Renewable Energy Management Policies for Smart IoT Devices

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Session: 2011–2012

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A project submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Computer Science and Engineering

DEPARTMENT OF COMPUTER SCIENCE AND ENGINEERING
UNIVERSITY OF DHAKA
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Declaration

We, hereby, declare that the work presented in this research work is the outcome of the investigation performed by us under the supervision of Dr. Md. Abdur Razzaque, Professor, Department of Computer Science and Engineering, University of Dhaka. We also declare that no part of this project has been or is being submitted elsewhere for the award of any degree or diploma.

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Abstract

Energy scarcity at homes is becoming a critical issue due to exponential growth of energy consumption by numerous smart home appliances. Renewable energy sources help to reduce the pressure of grid operation, enabling Smart Home Energy Management System (HEMS) using Internet of Things (IoT) devices. In this work, we have developed policies for parsimonious renewable energy management using smart IoT devices. With the help of Exponential Weighted Moving Average (EWMA), an HEMS predicts energy production and consumption. The results of the prediction decides whether to sell or purchase energy following it is in energy surplus or deficit, respectively. Our energy budget management follows max-min fairness algorithm. The performance evaluation of our proposed system shows that significant performance improvement in terms of monetary expense and user utility can be achieved compared to state-of-the-art works.
Acknowledgment

First of all, We would like to express our deepest gratitude to the almighty Allah, who gave us patience, strength and determination to complete this work.

We owe our heartiest thanks to our supervisor, Dr. Md. Abdur Razzaque, Professor, Department of Computer Science and Engineering, University of Dhaka, for his constant support and profound guidance. His endless patience, encouragement, valuable comments and suggestions made our work more perfect.

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Kazi Rashedul Islam
Subreena Tabassum
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Chapter 1

Introduction

1.1 Introduction

Around the globe the most concerning discussion is energy crisis. It has become an important issue. Industrial development and population growth have led to a surge in the global demand for energy in recent years. Again usage of energy in home areas has increased rapidly as more home appliances are being added in order to make human life easier. If the current circumstances continue, we will run out of energy soon. As a result, purchasing energy will be expensive. For this reason, user may also have to compromise with their comfort constraints. Energy production, power savings, renewable energy sources etc in [1] are considered as methods of solving the problem. Negligence may cause harm to the comfort level and economic issue will arise too. Optimization of home energy management system (HEMS) is needed to reduce energy usage, minimize cost and also guarantee highest user satisfaction. In this chapter, we briefly discuss about the Home Energy management System (HEMS), Renewable Energy(RE) and give an overview of our work.

1.2 Home Energy Management System (HEMS)

In order to reduce wastage of electricity, minimize electricity cost and to avoid the future energy scarcity HEMS is a fruitful system. This is an intelligent technology to prudent electricity usage. In a HEMS system smart devices e.g. smart meters, area management
So, home energy management service (HEMS) is a product or service that monitors, controls, or analyzes energy in the home. This definition includes residential utility demand response programs, home automation services, personal energy management, data analysis and visualization, auditing, and related security services.

The Internet of Thing (IoT) is the plexus of gadgets or objects such as cars, mechanical or electronic equipment, home. As the time moving forward, mechanical or electronic equipment rapidly find their way to Internet. An excessive amount of Thing’s around the home turning to intelligent gadgets, using the ability to connect to the Internet. Fig. ?? shows the home appliances which can be controlled using smart application.
1.3 Renewable Energy (RE)

Renewable energy is generally defined as energy that is collected from resources which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat. Rapid deployment of renewable energy results energy security and economical benefits. However, recent exponential growth of energy consumption by diverse home appliances has caused energy crisis. Residential areas are effected the most. The grid operation has been consistently failed to fulfill user requirements. User comfort constraints has always been broken due to energy scarcity. Among many energy resources Renewable Energy (RE) is considered the most efficient one. It has become indispensable alternate solution to the energy crisis problem. The mainstream technologies are wind
power, hydro power, solar energy, geothermal energy, bio energy, heat pump etc.

Since energy production from the Renewable Energy Sources (RES) varies over time [3, 4], a HEMS needs to purchase or sell energy at times when it experiences energy deficit or surplus, respectively. Accuracy in prediction of energy production from multiple renewable energy sources and consumption from different home appliances are very crucial for making these decisions judiciously. Again, energy produced from RES are accumulated in a storage with fixed capacity. Therefore, determining the optimal amount of energy to be purchased or sell at a given time, so that the user demands for the home appliances are met with good level of satisfaction while minimizing the energy cost, is a challenging problem. Fig.1.3 shows some renewable energy sources.
1.4 Challenge and Scope

A good number of works in the literature have explored the problem of home energy management for IoT enabled smart devices with the help of Home Energy Management System (HEMS). However, most of the works make effort to take decisions on optimal energy purchase and reduce energy usage through efficient appliance scheduling. The authors in [5] optimize the energy usage of IoT enabled home appliances considering both consumption and generation of energy from RESs. None of the existing works have considered the capacity limitation of storage system, which may lead to situations where optimal energy purchase decisions might become infeasible. Moreover exponential growth of energy consumption by diverse home appliances has caused energy crisis at homes. As a result the Renewable Energy (RE) sources have become an indispensable alternate solution to the energy crisis problem. However energy production from RE sources (E.g.: solar, wind, Bio-gas) varies over time and the home users often experience energy deficit or surplus. Therefore enhancing the utilization of produced energy and guarantee user satisfaction is a challenging problem in this domain.

However, establishment of such an energy management policy for IoT devices in real life is quiet challenging since the purchase and selling rates of energy varies at different hours of a day. Prices vary for variable demand and supply at different periods of a day. Again, building an energy production system and implementing it in real life, energy saving mechanism, dividing the energy among home appliances and also taking care of highest user satisfaction can be challenging here. Again, it is also a challenging part to find the optimal scheduling process, e.g., how much energy is needed to use,
which appliance will get the major priority and how much energy we need to save in
ahead of time considering possible zero energy production states in future. Therefore,
minimization of energy cost exploiting the energy time-of-use (ToU) price is another
major consideration for a suitable energy management policy. Also building an energy
production system and implementing it in real life, energy saving mechanism, dividing
the energy among home appliances and also taking care of highest user satisfaction can
be challenging here. Again, it is also a challenging part to find the optimal scheduling
process, e.g., how much energy is needed to use, which appliance will get the major
priority and how much energy we need to save in ahead of time considering possible zero
energy production states in future.

Ample researches have proposed smart HEMS for efficient regulation of IoT enabled
devices. An agent based model on HEMS was given in [6]. Various detail pricing schemes
were considered in [3] to encourage consumers for scheduling their home appliances.
In [2] a novel traversal-and-Pruning (TP) algorithm was presented for energy scheduling.
However, all of these works provide an energy scheduling system neglecting the energy
production uncertainties in RESs. Again optimization of home power consumption based
on power line communication (PLC) has been studied using Zigbee [5]. Although they
have used the RES, optimal storage management in respect of energy purchase and selling
maintaining user satisfaction has not been provided. In our work a dynamic and optimal
decision making methodology for buying and selling energy has been provided by taking
into account user satisfaction, storage limitation and energy purchase rate at different
time slots.

In this paper, we have considered multiple HEMS connected to each other through
Area Energy Management Server (AEMS). HEMS predicts energy production and consumption for each time slot using Exponential Weighted Moving Average (EWMA). Based on this prediction HEMS detects energy surplus or deficit. It distributes the total budget among the time slots using max-min fairness distribution. It purchase energy at energy deficit slots within this distributed budget. Load shifting from one slot to another is performed while purchasing energy considering user satisfaction and purchase rate.

The major contributions of this work can be summarized as follows,

- Predicted how much energy can be generated in real time using weighted average of the previous time slot data.
- Predicted how much energy can be needed in real time to perform daily work.
- Estimated storage energy level.
- Defined optimal energy threshold using weighted average of the previous time slot data.
- Distribution of monetary budget for different time frame has been performed using max-min fairness algorithm.
- Developed an algorithm that optimally takes decision on purchasing energy.

1.5 Organization of the Report

The rest of the paper is organized as follows. State-of-the-art works on HEMS along with their contribution and limitations have been presented in section 2. Section 3 provides the system architecture of smart energy management systems. Efficient energy
management system considering the limitaion of the storage systems and variability in energy production and consumption has been discussed in section 4. In section 5, we measure the system performance of our proposed energy management model and compare the results with the sate-of-the-art works. Finally, section 6 concludes the paper and offers insight for further works.
Chapter 2

Background and Motivation

2.1 Introduction

The previous chapter introduces the concept of Home Energy Management System and Renewable Energy. It also describes the scopes and the challenges in the field of HEMS in details. In this chapter, we mainly focus on the background of our work as well as the motivations that lead us to develop a new algorithm for HEMS. Furthermore, some state-of-the-art research works on HEMS, which are mostly related with ours, are described in details. We also find out their limitations and the points where further improvements are needed. A large number of existing works on Home Energy Management System (HEMS) have investigated ways to minimize the electricity cost and guarantee user comfort in terms of preferred home temperature. A smart home infrastructure has been provided in [7] where the smart meter receives the cost of electricity from the usage of appliances. Smart metering was used in [3,4] to reduce the electricity cost and minimize power loss. Their proposed system also helps in distributing quality power, i.e., supply complying with the necessity.

In this report, we have mainly concentrated on the Home Energy Management System and the following sections present the details of some of the recent works on this field.
2.2 Existing Works Review

The authors in [1] have considered the Heat Ventilation and Air Condition (HVAC) system among different loads of the house. A novel Traversal-and-Pruning (TP) algorithm has been used to find optimal day-ahead schedules for thermostatically controlled household loads. The schedules have also been designed in [2] considering both payment and comfort settings of the users. The authors in [8] have formulated a practical optimization model to schedule the home appliances under Time of Use (TOU) electricity prices. A novel energy management approach for smart homes has been proposed in [9]. Their proposed approach combines a wireless network, based on blue-tooth low energy (BLE) for communication among home appliances to develop a home energy management (HEM) scheme. A novel smart home architecture based on Resource Name Service (RES) was given in [10]. However none of the above works have taken renewable energy based system into consideration.

In [11], a green home energy management system has been proposed that can show energy usage profile of home appliances. It also provides a comparison on energy usage among the same kinds of home appliances. On the other hand, [12] presents a home energy management controller that uses a compendious and generalized optimization methodology. It minimizes energy cost while preserving user’s comfort level. A smart home with an HEMS and multi agent system including demand response (DR) enabled load models has been fabricated in [13]. Authors in [1] describe a PLC-based HEMS that can monitor and provide information of energy consumption patterns and can control appliances intelligently. The works presented above do not cogitate about renewable
energy and develop any model that can demonstrate trade-off between energy production or purchase and user comfort.

2.3 Different Type of Electricity Usage Model

Dynamic Pricing (DP) mechanism has been applied to both conventional home agent system and smart home agent system and the performance gain of the systems are compared in [6]. In this paper, an agent based model has been presented to evaluate the HEMS in residential demand-response implementation. Smart meters control all household appliances. Various pricing schemes have been given to encourage consumers for scheduling their home appliances at times with low purchase rate that will save energy, reduce cost and help grid operation. In [7, 9, 14–49] demand response modeling is discussed including renewable energy. In [50], a smart energy distribution and management system (SEDMS) has been proposed which operates through interaction between a smart energy distribution system and smart monitoring and control system. This work considers integration of a new renewable energy system with dynamic pattern based intelligent service. It also monitors the information about power consumption, user situation and surroundings.

Out of all existing systems, [5] is the most similar to our approach. However, there are a few structural and elementary differences between the two. First, in [5] only an architecture was proposed that study energy generation and expenditure based on ZigBee and PLC including renewable energy. Whereas it does not develop any mathematical model that can estimate the amount of production and expenditure in a time schedule. Second, it only mention about the correlation between energy generation and weather
information, but does not explain how to predict energy production based on this correlation. Third, it proposes remote energy management server (REMS) that can just calculate the energy usage for home appliances and develop energy usage pattern for the subscribers. However, it does not consider the energy saving limitations of storage devices and trading mechanisms in case of energy deficit and surplus. Finally, a decision making system has been designed in this work for regulating home appliances based on user preference and cost that ensures user satisfaction level.

2.4 Summary

In this chapter, we have discussed about some of the recent work based on Home Energy Management System, their contributions and limitations. This study of the existing literature reveals a bunch of sectors, where further improvement are needed. The limitation of these state-of-the-art have motivated us to develop a new algorithm for HEMS. In our proposed algorithm, we have tried to alleviate all the limitations that we have found from the study of the existing works.
Chapter 3

System Model

3.1 Introduction

Home Energy Management System is a promising technology which has been introduced to solve the problem of Demand response, energy scarcity problem and increase the user satisfaction. With the development of HEMS, HEMS have drawn much attention because of its cost effectiveness and characteristic. From the previous chapters, we have learned about Home Energy Management System and its architecture. Furthermore, we have studied the background an motivations behind our work. In this chapter, our proposed system architecture is described in details.

Modern smart homes are adorned with renewable energy sources such as solar energy, wind mill, Bio Gas etc. In this work, we have considered that there are \( n \) number of sources of renewable energy in a home and the set of all source is given by \( N \). In the context of solar, energy production gets higher as the day goes on. It reaches the highest pick at 11am and the production curve goes down slowly after 1pm in a typical sunny day. Energy generation is high at this time duration. Moreover we can assume that, production of energy from other renewable sources also follow a particular pattern which change gradually over time.

We divide the 24-hour period of a day into time scheduling slots of equal length and the set of all slots in a day is denoted as \( T = \{1, 2, 3, \ldots, T\} \). Notations used in this
paper are summarized in Table 3.1.

Table 3.1: Notations used in this paper

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>Set of all time slots</td>
</tr>
<tr>
<td>$R_b$</td>
<td>Set of Energy purchase rates</td>
</tr>
<tr>
<td>$P_{td}^i$</td>
<td>Energy production at time slot $t$ on day $d$</td>
</tr>
<tr>
<td>$C_{td}^i$</td>
<td>Energy consumption at time slot $t$ on day $d$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Weight parameter</td>
</tr>
<tr>
<td>$F$</td>
<td>Fairness index</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Budget allocation duration in days</td>
</tr>
<tr>
<td>$\Psi_{td}$</td>
<td>purchaseable energy</td>
</tr>
<tr>
<td>$S_t$</td>
<td>Storage at time slot $t$</td>
</tr>
</tbody>
</table>

3.1.1 Different Type of pricing schemes

As traditional meters are not fully replaced yet from the market so still most utility companies use old models for their customers that is based on fixed prices/kWh during all the time. But process of replacing old meters with smart meters is a continuous process where electricity consumption can be recorded in a real time with better output and less error. Different pricing schemes are like Time of use, Real Time Pricing, Critical Peak Pricing are very popular for residential users to facilitate the utility. In Time of Use (TOU) pricing model, prices of different time slot is known in advance and each day is divided into $n$ no of fixed time slots. Various type of peak hours like: high, mid, and low are enable so that customers can schedule their electrical home appliances in such way that electricity bill remain low. As example electricity demand is very high from 6pm to 10pm. During this time customer can turn-off unnecessary loads so that they can minimize the electricity bill. Difference between Time of Use and Day Ahead Planning (DAP) is in DAP energy pricing are fixed only for that particular day and prices of different time slot are known in advance too. In Real Time Pricing electricity prices
vary hourly basis. So, during low energy demand hours, electricity price will be low and during high energy demand time period, electricity price will be high. Another pricing scheme named Critical Peak Pricing uses predefined pricing rates where user are charged according to a rate. This scheme help to restrict the users to use less energy during peak hour.

Each smart home contains a home server that regulates the intelligent energy management activities of the smart home \cite{5}. Components of inter- and intra-smart home intelligent energy regulation is performed with the help of the following energy management servers.

1. Home Energy Management System (HEMS) HEMS is the home energy controlling decision maker. The HEMS uses Prediction Manager to estimate the amount of energy that will be produced from different RESs and consumed from the home appliances in a time slot $t \in \mathcal{T}$. It can analyze the data and make the energy usage profile. The Energy Production Controller in HEMS communicates with

![Figure 3.1: System Block Diagram.](image-url)
the RESs and collects production information. It can regulate the RESs and also collects the energy storage information. *Energy Consumption Controller* operates the home appliances. It turns on/off the appliances based on user preferences, energy availability and the energy consumption rate of the appliances. The data taken from different devices are collected, processed and stored with the help of *Data Aggregator* and *Information Database*. *Device Table* keeps track of the home appliances, their energy consumption rate and their state in any slot. *Fair Usage Manager* calculates the fair share of the monitary budget each slot $t \in \mathcal{T}$ should get from the total budget allocated for a $\mathcal{T}$. The lower level components provide support for communication with appliances and with AEMS and contribute to the smooth operation of HEMS. It also calculates the amount of profit can be made during each scheduling cycle by selling extra energy to others. The system components of an HEMS are shown in Fig. ??.

The HEMS uses *Prediction Manager* to estimate the amount of energy that will be produced from different RESs and consumed from the home appliances in a time slot $t \in \mathcal{T}$. The *Energy Production Controller* communicates with the RESs and collects production information. It can regulate the RESs and also collects the energy storage information. *Energy Consumption Controller* operates the home appliances. It turns on/off the appliances based on user preferences, energy availability and the energy consumption rate of the appliances. The data taken from different devices are collected, processed and stored with the help of *Data Aggregator* and *Information Database*. *Device Table* keeps track of the home appliances, their energy consumption rate and their state in any slot. *Fair Usage Manager* calculates the fair share of the monetary budget.
each slot $t \in \mathcal{T}$ should get from the total budget allocated for $\mathcal{T}$. The lower level components provide support for communication with appliances and with AEMS and contribute to the smooth operation of HEMS.

2. Inter Home Connection System (IHCS) Nearest homes within an area are connected through IHCS and all the IHCSs are connected with a central AEMS. Neighboring HEMS can buy or sell energy through IHCS based on the decision made by the AEMS.

3. Area Energy Management System (AEMS) An AEMS can monitor and communicate with all HEMS within an area through IHCS. If a home server produces extra energy, it can sell the additional energy to the AEMS. In cases, a home server needs
extra energy, it determines whom to purchase energy exploiting the connectivity support provided by the IHCSs.

Fig.3.3 depicts the inter-connection among the system components.

![Figure 3.3: System Architecture](image)

**3.2 Summary**

In our proposed architecture solar, wind energy and bio-gas is used as the sources of production and using the prediction manager necessary energy can be predicted and stored in the storage. Based on the user usage it detects the energy surplus or deficit
state user can give a monetary budge for a long time period and using all this HEMS can ensure energy usage threshold.
Chapter 4

Smart Energy Management System

4.1 Introduction

In the previous chapter, we have learned about the proposed system architecture. In this chapter, an algorithm is developed and analyzed that can predict energy production and consumption, define a threshold and distribute the user given budget for every time slot. In an area, every smart home has its own production unit. Analyzing previous data, a smart home can predict the amount of energy $\hat{P}_d^t$ that can be generated in a time slot $t \in T$ through HEMS. User allocates budget in currency for energy to be used in a long duration of time. Using this information, the HEMS decides how much energy the smart home can store and sell or borrow. In this section, we first predict the amount of energy that can be produced and the amount that can be consumed at the beginning of a time slot. We then make decision on energy purchase plan for the users based on this energy budget, production and consumption. Finally, we develop an algorithm that will make decision for buying energy prudently.

4.1.1 Prediction of Energy Production and Consumption

In this paper, we have predicted the amount of energy which can be generated from various RESs in a particular time slot. We have calculated the average power generation for each time slot in a day using exponentially weighted moving average (EWMA). At the beginning of a particular time slot we can assume that, generation of power in that slot
will follow the average energy generation for each source of the same slot from previous day. Estimated energy generation for each source \( n \in \mathcal{N} \) at time slot \( t \in \mathcal{T} \) can be given by

\[
\hat{P}_{d}^{n,t} = \alpha_n \hat{P}_{d}^{n,t-1} + (1 - \alpha_n)\mathcal{P}_{d}^{n,t-1} \tag{4.1}
\]

Therefore, the total energy generation is the summation of the energy generated from all \( \mathcal{N} \) RESs

\[
\hat{P}_{d}^{t} = \sum_{n=1}^{n} \hat{P}_{d}^{n,t}. \tag{4.2}
\]

Here, \( \hat{P}_{d}^{n,t-1} \) represents average power generation at time slot \( t \) from source \( n \in \mathcal{N} \). However the solar energy generation in a slot changes due to the variation of daylight-duration and the position of the sun at different seasons of the year. Energy generation from all the other sources also changes with time. Here \( \alpha_n \) is a weighted parameter for source \( n \in \mathcal{N} \). The value of \( \alpha_n \) depends on the weather condition and the production behavior of the energy source. Calculation of the value of \( \alpha_n \) is another research challenge.

Similarly, the energy consumption for time slot \( t \) is estimated as follows,

\[
\hat{C}_{d}^{t} = \beta \hat{C}_{d}^{t-1} + (1 - \beta)\mathcal{C}_{d}^{t-1} \tag{4.3}
\]

Here \( \beta \) is a weighted parameter and its value depends on user energy usage pattern. \( \hat{C}_{d}^{t} \) represent average consumption for a particular smart home. \( \hat{C}_{d}^{t-1} \) is the consumption for time slot \( t \) of previous day \( d - 1 \) which is calculated from smart meter connected with appliances through HEMS.
4.1 INTRODUCTION

4.1.2 Energy Storage Calculation

At the beginning of a month or for a long duration user provides a monetary budget $M$ to be used in $\delta$ days for purchasing energy. Then the monetary budget for a time slot $t$ can be given as

$$F = \frac{M}{\delta \times |T| - \sigma_t} \quad (4.4)$$

At starting of every time slot $t$ we can reckon the value of storage $S$ using following equation.

$$S_t = \max(0, S_{t-1} + P_{t-1} - C_{t-1}) \quad (4.5)$$

The value of minimum storage threshold $L_t$ is determined from the weighted average ratio of production and consumption for all time slots within $k$

$$L_t = \begin{cases} \frac{2 \times P_{t-1}^d}{k+1} \left( \frac{C_t}{P_t} + \frac{k-1}{k} \frac{C_{t+1}}{P_{t+1}} + \cdots + \frac{1}{k} \frac{C_{t+k}}{P_{t+k}} \right); & P_t > 0 \\ \frac{2}{k+1} (\hat{C}_t + \frac{k-1}{k} \hat{C}_{t+1} + \cdots + \frac{1}{k} \hat{C}_{t+k}) & \text{otherwise} \end{cases} \quad (4.6)$$

Here $k$ is called as load shifting window that indicates up to which time slot load can be shifted. Its value is determined based on duration of the time slot and user preference on load shifting. $L_t$ indicates the amount of energy that should be in the storage so that, chance of energy purchasing is minimum.

Considering both the stored energy $S_t$ and estimated safe minimum storage threshold $L_t$, the amount of energy required to purchase at time slot $t$ can be determined as

$$\Psi_t = \min(0, (P_t^d + S_t) - L_t) \quad (4.7)$$
4.1.3 Energy Management and Load shifting

Entire energy budget allocated for duration $\mathcal{M}$ has been divided among all time slots in a fair manner based on the energy demand using max-min sharing policy. Since there are $|\mathcal{T}|$ time slots, each time slot $t \in \mathcal{T}$ requires a portion of energy budget $\Psi_t^d$. The allocation of the energy budget proceeds as follows:

- Allocate energy budget equally among all users.
- if $\Psi_t^d < \mathcal{M}/(\mathcal{T} \times r_t)$ then purchase $\Psi_t^d$ where, $r_t$ represents energy purchase rate at time slot $t \in \mathcal{T}$.
- Allocate the remaining energy budget $M - \Psi_t^d$ equally among the remaining time slots.
- Repeat the procedure until $t = |\mathcal{T}|$ or energy budget = 0.

The steps of prudent energy purchase by the HEMS has been summarized in Algorithm 1. First, energy production and consumption for time slot $t \in \mathcal{T}$ is predicted and the storage at the beginning of the slot is calculated. Then, using the previously calculated production $\hat{P}_t^d$ and consumption $\hat{C}_t^d$, an energy threshold $\mathcal{L}_t^d$ is formulated. Using the updated storage value $S_t^d$, we can determine energy surplus or deficit state by comparing $S_t^d$ with $\mathcal{L}_t^d$ value.

4.1.4 Complexity Analysis

In this algorithm complexity mainly depends on $\Psi_t^d$ and $R_b$. As the value of both this parameter is linear so the complexity of PREMA algorithm is linear as well.
Algorithm 1 Parsimonious Renewable Energy Management Algorithm

**INPUT:** $R^b$: Set of energy buying rates, $F$: Fairness index

**OUTPUT:** $\Phi_t$: Buy amount at time slot $t \in T$, $\mu_t$: balance transfer

1. calculate $\hat{P}^d_t$ using equation (4.1)
2. calculate $\hat{C}^d_t$ using equation (4.3)
3. for $i = 1, \ldots, k$ do
4. calculate $S_{t+i}$ using equation (4.5)
5. end for
6. calculate $L^d_t$ using equation (4.6)
7. calculate $\Psi^d_t$ using equation (4.7)
8. if $\Psi^d_t > 0$ then
9. while $\Psi^d_t > 0$ do
10. $r_t = \min(R^b)$
11. $j = \text{argmin}(R^b)$
12. $\Psi^d_t = \min(\Psi^d_t, (F + \mu_j) \times \frac{1}{r_t})$
13. if $S_j + \Psi^d_t + \Phi_j \leq S_{\text{max}}$ then
14. $\Phi_j = \Phi_j + \Psi^d_t$
15. $\mu_j = \mu_j + \Psi^d_t \times r_t$
16. $F = F - \Psi^d_t \times r_t$
17. $\Psi^d_t = 0$
18. else
19. $\Psi^d_t = \Psi^d_t - (S_{\text{max}} - (S_j + \Phi_j))$
20. $\mu_j = \mu_j + (S_{\text{max}} - (S_j + \Phi_j)) \times r_t$
21. $F = F - (S_{\text{max}} - (S_j + \Phi_j)) \times r_t$
22. $\Phi_j = S_{\text{max}} - S_j$
23. end if
24. $R^b = R^b - R^b_j$
25. end while
26. end if
27. $M = M - (\frac{M}{\sigma^T} - (\sigma^T - F))$
28. calculate $F$ using (4.4)
In case of energy deficit, necessary amount of energy can be purchased in any slot inside load shifting window \( k \). While purchasing energy, optimal energy budget and storage constrain, \( S_{\text{max}} \geq S^d_t \) needs to be ensured. A slot within \( k \) is selected which have the minimum \( r_t \) value. If there are sufficient capacity in the storage device at slot with minimum \( r_t \), the required energy is fully purchased in that slot. Otherwise, another slot is selected within \( k \) to purchase the rest amount of energy. The amount of energy that could be bought in slot \( t \in T \) is determined using Max-min Fairness Scheduling.

4.2 Summary

In this chapter, an algorithm is developed that can ensure proper energy usage and make profit selling extra energy to other home server using Area Energy Management Server. Our proposed model provides a detailed representation of the states than other state-of-the-art models, as the existing works do not consider the selling and purchasing system while representing the states of their models. Thus, the results of the performance metrics obtained from the theoretical analysis of our algorithm gives more accurate values than the other existing models.
Chapter 5

Performance Evaluation

5.1 Introduction

For realizing the effectiveness of a research work, it is necessary to evaluate its performance in the real world. However, it is not possible to evaluate a proposed work in the real world, thus a simulator can be used to create a standard environment that suits properly with it. For evaluating the performance of our proposed algorithm, we have used MATLAB as the simulation tool and conducted several experiments for judging its performance.

In this chapter, we have evaluated the performance of our proposed algorithm and compared its performances with [5], [4]. In the subsequent sections, we present the simulation environment, performance metrics and simulation results.

We have used trace driven simulation to evaluate our proposed Parsimonious Renewable Energy Management Algorithm (PREMA). The simulation data for energy production from different sources are collected from [51] and [52]. We evaluate the execution of our PREMA using MATLAB. Then, we compare the performance of PREMA with Smart Home Including Renewable Energy (SHIRE) [5]. We also compare our work with another version of PREMA having storage capacity of 50KW. We have considered two versions of PREMA namely PREMA-v1 and PREMA-v2 while evaluating the performance having storage capacity of 100KW and 50KW respectively. In our simulation model we consider
5.1 INTRODUCTION

a smart home consisting of HEMS in a particular area connected with AEMS. Duration of each time slot \( t \in \mathcal{T} \) is considered to be 60 minutes.

5.1.1 Simulation Environment

A Simulation environment is considered where a smart home is equipped with household appliances. Energy consumption of the appliances are considered in such a way that reflects the house-hold energy consumption of the day-to-day life. For example, lights are considered to be turned on from 6pm to 6am. Whereas fan are considered to be running 24 hours at a stretch. Energy production from different sources has been estimated using the trace data. We have considered that the PREMA system have the control to turn an appliance on or off after user presses the switch. The price of each unit of electricity is considered in the interval \([3, 10]\) depending on the availability of energy and user demand. We have also considered that, energy can be sold to the AEMS at any time whenever the stored energy crosses \( L_t^d \).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of slots in each day</td>
<td>24</td>
</tr>
<tr>
<td>time slot duration</td>
<td>1 hour</td>
</tr>
<tr>
<td>Monetary Budget(( M ))</td>
<td>2000 ( tk )</td>
</tr>
<tr>
<td>Number of home appliances</td>
<td>12</td>
</tr>
<tr>
<td>Electricity price per unit</td>
<td>3 – 10</td>
</tr>
<tr>
<td>Maximum Storage Capacity(( S_{max} ))</td>
<td>100</td>
</tr>
<tr>
<td>Maximum Utility(( U_0 ))</td>
<td>( U_0 )</td>
</tr>
<tr>
<td>Load shifting window(( K ))</td>
<td>5</td>
</tr>
<tr>
<td>(( \Gamma_1 ))^2</td>
<td>0.9</td>
</tr>
<tr>
<td>(( \Gamma_1 ))^2</td>
<td>0.1</td>
</tr>
</tbody>
</table>
5.1 INTRODUCTION

5.1.2 Performance Matrices

We have evaluated our algorithm performance on the basis of some performance metrics. The performance of [5], [4] along with PREMA is also evaluated here. The performance metrics are described below.

Utility: In our simulation environment, we model the customer satisfaction based on the utility theory in economics. We define the utility of buying energy as a function of buying cost $B_C$ and the response time $t$ within $k$.

$$U = U_0 - \Gamma_1 \frac{B_C}{F} - \Gamma_2 \frac{t - 1}{k}$$

(5.1)

in which $U_0$ is the maximum utility that indicates user don’t require to buy any energy from other HEMS. $\Gamma_1$ and $\Gamma_2$ are coefficients. $\Gamma_1/\Gamma_2$ or $\Gamma_2/\Gamma_1$ is known as marginal rate of substitution in economics, denoting the rate at which the user willing to give up buying cost $B_c$ in exchange for response time slot without any satisfaction change.

Budget Consumption: The Budget consumption by different smart-home Energy management algorithm has been calculated for each time slot. The total budget consumption for a period is then obtained from the summation of budgets used in each slot within that period. The consumed total budget is then divided by total allocated budget.

5.1.3 Simulation Result

The results obtained by performance evaluation of different smart home algorithms have been shown in Fig.5.1 - Fig.5.3.

Fig. 5.1 depicts the budget consumption of different smart home energy management algorithms with time. The figure reveals the fact that, as the time of operation increases,
budget consumption increases proportionally. However, PREMA system incurs lower consumption compared to SHIRE, because energy purchase in PREMA is performed at slots with lower purchase rate within the load shifting window. Again, PREMA-v1 experiences a better budget consumption compared to PREMA-v2 because of having higher storage capacity.

Fig. 5.2 shows again the budget consumption for energy purchase by the smart home energy management algorithms. The figure reflects that, budget consumption increases linearly with the amount of energy purchased. However, since PREMA system buys energy at time of lower energy rates, it can reduce the budget consumption for buying the same amount of energy compare to state-of-the-art works. PREMA-v2 even works better as it can store more energy considering the energy requirement of the future slots of load shifting window.

The system utilities of different energy scheduling algorithms at different time slots
5.2 INTRODUCTION

![Budget consumption over energy purchase](image)

Figure 5.2: Budget consumption over energy purchase

![Utility change over time](image)

Figure 5.3: Utility change over time

have been shown in Fig. 5.3. For calculation the utility, we have taken the average of utility value of all days at same time slots. The figure shows that utility decreases as the energy production decreases and consumption increases. However, since PREMA system purchases energy at slots with low energy rate, it experiences better utility compare to SHIRE.
5.2 Summary

The previous analysis shows that, our proposed PREMA algorithm performs better than [5], [4] in terms of budget consumption, utility, energy consumption. These three performance metrics are widely used for evaluating the performance of HEMS, and thus we can conclude that, the proposed PREMA algorithm provides a better solution than the other studied algorithms.
Chapter 6

Conclusion

6.1 Summary of Our Work

In this work, we have developed a smart renewable energy management system for IoT devices, where each home contains a home server and they are connected with a local server. The local servers are connected with a main server called area energy management server (AEMS). Both local server and AEMS keeps information about the energy deficit or surplus of any particular house and area depending on their energy production and expenditure. Our policies on energy management target to increase the user utility while minimizing the cost for energy purchase. More specifically, we have developed a Parsimonious Energy Management Algorithm (PREMA) that judiciously purchases energy considering energy rates and storage capacity. The algorithm uses Max-min Fairness Scheduling to distribute the total monetary budget among all the time slots. The performance of PREMA have been evaluated through extensive simulations and the results show that it minimizes the electricity cost, curtails energy wastage, helps power grid to save energy resources without compromising user satisfaction.

We have studied the existing literature of HEMS and investigated the shortcomings of the studied algorithms. There are a number of algorithm for HEMS, which are developed in recent years. We have already discussed that, there is no buying and selling system in HEMS. Therefore, PREMA is perfect for HEMS, as it increase the profit and user
satisfaction. Among all these [5], [4] are most promising in terms of their performance, but they also have their own limitations. In our proposed work, we have tried to overcome the limitations of the existing works.

6.2 Discussion

While developing architecture for HEMS, we have faced lots of difficulties. We have to go through the existing literatures to get an insight into the current research state of HEMS and to find out the points where further improvements are needed. The main challenge is to cope up with the changing environment of the renewable energy. Making the best utilization of unused portion of the energy while maintaining the user satisfaction, is also very challenging. We faced difficulties to find out the alternative solutions of the existing works. We have to find out the methodology to make the solutions workable and develop an algorithm. Then we evaluated our algorithm performance and feasibility in the real world using a simulator. Comparing our protocol with [5], [4], we can observe a substantial improvement of the performance. Therefore, our proposed algorithm PREMA provides better solutions of the existing problems and shows promising development in the field of Home Energy management System.

6.3 Future Scope

Our proposed PREMA algorithm performs better than a number of state-of-the-art protocols, but still we have scopes of improvement. Firstly, in our proposed work, we didn’t model the whole Area Energy Management System. We should give more concentration in this part, so that we can gain better performance.
6.3 FUTURE SCOPE

Secondly, we have evaluated our algorithm performance with respect to [5], [4], but we have not implemented it in real life. Therefore, we want to complete this task as soon as possible.

Finally, in the analytical model of our proposed algorithm, load shifting window $k$ is not dynamic, which is fixed and need to be dynamic.


## Appendix A

### List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEMS</td>
<td>Area Energy Management System</td>
</tr>
<tr>
<td>CPP</td>
<td>Critical Peak Pricing</td>
</tr>
<tr>
<td>DAP</td>
<td>Day Ahead Programming</td>
</tr>
<tr>
<td>DR</td>
<td>Demand Response</td>
</tr>
<tr>
<td>HEMS</td>
<td>Home Energy Management System</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heat Ventilation and Air Condition</td>
</tr>
<tr>
<td>IHCS</td>
<td>Inter Home Connection System</td>
</tr>
<tr>
<td>PLC</td>
<td>Power line Communication</td>
</tr>
<tr>
<td>PREMA</td>
<td>Parsimonious Energy Management Algorithm</td>
</tr>
<tr>
<td>RE</td>
<td>Renewable Energy</td>
</tr>
<tr>
<td>SEDMS</td>
<td>Smart Energy Distribution and management system</td>
</tr>
<tr>
<td>TOU</td>
<td>Time of Use</td>
</tr>
<tr>
<td>TP</td>
<td>Traversal-and-Pruning</td>
</tr>
</tbody>
</table>
## Appendix B

### List of Notations

Table B.1: Notations used in this paper

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{T}$</td>
<td>Set of all time slots</td>
</tr>
<tr>
<td>$\mathcal{R}^b$</td>
<td>Set of Energy purchase rates</td>
</tr>
<tr>
<td>$\mathcal{P}^d_t$</td>
<td>Energy production at time slot $t$ on day $d$</td>
</tr>
<tr>
<td>$\mathcal{C}^d_t$</td>
<td>Energy consumption at time slot $t$ on day $d$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Weight parameter</td>
</tr>
<tr>
<td>$\mathcal{F}$</td>
<td>Fairness index</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Budget allocation duration in days</td>
</tr>
<tr>
<td>$\Psi^d_t$</td>
<td>purchasable energy</td>
</tr>
<tr>
<td>$S_t$</td>
<td>Storage at time slot $t$</td>
</tr>
</tbody>
</table>
Appendix C

List of Publications

International Conference Paper