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Smart Home Energy Management Algorithm Including Renewable Energy Sources

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Abstract
Increased power demand and integration of renewable energy sources is impossible with today's power grid infrastructure. To overcome these problems, smart grid is the new solution which is more reliable, flexible and controllable. Home Energy Management System (HEMS) in the smart home allows the customer to control, optimize and monitor the energy consumption and the energy conservation. In this paper, a brief overview on the architecture and functional modules of smart HEMS is presented. Then, the advanced HEMS infrastructures and home appliances in smart houses are thoroughly analyzed and reviewed. The home server monitors and controls the energy consumption and generation and controls the home energy use to reduce the energy cost. The remote energy management server aggregates the energy information from the home servers, compares them and creates statistical analysis information. We propose the control algorithm to efficiently manage the renewable energy and storage to minimize grid power costs at user's home. The proposed HEMS architecture is expected to reduce user's electricity cost significantly.

Keywords
Home Energy Management System, Control Algorithm, Renewable Energy.

I. Introduction
Smart grid is the integration network of information, communication and network technologies, which is able to utilize the electrical energy efficiently, sustainably, reliably and safely. The features of this power system should be more attractive, secure, reliable and intelligent comparing to the existing systems. A smart HEMS is a system between home appliances and energy providers to optimize energy consumption. Smart homes are characterized by the presence of smart devices, which give the opportunity to monitor and to remotely control key equipment within homes. Renewable Energy Sources (RES), such as wind power, solar power and fuel cell etc., should be utilized to fulfill energy demand as well as conventional energy sources based mainly on fossil fuels. A challenge is by integrating RES into the grid and increasing power demand causes the redesigning of the conventional power system architecture and infrastructure.

With the increased concerns on global energy security and environmental emissions, more and more distributed renewable energy generations, such as wind turbines, solar panels, and plug-in electric vehicles (PEVs), etc., would be grid-integrated into the active distribution networks. Coupled with the rapid development in advanced power electronics and alternative energy technologies, building renewable and stored energy sources installed at the residential premises can be incorporated in smart HEMS to improve the home efficiency of energy conversion and utilization [1].

One of the main research areas in the smart grid is energy management applications. Energy management applications provide several benefits to both utilities and consumers. Utilities are able to improve power with higher reliability and stability, and lower operational costs while consumers can utilize the energy in cost saving way. Another important valuable benefit with respect to environmental issues is reducing the greenhouse gas emission. Several Demand Response (DR) programs are widely implemented on the commercial and industrial side [2].

Smart HEMS is an essential home system for the successful demand-side management of smart grids [3]. It monitors and arranges various home appliances in real-time, based on user's preferences via the human–machine interface in smart houses, in order to conserve electricity cost and improve energy utilization efficiency [4,5,6].

HEM system, as important part of smart grid, provides a number of benefits such as savings in the electricity bill, reduction demand in high rate and meeting the demand side requirements.

Several HEM algorithms by which consumers are able to manage their electricity consumption have been proposed in the literature [7, 8, 9]. These algorithms are based on different methods such as: load shifting, optimal scheduling, charges the battery from renewable sources and from the grid during low rate period etc. Operating and duration time of home appliances can be shifted by load shifting and optimal scheduling methods [10]. Many of HEM system consider only grid supply. In [11], is proposed an optimal model for HEM in which wind and solar power sources are considered.

This paper proposes a HEMS framework that includes loads, batteries, and renewable generation interconnected with the grid through a home server. The proposed HEM control algorithm uses load shifting for smart homes. The algorithm schedules the operation of home appliances, batteries, and renewable generation as well as the optimal power distribution among loads, batteries, renewable sources, and power grids.

II. Architecture of Home Energy Management System Including Renewable Energy

A. System Architecture
Although numerous efforts are taken for energy-efficient home appliances [12-15], energy management can achieve more energy-efficient home. It provides an opportunity for economic benefits of smart home to manage the demand-side resources by shifting their electricity usage during peak-load periods in response to the changes in electricity prices. The economic incentives include the saving in electricity bill, the improvement in utilization efficiency of household appliances and residential energy conservation [16].
For an efficient smart home energy management, we use a new architecture, which, in terms of energy management, consists of

two parts: the part of energy consumption and the part for energy generation. [17]. Fig. 1 shows the smart HEMS architecture, where home appliances and lights belong to the energy consuming part, while wind and solar resources belong to the energy generation part [17].

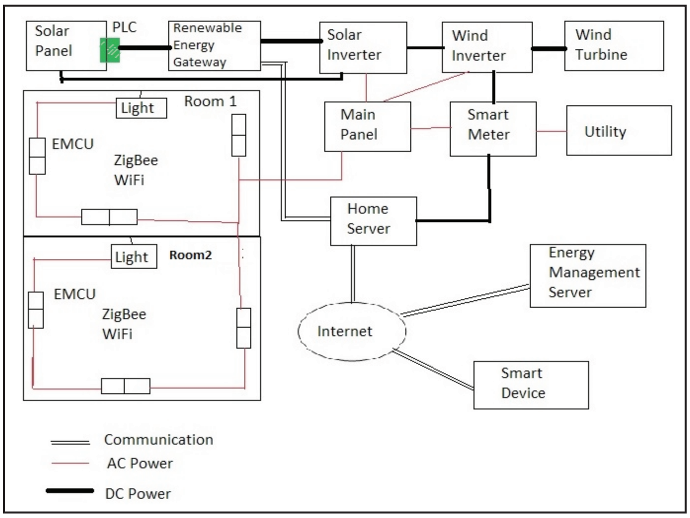

Fig. 1: Architecture of Smart Home Energy Management System (HEMS) [17]

In the energy generation part the energy generation from wind and solar sources, is monitored through renewable energy gateway (REG). In this structure, the solar system of the energy is consisted of: solar panels, PLC modems, solar inverters and an REG. The solar panel operation is controlled and monitored by PCL modem, which communicates with REG. The PLC modem monitors and controls the status of each solar panel and the gathered data from all panels are sent to REG. The generated DC energy by solar panels is converted to AC energy by the inverter, and it also monitors the accumulated energy.

The system of wind power consists of wind turbines and inverters. The accumulated DC energy by wind turbines is converted to AC energy by the wind inverter, and it also monitors the accumulated energy. REG gathers data about the solar panel and wind inverter status and transfers them to the home server via Ethernet. As a smart device of the HEMS system, the home server aggregates all information regarding the consumed and generated energy. It has both, the consumed and generated energy profile at over time. At any time, it estimates the potential amount of energy that can be generated by taking into account the atmospheric conditions obtained from Internet, such as: air temperature, fog, air humidity, wind speed.

The home server manages and controls energy consumption based on generation estimation. Considering the optimization of consumed energy, various aspects can be considered from various analyses and control plans which are based on different algorithms. But in all these systems, the user is interested to access the home server through their smart phones for detailed information on their home energy balance.

If every home individually sends information related to energy via the home server, then remote energy management server (REMS) aggregates that information from the home server. REM analyzes the gathered information and creates new information in numerous aspects.

B. Home Appliances

To implement optimal or coordinated planning strategies of devices, smart home appliances should be divides into two groups:

1. Non-schedulable home appliances, e.g. fridge, printer, microwave, TV, hair dryer, lights, computers;
2. Schedulable home appliances, which can be scheduled for an optimal function or switched on/off at any time, e.g. washing machine, air conditioner, iron, boiler, Electric Vehicle (EV). [17]

Devices which can perform their work in an automated form, such as the air conditioner and boiler, are schedulable. Whereas, non-schedulable devices, such as: lights, computers and TVs, rely on manual control to complete their operation and are needed only when users are at home. The users' comfort is quite sensitive towards services of non-schedulable devices at a real time.

Energy management researchers predict that the amount of EV will increase in a near future, which would help reduce air pollutants and greenhouse gas emissions (GHG) [18]. Since EV can be charged or discharged when connected to the power grid, an increasing number of practical services can now be realized in the power grid [19]. Vehicle-to-grid, as a new concept, enables the transmission of the stored power in the EV battery to the power grid [20-22]. In a smart HEMS, EV are able to balance the energy at high rates, which means that EV can supply energy during high rates, while consumer consume energy during low rates period.

C. Home Server

The home server manages all EMCUs installed on each outlet and on the light switch via ZigBee, Wi-Fi, UTP/ FTP cable. It also controls and monitors the performance of all EMCUs through control elements. The control table manages the home appliances and lights connected to the EMCU. Through this control table, the home server identifies home appliances and lighting. The data related to power consumption of appliances and lighting are stored in the database, so the aggregated data are accumulated at every moment. The Energy Consumption Manager (ECM) continuously analyzes the data collected on a daily, weekly and monthly basis [17].

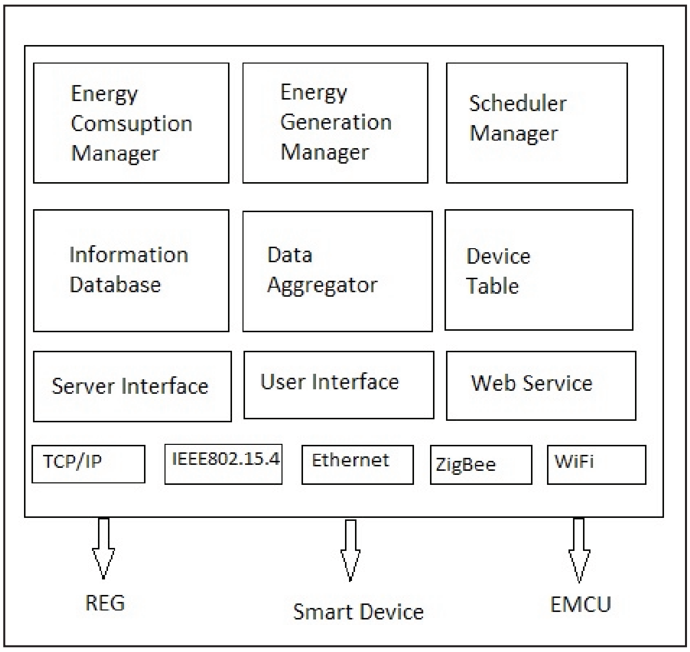

Fig. 2: Function Blocks of a Home Server [17]

Data from solar panels, solar inverters and wind inverters are collected in the REG, and then REG transmits them to the home server. The transmitted data in itself contains information about the performance of each solar panel, solar power system and wind power system. This classified data is gathered and stored in the database. Weather forecast data is used to estimate the amount of potential energy generated. The energy generation manager (EGM) analyzes the renewable energy generation. The solar energy generation is based on the solar radiation, amount of fog and the surface of solar panels, whilst wind energy generation relates to the wind speed. Accordingly, EGM can estimate renewable energy generation based on the weather conditions. As a result, based on the estimated energy generation, the home server can modify the home appliances schedule so that the energy cost is reduced. For example, during the time of the low renewable energy generation and in high rate time, the load of several home devices can be postponed to low rate time. The home server decides this based on the priority of the operation.

The User Interface (UI) in smart homes provides sufficient information to home users about energy consumption and generation. The UI shows the energy consumption and generation information over time. Users can check and browse energy usage of each appliance and each light. The home server provides information to smart devices on request, and they access it through smart applications. The home server transfers the home energy information to the REMS, which manages several client-homes.

D. Energy Management and Communication Unit (EMCU)

EMCU belongs to the energy consuming devices and consists of measurement and communication blocks. The measurement device block measures the consumed energy and the power factor of home appliances [17]. The power measurement is carried with UI measuring factor. The measurement block stores the information about the accumulated energy and calculates the power and power factor on demand. The measurement block, in its content, includes also the power control block which enables switching on or blocking the electric appliance to the connection to the electric energy. The communication device block enables the transfer of aggregated information between the EMCU and the home server. This communication is enabled by ZigBee, Wi-fi or UTP/STP cable and it transfers data about the voltage, current, power and power factor.

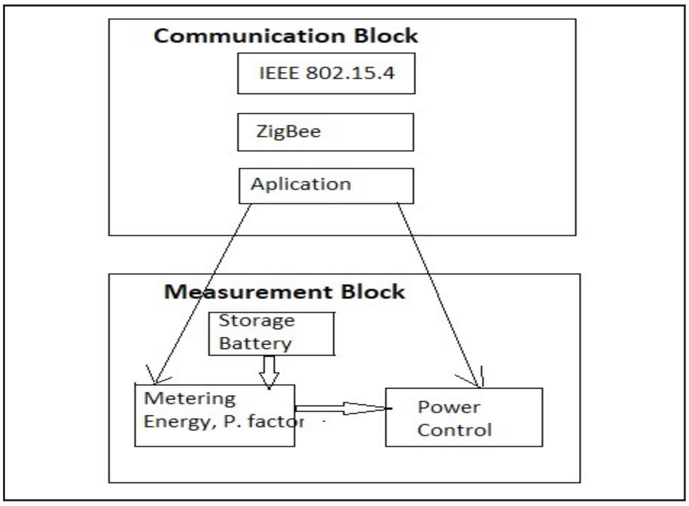

Fig. 3: Function block of Energy measurement and communication unit (EMCU) [17]

E. Renewable Energy Gateway and PLC Modem

The REG, as a key component in the energy generation part, communicates to the PLC modems, the solar and the wind inverters [17]. The PLC modems communicate through TCP/IP protocol, actually, and IP address is assigned by the router. The measuring devices of the control block continuously measure voltage and current in the solar panels. These read data are transferred from the PLC modem to the REG. Here, the REG has three communication interfaces: PLC for each solar panel, Ethernet for the home server, and an RS 485 for the inverter [23]. The PLC modems and Ethernet communicate through TCP/IP protocol. The solar and wind inverters are connected through RS 485 interface. The data aggregator sends a request message to each PLC modem and inverter, regarding their data status. Thus, the aggregated data are periodically sent to the home server.

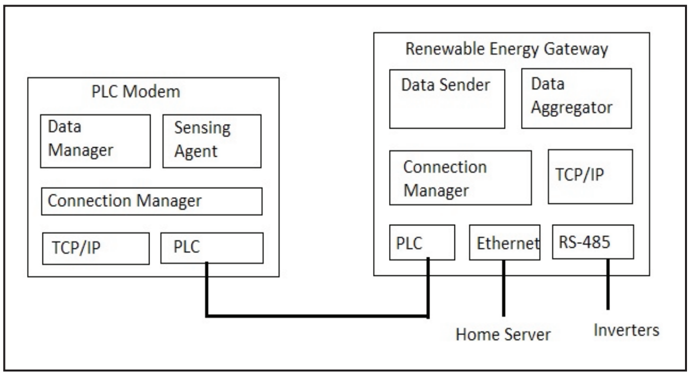

Fig. 4: Function block of PLC modem and Renewable energy gateway [17]

F. Remote Energy Management Server (REMS)

The home server from each home transfers the aggregated home energy information to the REMS [17]. The REMS aggregates all energy information from each home server, from which it aggregates data on the energy generation, energy consumption by home appliances and lights. All aggregated information is stored in the information database, from where, the REMS calculates the average, maximum, minimum of every home appliance. These calculated values help to create a standard energy usage pattern, which serves as a comparing pattern related to energy consumption by different clients.

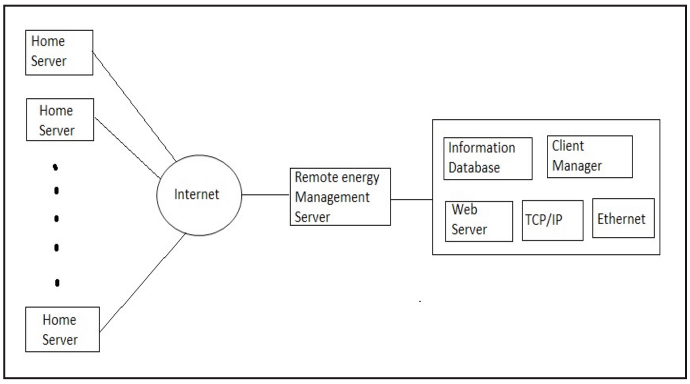

Fig. 5: Function block of Remote energy management server [17]

III. An Efficient HEM Control Algorithm

Fig. 6 shows the architecture of energy and communication flow in a Smart Home Energy Management System (SHEMS). The most important element of the system is the control center, which periodically transfers the data collected on energy consumption, and based on the data on previously consumed energy as a pattern, predicts the expected energy consumption for the next 48 hours. There are other assisting tools which help in gathering important information such as: motion sensors, smart phones (for GPS coordinates), Internet, etc. The control center can also predict the renewable energy for the next 48 hours, based on the atmospheric conditions and the weather forecast for the next 2 days. The control center uses weather forecast to determine how much energy it should accumulate in the battery, given the prediction on renewable energy and the expected energy consumption.

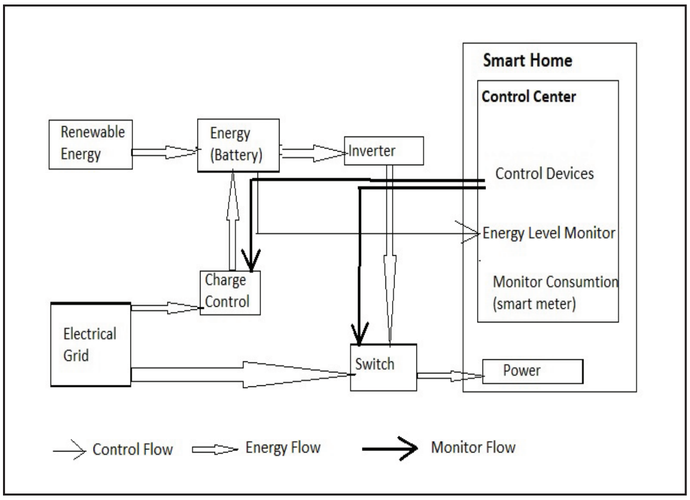

Fig. 6: Energy and communication flow in HEMS

A. Prediction of Renewable Energy

For renewable energy, we use the Sharma et al. [24] prediction model of generated energy, which enables the calculation of accumulated energy from solar or wind power, using National Weather Service (NWS) weather forecast of atmospheric conditions. In the following work, in order to simplify the work, we will only focus on solar energy as the predominant renewable energy, although the mentioned model enables the calculation of renewable energy from wind as well. Next, we describe the model, which depending on the amount of clouds in a percentage from 0% to 100%, enables the prediction of the generated solar energy. The Algorithm continuously needs weather conditions, sky condition and other weather parameters in the next 48 hours.

Based on the weather forecast percentage C(t), at any time instance t, the generated solar energy PS(t) can calculated as:

$$P_S(t) = P_{max} \cdot (1-C(t)) \quad (1)$$

Where P_{max} presents the maximum possible solar generated energy. Sharma et al. [25] quantify the Equation 1 as more effective than existing techniques that use the past to predict the future. According on Equation 1, at any time instance t, the predicted solar energy within the next 48 hours is as follows:

$$E_s(t+T) = \int_t^{t+T} P_s(x)dx \quad (2)$$

Where T equals 48 hours, and t = kT. The algorithm run every evening at the start of the 10 pm low rate period, rather than at midnight t = 0. For simplicity, we use $E_s(k+1)$ to represent $E_s((k+1)T)$

Thus, the Eq (2) can rewrite as follows:

$$E_s(t+T) = \int_{kT}^{(k+1)T} P_s(x)dx \quad (3)$$

B. Prediction of Energy Consumption

To predict home energy consumption, we rely on the daily home consumption of energy, while adapting to seasonal variations as well. On a normal day, we expect that the total energy consumption will be similar to the total energy consumption of previous days with minor differences due to the weather, e.g., a warm day that does not require air conditioning, or usual daily activities, such as: use of the clothes dryer, washing machine, etc. More sophisticated models are the ones which take into account the changing of standard week activities, weather conditions, or other information. The goal of this home energy prediction model is to reduce cost.

$E_C(t)$ presents the energy consumed in the t-th day and $E_{PC}(t+1)$ presents the predicted energy consumed on the (t+1)-th day:

$$E_{PC}(t+1) = \eta E_{PC}(t)+(1-\eta)E_C(t) \quad (4)$$

Where η presents a weighting factor of the prediction error over previous days. Since a pricing model has different electricity rates at different time intervals during the day, the predicted energy consumption at the lower rate and higher rate in the (t+1)-th day can be calculated by Equations (5) and (6),

$$E_{PCL}(t+1) = \eta E_{PCL}(t)+(1-\eta)E_{CL}(t) \quad (5)$$

$$E_{PCH}(t+1) = \eta E_{PCH}(t)+(1-\eta)E_{CH}(t) \quad (6)$$

Where $E_{CL}(t)$ and $E_{CH}(t)$ are the actual energy consumption at the lower rate and higher rate on the t-th day, respectively.

Our goal is to charge the battery when the electricity rate is low, and discharge the battery to power the home when the rate is high. Since we analyze the energy conversion efficiency of our system, i.e. charging the battery during low rate and discharging the battery to power the home during high rate and adding there and the inverter's efficiency [25]. If the energy conversion efficiency is less than the ratio of the low rate and high rate values, then storing energy in the battery during low rate periods is cheapest version than directly using it from the grid during high rate periods.

As an example, using R.N. Macedonia's model, the ratio of the lowest rate (2.78 Den/kWh) and the highest rate (5.54 Den/kWh) is 2.78/ 5.54 = 50.0%. If the energy conversion efficiency is less than 50.0%, directly using grid energy during the 5.54 Den/kWh period is more efficient than charging the battery at 2.78 Den/kWh and discharging the battery during the 5.54 Den/kWh time period. In this case, 5.54 Den/kWh is not high enough to incentivize battery-based storage during the high rate period. Since most lead-acid batteries have charging efficiencies greater than 85% [26] and most grid-tie inverters have efficiencies greater than 94%, the energy conversion efficiency is greater than 85%x 94% = 79.9%, which is greater than the ratio of the lowest rate (2.78 Den /kWh) and the highest rate (5.54 Den /kWh). Therefore, both the lowest rate and the highest rate in R. N Macedonia's model incentivize battery-based storage. We use $E_{PCH}(k+1)$ as the expected total energy consumption in the (k+1)-th day when the electricity rates are 5.54 Den/kWh.

C. Description of the HEM Control Algorithm

We propose an algorithm to minimize the cost of electric energy from the power grid. The algorithm determines based on: generated energy in the battery, remaining battery energy (when more home appliances are switched on), the forecast for energy generation and consumption for the next 48 hours. Following is presented the pseudo-code and block scheme of the algorithm. $E_{ER}(t+1)$ presents the expected energy remaining inside the battery that can be consumed in the (t +1)-th day. $E_{ER}(t+1)$ can be calculated as follows:

$$E_{ER}(t+1) = \sigma E_R(t) \quad (7)$$

Were $E_R(t)$ is the remaining energy in the battery at the beginning of low rate during the day (t), and σ is the inverter efficiency coefficient.

ALGORITHM 1: Efficient control

1. if $E_{ER}(t+1)+ E_{PS}(t+1) >=E_{ECH}(t+1)+ E_{ECL}(t+1)$
then

2. Use the battery to power the house;

3. else if $E_{ER}(t+1)+ E_{PS}(t+1) > = E_{ECH}(t+1)$
then

4. while $E_{ER}(t+1)+ E_{PS}(t+1) -E_{ECH}(t+1)>0$
do

5. use the battery to power the house;

6. else if $E_{ER}(t+1)+ E_{PS}(t+1)<E_{ECH}(t+1)$
then

If (low rate)

7. while $E_{ER}(t+1)< E_{PS}(t+1)-E_{ECH}(t+1)$
do

8. Charge the battery;

9. while $E_{ER}(t+1)+ E_{PS}(t+1)<E_{ECL}(t+1)$
do

Postpone Schedulable load

- If the amount of battery energy $E_{ER}(t+1)$ and the expected solar energy generation $E_{PS}(t+1)$ is higher than the general expected consumption, during both, low and high rates, than the energy from the power grid should not be used in the house. In this case, the home server commands using battery energy for home appliances' operation.
- If the amount of battery energy $E_{ER}(t+1)$ and the expected solar energy generation $E_{PS}(t+1)$ is higher or equal to the general expected consumption only during high rate $E_{ECH}(t+1)$, respectively, $E_{ER}(t+1)+ E_{PS}(t+1)>=E_{ECH}(t+1)$ than during low rate, if there is sufficient battery energy, that will be used first, then the energy from the power grid.
- If the amount of battery energy $E_{ER}(t+1)$ and the expected solar energy generation $E_{PS}(t+1)$ is lower than the general expected consumption during high rate $E_{ECH}(t+1)$, then home server charges the battery during low rate with the sufficient charge for the expected general consumption during high rate, i.e. $E_{ER}(t+1)+ E_{PS}(t+1)=E_{ECH}(t+1)$.
- If during low rate there is not enough generated energy for appliance operation (battery empty), schedulable equipment operation is postponed for the time when the battery will have sufficient power generated, according to the available postponing operation coefficient of the appliance.

IV. Conclusion and Future Studies

This paper presents a new Home Energy Management (HEM) algorithm for home to efficiently manage renewable energy, battery storage, and power grid, implemented in the description system architecture. Our control algorithm makes the decision based on the predicted future renewable energy generation and energy consumption. In this paper, a theoretic detailed description of the algorithm for home energy management is done, where RES is connected or not (without RES system) in the system. The practical implementation of the algorithm will be realized in the future since it presents a very complex system, especially the architecture of the control system. The architecture of the control system, which we have chosen for the implementation of the HEM algorithm, is also described in this paper. We will have closer values of cost reduction after the practical implementation of the algorithm.

In the future, building upon the simulation results of this study, we will continue to develop our home energy management algorithm using the real smart home prototype. So the performance of the algorithm would be evaluated in real environment.

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