl. TV
Computer site
Miscellaneous

Figure 4



0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
Price (USD)
0
2
4
6
8
10
12
14
16
18
20
22
24
Time (hour)

Figure 5



Start
Receive a request from electrical appliance
Check the electricity price,S
Cheap
S=0
Yes
Start immediately on Grid
(Battery is charging through grid)
No
Check the pbt, pbm, S
SOb≥ Pe
S=1
Yes
Start immediately on Battery
No
Check the gbm
gbm≥ Σ Pe
Yes
Start immediately on Grid
No
Increase the thermal setpoint temperature
gbm≥ Σ Pe
Yes
Start immediately on Grid
No
Check the electricity price
Average
Yes
Start immediately on Grid
No
Warn the customer
Update system task

Figure 6

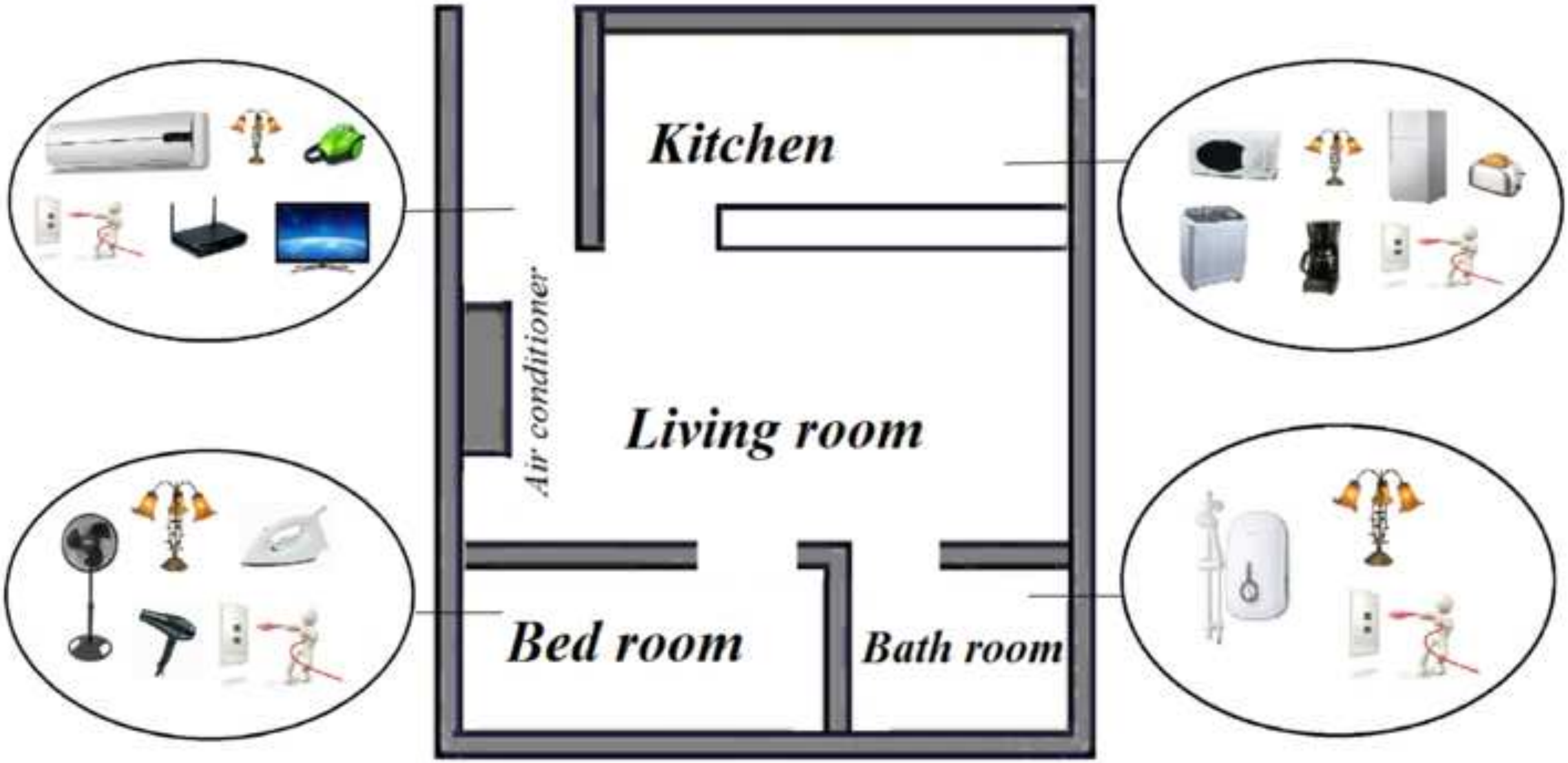


Figure 7a

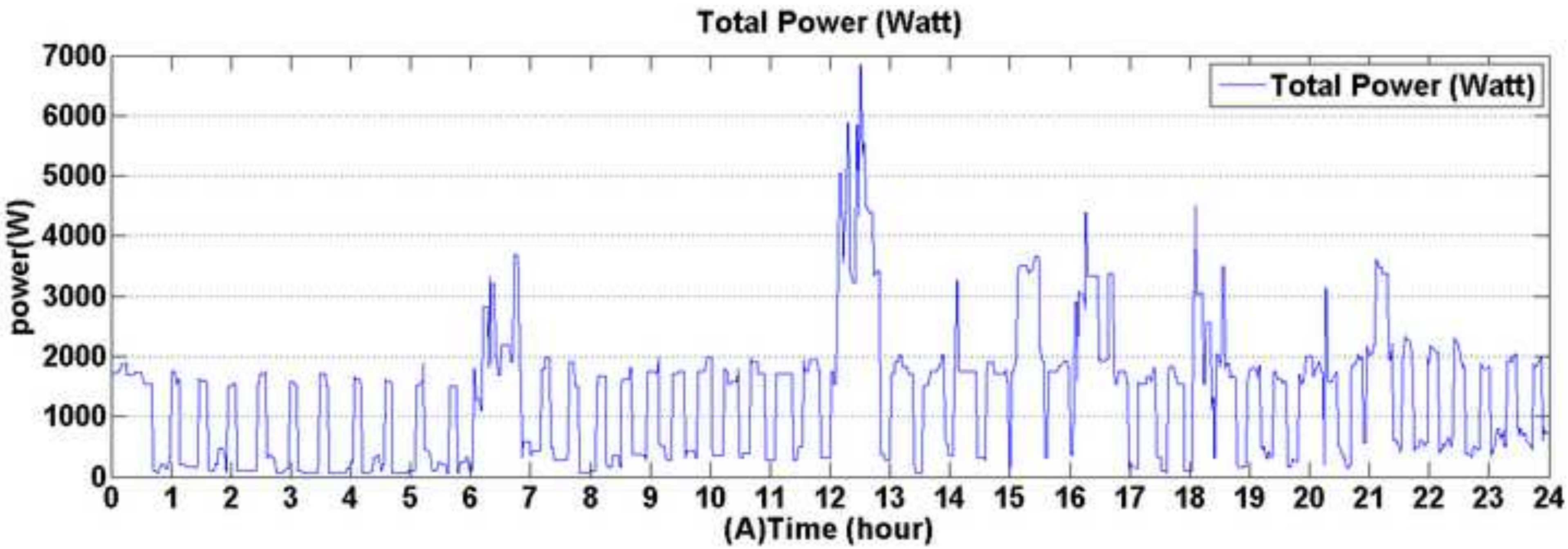
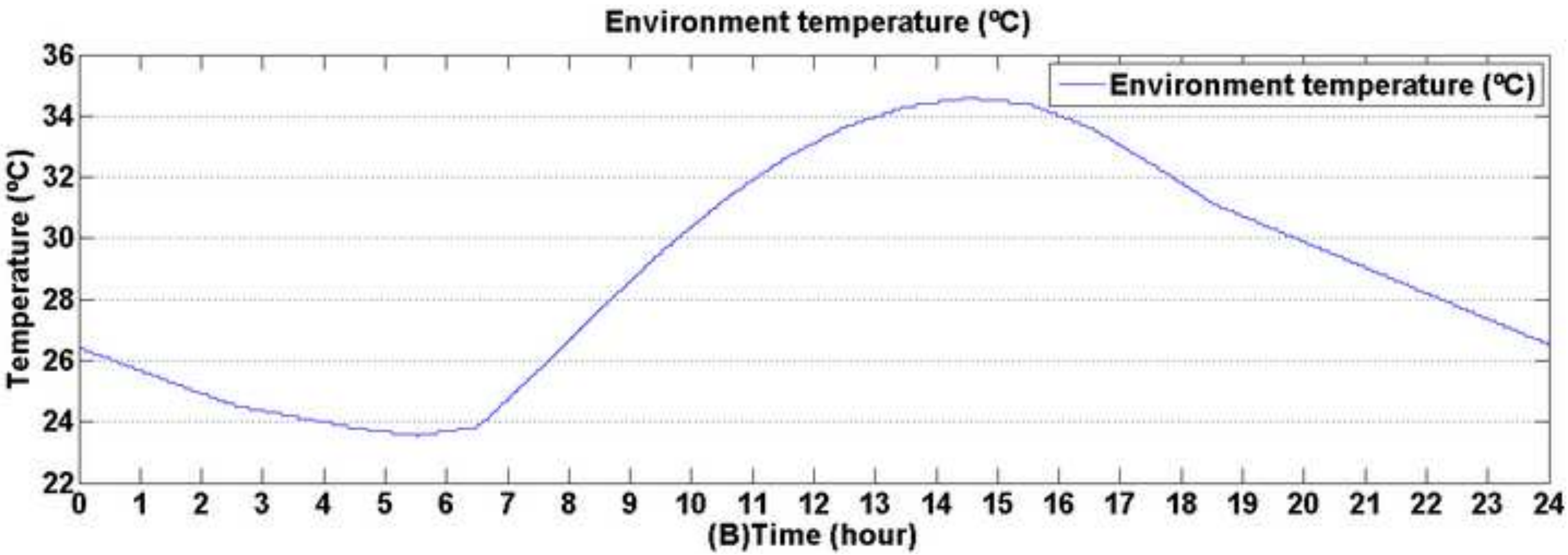
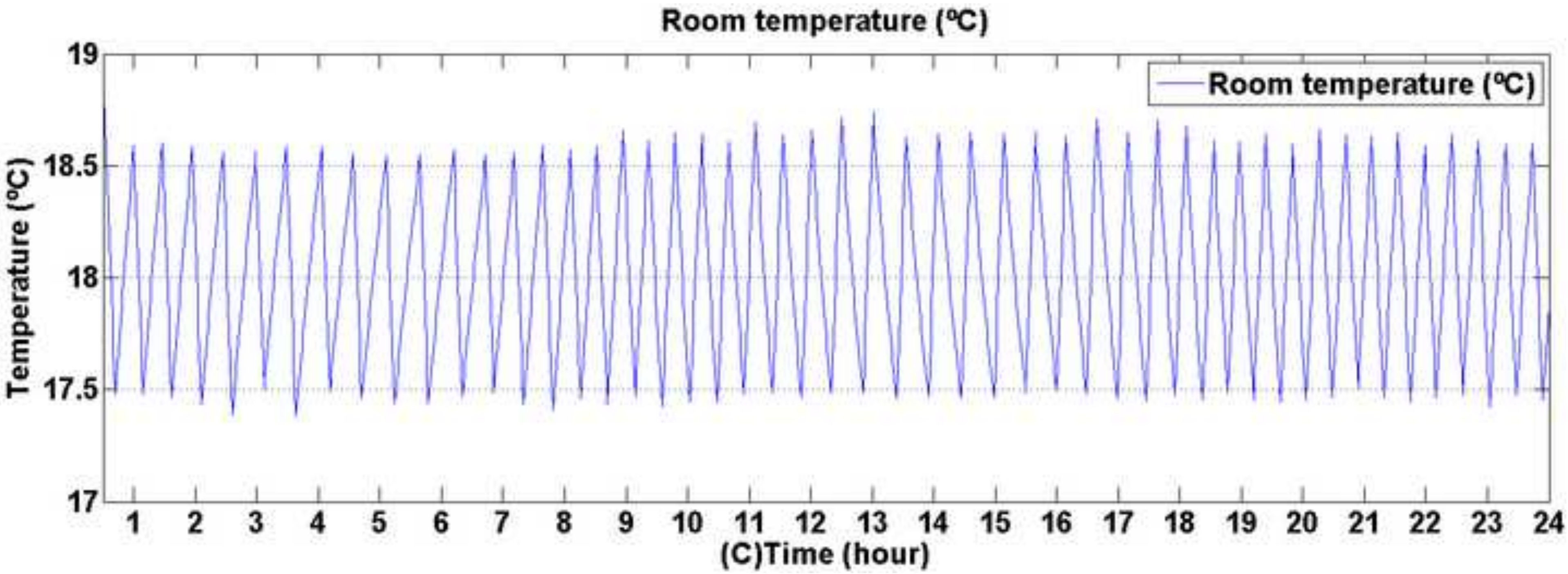

Total Power (Watt)
Total Power (Watt)
power(W)
7000
6000
5000
4000
3000
2000
1000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
(A)Time (hour)

Figure 7b



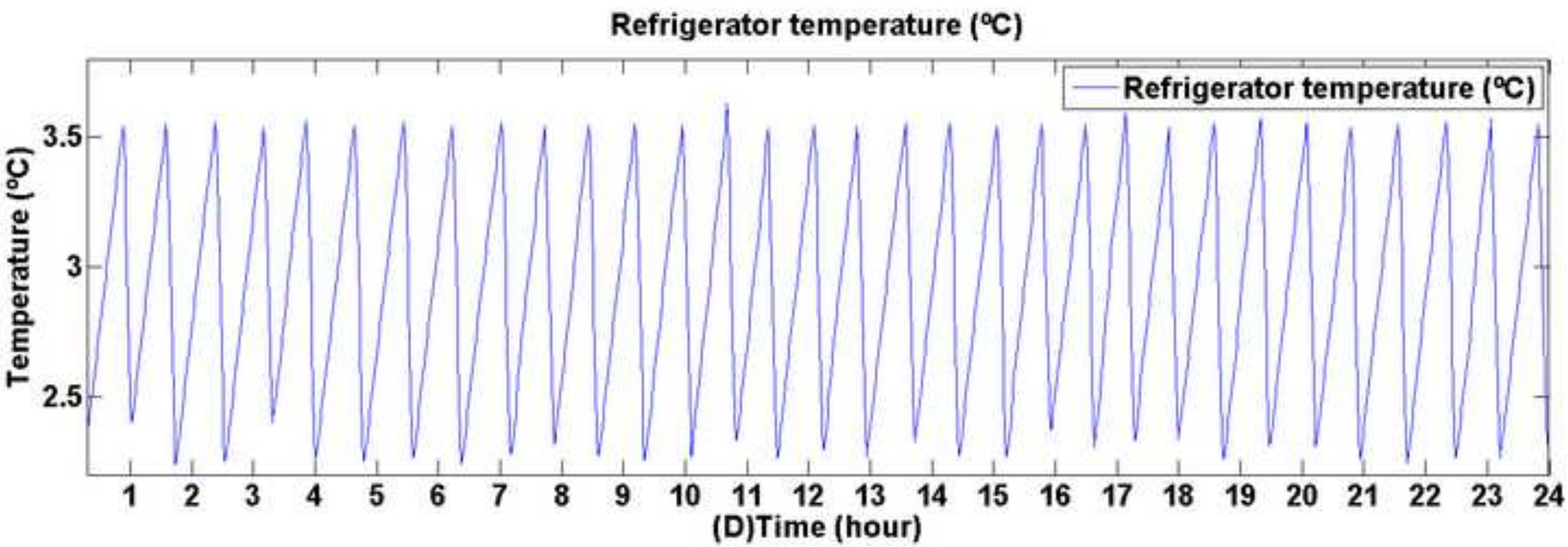
Environment temperature (ºC)
Environment temperature (ºC)
Temperature (ºC)
36
34
32
30
28
26
24
22
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
(B)Time (hour)

Figure 7c



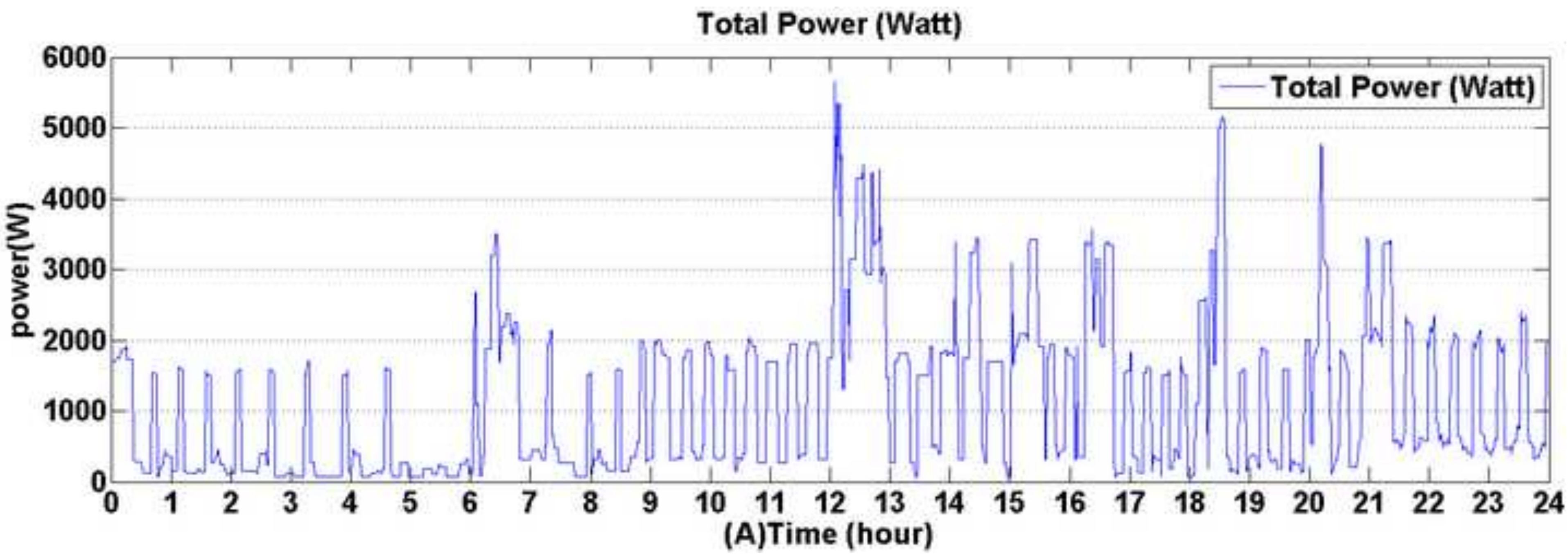
Room temperature (ºC)
Room temperature (ºC)
Temperature (ºC)
19
18.5
18
17.5
17
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
(C)Time (hour)

Figure 7d



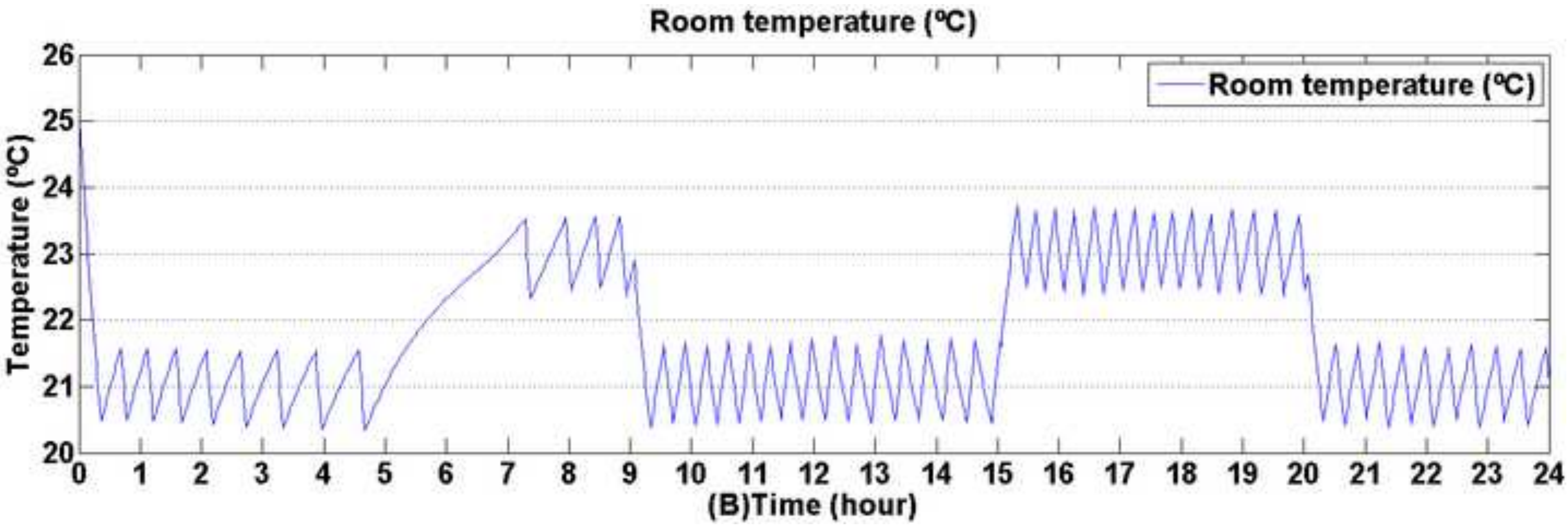
Refrigerator temperature (ºC)
Refrigerator temperature (ºC)
Temperature (ºC)
3.5
3
2.5
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
(D)Time (hour)

Figure 8a



Total Power (Watt)
Total Power (Watt)
power(W)
6000
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
(A)Time (hour)

Figure 8b



Room temperature (ºC)
Room temperature (ºC)
Temperature (ºC)
26
25
24
23
22
21
20
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
(B)Time (hour)

Figure 8c

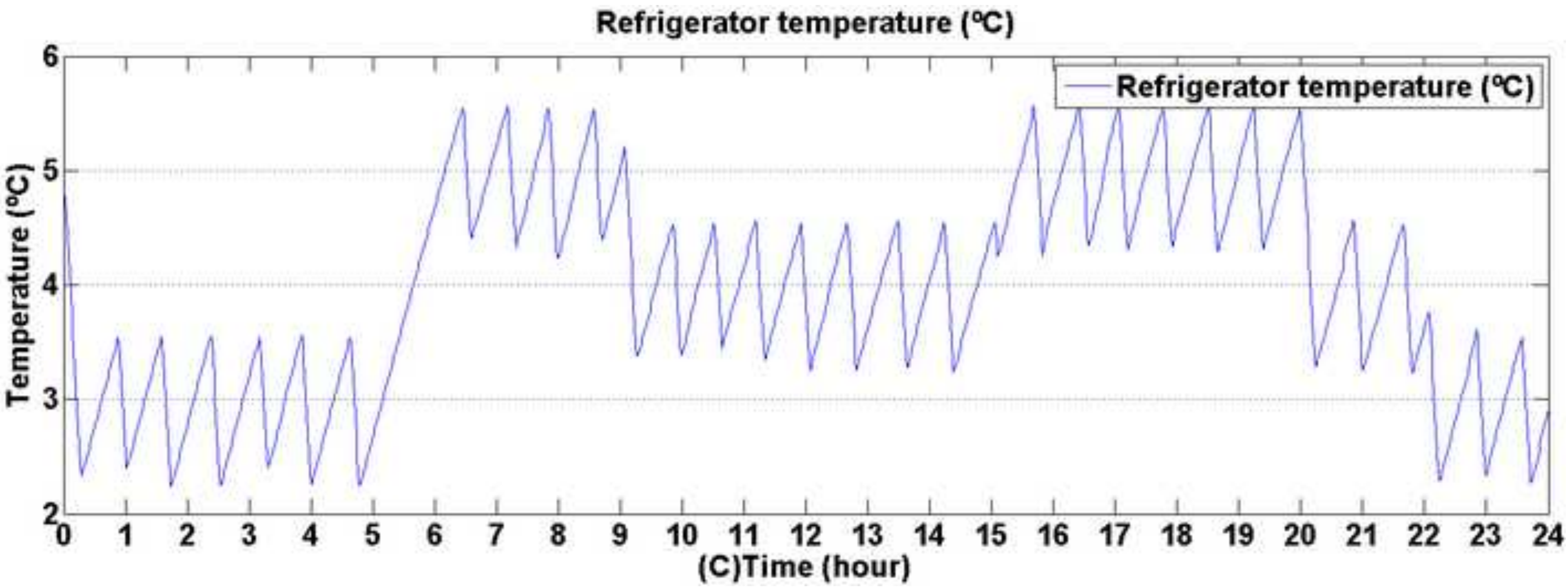
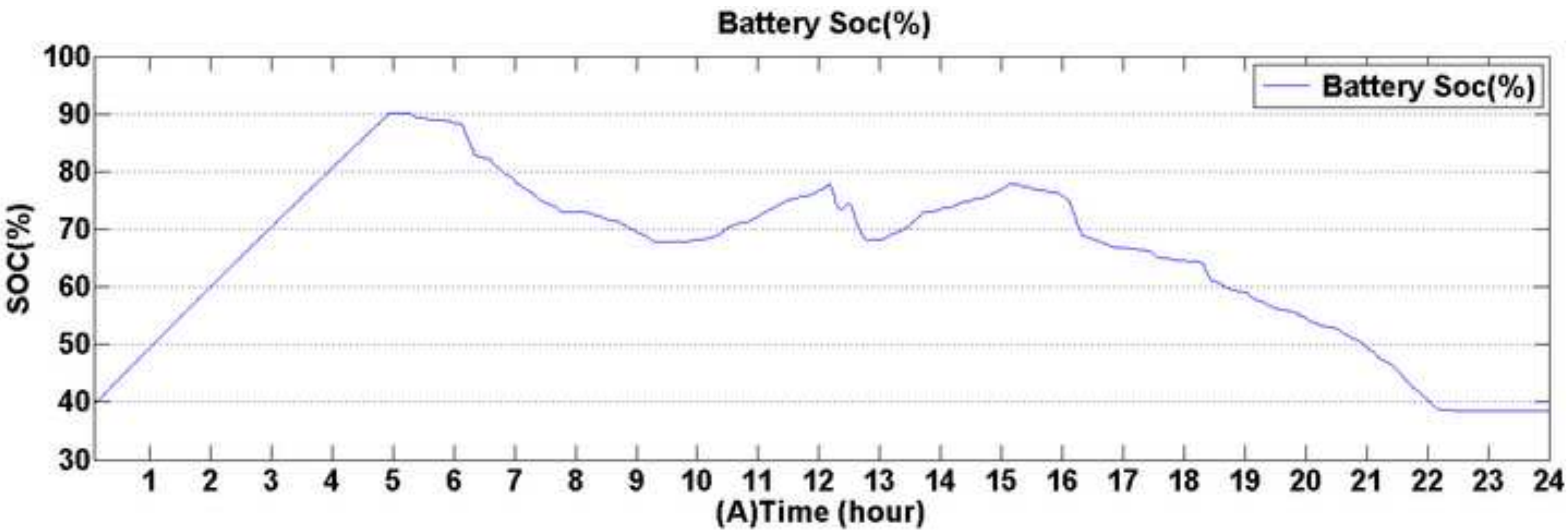
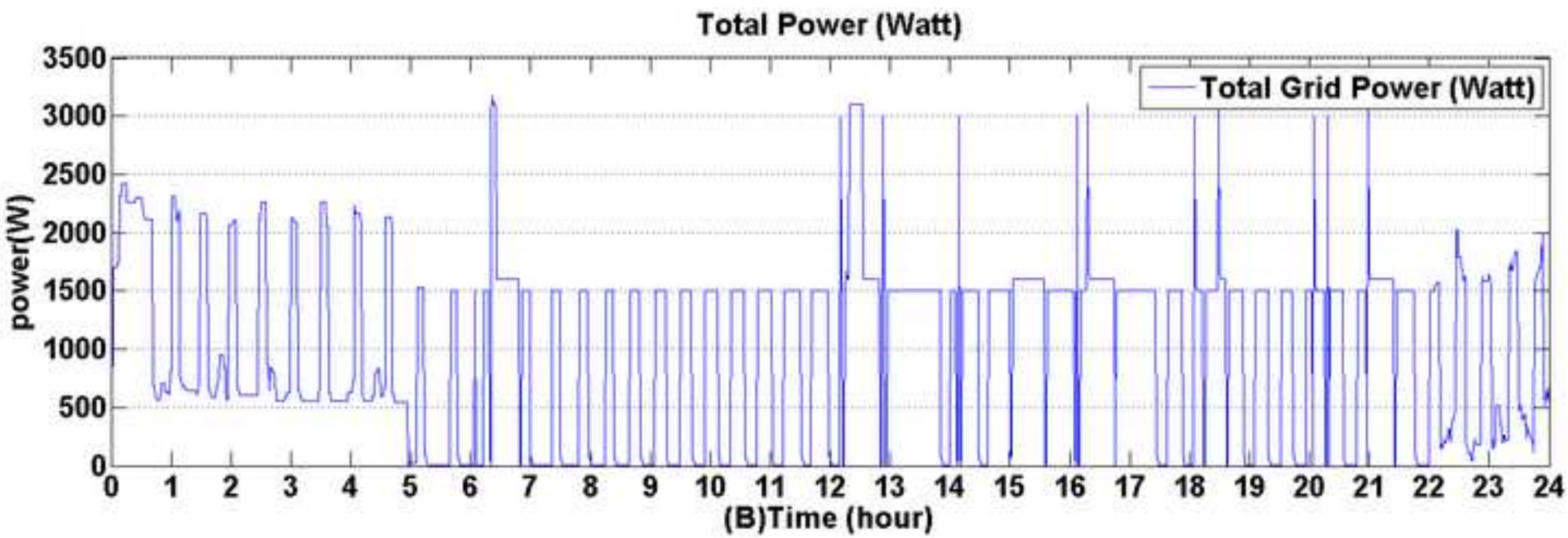

Refrigerator temperature (ºC)
Refrigerator temperature (ºC)
Temperature (ºC)
6
5
4
3
2
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
(C)Time (hour)

Figure 9a



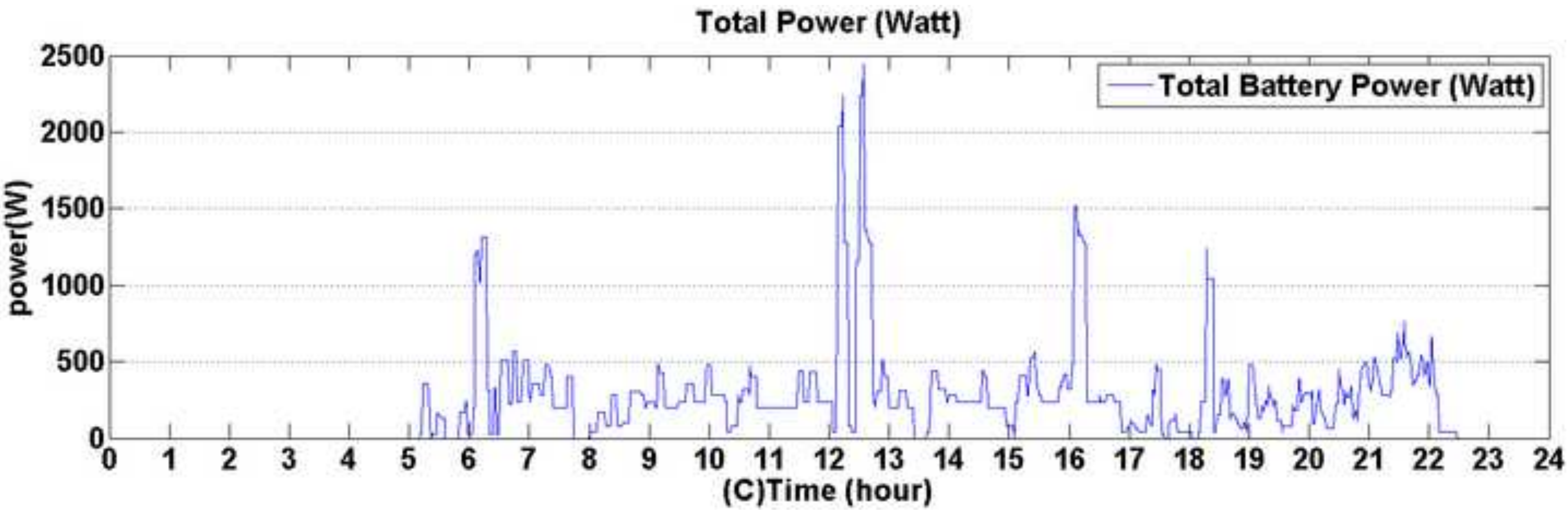
Battery Soc(%)
Battery Soc(%)
SOC(%)
100
90
80
70
60
50
40
30
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
(A)Time (hour)

Figure 9b



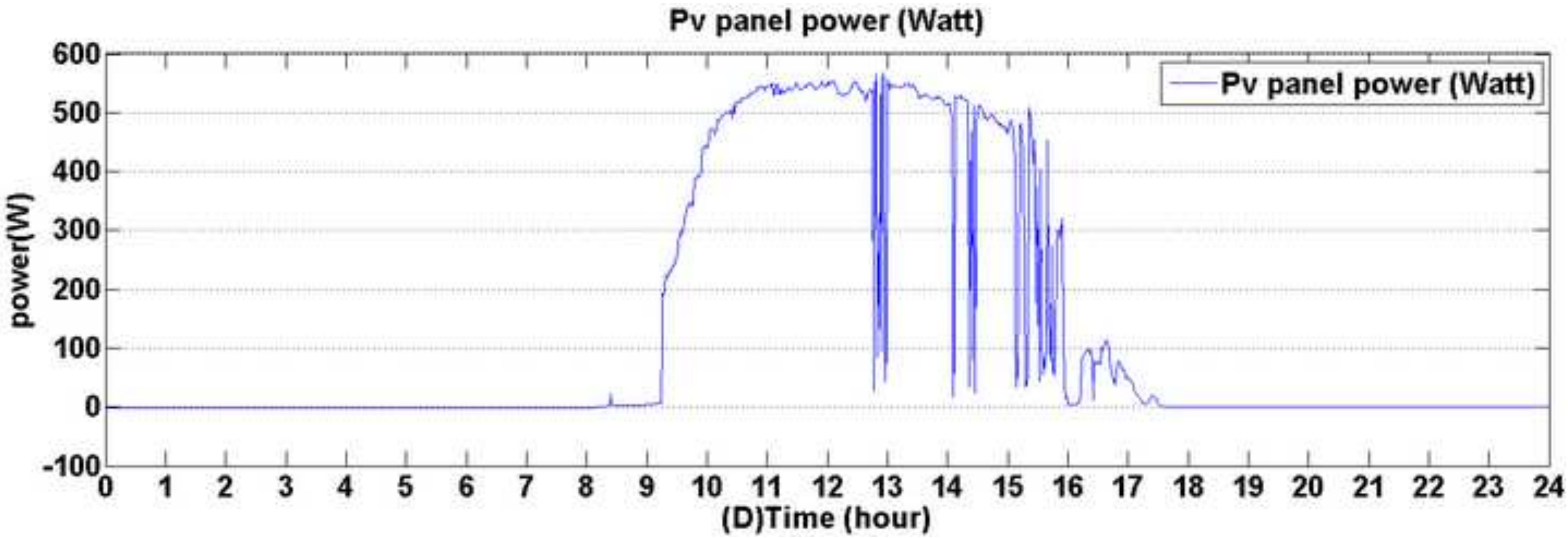
Total Power (Watt)
Total Grid Power (Watt)
3500
3000
2500
2000
1500
1000
500
0
power(W)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
(B)Time (hour)

Figure 9c



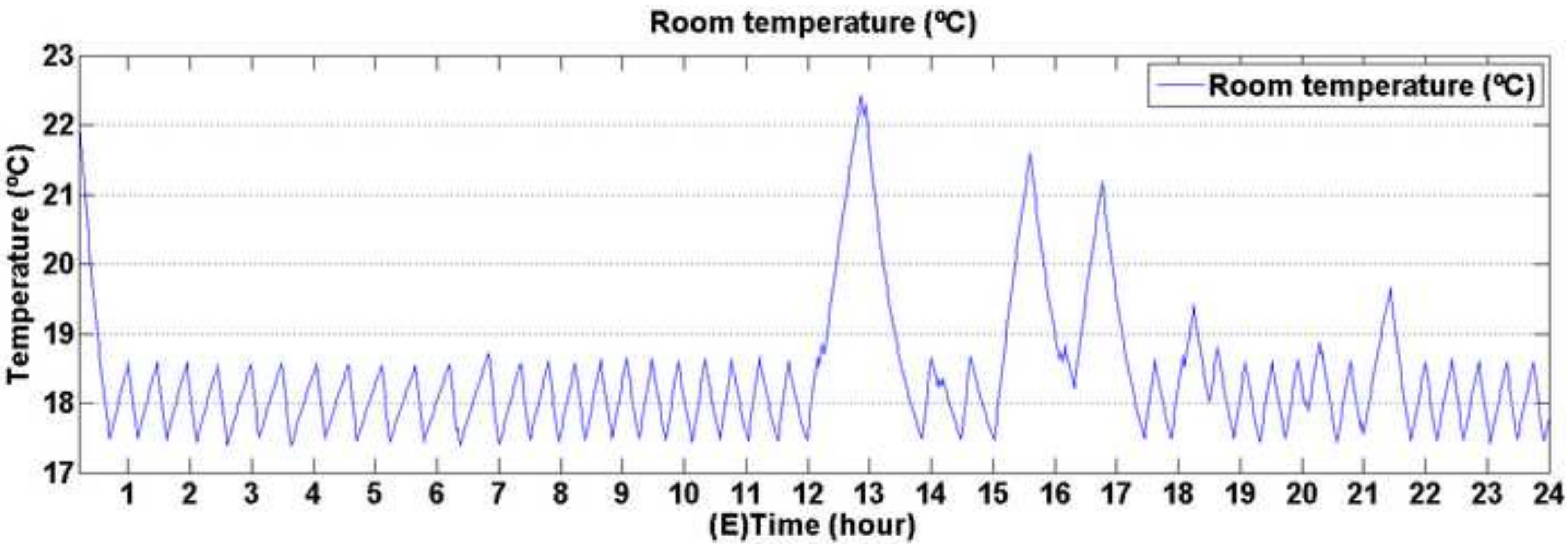
Total Power (Watt)
Total Battery Power (Watt)
power(W)
2500
2000
1500
1000
500
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
(C)Time (hour)

Figure 9d



Pv panel power (Watt)
Pv panel power (Watt)
power(W)
600
500
400
300
200
100
0
-100
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
(D)Time (hour)

Figure 9e



Room temperature (ºC)
Room temperature (ºC)
Temperature (ºC)
23
22
21
20
19
18
17
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
(E)Time (hour)

Figure 9f
Click here to download high resolution image

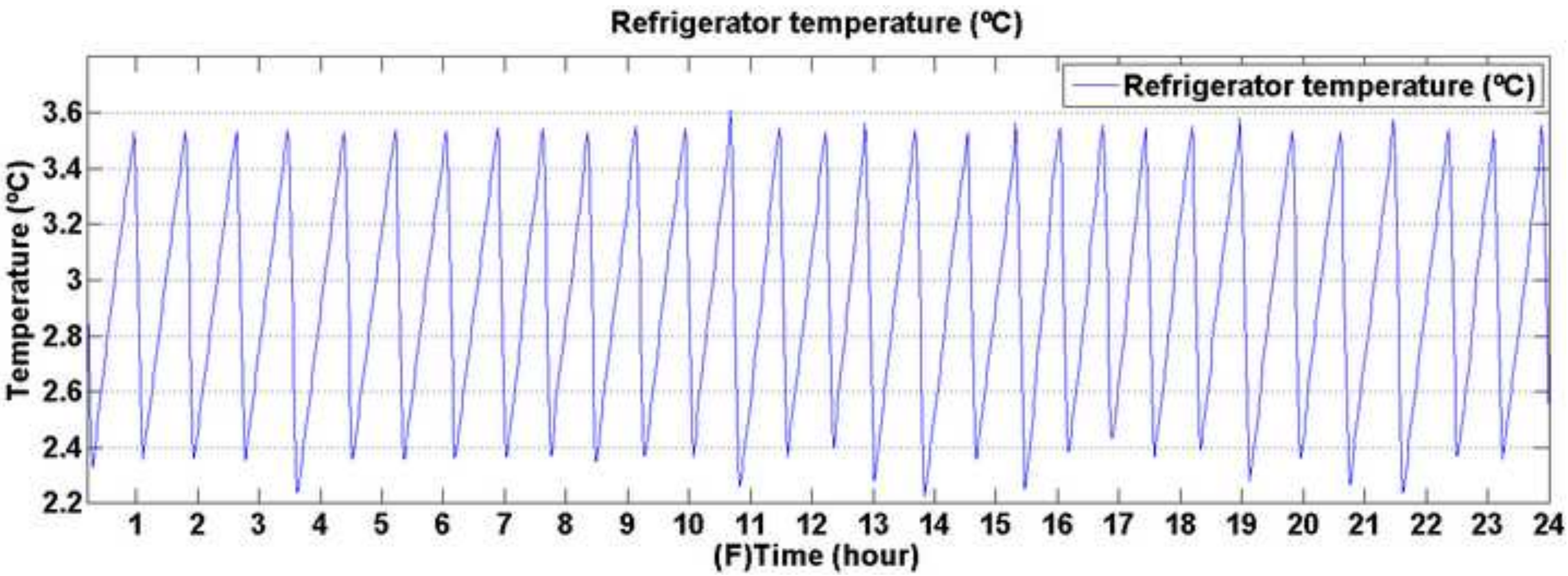
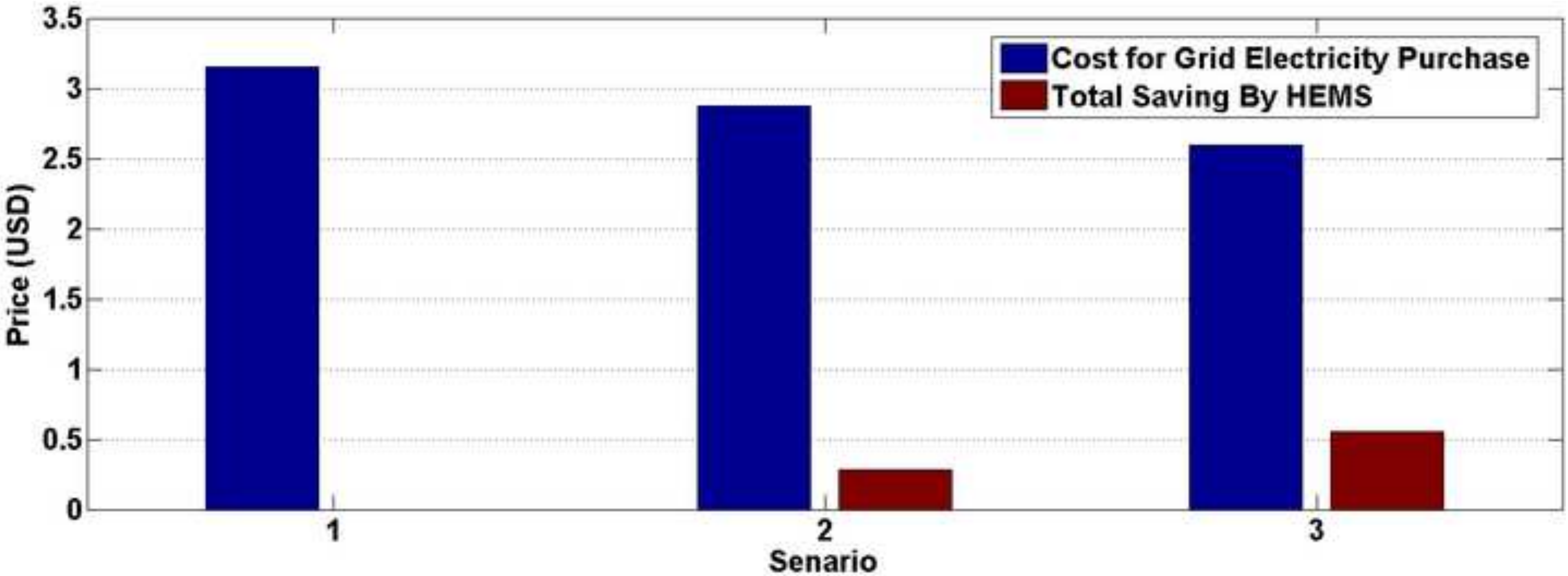


Figure 10
Click here to download high resolution image



ACCEPTED MANUSCRIPT

Table 1 The parameters of the proposed thermal model of the house

Parameters	Values	Unit
$\boldsymbol{C}$	8.12	$\frac{kWh}{℃}$
$\boldsymbol{C_{iw}}$	0.055	$\frac{kWh}{℃}$
$\boldsymbol{C_{ow}}$	293	$\frac{kWh}{℃}$
$\boldsymbol{R_t}$	8.02	$\frac{℃}{kw}$
$\boldsymbol{R_{iw}}$	46.8	$\frac{℃}{kw}$
$\boldsymbol{R_{ow}}$	1.81	$\frac{℃}{kw}$
$\boldsymbol{R_t}$	0.084	$\frac{℃}{kw}$
$\boldsymbol{T_{out}}$	$24-30$	℃
$\boldsymbol{p}$	*0.995*	----
$\boldsymbol{A}$	20	m^2

Table 2 The parameters of the grey-box model of the refrigerator

$\boldsymbol{C_i}(\frac{\boldsymbol{kWh}}{℃})$	$\boldsymbol{C_e}(\frac{\boldsymbol{kWh}}{℃})$	$\boldsymbol{R_i}(\frac{℃}{\boldsymbol{kw}})$	$\boldsymbol{R_o}(\frac{℃}{\boldsymbol{kw}})$	$\boldsymbol{cop}$	$\emptyset_e(\boldsymbol{kWh})$
8970	218	1.1	0.519	0.677	0.0244

Table 3 Characteristics of MSX-60 PV panel

$\boldsymbol{V_{mp}}$(V)	$\boldsymbol{V_{Oc}}$(**V**)	$\boldsymbol{I_{mp}(A)}$	$\boldsymbol{I_d(A)}$	$\boldsymbol{I_{Ph}(A)}$	$\boldsymbol{I_{Sc}(A)}$	$\boldsymbol{N}$
24.7	30.8	7.72	7.96e-08	8.26	8.23	1.3

ACCEPTED MANUSCRIPT

Table 4 Rated power of electrical appliances

Electrical appliance name/type	Rated power (W)	Number of appliances
Refrigerator	200	1
Thermal appliances	1500	1
Washing mashing	331	1
Coffee maker	1000	1
Toaster	1600	1
Microwave	1500	1
Television	200	1
Vacuum cleaner	1600	1
Fan	70	1
Hair dryer	1000	1
Water heater	1600	1
Lamps	40-100	10
Random loads	50-150	5

Table 5 Comparison among the scenarios

Case studies	Consumption (kWh)	Consumption from grid (kWh)	Consumption from battery (kWh)
Scenario 1	33.5	33.5	0
Scenario 2	28	28	0
Scenario 3	32.5	26	6.5

ACCEPTED MANUSCRIPT