Smart Optimal Charging Scheduling of EVs with Rooftop Solar Charging Park

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Abstract: The proposed work is projected as how to manage the charging process caused by increased number of EVs. Parking-lot must be designed ensuring of optimal charging scheduling of EV fleet with the primary objective for maximizing profit of PLO. Installation of solar rooftop PV array at work-place provide the key solution of aforementioned challenges. Energy price of grid vary due to load demand on grid and PLO faces price volatility issue. To resolve this issue, PLO computes Quantity Bound (QB) of uncoordinated EV charging load by estimating overlying area. QB indicates higher usage of the available solar generation so that extreme number of EVs are charged over the solar generation and small amount of electricity is drawn at peak hours when price of energy is relatively high. The algorithm used to reduce the dependency on the grid and shift a load of EV fleet from the grid to PV generation that increases the profit of PLO for coordinated charging of EVs by using the solar output from PV array and also reduces the charging cost of EV owners.

Keywords- Parking-lot operator (PLO), Quantity Bound (QB), Electric vehicle (EV), System Operator (SO).

I. INTRODUCTION

Nowadays world is facing shortage of fossil fuels and pollution problems. If the maximum power generation of the electric power system is based on coal-fired plants and charging of EVs done by coal-fired plants than EVs will not considerably reduce emission of ‘carbon’ level in the atmosphere. Therefore, charging of EV fleet could be done by renewable resources, it will help environmental pollution problems remarkably. Therefore, addition of PV roof-top array with EV charging systems may help in reduction of GHG emission. So, utilizing this the day time charging demand of EVs may be fulfilled. Thus, this relax the grid by minimizing the power drawn from the grid for charging of EV fleet. At present consumption of fossil fuel is increasing causing environmental hazards such as emission of greenhouse gas (GHG) [3]. Presently corona virus shows if EVs are in the norms then it purifies the atmosphere and drastically reduces the Greenhouse Gas emission (GHG) [2]. So, if EVs are introduced on surface transport it may help to purifying atmosphere.

Transportation sector releases considerable amount of CO_2 in the atmosphere. So, to reduce this emission electrification of transport sector is necessary throughout the world. Successful implementation of EVs will depends on how easily we use renewable generation to avoid customers apprehension. EV implementation will also increase load on electric grid. So electric grid may also require some additional alternates to make it successful. Further it also needs convincing management system to make entire system attractive for EV owners. Hence need to develop smart charging and discharging stations and ensure minimum adverse effect on electric grid as well as it should be owner friendly and charging cost of EVs should be minimum.

PLO plays an important role like a mediator between EV and the utility. EVs charging scheduling and participation in the energy market for providing ancillary services are also the task related control and management controlled by the entity called parking-lot operator [5]. Many work in the existing literature focus on the independent objectives such as greenhouse gas emission reduction[1,20], line loss minimization from EV fleet charging load on grid focus on SO interest to alleviate the EV charging impacts on the electric network [7,8,10,16] siting and sizing of EV charging infrastructure [22-24] , EVs charging cost minimization, PLO's revenue maximization from ancillary services to SO [17-18].

In this background if an EV fleet is charged from the grid without any planning it may create the burden on the grid and treated like a huge load and increased load requires more generation to satisfy the demand. This may create problems for electric utilities and develop several problems like overloading, phase imbalances, development of harmonics, etc. And also need to change the existing setup of the distribution system like the need to change the capacity of the distribution transformer. In this context, optimal charging/discharging scheduling of EVs while mitigating the intermittency of renewable generation are the major challenges faced by PLO.

To fulfil these two challenges PLO needs to utilize maximum intermittent PV generation for charging of EV fleet at Parking-lot developed near the office premises or other commercial building to coordinate between grid and EV owners. So, the development of EV owner-friendly PV assisted coordinated charging strategy to diminish the harmful impression of EV charging load on the grid and also maximize the profit of PLO and providing cheaper charging cost for EV owners.

The rest of the paper is structured as follows: Section II and III, defines system model and problem formulation respectively. Simulation results are discussed in section IV and conclusion is specified in Section V.

II. SYSTEM MODEL

Consider a case of the parking lot of company at the workplace, that having office hours i.e. from 7.00 am to 7.00 pm. Work-place parking-lot having N number of charging poles with AC level-2 charging mode. Work-place parking-lot power bus is connected by the centrifugal switch and do the charging of each EV by charging pole that can be managed by parking lot operator. The power bus receives the power from roof-top PV array and power-grid.

Parking lot operator accumulates the data of the PV Array output, power drawn from grid and EVs and also accomplish the charging processes of all the EVs by touching the centrifugal switches of charging pole. According to system model of work-place parking-lot the roof-top PV array output is unilateral only used for charging of EVs for maintaining stability of the grid.

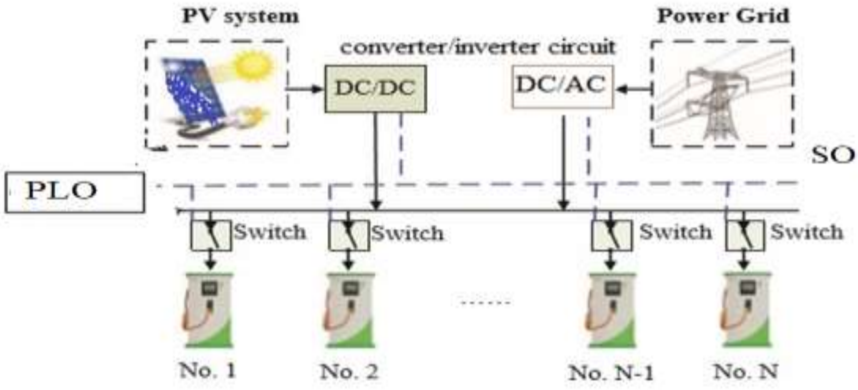


Fig.1 System Model of smart PLO

(A) Characteristics of Solar PV Array

According to available data volume of rooftop PV array is 200 kW. From the reference [20] we consider that for fixing roof-top PV array with 1kW capacity area required on roof 10 m^2 . So, the area desired to cover a 200 kW PV system of about 2000 m^2 . Solar PV arrays are installed on the roof of the building of the work-place to charge the EVs at the parking lot. The weather forecast information [20] obtained from the weather forecast website. Fig. 2 illustrates Workplace PV output power in different weather conditions.

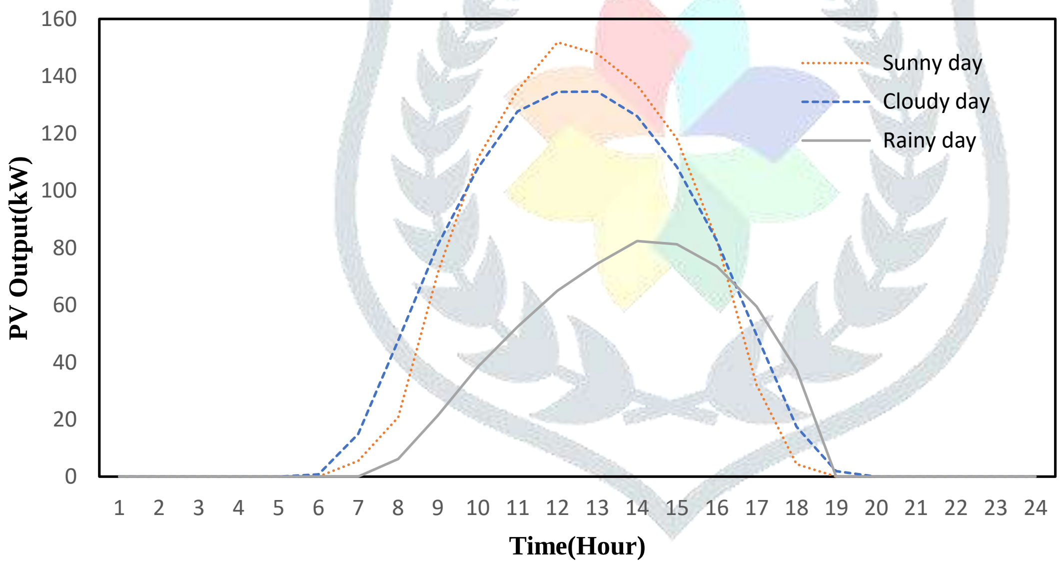


Fig.2 Workplace PV Output Power in Different Weather Condition

(B) Parking Lot Charging Management System (PL-CMS)

Development of Parking Lot Charging Model for EVs considers (1) Arrival time; (2) Departure time; (3) EV battery information (SOC of the battery) ;(4) Making daily charging scheduling of EVs by considering their distance of movement. The planning of the customer to travel the distance also an important parameter for consideration. For a stated EV the average distance covered consider as 40 km and requirement of SOC is 30%. EVs can be categorized into two sets based the behaviour of their movement pattern:

(1) Systematic EVs and (2) Casual EVs. Systematic EVs are those which follow a systematic pattern between their residence and work-place throughout a week. Casual EVs are those comes rarely to visit the work-place parking-lot from outside of the city and do not follow a typical moving similar pattern.

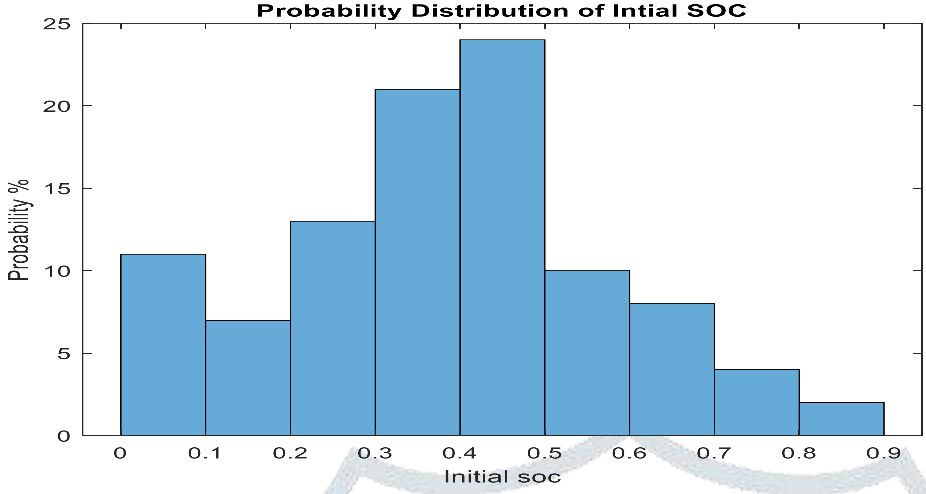


Fig.3 Probability distribution of initial soc

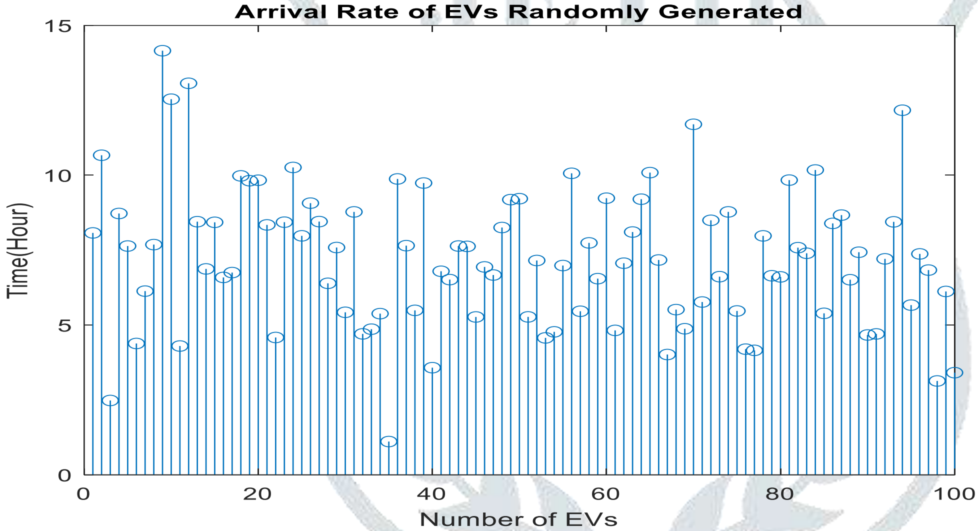


Fig.4 Arrival time of EVs randomly generated

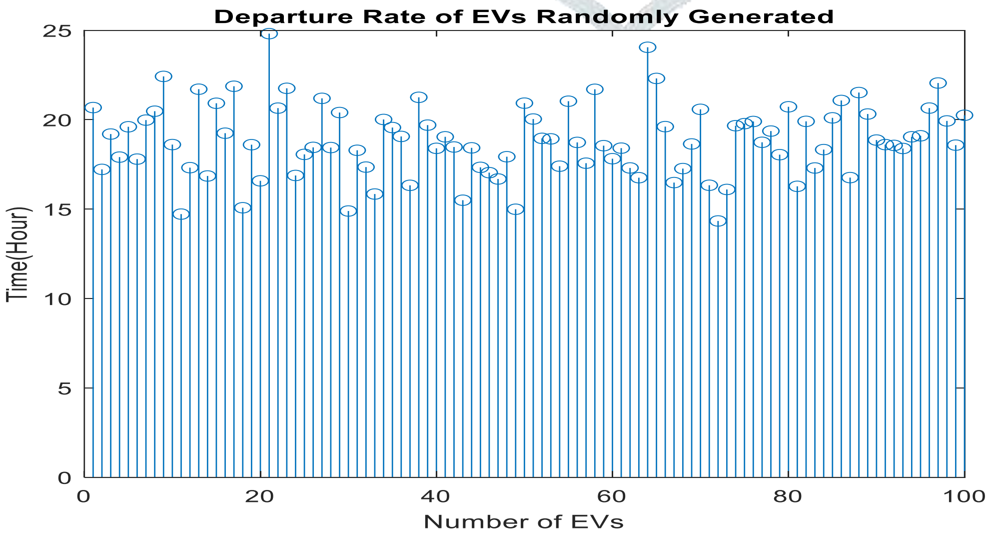


Fig.5 Departure rate of EVs randomly generated

Fig. 3 illustrates the probability distribution of initial SOC. The lower limit of battery soc avoids fast deprivation and upper limit of battery capacity to avoid fire hazard so consider 90% charging as the desired level of soc. Fig.4 depicts the randomly generated arrival rate of EVs. From the result analysis most of the EVs are regular EVs comes at the parking lot between 6.00 am to 8.00 am and remaining EVs are random EVs comes randomly any time. Fig.5 illustrates the randomly generated departure time of EVs show that most of the EVs are regular EVs depart from parking lot between 6.00 pm to 8.00 pm and remaining EVs are random EVs depart randomly any time.

(C) Calculation of Quantity Bound for Uncoordinated EV Charging load by Calculating Overlapping Area

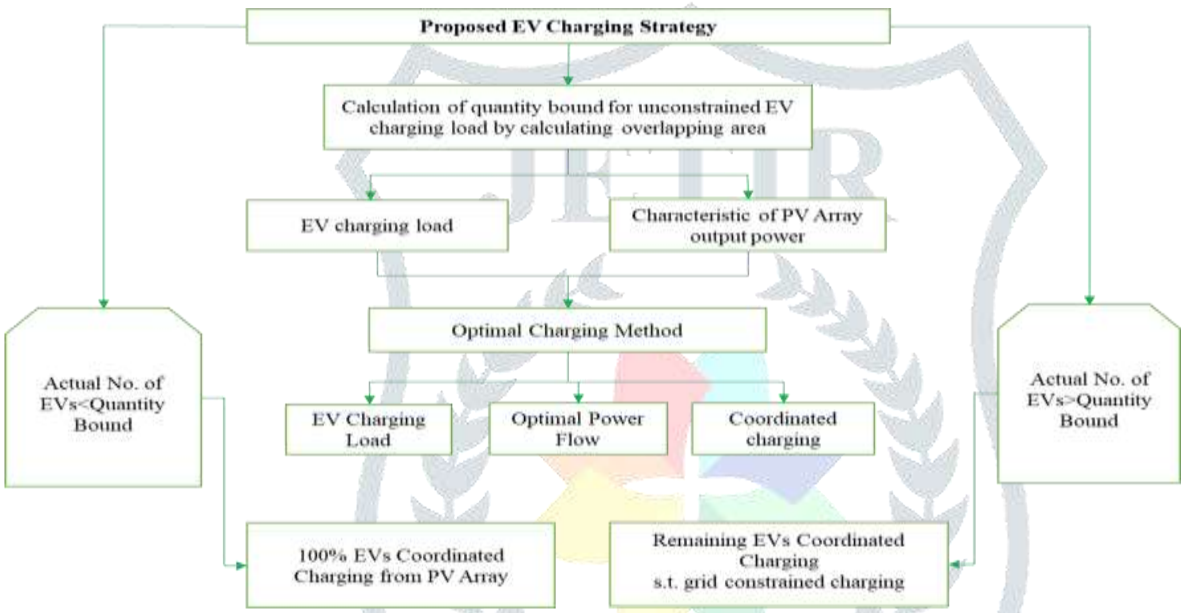


Fig.6 Framework of proposed EV charging strategy of PLO

In this sector MATLAB programming is used for justify the below-mentioned algorithm. For simulation we study the case of workplace parking-lot where 100 EVs visit the parking-lot during the day. QB specifies the overlapping area among the unconstrained EV charging load curve & roof-top PV Array output curve. Objective to maximize overlapping area between unconstrained EVs charging load curve and PV Array output curve.

$$Max\ \ Q(EV_{load}, PV_{output})$$

Calculation of QB in different weather situations (i.e. sunny day, cloudy day, rainy day). Normal distribution is used to approximate the time of arrival of EVs with mean and standard deviation are μ_a and σ_a, for approximation of their time of departure mean and standard deviation are μ_l and σ_l with normal distribution, so initialization and generation of probability density function for analysis of EVs arrival time, departure time, and initial SOC are generated using National Household Travel Survey (NHTS) data with respective means (7,19,0.3) and standard deviations (2, 2, 0.1).

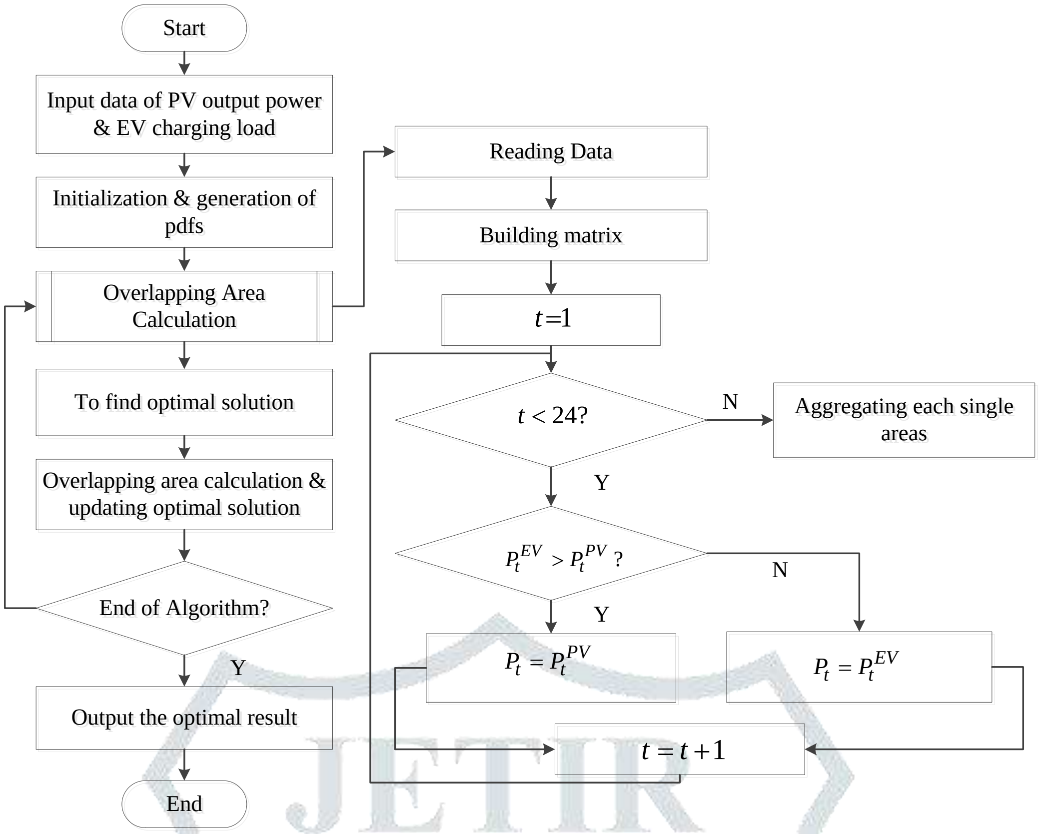


Fig.7 Flow diagram for calculating the overlapping area

III. PROBLEM FORMULATION

A day is divided into slots of equally sized time-period (t) and t is selected as one hour. The work-place parking lot capacity is separated into two portions: (1) regular layer defined as parking lot reserved for the regular vehicle follow the routine and (ii) random layer means EVs comes in random fashion.

Each EV comes at work-place parking-lot once throughout a specified day (during 24 hours a day) and stay there minimum for t time length. $s_{i,t}$ denotes the decision of PLO for charging of the i^{th} EV through t ($t \in T$) time period.

Entire quantity of energy desired to charge i^{th} EV throughout t time period

$$E_t^{EV} = s_{i,t} \cdot P_{i,t}^{ch} \tag{1}$$

where $P_{i,t}^{ch}$ denotes the regular charging power of one charging pole during one-time slot (say 1 hour). EVs comes at work-place parking-lot with different time of arrival, different time of departure with different soc level of battery which influence the PLO decision for charging scheduling of EVs.

(A) PV supported unconstrained EV charging

Connection hours

$$h_i = ta_i - td_i \tag{2}$$

Real duration of charging

$$t_{ch,i}^{actual} = \begin{cases} h_i & \left(h_i < t_i^{req}\right) \\ t_i^{req} & \left(h_i \geq t_i^{req}\right) \end{cases}$$

$$t_i^{req} = \frac{(soc_i^{des} - soc_i^{ini})}{p_{i,t}^{EV}} batcap \tag{3}$$

Unconstrained EV charging load

$$P_{i,t}^{EV} = \sum_{i=1}^{N} \sum_{t=1}^{T} P_{i,t}^{ch} \cdot s_{i,t} \tag{4}$$

Amount of charging power required for EV at t time slot

$$s_{i,t} = \begin{cases} 1 & ta_i \leq t \leq td_i \\ 0 & otherwise \end{cases} \tag{5}$$

Power consumed by EV fleet remain in their designated limit

$$P_{i,t}^{ch,\min} \cdot s_{i,t} \leq P_{i,t}^{ch} \leq P_{i,t}^{ch,\max} \cdot s_{i,t} \quad \forall i,t \tag{6}$$

$$soc_{i,t} = soc_{i,t-1} + \frac{(soc_i^{des} - soc_i^{ini})}{t_{d,i} - t_{a,i}} \tag{7}$$

$$P_{i,t}^{ch,\max} = \frac{(soc_{i,t}^{des} - soc_{i,t}^{ini.}) s_{i,t} batcap_i}{\eta_{ch}} \tag{8}$$

$$soc_{i,t}^{\min} = \text{Minimum} \quad \text{At} \quad t < t_a \tag{9}$$

$$soc_{i,t} = soc_i^{ini.} \quad \text{At} \quad t = t_{a,i} \ \text{(10\% rating of battery)} \tag{10}$$

$$soc_{i,t} = soc_i^{des} = soc^{\max} \quad \text{At } t = t_{d,i} \ \text{(90 \% rating of battery)} \tag{11}$$

$$soc_{i,t} = soc_i^{ini.} \quad \forall t \geq t_{a,i} \tag{12}$$

$$soc_{i,t} = soc_{i,t-1} + \frac{P_{i,t}^{ch} s_{i,t} \eta_{ch} \Delta t}{batcap_i} - \frac{Trip}{batcap_i} \sum_{t=1}^{T} Flag_{i,t}^{Trip} \tag{13}$$

$$soc_{i,t}^{ini.} \leq soc_{i,t} \leq soc_{i,t}^{des.} < batcap_i \forall t \in T \tag{14}$$

Essential duration of charging of EV fleet batteries from initial to required SOC is given by (3)

Unconstrained EV charging load is denoted by (4) $s_{i,t}$ is a variable with dual state having values (0 and 1) shows charging condition of i^{th} EV at t time period , $s_{i,t} = 1$ means availability (charging) of EV_i at parking-lot at time t , $s_{i,t} = 0$ (denote the i^{th} EV is not available at work-place parking-lot or fully charged) denoted by (5) $P_{i,t}^{ch}$ is the amount of charging power required for EV at t time slot (8) The lower limit of battery soc evades quick deprivation and higher limit of battery capacity to evade fire hazards so consider 90% charging as the desired soc level(9-12) . Updating the energy level for fulfilling the EVs movement by consumption of stored energy of battery and charging requirement of EVs (13) To ensure that SOC remains within limits (14).

(B) Work-place parking-lot demand-supply model of energy

$$E_t^{EV} = E_t^g + E_t^{PV} \tag{15}$$

Total amount of energy required to charge EV during time t is sum of the energy required from the grid and energy required from PV as illustrated by (1).

When EV fleet load is limited due to a smaller number of EVs then power required from grid calculated from (2):

$$E_t^g = \min\{E_t^{EV} - E_t^{PV}\} \tag{16}$$

So, total power drawn from the grid depends on two parts: (1) Charging load of EV fleet and (2) Power received from roof-top PV array

$$E_t^{EV} \le E_t^{PV} + E_t^g \quad \forall t \tag{17}$$

It is difficult to precise the solar energy parking lot operator (PLO) requires to calculate the solar energy from previous years of historical data.

Objective of the parking lot operator

$$Maximize \quad \Pr ofit = Max.(\mathrm{Re}venue - \mathrm{Cos}t) \tag{18}$$

$$\mathrm{Cos}t \quad C_t^g = \sum_{i=1}^{N}\sum_{t=1}^{T} P_{i,t}^{ch} \cdot s_{i,t} \cdot EP_t^{RTP} \tag{19}$$

$$\mathrm{Re}venue = \sum_{i=1}^{N}\sum_{t=1}^{T} P_{i,t}^{ch} \cdot s_{i,t} \cdot EP_t^{TOU} \tag{20}$$

Subject to :-

$$E_t^{EV} \le E_t^{PV} + E_t^g \quad \forall t, \in T \tag{21}$$

$$0 \le s_{i,t} \le 1 \quad \forall i, \in I, t \in T \tag{22}$$

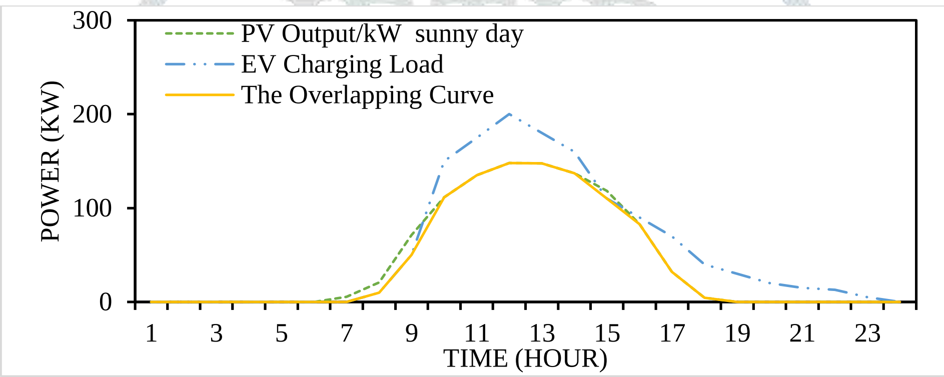
$$P_t^{EV} = \sum_{i=1}^{N}\sum_{t=1}^{T} P_{i,t}^{ch} \cdot s_{i,t} \quad (23)$$

Eq. (21) shows the upper limit of the charging load. Eq. (22) ensures the decision for EVs are in charging condition $s_{i,t} = 1$ when connected to the charger otherwise 0. Eq. (23) computes the total charging of EV fleet batteries at time t for fulfilling charging requirement of all connected EVs to the charger.

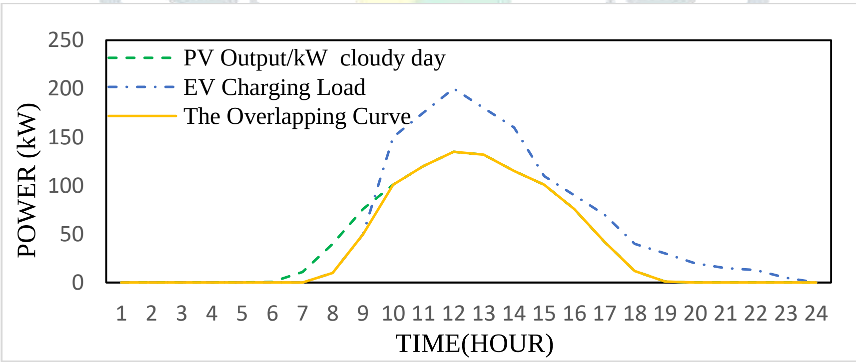
IV RESULTS AND DISCUSSION

Calculation of optimal QB for unrestrained EV fleet load using roof-top PV array output in different weather conditions: -

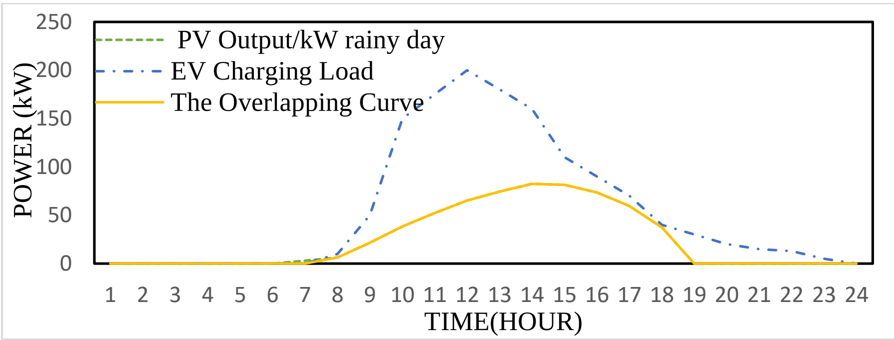
Type of Weather	Sunny Day	Cloudy Day	Rainy Day
Calculated Overlapping Area/kWh	964	834	588
Number of EVs Compensated by PV Output throughout a Day	71	62	44



(A)



(B)



(C)

Fig. 8 Calculation of optimal QB for unrestrained EV fleet in different weather conditions (A) optimal QB in sunny day (B) optimal QB in cloudy day (C) optimal QB in rainy day

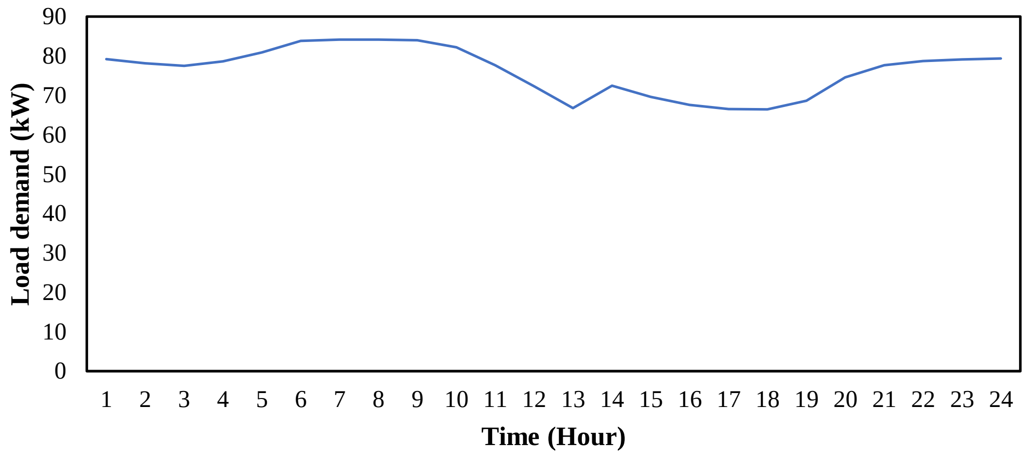


Fig.9 Baseload of the work-place

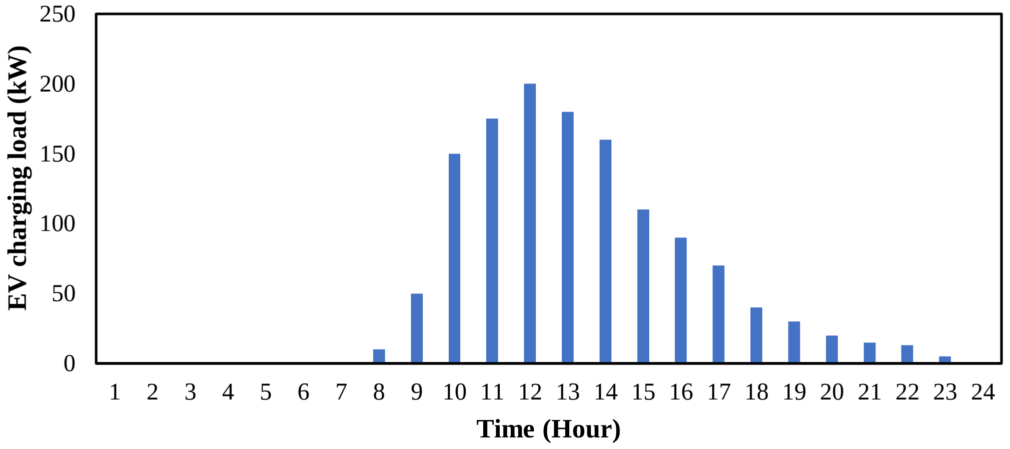


Fig.10 EV charging load

Fig.9 illustrates the base load of the work-place. Generally, work-place runs in shifts so the main parts of baseload are lightning load and air conditioning load. During after-noon load reduces due to break and onward variation in load due to number of connected loads and in night-time main part of load due to lightning load. Fig.10 explains the hourly EV fleet charging load profile. Fig.11 shows the power drawn from the power-grid by EV fleet charging load with traditional charging scheme in an uncoordinated manner and reduction of EV fleet charging load on the grid using PV assisted coordinated charging method. So, reduction in the peak load and adverse impact on the grid due to EV fleet charging load.

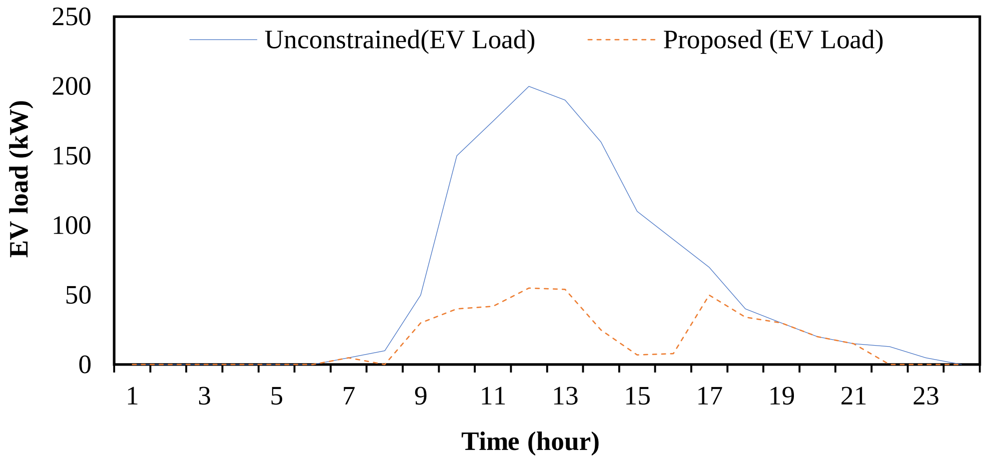


Fig 11 Power drawn by EV fleet from grid

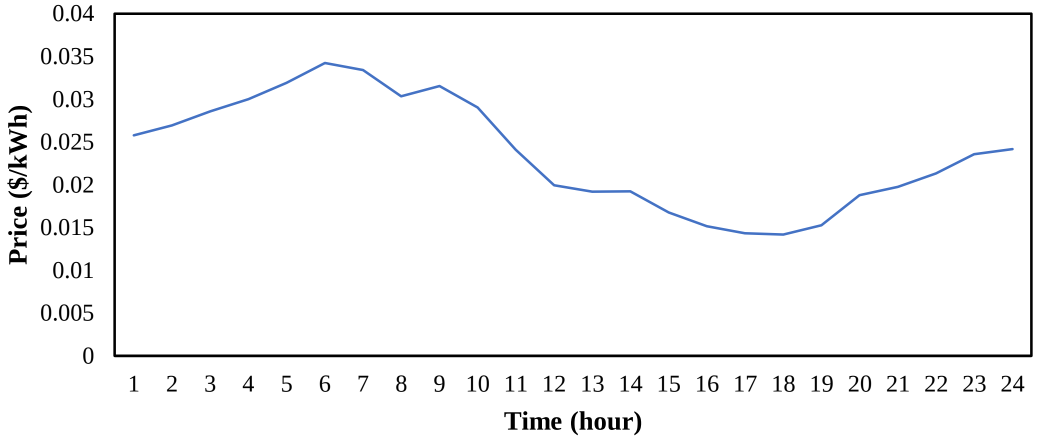


Fig.12 Hourly Energy Price in ($/kWh)

Hourly electricity price is forecasted from New York Independent System Operator (NYISO) using historical Locational Marginal Price (LMP) data from day-ahead market [33]. According to driving behaviour of EV fleet aggregator submit the bids with increase or decrease in demand with (energy [kWh] and price [$/kWh]. This model takes the commercial building work for the parking lot of EVs for study purpose. Fig.12 shows that hourly energy prices forecasted from NYISO and fig.13 depicts TOU prices designed by the PLO from hourly energy prices to charge the remaining EV fleet charging load after compensation of roof-top PV generation.

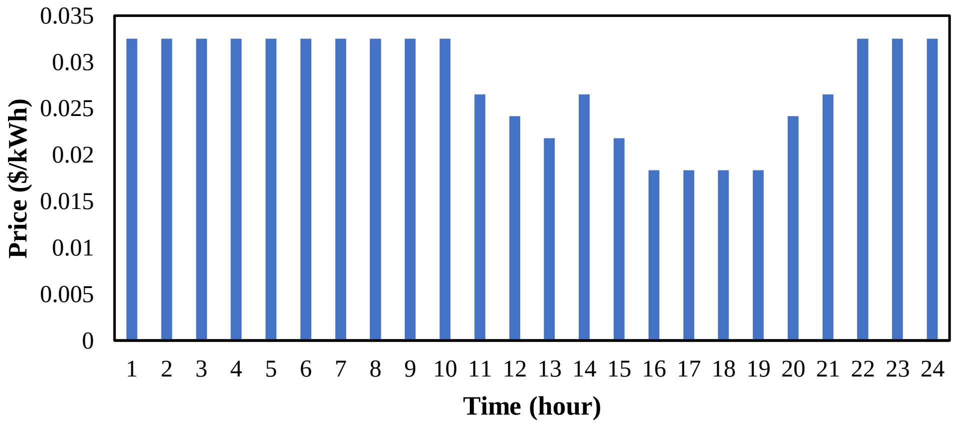


Fig. 13 TOU price designed by PLO from hourly energy price in ($/kWh)

Table-1 Performance parameters of PLO with PV assisted coordinated charging

	Sunny Day		Cloudy Day		Rainy Day	
	Case1	Case2	Case1	Case2	Case1	Case2
Revenue($)	84.2282	84.2282	84.2282	84.2282	84.2282	84.2282
Cost($)	71.3848	50.9715	71.3848	51.59243	71.3848	52.6072
Profit($)	12.8434	33.2567	12.8434	32.63578	12.8434	31.621

Case-1 Uncontrolled Charging Load on Grid (Traditional Scheme)
Case-2 PV Assisted Coordinated Charging Load on Grid (proposed Scheme)

Table-1 displays the assessment of the traditional charging scheme by proposed PV assisted coordinated charging scheme and calculate the profit of the PLO in different weather conditions.

Profit of the PLO increases by more utilization of solar PV generation.

$$profit_{sunny} > profit_{cloudy} > profit_{rainy} > profit_{traditional}$$

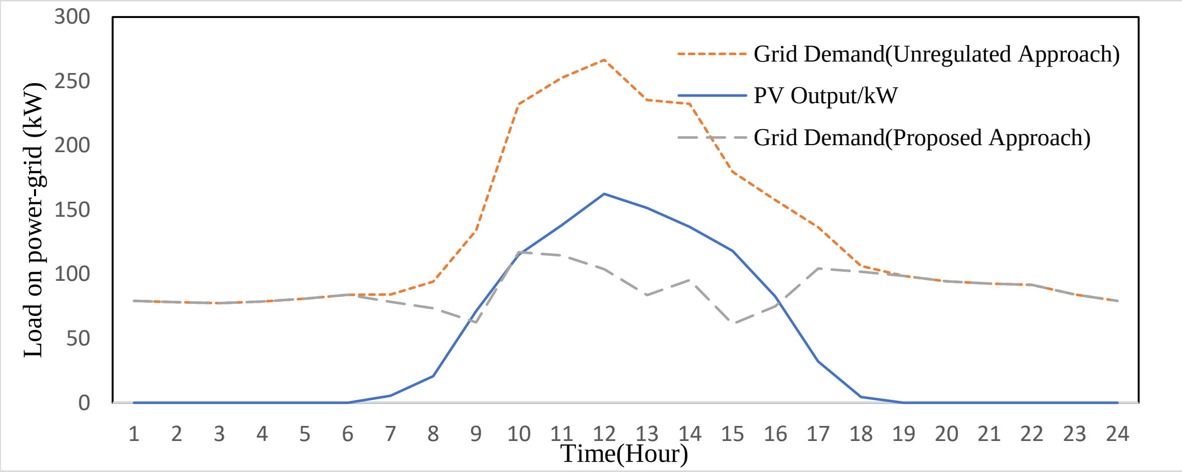


Fig. 14 Power drawn from the power-grid with offered and unregulated approaches

Fig.14 exemplifies the total demand of the work-place on the grid with a traditional approach with unbalanced EV fleet charging load and with PV assisted coordinated charging scheme.

V CONCLUSION

The proposed strategy promotes the consumption of renewable energy termed as eco-friendly charging strategy.Calculating the EV charging load at different sampling period and calculation of quantity bound in different weather conditions so by utilizing maximum PV generation charging scheduling of a maximum number of EVs directly from solar generation with minimum constraints and charging of remaining EVs done by PV assisted coordinated charging by reducing demand from the power-grid at high price time period. So profit of parking lot operator significantly increases with the development of the environment-friendly charging scheduling strategy for EV owners. The intensity of solar radiation is different in different weather conditions. This is evident that roof-top PV Array compensates the EV fleet charging load when available and reduces the high load demand on the grid meanwhile minimize negative impact of grid. So, no need to expand the existing distribution structure. By this power-grid comes in stability zone during high price period when load demand is high.

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