# CHARGE SCHEDULING OF PLUG-IN ELECTRIC VEHICLES IN DC NANOGRID

A PROJECT REPORT

Submitted by

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KOLLAM

# CERTIFICATE

This is to certify that the Project report entitled ‘**CHARGE SCHEDULING OF PLUG-IN ELECTRIC VEHICLES IN DC NANOGRID’** submitted by ‘**VAISHNAVI VIJAYAN’** to the APJ Abdul Kalam Technological University in partial fulfillment of the requirement for the award of the Degree of Master of Technology in Power Systems, Electrical & Electronics Engineering is a bonafide record of the project work carried out by her under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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# CONTENTS

**Contents** **Page No.**

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# ABSTRACT

The rapid increase in environmental issues lead to the development of Plug-In Electric Vehicle (PEV). PEVs are environmentally friendly and have a lower operating cost. However, the large-scale deployment of PEVs can cause several detrimental effects on power distribution systems. To address these issues, scheduled charging schemes for PEVs are formulated. Charging of PEVs using renewable energy sources can reduce the demand on the grid. However, renewable energy sources are intermittent and require grid connection for reliable power supply. The development of smart grids and technologies lead to the evolution of nanogrids, which overcome the innate flaws of conventional power distribution systems. DC nanogrids provide suitable provisions for the incorporation of sustainable energy sources and PEV charging stations. In this paper, an optimal PEV charge scheduling algorithm is presented for charging PEV in a DC nanogrid with solar photovoltaic (PV) system. The charge scheduling algorithm is based on the Time of Use Price (ToUP) tariff scheme. The algorithm schedules the charging of PEVs in slots with minimum cost and interrupts the charging during peak hours. The main aim of the charge scheduling algorithm is to minimize the charging cost of PEVs. The charging of different PEVs using the scheduling algorithm under different cases were carried out to analyze the reliability and efficacy of the scheduling algorithm. The algorithm is developed using MATLAB.

# LIST OF FIGURES

# LIST OF TABLES

# ABBREVIATIONS

| | |
|---|---|
| DP | Dynamic Programming |
| EV | Electric Vehicle |
| ICEV | Internal Combustion Engine Vehicle |
| LP | Linear Programming |
| MILP | Mixed Integer Linear Programming |
| MPA | Modified placement algorithm |
| MPC | Model Predictive Control |
| PEV | Plug-in Electric Vehicle |
| PSO | Particle Swarm Optimization |
| QP | Quadratic Programming |
| RES | Renewable energy source |
| ToUP | Time-of-Use Pricing |

# NOTATION

| | |
|---|---|
| $A$ | Area |
| $D$ | Duration of charging |
| $E_t$ | Entry time of PEV |
| $I$ | Solar irradiation |
| $L_t$ | Leaving time of PEV |
| $P_{ev}$ | Charging rate of PEV |
| $P_{pv}$ | Solar PV power |
| $P_h$ | Residential load |
| $t_o$ | Outdoor temperature |
| $T_r$ | Tariff rate |

# CHAPTER 1

# INTRODUCTION

## 1.1 PREAMBLE

This chapter introduces the general background, motivation, main objectives, and organization of the thesis work. The need for the deployment of PEVs, the impact of unscheduled charging of PEVs on the grid, and the need to adopt proper charge scheduling techniques are presented in this chapter.

## 1.2 GENERAL BACKGROUND

An increase in the use of internal combustion engine vehicles can cause adverse environmental effects such as fossil fuel scarcity, emission of greenhouse gases, and pollution. Around 60% of carbon monoxide emissions, 50% of nitric oxide emissions, and 30% of hydrocarbon emissions are generated by internal combustion engine (ICE) vehicles [1]. These environmental issues lead to the development of plug-in electric vehicles (PEVs) as an alternative to ICE vehicles. PEVs are environmentally friendly and are more convenient to use. It has a lower operating cost and produces less pollution compared to ICE vehicles. Global EV production has increased around 36% compared to previous years. EV production will reach around 140 million by 2030. Expanding EV production helps to minimize carbon footprint and cut down the dependency on fossil fuels [2].

However, there remain barriers to the widespread adoption of PEVs. Currently, there is relatively little access to charging stations, and building a public charging infrastructure would need substantial capital investment. The uncontrolled charging of huge number of PEVs can result in severe impacts on grid operations such as an unanticipated rise in electricity demand, voltage variations, as well as other technical challenges. The sporadic and unanticipated connection of PEVs to the grid for charging is the cause of grid-related challenges. Scheduled charging of PEV is the best way to solve these grid-related problems. Charge scheduling methods are intended to maintain grid stability and minimize the charging cost [3]. In a scheduled charging method, PEVs are usually charged during off-peak hours. The two main approaches for charge scheduling of PEV are centralized and decentralized scheduling methods. In the centralized method, charge scheduling is decided centrally. The aggregator collects information on PEV such as the amount of power required to charge the vehicle and charging time. Based on this information, the system operator who controls the transmission system provides power to the aggregator, and the aggregator schedules the charging of PEV based on the requirements. Centralized charge scheduling strategies are proposed in [4]-[6]. In the decentralized method, the PEV user can determine whether to charge or not and a system operator is not required. This method is more convenient for users since they can schedule the charging individually and PEVs can be charged at a low cost. The infrastructure cost required for the decentralized method is less compared to the centralized method. Decentralized charge scheduling strategies are proposed in [7]-[8].

The cost of charging is also an important element that encourages people to choose PEV. Charge scheduling of PEV can be done based on dynamic pricing schemes. The pricing schemes can control the charging manner of PEV users and provide flexible operation. The price variations of the tariff schemes depend on demand. These policies encourage users to shift the charging from peak time to off-peak time [9].

PEVs become more sustainable when they are charged using Renewable Energy Sources (RESs). Conventional power distribution systems depend on fossil fuels to generate electricity, which causes the release of pollutants that are harmful to the environment. Implementation of renewable energy for charging can reduce greenhouse gas emissions and pollution generated from power plants. In most of the works, solar energy is considered to meet the energy demand for charging PEV since it is abundantly available [10]. According to the reports, PV technologies will deliver around 1081 GW by 2030 [11]. Solar PV has several advantages such as solar PV power can be generated locally and is ecologically sound. It has low working and maintenance cost, noiseless operation, and zero waste generation. Above all, the energy generation cost is zero. Solar PV panels mounted on building roofs and parking areas can function as a shed and can avert the heating of buildings and vehicles [12]. Solar PV can be used as a backup power source in case of any failure in grid operation and also it can improve power factor [13]. Scheduled charging of PEV using solar PV power is proposed in [14]-[17]. However, power generated by the PV system is intermittent and variable. Diurnal, seasonal, and environmental fluctuations have an impact on the output of solar PV power. Therefore, a grid connection is necessary to guarantee a consistent power supply for PEV charging [18]. The development of smart grids and technologies lead to the evolution of nanogrids, which are ideal for the optimal integration of RESs and PEV charging provisions. In DC nanogrid charging provisions can be directly connected to a DC bus through a DC-DC converter and thus reduce the system requirements [19]. A charge scheduling algorithm to charge PEV in DC nanogrid with a solar PV system is proposed in this work. The algorithm interrupts the charging of PEVs during peak hours and reduce the charging cost of PEVs.

## 1.3 MOTIVATION

PEVs can reduce the emission of pollutants and have a minimum operating cost compared to ICE vehicles. However, uncoordinated charging of PEVs from the grid can cause several technical and economical challenges. One of the most economical approaches to lessen the detrimental effects of PEVs on the power grid is to implement a scheduling algorithm for charging PEVs. The PEV charge scheduling algorithm can improve the economic benefits of PEV users.

## 1.4 THESIS MAIN OBJECTIVES

- To develop an optimal scheduling algorithm for charging Plug-In Electric vehicles in DC nanogrid with solar PV power.
- To reduce the overall charging cost of Plug-In Electric vehicles.
- To verify the effectiveness of the charge scheduling algorithm under different cases.

## 1.5 ORGANIZATION OF THESIS

The entire thesis organization is as follows:

It consists of 6 chapters. Chapter 1 includes a brief introduction, motivation and objective of the problem. Chapter 2 deals with the literature review. Chapter 3 focuses on the development of a charge scheduling algorithm for charging PEV in DC nanogrid which include the problem statement and objective functions of the charge scheduling algorithm and formulation of the scheduling algorithm. Chapter 4 deals with the system modelling which includes solar PV modelling, residential load, tariff scheme and PEV data required for simulation studies. Chapter 5 deals with results and discussion in which charging of PEV in DC nanogrid under four different cases were analyzed. A long-term analysis is also conducted to confirm the effectiveness of the algorithm and the results are presented and discussed. Chapter 6 concludes the work.

## 1.6 SUMMARY

The general background, motivation, and aim of the thesis work were discussed in this chapter. From this chapter, it can be concluded that the scheduled charging of PEV is necessary to minimize the negative impact of PEV on the grid and to minimize the charging cost of PEV. In this work, the scheduling algorithm for charging PEV in DC nanogrid aims to minimize the charging cost of PEV.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 INTRODUCTION

This chapter mainly describes the literature survey of the thesis work. It includes a detailed review of different scheduling methods and the interruptible charge scheduling algorithm employed in this work and the scope of the thesis work.

## 2.2 LITERATURE SURVEY

Charging of PEV can be unscheduled or scheduled. In unscheduled charging, PEVs begin charging instantly when plugged in and carry on charging until they are completely charged. Unscheduled charging of PEVs may cause an increase in demand on the grid, power losses, and other technical issues. In the scheduled charging method, PEVs are charged only during scheduled hours which are usually off-peak hours [20]. It can provide a balance between power supply and demand. Charging scheduling can create communication between the grid and PEV [21]. Numerous constraints are taken into account while formulating the scheduling algorithms for EVs such as EV design, EV profile, grid framework, and other parameters. EV data such as entry time, leaving time, charging rate, and charging duration are some of the important EV profiles considered for scheduled charging.

### 2.2.1 Charge Scheduling Methods

Various optimization techniques are established to schedule the charging of EVs. Generally, optimization methods for charge scheduling can be classified into three, namely numerical methods, meta-heuristic methods, and heuristic methods [22]. Linear programming (LP), dynamic programming (DP), quadratic programming (QP), and mixed-integer linear programming (MILP) are some of the numerical methods used for charge scheduling. A LP-based algorithm is proposed in [23] for optimal charge scheduling of EVs. A MILP-based model is formulated to reduce the cost of power on the network model. In paper [24] an EV parking station powered by both PV and utility grid is considered. The paper studies the V2G ability of EVs and the merit of the energy storage system. The MILP-based optimization technique is used to manage the charging and discharging operation of PEVs. It aims to improve the comfort level of EV owners by satisfying their charging requests and minimize the running price of the parking station. In [25], an Integer Linear Programming (ILP) based charging technique is proposed for the charging stations. The charge scheduling technique aims to reduce the charging cost of EVs. In order to make a quick decision-making process, two game-theoretic decentralized models are considered. It helps to recognize the significance of forthcoming load in charge scheduling. A quadratic price function is proposed to assure fair play among EVs. EV users have to pay extra to relish a greater charging rate. The primary aim of the proposed technique is to reduce the charging cost for all EVs. An optimal charge scheduling method for EV throughout 24 hours using serial quadratic programming is presented in [26]. A dynamic charge scheduling scheme is proposed in [27] for charging EVs. It has the capability to revise the charging decisions subjected to the gathered data. However, numerical methods are not suitable for multiple objective situations and complex frameworks.

The meta-heuristic methods can overcome the limitation of numerical methods. This method is suitable for non-linear and non-convex systems for charge scheduling and can also resolve problems having multiple objective functions. Genetic algorithm (GA) and particle swarm optimization (PSO) are some of the meta-heuristic methods used for EV charge scheduling. GA-based optimization technique on a low voltage system is proposed in [28]. In [29], the charging cost of EVs in each region is determined with the help of an optimization scheme built using GA. In [30], the PSO method and grey wolf optimization method are used for optimal charge scheduling. A heuristic method is capable of providing fast solutions to complex problems. Charge scheduling of EVs based on heuristic approaches are presented in [31-32].

Most of the charge scheduling approaches discussed above, give precise results. However, many of these techniques have substantial computational and operational complexity and also require pre-training. In this thesis work, a heuristic algorithm-based charge scheduling technique for charging PEVs in DC nanogrid is proposed. The algorithm is easy to apply and it doesn’t require a fast processor. It works without any pre-training [33]. The algorithm schedules the charging of PEV in an interruptible manner to reduce the charging cost. The proposed charge scheduling algorithm is based on the placement algorithm proposed in [34] and the modified placement algorithm (MPA) proposed in [35]. The placement algorithm schedules the charging of PEV to minimize the charging cost. However, the algorithm is incapable to operate if the PEV exit the charging station on the next day. MPA is suitable for night-time charging that continues to the next day and schedules the charging of PEV in slots with the least cost. However, the algorithm schedules the PEV charging in an uninterruptible manner, and thereby charging the cost of PEV would be higher compared to the interruptible charge scheduling method.

### 2.2.2 Charge Scheduling of PEV in DC Nanogrid

Electric grids have grown toward the idea of "Smart Grids," which allow communication between the various entities involved in the system operation and significantly enhance the performance. The development of smart grids and technologies leads to the evolution of microgrids and nanogrids, which have become the crucial structures for the optimal integration PEVs and RESs [36]. In this thesis work, scheduled charging of PEV in DC nanogrid is proposed. In DC nanogrid charging provisions can be directly connected to a DC bus through a DC-DC converter and thus reduce the system requirements. DC nanogrid has a higher power transfer capability and has fewer losses. It is more reliable and has a simple operation scheme [37]. In paper [38], the scheduled charging of EVs in DC nanogrid is presented. However, EVs are charged in an uninterruptible manner. The charging cost of EVs can further be minimized by using the interruptible charge scheduling technique.

## 2.3 SCOPE OF THE WORK

The main focus of the work is to create a charge scheduling algorithm that will reduce the cost of PEV charging in a DC nanogrid. The algorithm uses a ToUP tariff scheme for price analysis where the tariff rate varies according to the demand on the grid. The charging of PEV is interrupted during peak hours and schedules the charging during off-peak hours till the PEV is charged for the required charging duration. A solar PV integrated nanogrid is considered in this thesis work for the analysis of PEV charge scheduling. The sole objective of the algorithm is to reduce the overall cost of energy consumed. The proposed charge scheduling method is compared with the unscheduled charging method to verify the effectiveness of the algorithm. Chapter 5 describes the development of the charge scheduling algorithm. The comparison of PEV charging using scheduled and unscheduled charging methods are depicted in chapter 6.

## 2.4 SUMMARY

In this chapter different charge scheduling approaches for charging EVs were discussed. However, most of the existing approaches are complex and require fast processors. This chapter has shown that a significant portion of the suggested works concentrate on uninterrupted EV charging patterns. The cost of EV charging can be minimized more by using interruptible charge scheduling algorithm. The proposed charge scheduling method is simple to use and it doesn’t require any pre-training process compared to other method.

# CHAPTER 3

# DEVELOPMENT OF CHARGE SCHEDULING ALGORITHM

## 3.1 INTRODUCTION

This chapter introduces the development of the charge scheduling algorithm for charging PEV in a DC nanogrid. The problem statement and objective functions of the charge scheduling algorithm are presented in this chapter. An interruptible charge scheduling algorithm is formulated to optimally schedule the charging of PEV

## 3.2 PROBLEM STATEMENT AND OBJECTIVE FUNCTIONS OF CHARGE SCHEDULING ALGORITHM

Large-scale integration of PEV into power distribution systems has several negative impacts. In unscheduled charging, PEVs begin charging instantly when plugged in and carry on until they are completely charged. Unscheduled charging of PEV can cause a rapid rise in electricity demand and charging costs. To avert the negative impact of PEV on power distribution systems, proper charge scheduling schemes are necessary. The charge scheduling techniques aim to enhance the economic benefits of users and minimize power quality issues. The objective of the proposed work is to apply a charge scheduling technique for charging PEV in DC nanogrid at minimum cost. The charge scheduling algorithm interrupts the charging of PEV during peak hours and schedules charging during off-peak and super off-peak hours to minimize the charging cost and energy demand on the grid. The factors required to schedule charging of PEV in a DC nanogrid are as follows:

i) Entry time of PEV ($E_t$)
ii) Leaving time of PEV ($L_t$)
iii) Duration of charging (D)
iv) Charging rate of PEV ($P_{ev}$) in kW
v) Solar PV power ($P_{PV}$) in kW
vi) Residential load ($P_h$) in kW

vii) Tariff rate ($T_r$)

The above-mentioned are some of the key constraints in the scheduling algorithm for charging PEV in DC nanogrid. The objective of the algorithm is to minimize the cost required to charge PEV.

## 3.3 INTERRUPTIBLE CHARGE SCHEDULING ALGORITHM

An interruptible charge scheduling technique is used in the proposed work to schedule the charging of PEV in DC nanogrid and it is based on the heuristic algorithm. A ToUP-based pricing scheme is used for the price analysis. In this pricing scheme, the tariff of a day varies depending on peak hour, off-peak hour, and super off-peak hour. The scheduling algorithm in the proposed work is formulated on the basis of the placement algorithm proposed in [34]. The placement algorithm optimally schedules the charging of PEV at minimum cost. However, it is not suitable for scheduling PEV charging from overnight to the next day. The advanced placement algorithm proposed in [35], overcomes the limitation of the conventional algorithm. It is suitable for scheduling night-time residential PEV charging that continues to the next day. All the available slots between the entrance and leaving time of the PEV are recognized, the cost required to charge the PEV in each slot is calculated and determine the slots with minimum price among the possible slots for charging PEV. This algorithm is able to produce precise scheduling throughout a 24-hour period with the least amount of charging cost. If the entry time and the leaving time are on the same day, then the algorithm operates normally. The algorithm operates in a revised manner to find the charging cost and to determine the optimized charging slot if the charging continues for the next day where the entrance time is greater than the leaving time. However, the algorithm schedules the charging of PEV in an uninterruptible manner. An interruptible charge scheduling approach can lower the PEV charging costs even more.

In the interruptible charge scheduling technique, each hour of the day is taken as a slot. The algorithm continuously searches for slots and chooses the one with the lowest cost between the specified entrance and leaving time. Once the slots with minimum cost are chosen, PEV charging is only scheduled for that specific slot. The interruptible charge scheduling algorithm avoids peak hours during the charging process and schedules charging only on off-peak and super off-peak

Table. 3.1 Charge scheduling algorithm

| | |
|---|---|
| Step 1: | Start |
| Step 2: | Initialize entrance time of PEV ($E_t$), leaving time of PEV ($L_t$), duration of charging PEV ($D$), charging rate of PEV ($P_{ev}$), and Tariff ($T_r$) |
| Step 3: | Load irradiation data, temperature data, and residential load data. |
| Step 4: | For y =*1: n*<br>Load $EV_y$ = [$E_{ty}$ $L_{ty}$ $D_y$ $P_{ev}$] |
| Step 5: | Initialize Slot ($S_x$ = [0 0 0. . . .0]); Cost ($K_x$ = [0 0 0. . . .0]);<br>$x$ = 1, 2...,24 ; Charging cost $C_y$ = 0; |
| Step 6: | Calculate the solar PV power<br>$P_{PV}(x) = \eta * A * 0.9 * I * \left(1 + \gamma(t_o - 25)\right)$ |
| Step 7: | Split the tariff price between $E_t$ and $L_t$ and find the number of possible slots available ($SP$)<br>$ST_y = \begin{cases} T_r\left(E_{ty}: L_{ty} - 1\right);\ E_{ty} < L_{ty} \\ T_r\left(1: L_{ty} - 1,\ E_{ty}: 24\right);\ E_{ty} > L_{ty} \end{cases}$<br>$SP$ = length ($ST_y$) |
| Step 8 | Initialize max = max ($ST_y$) and assign i = $L_y$ |
| Step 9: | For z = 1: $SP$<br>min = $ST_y$(z) if 0 < $ST_y$(z)< max<br>otherwise go to step 11 |
| Step 10: | Update the slot with minimum cost<br>$slot = \begin{cases} z;\ L_{ty} < E_{ty}\ and\ z < L_{ty} \\ z + E_{ty} - L_{ty};\ L_{ty} < E_{ty}\ and\ z \geq L_{ty} \\ z + E_{ty} - 1;\ L_{ty} > A_{ti} \end{cases}$ |

| | |
|---|---|
| Step 11: | Update the corresponding cost and slot array<br>$K_y(slot) = min$<br>$S_y(slot) = 1$ |
| Step 12: | slot = z;<br>$K_y(slot) = 0$<br>$S_y(slot) = 0$ |
| Step 13: | Increment the value of z till z = SP and decrement the value of i by 1 and repeat from step 9 if i >= 1 |
| Step 14: | Find the grid power required to meet the home load<br>$$P_{ghy} = \begin{cases} 0;\ P_{pv}(x) \geq P_h(x) \\ P_h(x) - P_{PV}(x); 0 < P_{PV}(x) \text{ and } P_{PV}(x) < P_h(x) \\ P_h(x);\ P_{PV}(x) = 0 \end{cases}$$ |
| Step 15: | Calculate the solar PV power available for charging EV<br>$$P_{avy}(x) = P_{PV}(x) - P_h(x)$$ |
| Step 16: | Calculate the grid power required to charge the EV<br>$$P_{gevy}(x) = \begin{cases} 0;\ P_{avy}(x) \geq P_{evy} \\ P_{evy} - P_{avy}(x);\ 0 < P_{avy}(x)\ and\ P_{avy}(x) < P_{evy} \\ P_{evy};\ P_{avy}(x) \leq 0 \end{cases}$$ |
| Step 17: | Calculate the cost of energy consumed from the grid to meet the house load<br>$$C_{hy} = \sum_{x=1}^{24} T_r(x) \,.\, P_{ghy}(x)$$ |
| Step 18: | Calculate the charging cost of PEV<br>$$C_y = \sum_{x=1}^{24} K_y\ (x) \,.\, P_{gevy}(x) .\, S_y(x)$$ |
| Step 19: | End |

hours. It is also suitable for scheduling overnight to next day charging of PEV. The charge scheduling algorithm for the proposed work is shown in Table 1. After loading the data required for the analysis, the algorithm separates the tariff based on entry and leaving time and find the available slots for charging. If $y^{th}$ PEV is plugged in for charging at an entry time $E_{ty}$ and leaving time $L_{ty}$. Then, the number of slots available for charging can be determined by using,

$$ST_y = \begin{cases} T_r(E_{ty}: L_{ty} - 1);\ E_{ty} < L_{ty} \\ T_r(1: L_{ty} - 1,\ E_{ty}: 24);\ E_{ty} > L_{ty} \end{cases} \tag{2}$$

$SP$ = length ($ST_y$)

Where $S_{ty}$ is the separated tariff of the $y^{th}$ PEV. SP is the length of the separated tariff, which gives the slots available for charging. The maximum value of the tariff in the available slots are identified by the algorithm and select the slot with the least tariff price. The slots with higher tariff price are eliminated from charging. The process is repeated until the required slots to charge PEV for the specified charge duration is identified. The algorithm determines the generated solar PV power based on the equation (1). The solar PV available to charge the vehicle in the selected slots after meeting the residential load is calculated. In this proposed method the power required to meet home load and to charge PEV is mainly taken from solar PV power. The excess PV power after meeting the load requirement is sold to the grid. The grid power is utilized only when solar PV power is not available. The grid power required to charge PEV and to meet residential load when PV power is not available is determined by the algorithm. The power needed from the grid is calculated for each slot in the time between the beginning and end time of the charging process. The cost of energy consumed to meet residential load while charging $y^{th}$ PEV is determined by,

$$C_{hy} = \sum_{x=1}^{24} T_r(x) \,.\, P_{ghy}(x) \tag{3}$$

Where $C_{hy}$ is cost of energy consumed to meet load, $P_{ghy}$ is the grid power used and $T_r$ is the tariff price. The cost of charging $y^{th}$ PEV, $C_y$ is calculated as,

$$C_y = \sum_{x=1}^{24} K_y\,(x) \,.\, P_{gevy}(x) .\, S_y(x) \tag{4}$$

Where $K_y$ is tariff at selected slot, $P_{gevy}$ is the power taken from the grid to charge PEV and $S_y$ is the selected slot.

## 3.4 SUMMARY

An interruptible charge scheduling algorithm for charging PEV in a DC nanogrid is developed in this chapter. The developed algorithm interrupts the charging of PEV in peak hours and schedules charging only on chosen slots with minimum charging price between the entry time and leaving time. The algorithm utilizes the available PV power for charging PEV so that the price of charging PEV can be further minimized. The cost of charging PEV and the total cost of energy consumed for meeting the load is also calculated.

# CHAPTER 4

# SYSTEM MODELLING

## 4.1 INTRODUCTION

This chapter covers the modelling of the system used for the analysis. The layout of the system is depicted in Fig. 4.1. The system includes a solar PV system, power grid, residential load and PEV charging provision. The different components of the system are interconnected with a common DC bus.

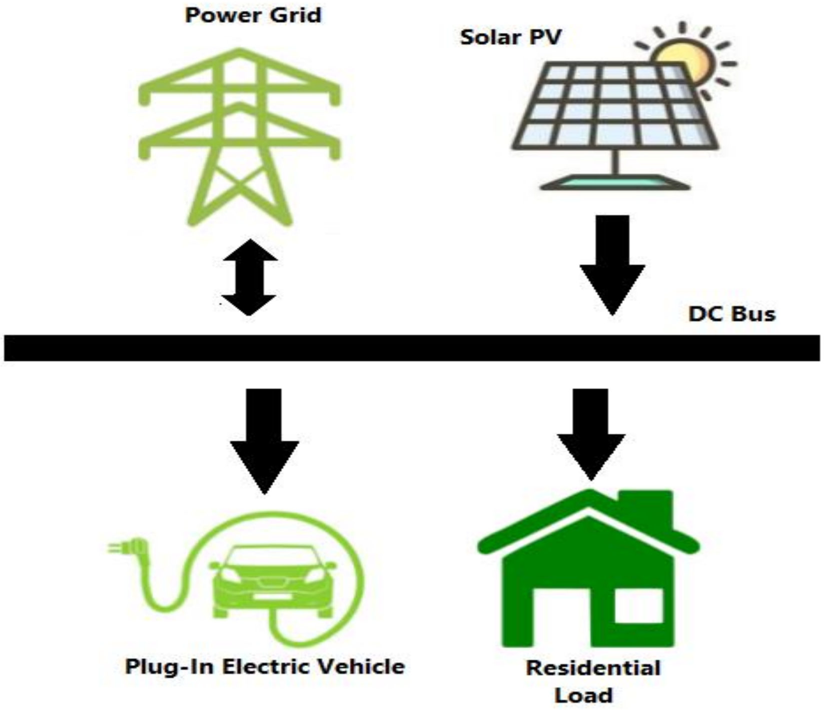

Fig. 4.1 The layout of the proposed system

The utility grid and solar PV system supply the power required to meet home load and to charge PEV. The excess PV power after meeting the load requirement is sold to the grid.

## 4.2 SOLAR PV MODELLING

The power generated by the PV panel depending on the temperature, irradiance, and area of the panel can be calculated using the equation [39] as follows;

$$P_{PV}(x) = \eta * A * 0.9 * I * \left(1 + \gamma(t_o - 25)\right) \qquad (1)$$

Where, $P_{PV}$ is the output PV power generated, η and A are the overall efficiency and area of the solar PV panels. Solar irradiation is represented as I and $t_o$ is the outdoor temperature. γ denotes the temperature coefficient of the PV module. The parameters required to determine the solar PV output power is shown in Table 4.1.

Table 4.1 Input parameter

| **Parameter** | **Value** |
|---|---|
| Maximum Power ($P_{max}$) | 330 W |
| Overall area of PV panels | 37 $m^2$ |
| Efficiency | 19.6% |
| Temperature coefficient | -.29%/°C |

## 4.3 RESIDENTIAL LOAD

A 24-hour residential load profile shown in Fig. 4.2 is used for the analysis. It depicts the energy consumption of the basic household devices in a 24-hour period []. The maximum demand of the home is 6.399 kW. The total energy consumed to meet residential load in DC nanogrid varies

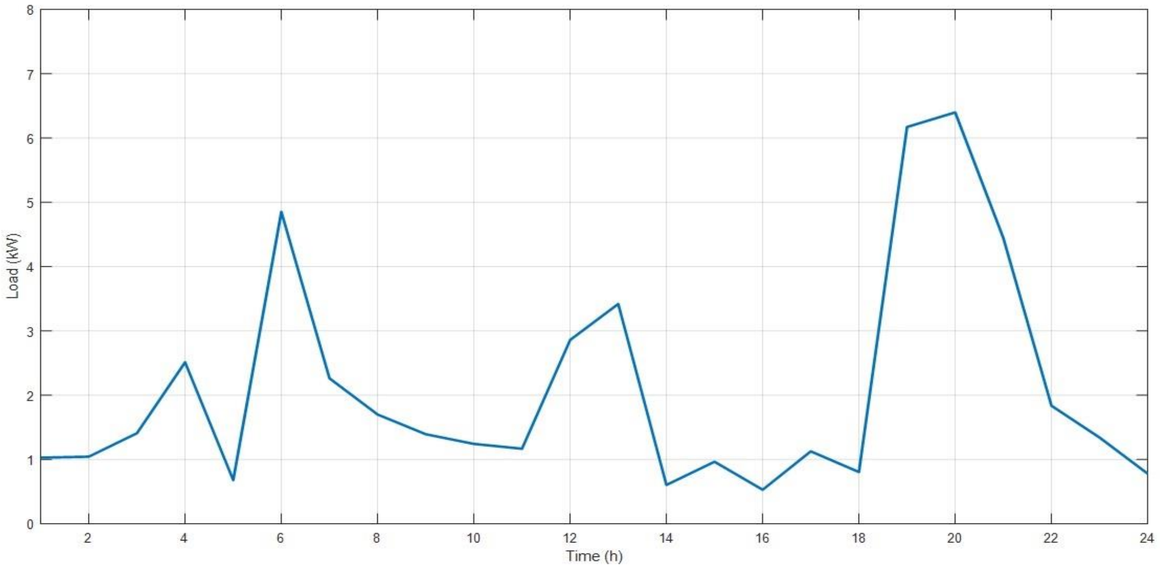

Fig. 4.2. Residential load

based on the PEV penetration.

## 4.4 TARIFF SCHEME

A ToUP tariff scheme is used for cost analysis. In this tariff scheme, each hour of a day has to be considered as a slot, and each slot has different pricing. Electricity pricing of a day is divided based on peak hours, off-peak hours, and super off-peak hours. The price of the slot can also vary according to the season [24]. In this study, ToUP scheme of the Australian Capital Territory (ACT) is used for the analysis [33].

Table 4.2. The ToUP tariff schemes of Australian Capital Territory (ACT) – Australia [33]

| **Slot** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Cost (AUS$)** | 0.1 | | | | | | 0.21 | | 0.14 | | | |

| **Slot** | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Cost (AUS$)** | 0.14 | | | | 0.21 | | | 0.14 | | | 0.1 | |

Here each hour of the day is considered as a slot. From Table 4.2, it can be seen that the tariff rate from slot 1 to slot 6 and slot 22 to slot 24 is 0.1 AUS$. Tariff rate from slot 9 to slot 16 and slot 20 to slot 21 is 0.14 AUS$. Tariff rate from slot 7 to slot 8 and slot 17 to slot 19 is 0.21 AUS$.

## 4.4 PLUG-IN ELECTRIC VEHICLE DATA

The PEV data required for the simulation studies such as vehicle entrance time, leaving time, charging power, and charging duration are shown in Table. 4.3. Three vehicles with different charging rate and charging duration are considered for the analysis. The three vehicles are denoted by the vehicle ID as PEV 1, PEV 2 and PEV 3 respectively. Real-time patterns of car parking at residences were taken into consideration while selecting the vehicle data such entry time and leaving time for scheduling.

Table 4.3. PEV data for simulation studies

| **Model** | **Vehicle ID** | **PEV entry time ($E_t$)** | **PEV leaving time ($L_t$)** | **Charging power (P) in kW** | **Duration of charging (D) in hours** |
|---|---|---|---|---|---|
| Nissan Leaf | PEV 1 | 23 | 12 | 3.6 | 11 |
| Mini Cooper SE | PEV 2 | 8 | 15 | 11 | 3 |
| Honda Fit | PEV 3 | 6 | 13 | 6.6 | 4 |

## 4.5 SUMMARY

In this chapter the various component of the system used for analysis is modelled. The output power generated by PV system for 24 hours is calculated. A residential load of 24 hour is considered for the analysis. In this work the ToUP tariff of Australian Capital Territory is taken as the pricing scheme. Charge scheduling of three PEVs were considered in this analysis. PEVs data such as entry time and leaving time were chosen based on the real-time residential parking pattern of the vehicles.

# CHAPTER 5

# RESULTS AND DISCUSSION

## 5.1 INTRODUCTION

In this section, charging of PEVs in DC nanogrid under four different cases are studied to evaluate the overall cost incurred while charging PEVs. ToUP tariff of ACT shown in Table 4.2 and PEV data shown in Table 4.3 is used for a 24-hour long analysis. In addition, a long-term analysis of PEV charge scheduling is conducted for various cases to verify the efficiency and reliability of the algorithm.

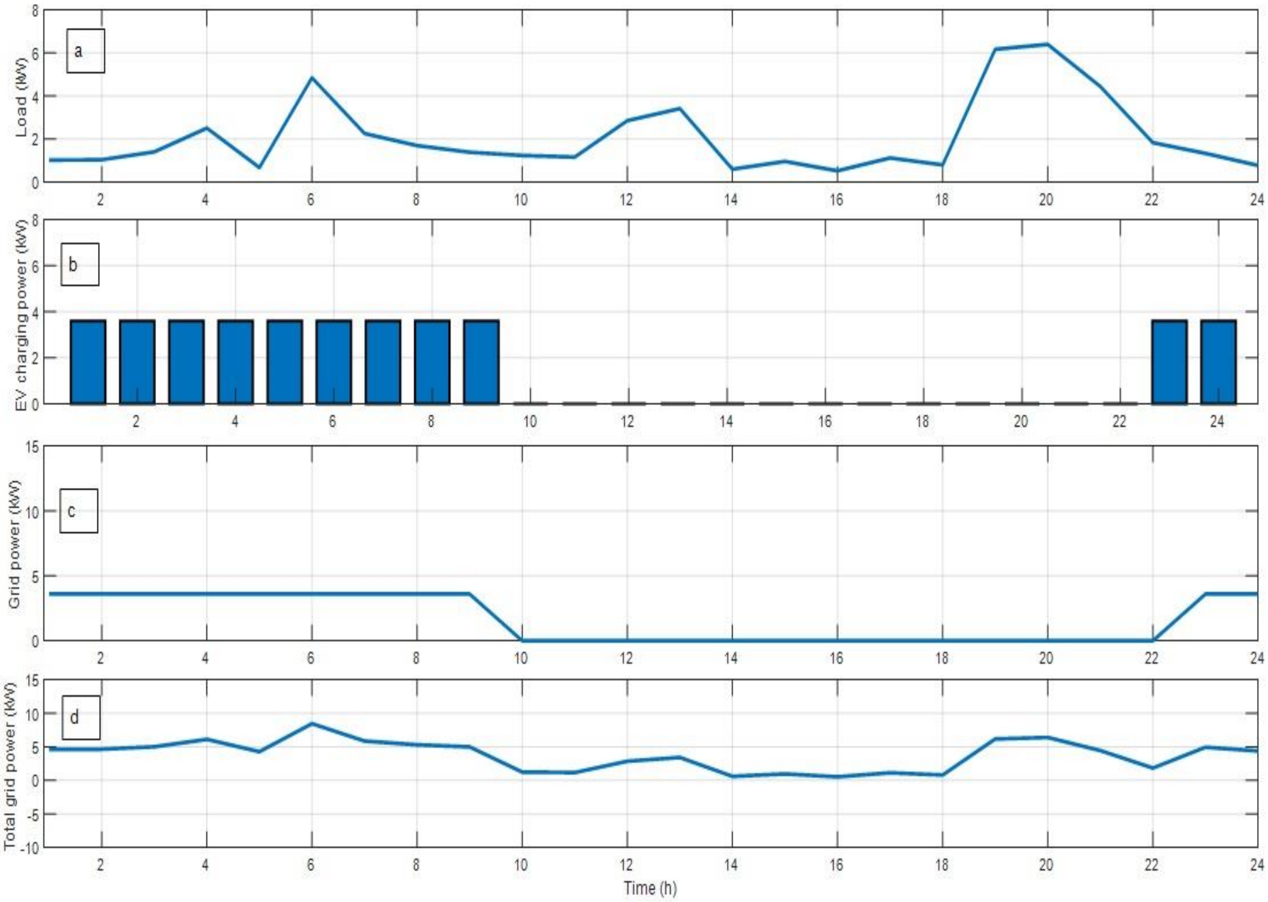

Fig. 5.1. Unscheduled charging of PEV 1 without solar PV power

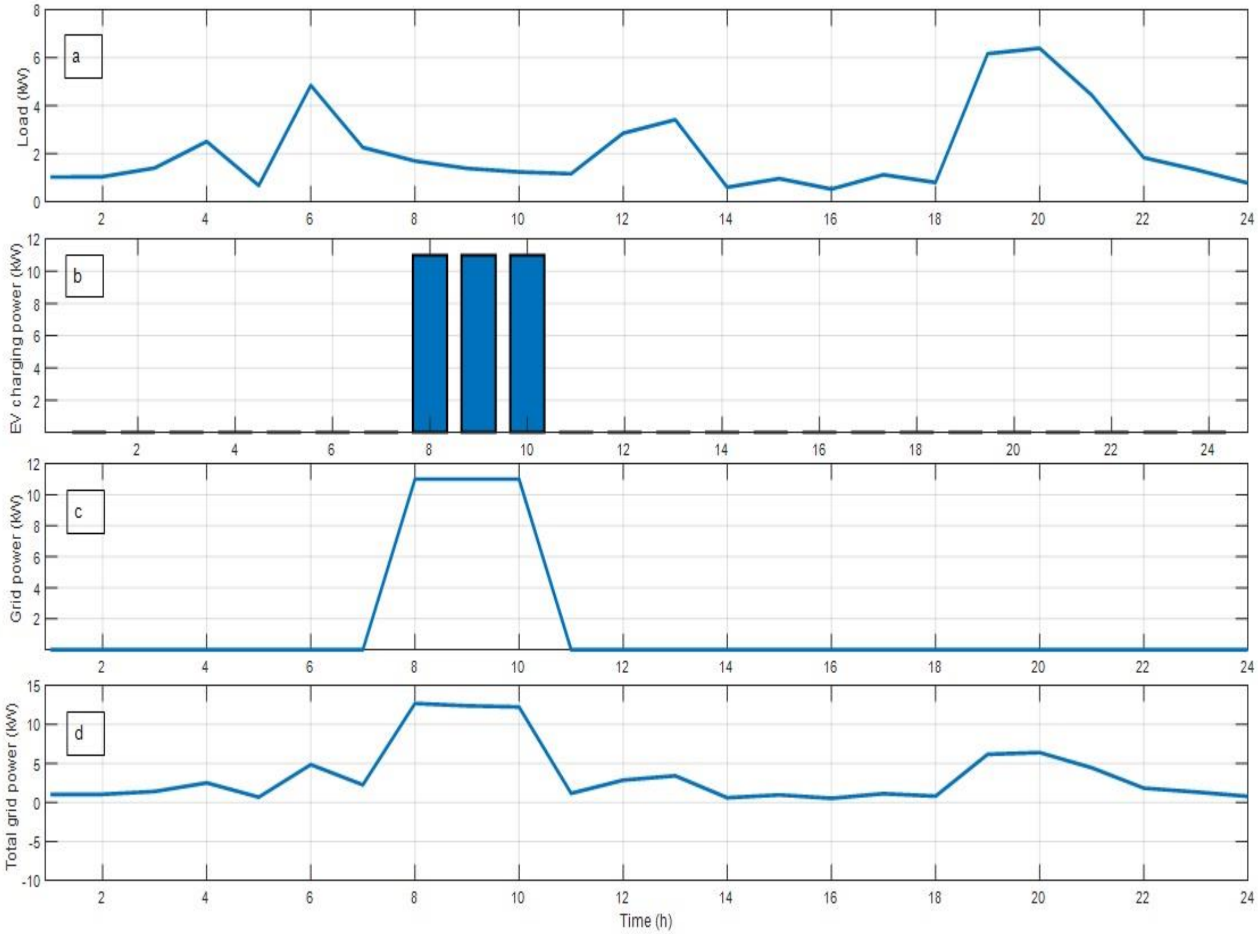

Fig. 5.2. Unscheduled charging of PEV 2 without solar PV power

## 5.2 ANALYSIS OF PEV CHARGE SCHEDULING

In order to verify the efficiency of the algorithm, four different cases namely, (i) unscheduled charging of PEV without solar PV power, (ii) unscheduled charging of PEV with solar PV power, (iii) scheduled charging of PEV withoutsolar PV power, (iv) scheduled charging of PEVs with solar PV power are analysed and charging the cost of each PEV under different cases are calculated.

### 5.2.1 Case 1 - Unscheduled Charging of PEV Without Solar PV Power

The unscheduled charging of PEV 1 without solar power in the nanogrid is shown in Fig. 5.1. The residential load is illustrated in Fig. 5.1 (a) and Fig. 5.1 (b) shows the grid power required to charge PEV 1 in the available slots between entrance time and leaving time.

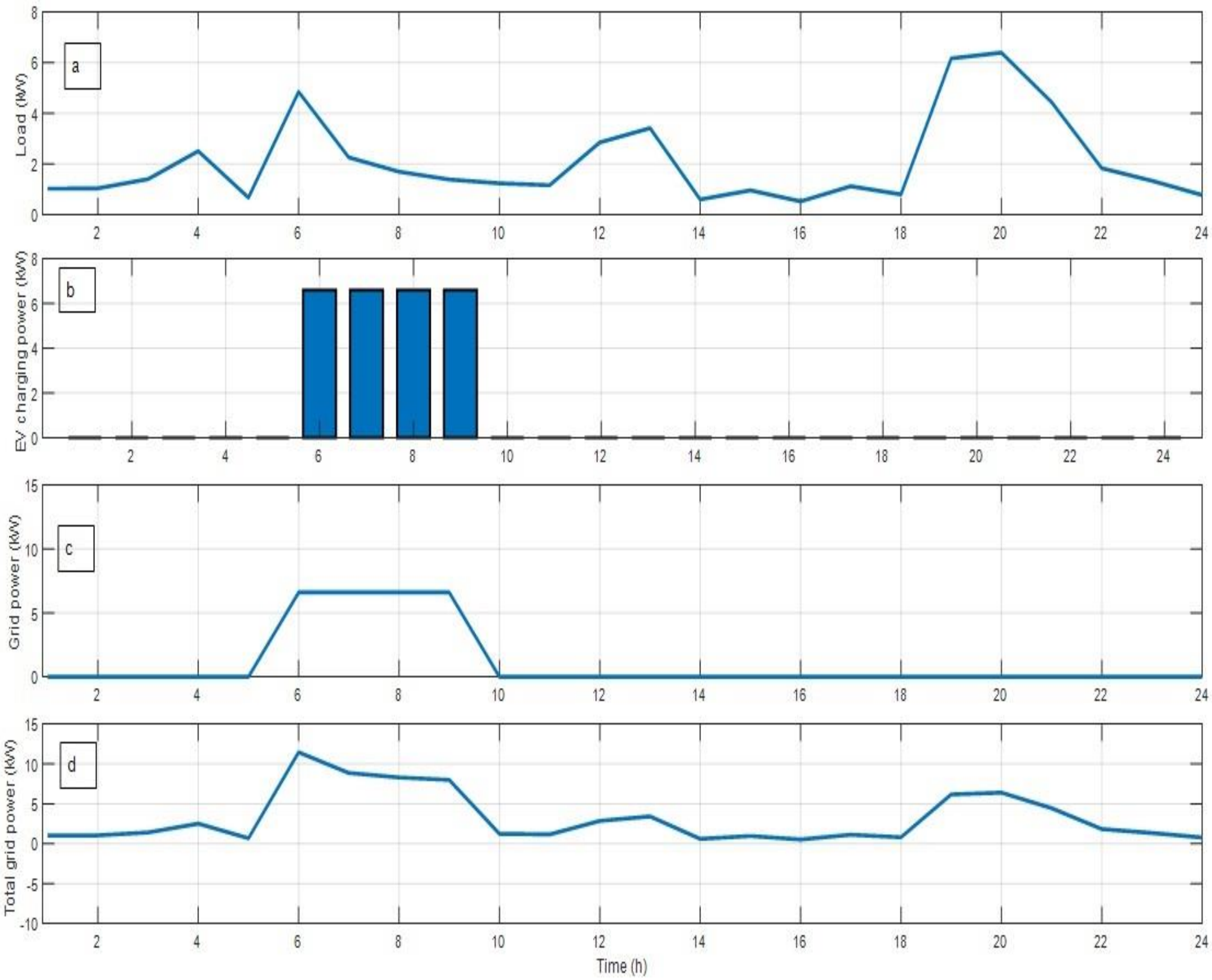

Fig. 5.3 Unscheduled charging of PEV 3 without solar PV power

In unscheduled charging, the PEV began charging at the instant it is connected to the charging unit and it continuously charges without any interruption till the required charge duration of PEV is attained. PEV 1 began charging from slot 23 to slot 9 continuously for 11 hours. The grid power used for charging PEV 1 and total power taken from the grid to meet both PEV charging demand and residential demand, are depicted in Fig. 5.1 (c) and Fig 5.1 (d) respectively. The cost incurred for charging PEV 1 in this case is 4.8960 AUS$. Charging of PEV 2 using an unscheduled algorithm without solar PV power is shown in Fig. 5.2. The charging rate of PEV 2 in available slots is illustrated in Fig. 5.2 (b). PEV 2 begins charging immediately after it is connected to the charging point from slot 7 to slot 9 continuously for a charge duration of 3 hours. Fig. 5.2 (c) depicts the grid power used to charge PEV 2 and Fig. 5.2 (d) shows the total power taken from the

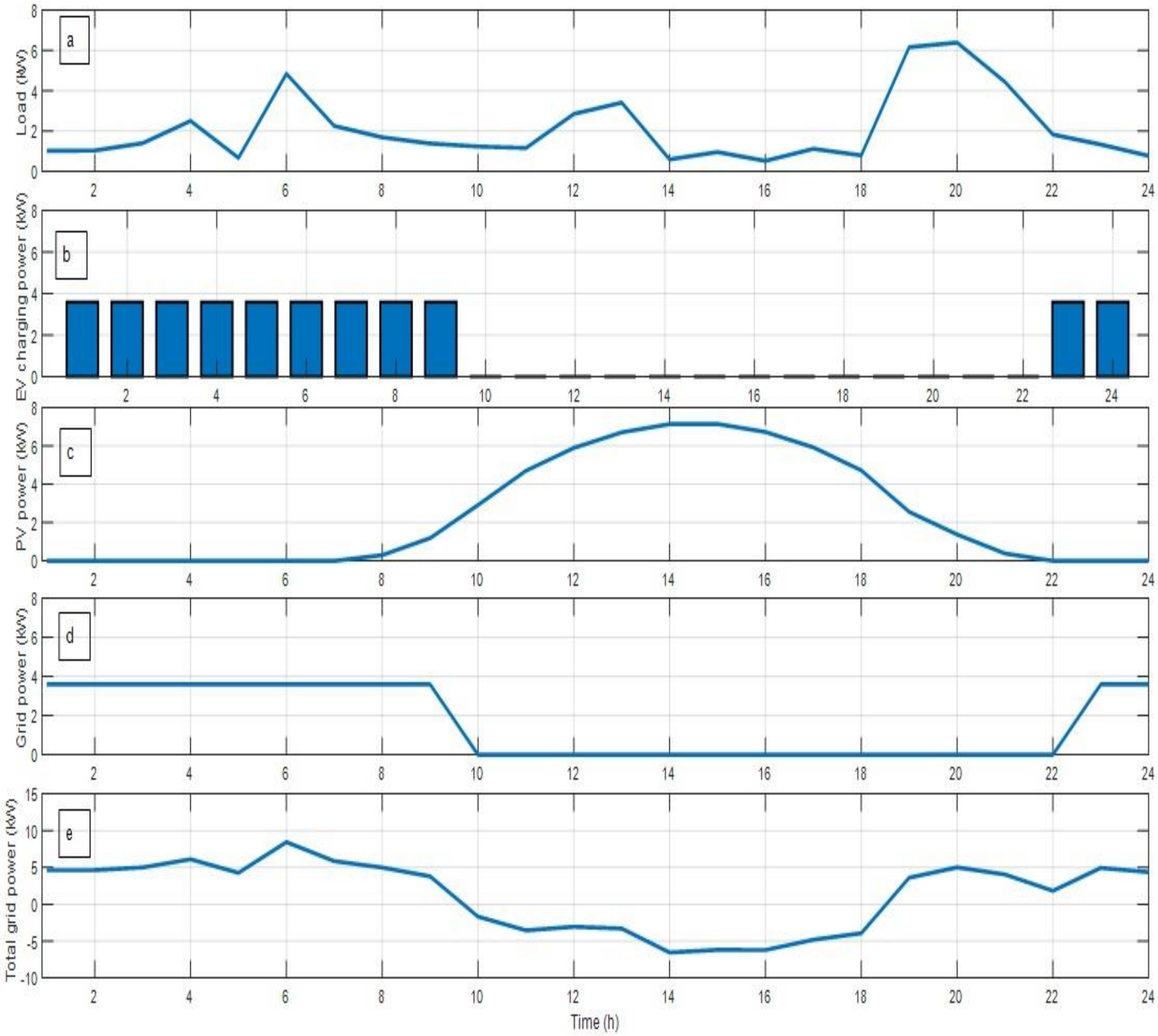

Fig. 5.4. Unscheduled charging of PEV 1 with solar PV power

grid to charge PEV 2 and to meet residential demand. The charging cost of PEV 2, in this case is 5.3900 AUS$. The unscheduled charging of PEV 3 without solar PV power is shown in Fig. 5.3. The charging power of PEV 3 is depicted in Fig. 5.3 (b). PEV 3 initiate the charging at the instant it is plugged-in. is charged from slot 6 to slot 9 continuously for 4 hours. The grid power required to charge PEV and the total grid power required to meet total demand which includes both PEV and residential demand are shown in Fig. 5.3 (c) and Fig. 5.3 (d) respectively. The cost of charging PEV 3 is 4.3560 AUS$.

### 5.2.2 Case 2 - Unscheduled Charging of PEV With Solar PV Power

Fig. 5.4 illustrates the unscheduled charging of PEV 1 in with solar PV power. The residential load demand and generated PV power are depicted in Fig. 5.4 (a) and Fig 5.4 (c) respectively.

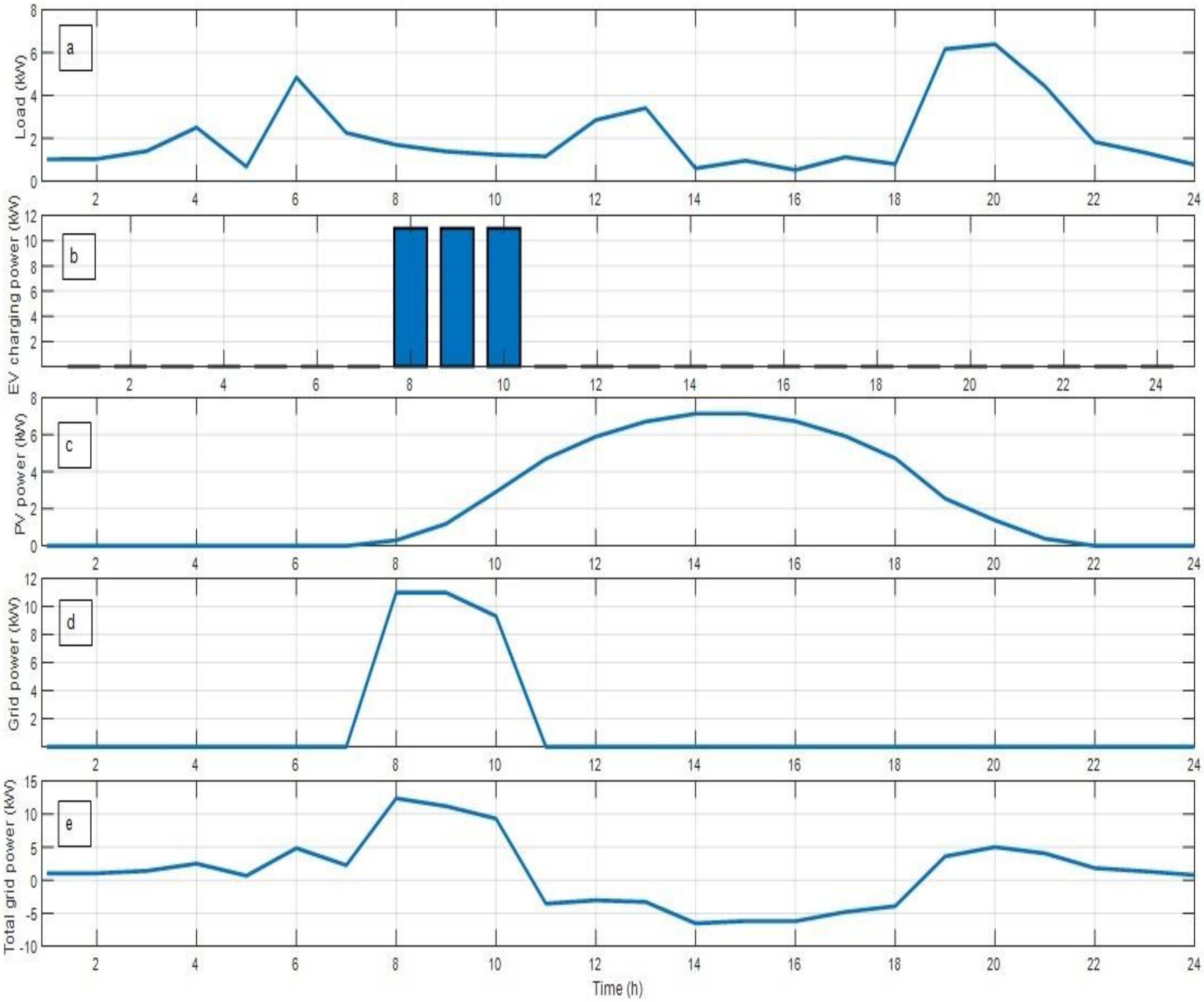

Fig. 5.5. Unscheduled charging of PEV 2 with solar PV power

The maximum output power produced by the solar PV system using the equation (1) considering the chosen parameter for a specific day is 7.260 kW, which is meant to meet the residential load and PEV charging demand. The PV power available after meeting the demand is sold to grid. Fig. 5.4 (b) shows the power required to charge PEV 1 in the available slots between entrance time and leaving time. PEV 1 began the charging process from slot 23 to slot 9 continuously for 11 hours.

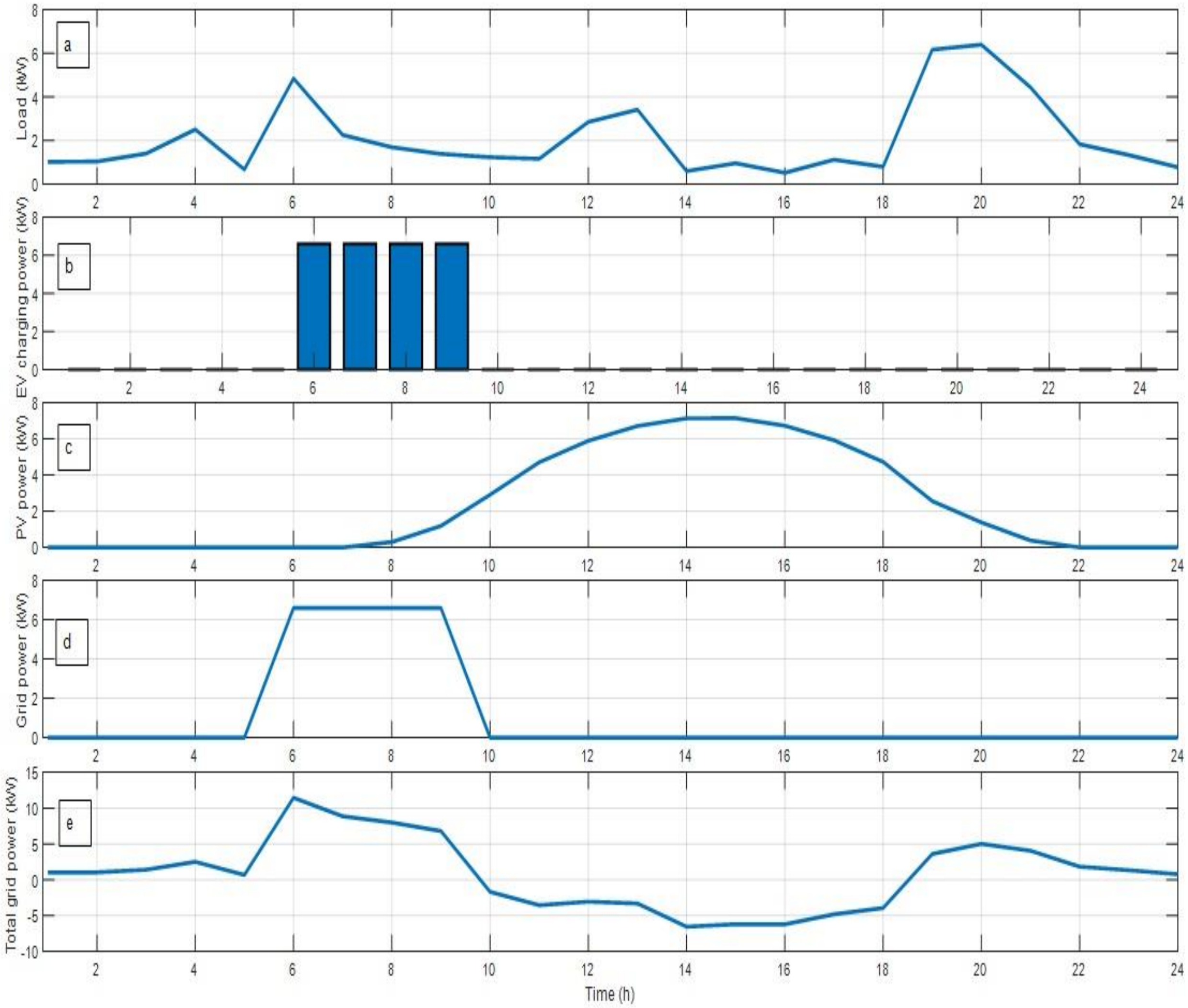

Fig. 5.6. Unscheduled charging of PEV 3 with solar PV power

The grid power required for charging PEV 1, in this case is illustrated in Fig. 5.4 (d) and the total grid power required to meet both residential demand and PEV demand is depicted in Fig. 5.4 (e). The charging cost incurred for PEV 1 using the unscheduled algorithm is 4.8960 AUS$. Unscheduled charging of PEV 2 with solar power is illustrated in Fig. 5.5. The power required to charge PEV 2 is shown in Fig. 5.5 (b), where PEV 2 began charging from the slot 12 immediately after it is connected for charging and continue to charge till slot 14 for a charge duration of 3 hours. PEV 2 uses both PV power and grid power for charging at a rate of 11 kW. Power taken from the grid for charging PEV 2 and generated PV power are depicted in Fig. 5.5 (d) and Fig. 5.5 (c) respectively. In this case, the charging cost of PEV 2 is 5.1555 AUS$. Similarly, the unscheduled

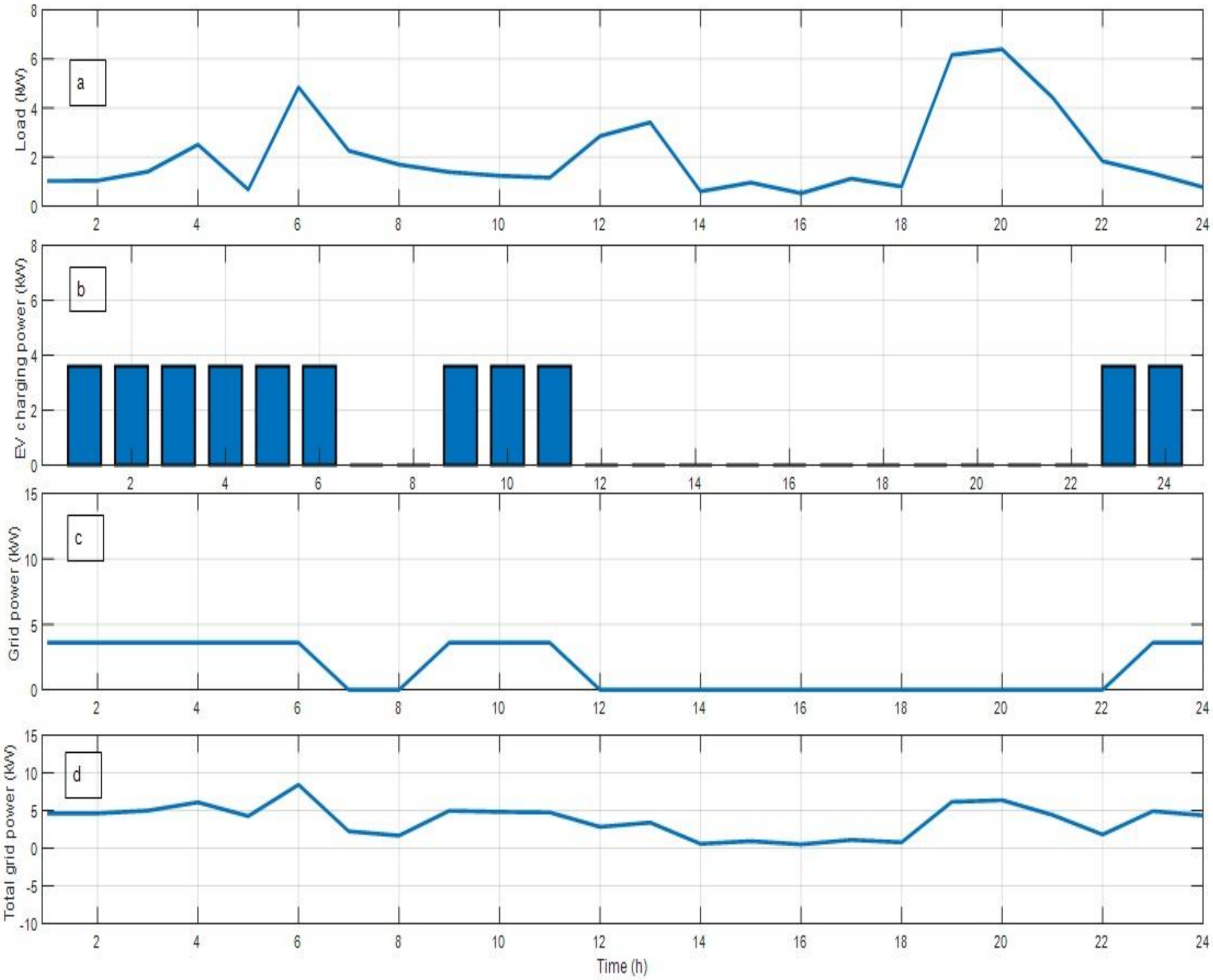

Fig. 5.7. Scheduled charging of PEV 1 without solar PV power

charging of PEV3 with solar PV power is shown in Fig. 5.6. Fig. 5.6 (b) shows the power required to charge PEV at a charging rate of 6.6 kW. From Fig. 5.6 (b) it can be seen that PEV 3 begins charge scheduling from slot 6 to slot 9 for a charge duration of 4 hours. Generated PV power and grid power required to charge PEV are shown in Fig. 5.6 (d) and Fig. 5.6 (c) respectively. Fig. 5.6 (e) illustrates the total grid power utilized for load and PEV 3. The charging cost of PEV 3 using an unscheduled algorithm with PV power is 4.3560 AUS$.

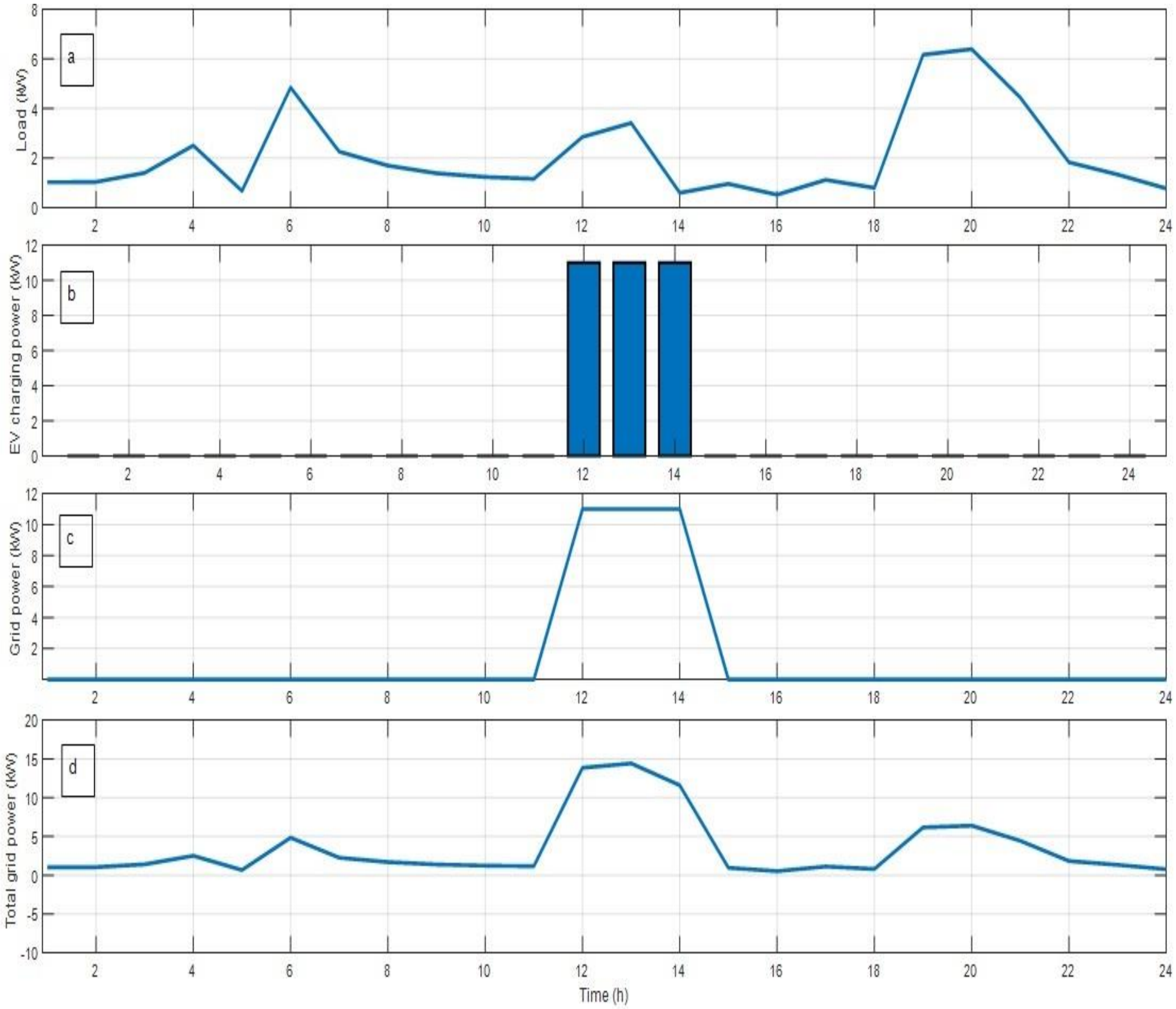

Fig. 5.8. Scheduled charging of PEV 2 without solar PV power

### 5.2.3 Case 3 - Scheduled Charging of PEV Without Solar PV Power

The scheduled charging of PEV 1 without solar PV power is shown in Fig. 5.7. Fig. 5.7 (b) depicts the power required to charge PEV 1 at the scheduled slot at a charging rate of 3.6 kW. The charging of PEV is scheduled in such a way that the charging process interrupts during the peak hours based on the ToUP tariff so that the charging cost and grid demand can be minimized. PEV 1 is scheduled to charge from slot 23 and interrupted at the of slot 6 and then begins the charging from slot 9 to slot 11. Here grid power is solely used for the PEV charging process and to satisfy the load demand. The residential load profile and grid power required for charging PEV 2 are shown in Fig. 5.7 (a)

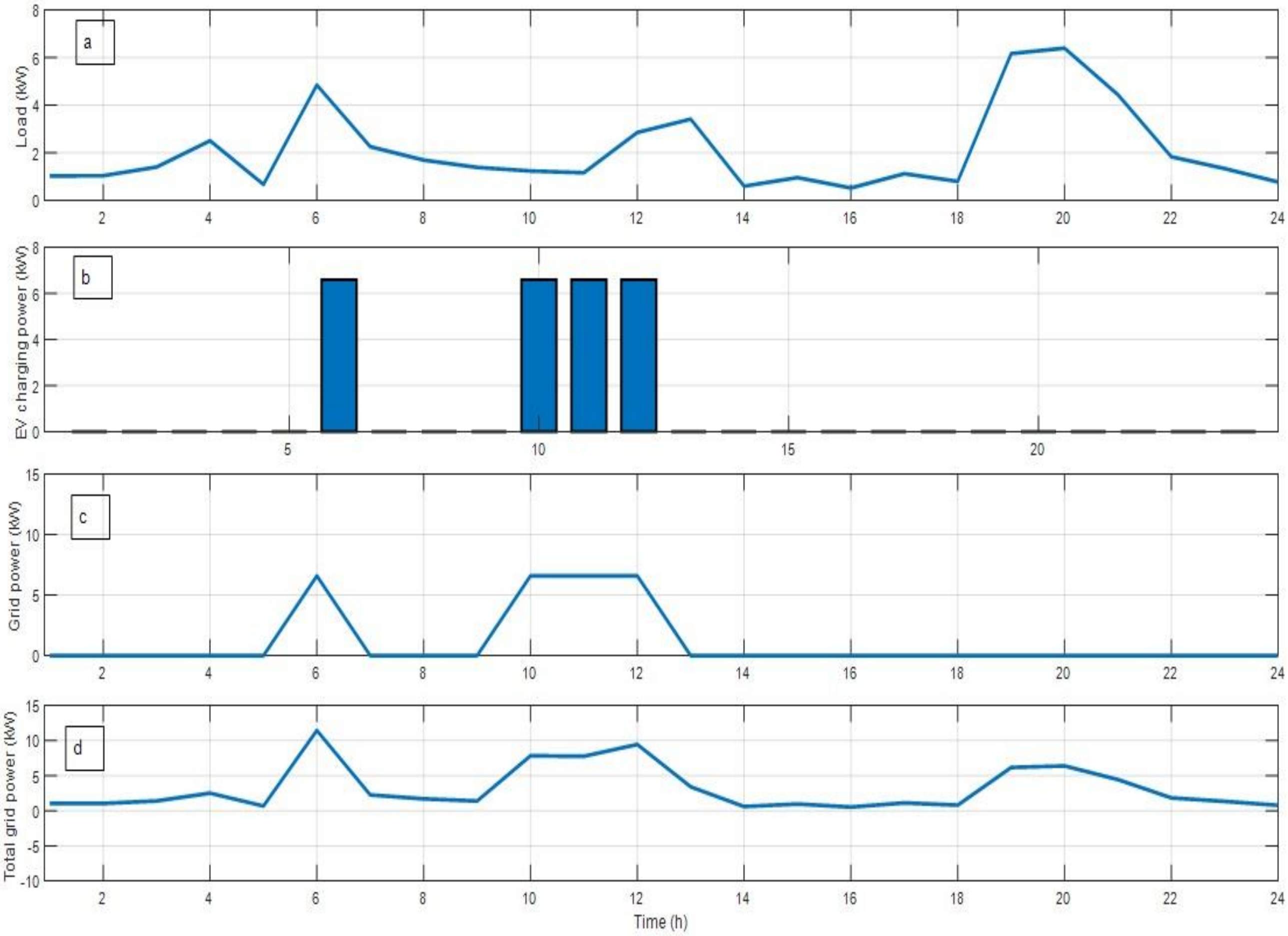

Fig. 5.9. Scheduled charging of PEV 3 without solar PV power

and Fig. 5.7 (c) respectively. Total grid power consumed is shown in Fig. 5.7 (d). The cost incurred for charging PEV 1 using the scheduled algorithm without PV power is 4.3920 AUS$. The charge scheduling of PEV 2 in DC nanogrid without a solar PV system is depicted in Fig. 5.8. Fig. 5.8 (b) shows the power required to charge PEV 2 at the scheduled slot at a charging rate of 11 kW. From Fig. 5.8 (b) it can be seen that PEV 2 is scheduled to charge from slot 14 to slot 16. Fig. 5.8 (c) shows the grid power required to charge a PEV and Fig. 5.8 (d) shows the power taken from the grid to satisfy the residential load and PEV charging power. The cost of charging PEV 2 using a schedule without PV power is 4.6200 AUS$, which is high compared to the previous case. Charge scheduling of PEV 3 without PV power is illustrated in Fig. 5.9. Fig. 5.9 (b) shows the power required to charge PEV 3 at the scheduled slot at a charging rate of 6.6 kW. PEV 3 begins charging from slot 6 and it is interrupted at the end of slot 6. Then again initiate the process from slot 10 to slot 12. The charging cost has been increased to 3.4320 AUS$. The grid power required for charging PEV 3 and total grid power is shown in Fig. 5.9 (c) and Fig. 5.9 (d).

### 5.2.4 Case 4 - Scheduled Charging of PEV With Solar PV POWER

The scheduled charging of PEV 1 in DC nanogrid with solar PV power is shown in Fig. 5.10. The residential load profile and generated solar PV power are shown in Fig. 5.10 (a) and Fig. 5.10 (c) respectively.

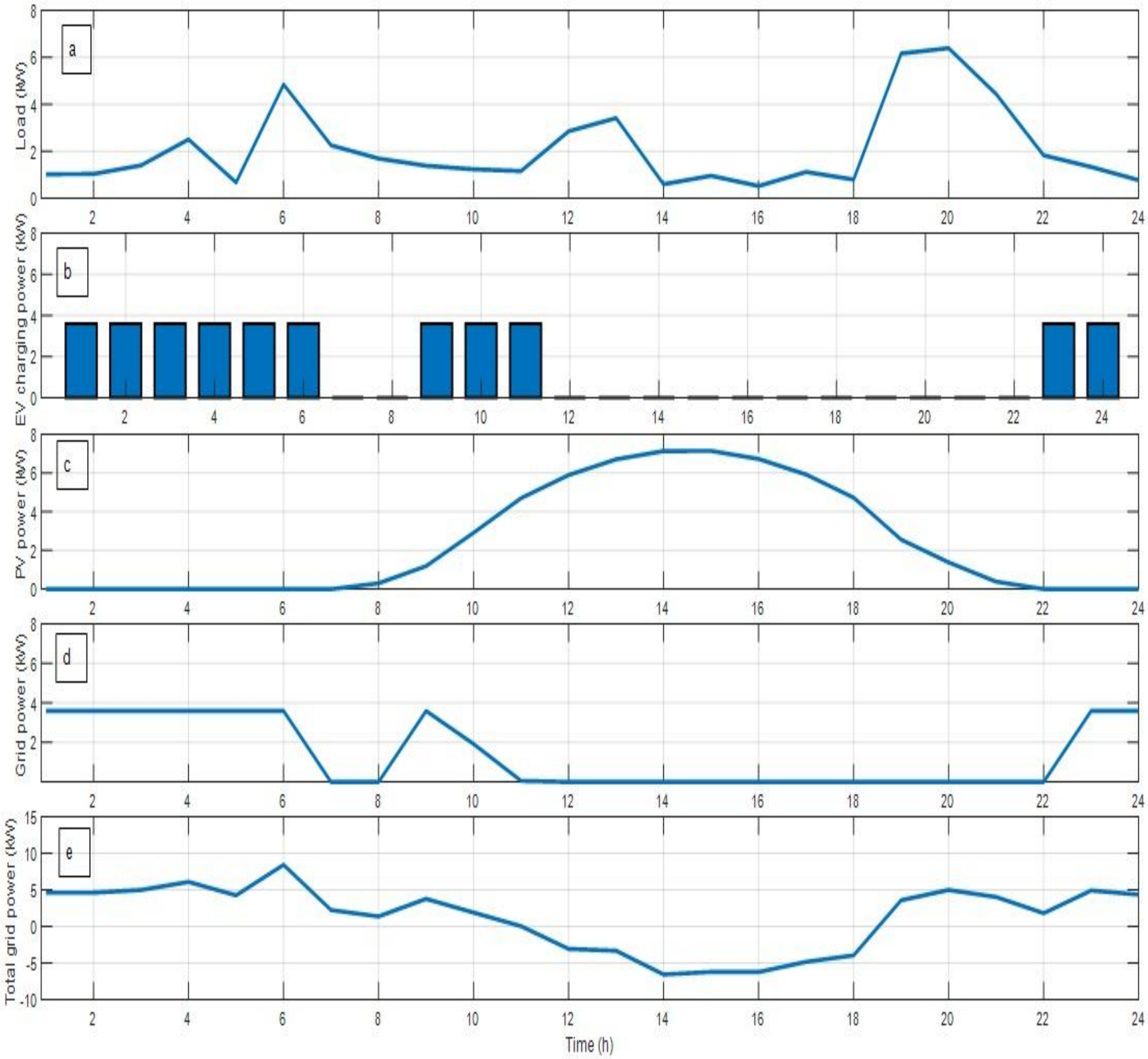

Fig. 5.10 Scheduled charging of PEV 1 with solar PV power

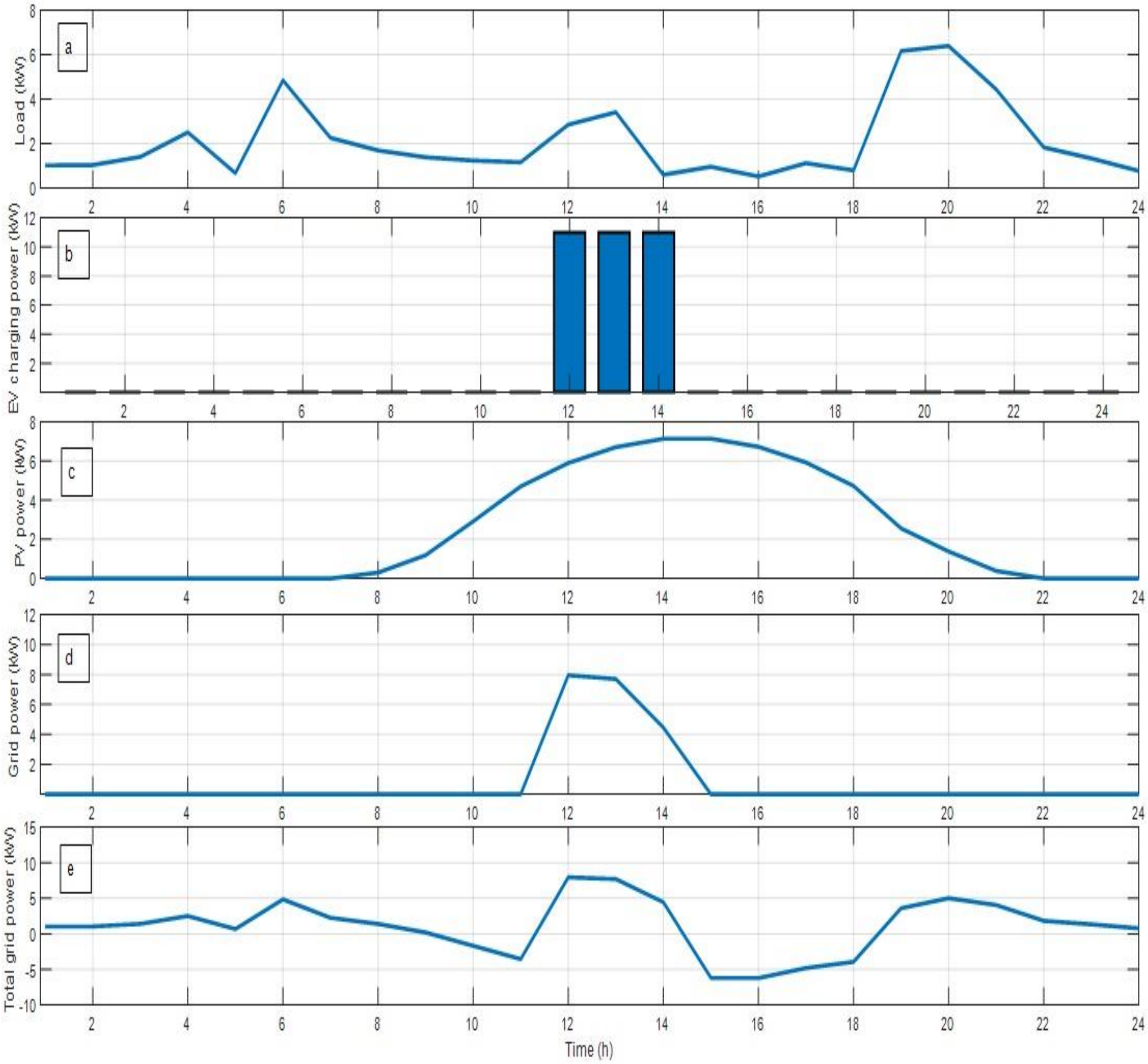

Fig. 5.11. Scheduled charging of PEV 2 with solar PV power

Here the charge scheduling of PEVs are similar to the above case. The charging of PEV 1 is scheduled in such a way that the charging process interrupts during the peak hours based on the ToUP tariff so that the charging cost and grid demand can be minimized. Fig. 5.10 (b) shows the power required to charge PEV 1 at the scheduled slot with a charging rate of 3.6 kW. PEV 1 is scheduled to charge from slot 23 and continue the charging process to the next day. The charging is interrupted at the end of slot 6 and again initiated from slot 9 to slot 11. The PV power available after meeting the residential load demand is used for charging PEV and grid power is used for

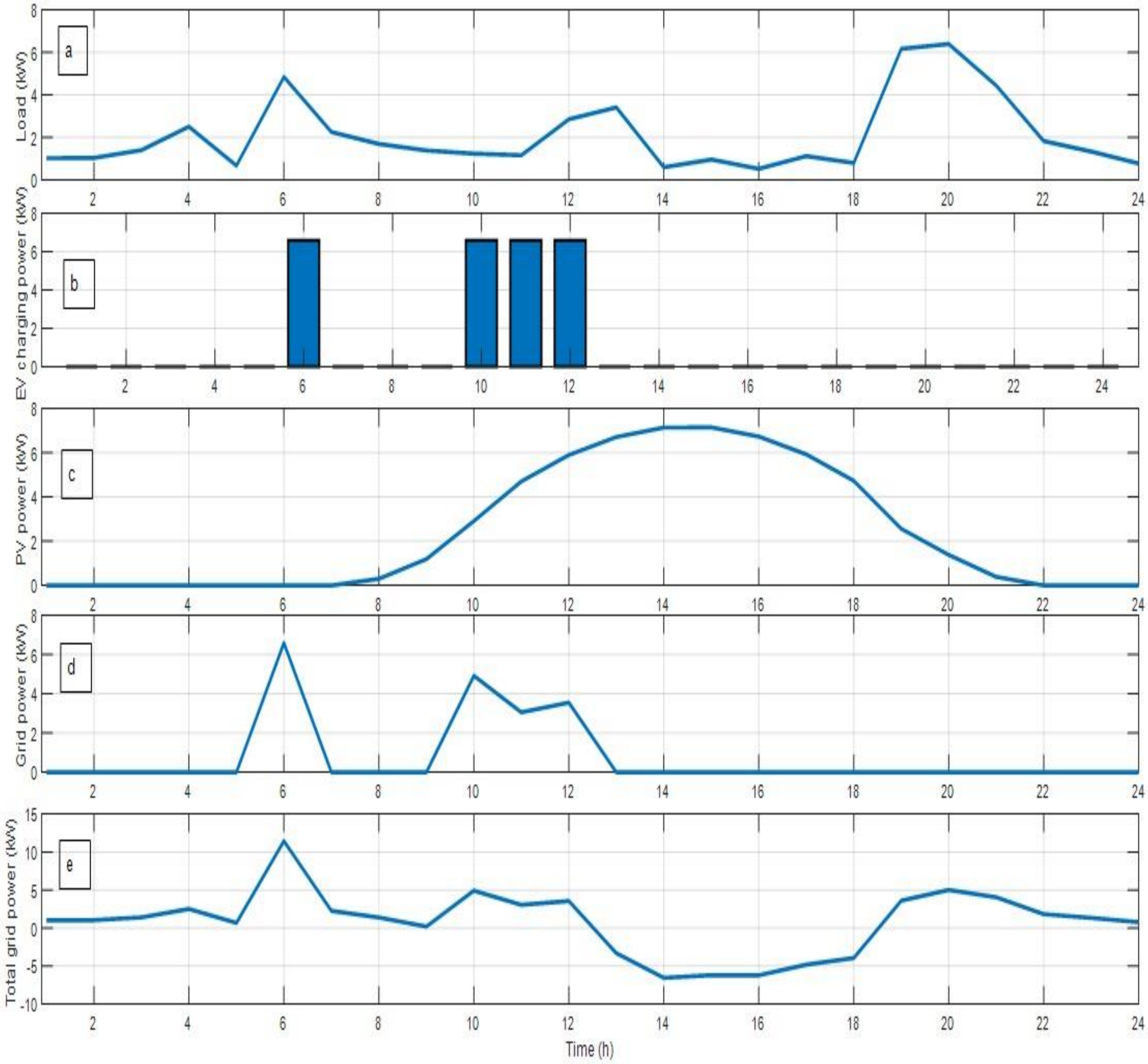

Fig. 5.12. Scheduled charging of PEV 3 with solar PV power

charging PEV when PV power is not available. The grid power required to charge PEV 1 is depicted in Fig. 5.10 (d) and the total grid power required for both residential load and PEV 1 is shown in Fig. 5.10 (e). The negative power in the Fig. 5.10 (e) represents the excess power supplied to the grid. In this case, the charging cost for PEV 1 is 3.6618 AUS$. The scheduled charging of PEV 2 in DC nanogrid with solar PV power is shown in Fig. 5.11. Fig. 5.11 (b) illustrates the power required to charge PEV 2 at the scheduled slot. The charging rate of PEV 2 is 11 kW. PEV2 is scheduled to charge from slot 14 to slot 16 for a required charge duration of 3 hours. Charging

Table 5.1. Charging cost of PEVs

| **Vehicle ID** | **PEV 1 (in AUS$)** | **PEV 2 (in AUS$)** | **PEV 3 (in AUS$)** |
|---|---|---|---|
| Unscheduled Charging of PEV without solar PV power | 4.8960 | 5.3900 | 4.3560 |
| Unscheduled Charging of PEV with solar PV power | 4.8960 | 5.1555 | 4.3560 |
| Scheduled charging of PEV without solar PV power | 4.3920 | 4.6200 | 3.4320 |
| Scheduled charging of PEV with solar PV power | 3.6618 | 2.8168 | 2.2757 |

of PEV 2 depends on both grid power and PV power. When the solar PV power is not sufficient for charging, PEV charges from the grid. Fig. 5.11 (c) and Fig. 5.11 (d) depict the generated PV power and grid power are required for charging PEV 2 respectively. The total power consumed from the grid to charge PEV 2 and to meet the residential load demand is shown in Fig. 5.11 (e). The cost incurred for charging PEV 2 using the scheduled algorithm with solar PV power is 2.8168 AUS$. Similarly, the charge scheduling of PEV 3 with solar PV power is shown in Fig. 5.12. Fig. 5.12 (b) shows the power required to charge PEV 3 the at scheduled slot with a charging rate of 6.6 kW. From Fig. 5.12 (b) it can be seen that charging of PEV 3 is started from slot 6 and interrupt at the slots where charging cost is high and again initiate the charging from slot 10 to slot 12. Residential load profile and generated solar PV power are illustrated in Fig. 5.12 (a) and Fig. 5.12 (c) respectively. Fig. 5.12 (e) shows the total grid power required to meet both residential demand and PEV 3 charging demand when PV power is not available. The cost incurred for charging PEV 3 using charge scheduling algorithm with solar PV power is 2.2757 AUS$. From Table 5.1, it can be seen that the charging cost of PEVs are minimum during scheduled charging of PEV utilizing solar PV power compared to all other cases. In that case, the scheduling algorithm schedules the charging of PEV only on the slot with minimum cost. The available solar PV power after meeting the residential demand is used for PEV charging and thus, the charging cost of PEVs are reduced.

Table 5.2. Total cost of energy consumed

| **PEV charging cases** | **Total cost during unscheduled charging of PEV without solar PV power (in AUS$)** | **Total cost during unscheduled charging of PEV with solar PV power (in AUS$)** | **Total cost during scheduled charging of PEV without solar PV power (in AUS$)** | **Total cost during scheduled charging of PEV with solar PV power (in AUS$)** |
|---|---|---|---|---|
| PEV 1 | 12.2056 | 9.2704 | 11.7016 | 8.0362 |
| PEV 2 | 126996 | 9.5299 | 11.9296 | 7.1912 |
| PEV 3 | 11.6656 | 8.7304 | 10.7416 | 6.6501 |

The unscheduled PEV charging without using solar PV power has the highest charging cost since PEVs are charged in an uncontrolled manner. The total energy consumed from the grid to meet the residential load and PEV demand is minimum while solar PV power is integrated compared to other cases. This implies that the integration of renewable energy sources can reduce the demand on grid and minimize the overall cost of energy consumed. Table. 5.2 shows the overall cost of energy consumed in the DC nanogrid under different cases. The results of 24-hour long analysis show that the total cost of energy consumed is less during the scheduled charging of PEV using solar PV power. The charge scheduling algorithm shifts the charging of PEV from peak hours to off-peak and super off-peak hours based on the tariff scheme, so that the PEV can be charged at a minimum tariff, and thereby the cost of energy taken from the grid can be reduced. Integration of solar PV power to meet residential and PEV charging demand can reduce the load on the grid and thus, overall charging cost of the system can further be minimized. Unscheduled charging of PEV without using solar PV power has maximum charging cost compared to all other cases. These results validate that the charging scheduling algorithm presented in this paper is very effective and provide reliable charging operation.

## 5.3 LONG TERM ANALYSIS

To evaluate and verify the efficacy of the algorithm, two months long analysis of charging PEV in DC nanogrid were carried out under different cases. In order to conduct the analysis various parameters such as vehicle entrance time, leaving time, charge duration and charge rate of three PEVs over 61 days were considered.

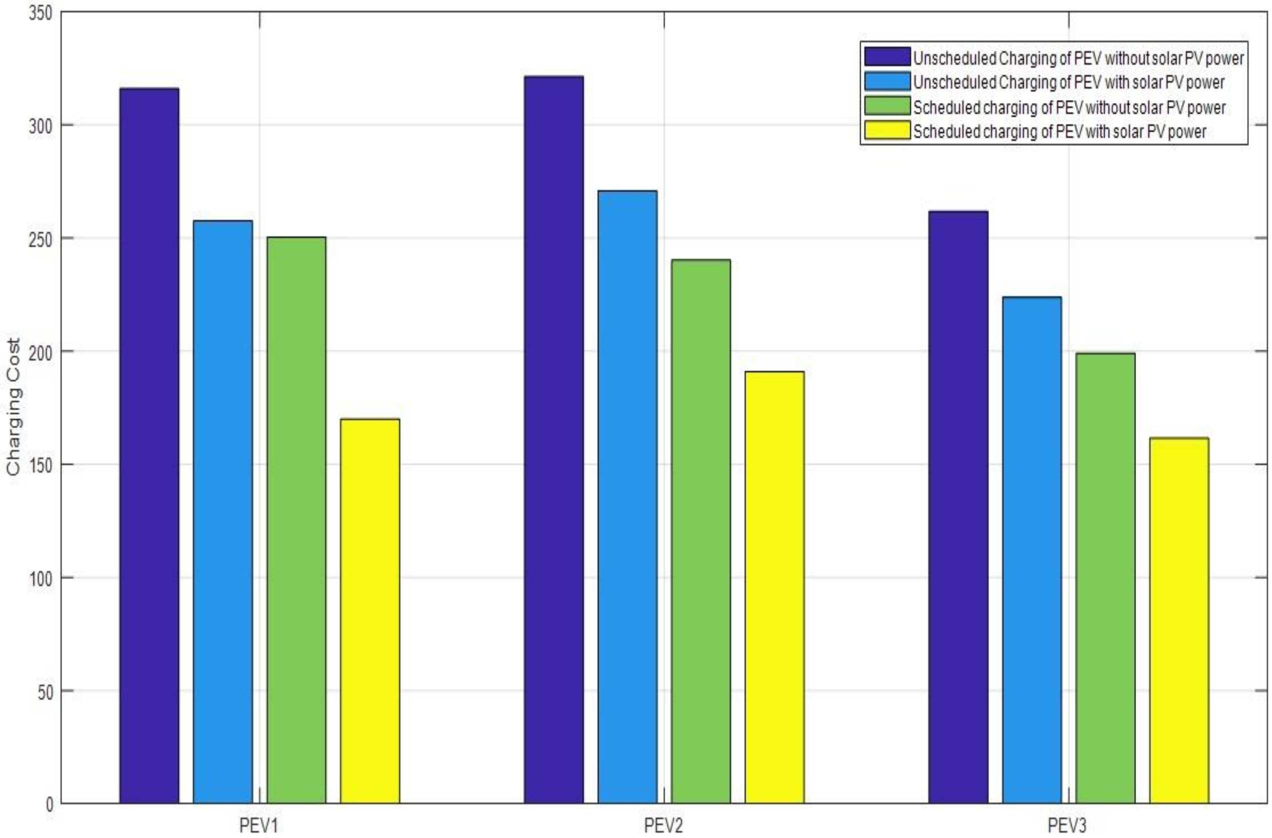

Fig. 5.13. Total charging cost of PEVs under different cases

Real-time patterns of car parking at residences were taken into consideration while selecting vehicle data for scheduling. A thorough comparison between unscheduled PEV charging without solar PV power, unscheduled PEV charging with solar PV power, scheduled PEV charging without solar PV power and scheduled PEV charging with solar PV power were conducted for different PEV to analyse the feasibility and efficiency of the proposed algorithm. The total charging cost of three PEVs for 61 days under different cases are shown in Fig. 5.13. In the case, unscheduled PEV charging without solar PV power. PEVs began charging at the instant it is connected to the charging provision. The total charging cost of PEV1, PEV2 and PEV3 under unscheduled charging

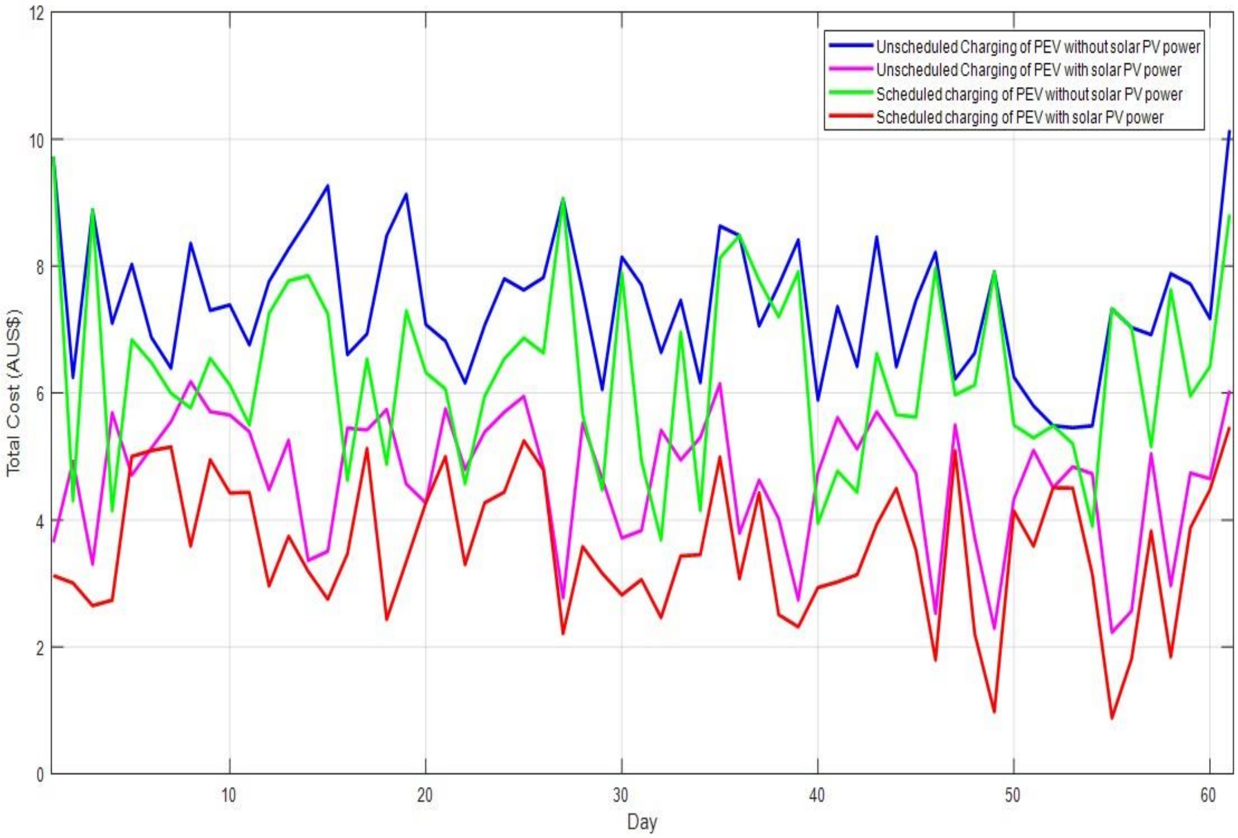

Fig. 5.14. Daily cost of energy consumed while charging PEV 1

condition scenario without solar PV power are 316.0080 AUS$, 321.4200 AUS$ and 261.7560AUS$ respectively. Similarly, for unscheduled charging with solar PV power, PEVs begin charging at the instant it is plugged-in. Since solar PV power is available for PEV charging, the power from the grid required to charge PEV is minimized and thereby, the charging cost of PEV is reduced compared to the former case. The charging cost of PEV1, PEV2, and PEV3 during unscheduled charging of PEVs with solar PV power is 257.5466 AUS$, 270.8023 AUS$ and 223.8611 AUS$ respectively. In scheduled charging technique, PEVs are allowed to charge only on the selected slot with minimum charging price between the entrance and leaving time of the vehicle and thereby, decrease the overall charging cost of PEVs. The charging cost of PEV1, PEV 2 and PEV 3 under scheduled charging condition without solar PV power are 250.3800 AUS$, 240.2400 AUS$ and 199.0560 AUS$ respectively. The charging cost of PEVs are further reduced by using charge scheduling algorithm with solar PV power. The charging cost of PEV1, PEV2 and

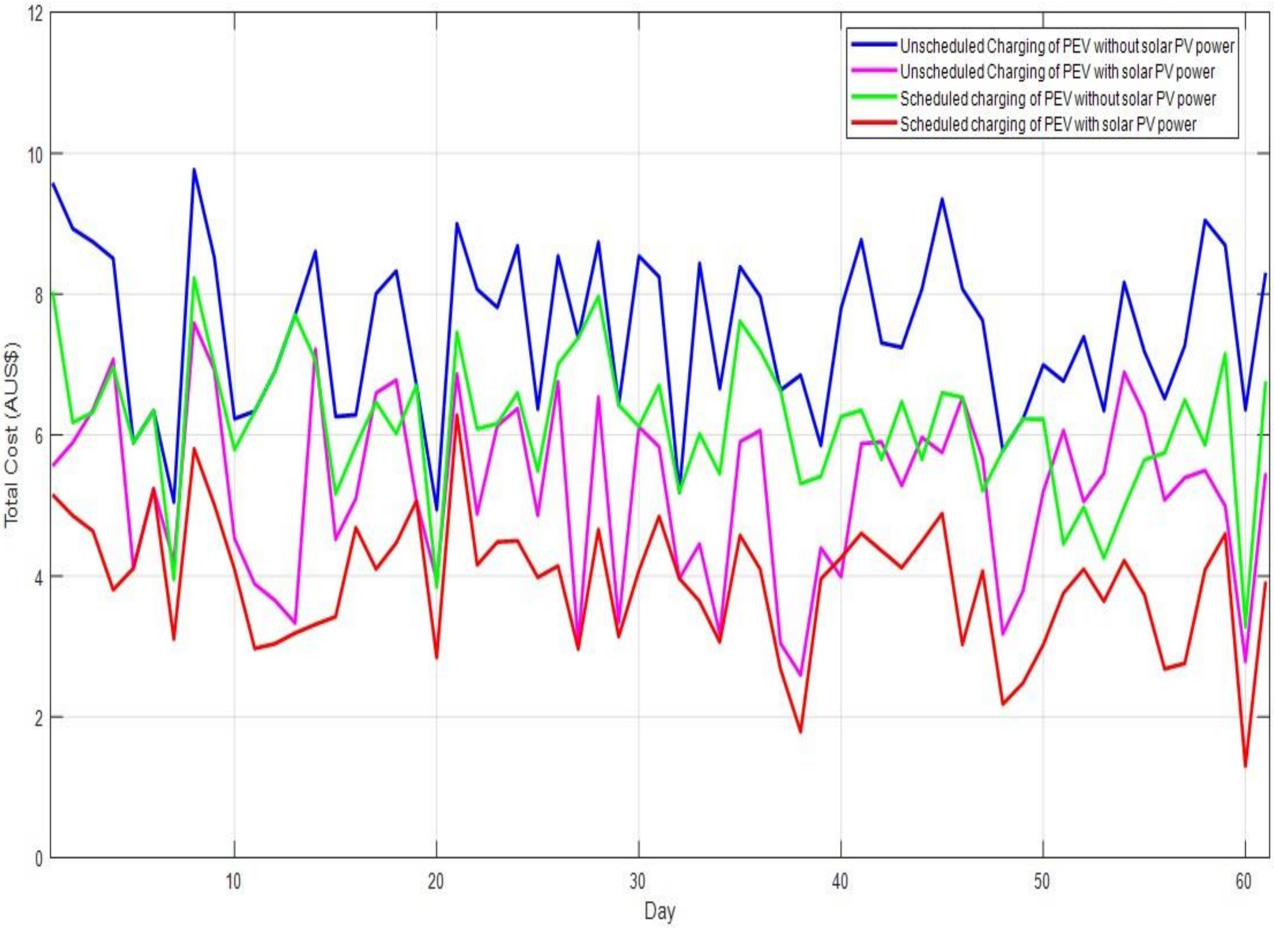

Fig. 5.15. Daily cost of energy consumed while charging PEV 2

PEV3 during scheduled charging condition with solar PV power are 169.9683 AUS$, 190.9828 AUS$ and 161.5517 AUS$ respectively. Fig. 5.14 shows the daily cost of energy consumed to meet PEV and residential demand. The daily cost of energy consumed is least while using scheduling algorithm to charge PEV 1 using solar PV power. However, the total cost of energy consumed to meet residential load and PEV demand is maximum while using unscheduled algorithm. Similarly, Fig. 5.15 and Fig. 5.16 shows the daily cost of energy consumed while charging PEV 2 and PEV 3 under four different cases. The daily cost of energy consumption while charging PEV 2 and PEV 3 is lower when PEVs are charged using scheduled algorithm with solar PV power compared to other cases based on the vehicle data and the chosen pricing schemes. Table 5.2 shows the total cost of energy consumed to meet home load and PEV demand for two months. The results show that the proposed algorithm for scheduling the charging of PEV in DC

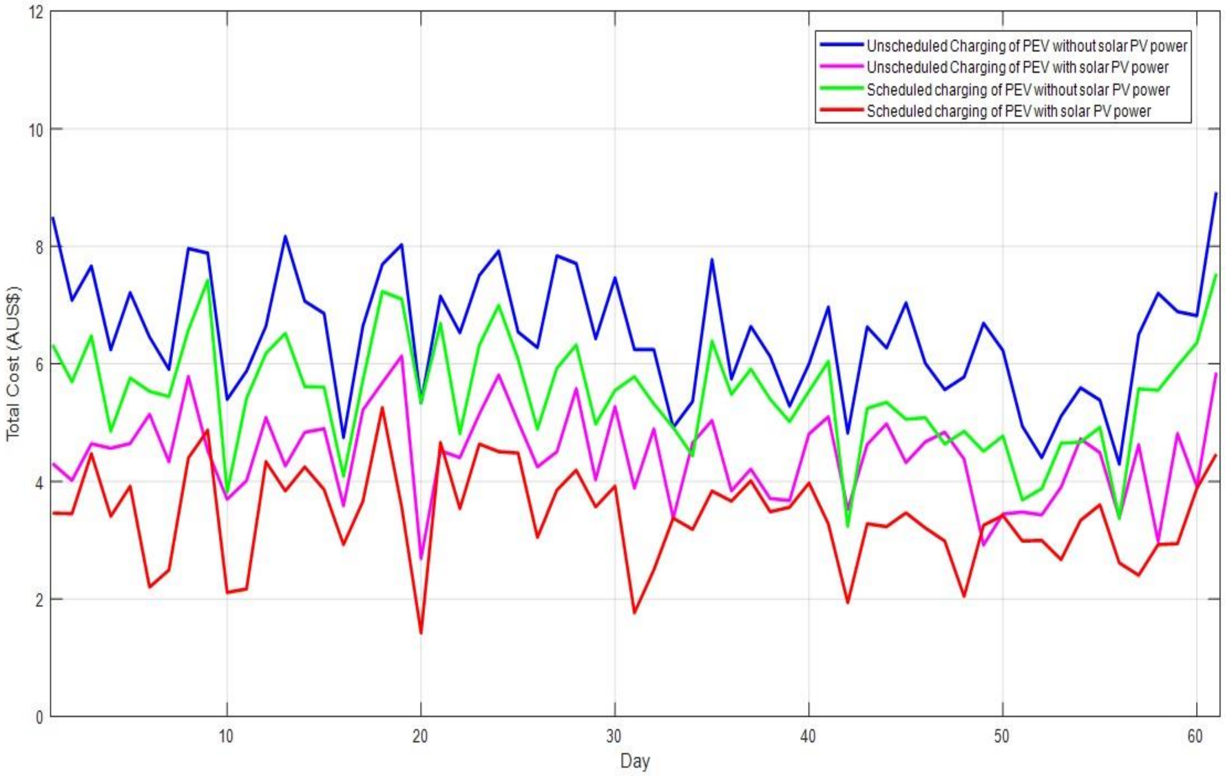

Fig. 5.16. Daily cost of energy consumed while charging PEV 3

Table 5.3. Total cost of energy consumed in two months

| PEV charging cases | Total cost during unscheduled charging of PEV without solar PV power (in AUS$) | Total cost during unscheduled charging of PEV with solar PV power (in AUS$) | Total cost during scheduled charging of PEV without solar PV power (in AUS$) | Total cost during scheduled charging of PEV with solar PV power (in AUS$) |
|---|---|---|---|---|
| PEV 1 | 451.3576 | 284.7907 | 385.7296 | 217.2123 |
| PEV 2 | 456.7696 | 318.0464 | 375.5896 | 238.2268 |
| PEV 3 | 397.1056 | 271.1052 | 334.4056 | 208.7957 |

nanogrid using solar PV system, effectively optimize the charging of PEV with minimum cost.

## 5.4 SUMMARY

The charge scheduling of PEV under different cases were conducted to analyse the efficiency of the proposed charge scheduling method. From this chapter it can be concluded that the proposed scheduling method for charging PEV in DC nanogrid incurred minimum charging cost compared to unscheduled charging method. A long-term analysis was conducted and the results of the analysis illustrated that the total cost incurred for charging is minimum for the proposed method.

# CHAPTER 6

# CONCLUSION AND FUTURE WORK

## 6.1 CONCLUSION

Charge scheduling of PEV in DC nanogrid is presented in this paper. The scheduled charging of PEV aims to minimize the charging cost, and to minimise the adverse impact of PEV on the grid. The charge scheduling algorithm uses a ToUP tariff system to schedule the charging of PEV. The proposed algorithm finds the charging slot with minimum cost and schedules PEV charging only on that particular slot. First, the algorithm separates the tariff based on entrance and leaving time and searches for the slot with a minimum tariff rate, and eliminates the slot with a higher tariff rate. The algorithm calculates the solar PV power available to charge the vehicle in the selected slots after meeting the residential load demand. The algorithm optimally schedules the charging of PEV during off-peak and super off-peak and utilize the available solar PV power to charge PEV at minimum cost. Charging of PEV in DC nanogrid under four different cases are analysed using the MATLAB platform. A long-term analysis for two months was carried for different PEVs to confirm the efficacy of the proposed algorithm. The obtained results show that the charging cost of PEV in DC nanogrid using the proposed scheduling algorithm generate lower charging cost compared to unscheduled charging method. The proposed algorithm minimizes the overall cost of energy consumed from the grid and also minimize the demand on the grid.

## 6.2 FUTURE WORK

In this thesis work, only ToUP tariff scheme is used for the price analysis. The proposed work can be further modified to make suitable for different pricing schemes to schedule the charging spot based on the preferences.

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