Coordinated V2G Scheduling of EV Aggregator with Rooftop Solar Charging Park

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***Abstract*- Renewable generation intermittency and Electric Vehicles (EVs) charging/discharging scheduling are two significant foreseeable operational challenges in the future grid for System Operator (SO). To meet these challenges, smart scheduling coordination between SO and EV owners is required to synergize grid integration of renewable and EVs. The scheduling coordination between SO and EV is being established by an EV Aggregator (EVA), to offer ancillary services via bidirectional Grid-to-Vehicle-to-Grid (G2V2G) technology i.e. scheduling of EVs' charge/discharge. In this context, proposed work aims an effective utilization of intermittent photovoltaic (PV) generation from rooftop solar charging park and maximization of EVA's profit. Revenue of EVA is due to regulation services to SO and charging services to EV owners. The operational cost of EVA considers the cost of procuring energy requirements from wholesale electricity market for EVs' charging and battery degradation cost while ensuring EV owners' driving necessities. The proposed V2G scheduling also provides congestion management, through Time-of-Use (TOU) price-based demand response program (PBDRP) and considering system constraints presented by SO i.e. transformer delivery capacity and baseload profile. The efficacy of the model is being validated through simulation results analyzing two cases: with and without PBDRP. The proposed model would help SO to maintain technoeconomic consistency by increase of PV integration, and peak load management.**

Keywords: Electric Vehicle Aggregator (EVA); price-based demand response (PBDR); Time-of-Use (TOU); Grid-to-Vehicle-to-Grid (G2V2G).

I. INTRODUCTION

In the global power generation mix scenario on the way towards sustainable development, electric vehicles (EVs) are sustainable only if they are charged from sustainable wind/solar power resources [1]. However, due to inherent intermittency, large scale renewables may place threats to power grid in the form of violations of frequency/voltage limits and supply-demand inconsistencies [2]. It necessitates enhanced flexibility to balance generation and demand, extra reserves, and better generation dispatch capabilities.

Charging flexibility is described as the variance of charging duration from total connection hours, to allow EVs' charging at off-peak times or surplus renewable generation [3]. However, EV owners who park their vehicles at workplace or carrying out vacation events necessitates charging during peak periods in daytime. Concentrated simultaneous charging of multiple EVs at same location thus overloads distribution system and would severely affect its operation and grid stability [4-5]. Thus, EV owner friendly smart grid-to-vehicle (G2V) charge scheduling algorithms are required within parking places near shopping malls and office buildings to manage their energy and ensure that system limits are respected as well [6].

Synergizing flexible electrified transportation can provide a feasible means to improve RE integration in the grid [7]. EVs allows renewable production to be stored whenever the grid is not ready to take it and sold when market conditions are favorable. Pragmatically, the onboard EVs batteries can be operated either as a provisional resource while discharge (V2G) or a demand response provider as a charge load (G2V) for alleviating the variability of RE generation [8-9].

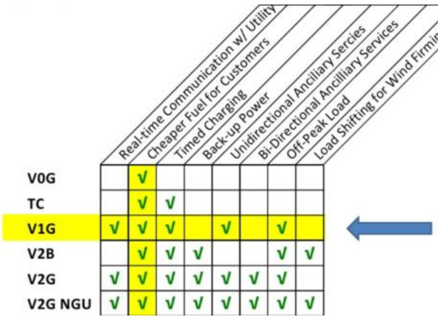
EV owner concerns regarding battery lifetime is challenge for V2G implementation [10]. Therefore, optimal charge-discharge V2G scheduling of EVs can maximize the value of EVs by value stacking, using them to carry out multiple applications and thus tap into multiple revenue streams by an EV Aggregator (EVA). It acts as a scheduling coordinator between the system operator (SO) and EV owners. EVA, as an ancillary service provider, facilitates market participation of EV owners [11].

Integrated price-based demand response can facilitate synchronization of renewable resources' availability with crest of charging demand profile [12]. However, short-term regulation and reserve provision is more beneficial rather than peak load reduction/load shifting for large scale renewables where inertia of system is a threat. Massive EVs, as a large battery storage unit, can help mitigate the inertial loss in case of large-scale renewables [13].

The cost and emission reductions in a smart grid are worked out by maximizing utilization of EVs and renewable (solar/wind) generation. V2G allows merging of two large sectors – transportation and electric grid system. Integration/bridging of these two large sectors allows smart interaction between vehicle fleet, grid and intermittent renewables. EVA provides large, low-cost storage for renewables. Renewable generation fulfills EVs' charging demand. EVs act as distributed energy resources by discharging energy to the grid.

Figure 1 illustrates different possible plug-in scenarios of EVs and associated benefits if any. EVA manages unidirectional flow of electricity from grid to vehicles in G2V mode, respecting the constraints of EV owners by developing smart charging algorithms. In unidirectional G2V mode, EVA modulates rate of charging to lower value during peak load period to meet SO's necessities and to higher value under surplus renewable generation. With V2G, EVA manages the two-way flow of power to between EVs and the grid. Electricity can be stored in the EV and returned to the grid as needed. V2G technology make available a platform to EV owners to communicate with SO. V2G technology provides DR facilities to the SO for improve the grid's economic efficiency during peak times. One of the main motivations of V2G technology in the energy market is its capability to satisfy large electrical load demands. V2G technology enables the use of EVs as distributed storage devices, with the stored power being utilized to feed the system in situations of peak load or for usage in homes or offices.

Managing DR service by an EV battery represents some specific constraints such as: Every dispatch order must match the power capacity of the line and EV's level of charge called state of charge (SOC). The EVA and SO can no longer ask for down regulation beyond battery full charge as well as no further injection into the grid beyond battery dead level. These constraints are satisfied for contracted EVs respecting a minimum number of connection hours per day in service. Billing process is then performed on the stipulated hours.



	Real-time Communication w/ Utility	Cheaper Fuel for Customers	Timed Charging	Back-up Power	Unidirectional Ancilliary Sercies	Bi-Directional Ancilliary Services	Off-Peak Load	Load Shifting for Wind Firming
V0G		√						
TC		√	√					
V1G	√	√	√		√		√	
V2B		√	√	√			√	√
V2G	√	√	√	√	√	√	√	
V2G NGU	√	√	√	√	√	√	√	√

Fig.1. Plug-in EVs scenarios possible: Immediate charging, delayed charging, smart V1G or G2V charging (DR or limited ancillary services), Vehicle-to-Building (V2B), and V2G

In this context, in proposed work, EVA regulates EVs' charge/discharge day-ahead plan. In the static V2G scheduling, the EV owners are compelled to make available their times of arrival/departure, desired SOC, and minimum SOC, in advance of scheduling day. In addition. the initial SOC and the EV profile information viz. replacement cost of battery, battery capacity, and receiving rate are pre-acknowledged to EVA. The PV generation and electricity price for the upcoming day is precisely forecasted. With aforementioned information, EVA regulates the EVs' charge/discharge schedule for upcoming day. It splits scheduling horizon into discrete intervals of equal sizes. This smart static V2G scheduling is governed aiming at minimization of EVs' charging cost, maximization of PV utilization, and minimization of charging load on the grid. Static V2G model results could be utilized for evaluation of the dynamic scheduling model's performance.

II. RELATED WORK

Charging/discharging integrated operational management of renewable generation and EVs is presented in [14] to analyze EVs capability in providing reserve, considering technical features of EV's batteries. However, it neglected the charging cost minimization concern of EV owners. The energy management algorithm is developed in [15] to decrease the contracted EVs' total daily charging cost through charging park owner (EVA), and alleviate the adverse impacts of charge scheduling on the main grid by shaving peak of the load curve. However, ancillary services were not provided to SO. Similarly, in [16] a DER energy trader (EVA) in-apartment buildings is modelled to offer load shifting, bill savings, and fairly distribute demand response (DR) benefits. Three pricing schemes, i.e., real time pricing (RTP), flat rate, and time-of-use (TOU) are competed in decreasing the investment recovery periods. However, ancillary services provision is disregarded.

Smart EVA's self-scheduling model considering PV and distributed generators is presented in [17] considering satisfaction index of EV owners, technoeconomic concerns, stochasticity of solar radiation, requirements of spinning reserve. EV owners earned profit by EVs' discharging and desired SOC by departure time. However, DR benefits are overlooked.

[18] emphasizes PV charger summarizing completely the associated features on EV–PV charging, which comprise the different topologies of power converter, methodologies of charge scheduling and regulation for different cases: PV–grid and PV-standalone/hybrid systems. In [25], the sensitivity analyses on the size of RES, number of EVs, and the percentage of customer participation in the DR program is performed addressing operational scheduling of EVA integrating renewables. However, dynamic coordination under pragmatic charging management was ignored. An algorithm is built for coordinated online charge/discharge scheduling of EVs aiming at maximization of EV owners' satisfaction from entire charge/discharge requirements, and minimization of parking station's operational cost by ranking energy utilization from PVS based on the electricity price preferences [19]. However, its disregarded EVA's market participation to maximize its profit.

Parking lot operator (EVA) aiming at profit maximization through its participation in multiple markets (energy and ancillary service), controls its contracted parked EVs [20]. SO, goals are minimization of operating cost, curtailment/wastage of renewable power, and issues related to renewables' intermittency. [21] compares different scenarios of integrated solar parking lot operation regarding load variations for different seasonal conditions, reduction of its charging demand on grid, system losses, main feeder ampacity, and voltage profile restoration. In [22], stochastic problem of upstream grid price uncertainty-based EVA's profit is transformed to deterministic problem with multiple objectives of mean profit maximization and profit variance minimization. In [23], a planning framework including resources is modelled considering operating and investment costs. Stochastic model for EVs' charging is analyzed to evaluate their load shift potential, maximizing PV utilization, and minimizing EV's charging cost [24]. In [26], a transactive online charge scheduling of EVs is modelled for commercial building operators with PV on-site generation and EV charging services facilitation. EVA maximizes its profit from net power flow from/to grid considering uncertainties of PV power and EV availability. EVA incentivizes EV owners which participate in its offered price-based demand response program (PBDRP). The reliable grid operation with reduced charging energy consumption from main grid is attained under dynamics of solar power and EV charge scheduling considering different mobility scenarios [27]. However, smart coordination and DR effects was disregarded [20-24,26-27,36]. [37] considers TOU-PBDR and smart coordination. However, its disregarded PV-based charging management. [38] considers charging management. However, it disregarded discharging management. [28] determines a smartly coordinated charging-discharging plan of EVs managing efficiently use of solar output among home and grid. However, DR programs were not incorporated concerning EV owners [29].

In this aforementioned context, proposed work models the smart V2G scheduling for EVA in a specific parking place to earn revenue by multi-market (energy and regulation markets) participation. TOU-PBDR is implemented for distributing the power consumption to reduce the peak-valley ratio of system and enhancing customer satisfaction by reducing charging tariff to EV owners.

III. SYSTEM MODEL

Fig.2 gives the schematic of V2G scheduling algorithm of EVA at a workplace with rooftop PV and SO grid. As shown in Fig.2, parked EVs, with their bidirectional dc–dc chargers, and PV source, with its dc–dc regulating interface, share a common dc bus. Therefore, workplace system with rooftop PV based charging is equivalent to dc microgrid with capability of dispatching or receiving power from SO grid. The amount of power transferred depends on decision-making algorithm of EVA. On weekdays, EV owners park EVs at workplace during office hours. They submit to EVA information about battery capacity, charging/discharging efficiencies, departure time, SOC desired at departure time, upper and lower bounds of SOC.

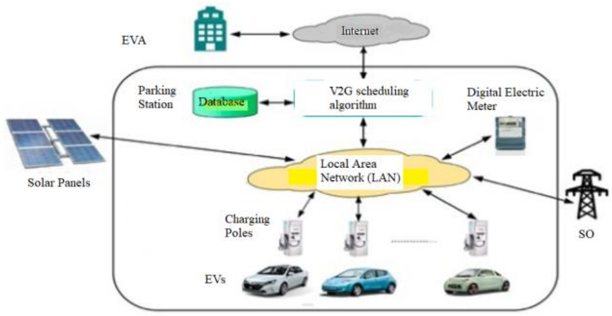


Fig. 2 The schematic of the V2G scheduling algorithm of EVA at workplace with rooftop PV and SO grid [19].

Using this information from EV owners and base load profile from SO, EVA modulates set operating point of EVs, changes their rates of charging/discharging based on energy prices, PV output and load profile information. Accordingly, there will be provision of services from EVA to SO like peak load management through TOU-PBDR, regulation services. EV owners are incentivized through reduced charging cost and enhanced battery life due to coordinated V2G scheduling.

IV. PROBLEM FORMULATION

EVA controls the EVs' charging/discharging powers, regulation (up and down) capacities and solar power consumption for each interval of time. Charging power of EV would be zero for time before arrival or after departure (1-2). The charging/discharging powers $POP_{i,t}^{G2V}$ *or* $POP_{i,t}^{V2G}$ should respect charger power limits $P_i^{\min}$ and $P_i^{\max}$ and the power limits set by EV owners (3-4). The upper limit of EVs' charging/discharging powers are decided from their SOC. Charging cannot be done beyond 80% SOC of EV. Similarly discharging cannot be done below 10% SOC. To cast the problem linearity, it is presumed that charging/discharging maximum power reduces linearly from upper/lower limit to zero whenever charged/discharged beyond (80-100) % /(10-0)% SOC.

Binary variable $h_{i,t}$ is used to indicate whether EV is plugged into system or not to provide regulation services by charging/discharging (5). An individual EV either charges or discharges. Therefore, another binary variable is used to ensure that for a given time only one of the two operations exist and has value one. This binary variable $u_{i,t}^{G2V}$ is 0 for discharging (V2G) and 1 for charging (G2V). Change in SOC from previous interval is estimated using (6). Before arrival SOC set to zero (7). On arrival SOC is EV's initial value (8). On departure, SOC must reach its desired value (9).

EVA respects the SOC bounds $SOC^{\min}$ and $SOC^{\max}$ as set by EV owners (10-11). It is presumed that net energy delivered/absorbed due to offer of ancillary services by the EV over one timeslot is zero. Hence, regulation up/down terms are absent in equation for SOC estimation. SOC of EV is updated from its initial value as per their efficiencies of charging/discharging η_{ch} or η_{dch} and charging/discharging power (12). Equation (13) indicates maximum possible charging rate for charging EV to desired SOC from current SOC in one timeslot. Constraint (14) represents congestion management to avoid overloading of transformer. (15) is the power balance equation for supply-demand matching. (16) and (17) depicts respectively the up and down capacities provided by EV.

V2G scheduling should consider battery degradation from EV owners' perspective. Battery degradation from charging is negligible and hence ignored. Therefore, battery degradation cost considers EVs' discharging only as in the equation (19-20), in which $Batc_i$ represents battery replacement cost. $\deg_i$ signifies the equivalent cost of battery degradation from EVs' discharging behaviour and it is computed as (19).

The first term in (19) is the normalized battery replacement cost as derived in [30], [31]. This cost is multiplied by the degradation cost of a kWh of energy throughput that was initiated in the same works. Battery degradation from depth of discharge effects are ignored, due to use of average calculated cost of V2G. The second term of the degradation cost is a balancing term so that there is no incentive for the EVA to overcharge the customers.

$$POP_{i,t}^{V2G}, POP_{i,t}^{G2V}, ruc_{i,t}, rdc_{i,t}, h_{i,t} = 0 \;\; \forall t < t_{a_i} \tag{1}$$

$$POP_{i,t}^{V2G}, POP_{i,t}^{G2V}, ruc_{i,t}, rdc_{i,t}, h_{i,t} = 0 \;\; \forall t > t_{d_i} \tag{2}$$

$$P_i^{\min} \cdot u_{i,t}^{G2V} \le POP_{i,t}^{G2V} \le P_i^{\max} \cdot u_{i,t}^{G2V} \;\forall i,t \tag{3}$$

$$P_i^{\min} \cdot \left(1 - u_{i,t}^{G2V}\right) \le POP_{i,t}^{V2G} \le P_i^{\max} \cdot \left(1 - u_{i,t}^{G2V}\right) \forall i,t \tag{4}$$

$$h_{i,t}, u_{i,t}^{G2V} \in \{0,1\} \;\forall i,t \tag{5}$$

$$SOC_{i,t} - SOC_{i,t-1} = \left(SOC_i^{Des} - SOC_i^{INI}\right) \Big/ \left(td_i - ta_i\right) \tag{6}$$

$$SOC_{i,t} = 0, t < t_{a_i} \tag{7}$$

$$SOC_{i,t} = SOC_i^{ini}, t = t_{a_i} \tag{8}$$

$$SOC_{i,t} = SOC_i^{des}, t = t_{d_i} \tag{9}$$

$$SOC_{i,t} \ge SOC_i^{min}, \forall t \ge t_{a_i} \tag{10}$$

$$SOC_{i,t} \le SOC_i^{\max}, \forall t \ge t_{a_i} \tag{11}$$

$$SOC_{i,t} = SOC_{i,t-1} \cdot h_{i,t-1} + \left(\begin{array}{c} POP_{i,t}^{G2V} \cdot u_{i,t}^{G2V} \cdot \dfrac{\eta_{ch}}{BC_i} \\ -\dfrac{POP_{i,t}^{V2G} \cdot \left(1-u_{i,t}^{G2V}\right)}{\eta_{dch} \cdot BC_i} \end{array} \right) \forall i,t \qquad (12)$$

$$Pm\max_{i,t} = \frac{\left(SOC_i^{DES} - SOC_i^{INI}\right) \cdot h_{i,t} \cdot BC_i}{\eta_{ch}} \qquad (13)$$

$$\sum_{i=1}^{N} POP_{i,t}^{G2V} + Load_t + \sum_{i=1}^{N} dc_{i,t} \le TDC \qquad (14)$$

$$PV_t + \sum_{i=1}^{N}\left(1-u_{i,t}^{G2V}\right) \cdot POP_{i,t}^{V2G} + \sum_{i=1}^{N} uc_{i,t} = Load_t + \sum_{i=1}^{N} u_{i,t}^{G2V} \cdot POP_{i,t}^{G2V} + \sum_{i=1}^{N} dc_{i,t} \qquad (15)$$

$$uc_{i,t} = POP_{i,t}^{V2G} \cdot \left(1-u_{i,t}^{G2V}\right) \qquad (16)$$

$$dc_{i,t} = \min\left(Pm\max_{i,t}, P_i^{\max}\right) - POP_{i,t}^{G2V} \cdot u_{i,t}^{G2V} \qquad (17)$$

$$\mathrm{Re}venue = \sum_{i=1}^{N}\sum_{t=1}^{T}\left(dc_{i,t} \cdot RDP_t + uc_{i,t} \cdot RUP_t\right) + \sum_{i=1}^{N}\sum_{t=1}^{T}\left(M_k + EP_t\right) \cdot POP_{i,t}^{G2V} \cdot u_{i,t}^{G2V} \cdot h_{i,t} \qquad (18)$$

$$\deg_i = \left(0.042 \cdot Batc_i / 5000\right) + \left(0.15 \cdot \frac{\left(1-Ef_i^2\right)}{Ef_i}\right) \qquad (19)$$

$$Cost_{\deg} = \sum_{i=1}^{N}\sum_{t=1}^{T} \deg_i \cdot \left(1-u_{i,t}^{G2V}\right) \cdot POP_{i,t}^{V2G} \qquad (20)$$

$$Cost = \left(\sum_{i=1}^{N}\sum_{t=1}^{T} POP_{i,t}^{G2V} \cdot h_{i,t} \cdot EP_t^{RTP}\right) + Cost_{\deg} \qquad (21)$$

$$\max \mathrm{Pr}ofit = \max\left(\mathrm{Re}venue - Cost\right) \qquad (22)$$

(18) represents revenue earned by EVA due to provision of regulation and charging services. (21) indicates total operational cost as sum of procurement cost and battery degradation cost. EVA aims at profit maximization (22) in the problem. Selling price could be real-time price (without TOU-PBDR) or TOU price (with TOU-PBDR).

V. RESULTS AND DISCUSSION

Hourly electricity price is forecasted from California Independent System Operator (CAISO) using historical Locational Marginal price (LMP) data for day-ahead market [32]. EV arrival times are captured using travel time data related to trips with work of National Household Travel Survey (NHTS) [33]. It is assumed that workplace has capacity to charge 200 EVs. Gaussian normal pdfs of EVs arrival time, departure time, and initial SOC are generated using National Household Travel Survey (NHTS) data with respectively means (7,19,0.3) and standard deviations (2, 2, 0.1). The EVs charging characteristics are based on their specifications in the market as per 2018 statistics [34].

The EV battery information is summarized in Table I. V2G scheduling optimization is performed in GAMS [35]. It is solved by Interior Point Optimization (IPOPT) , MINLP solver.

TABLE I. EV CHARACTERISTICS

Vehicle	Battery Capacity (kWh)	Charger Capacity (kW)	Battery Cost ($)
Tesla Model S	80	15.4	13000

TABLE II. PERFORMANCE METRICS OF EVA WITH AND WITHOUT TOU-PBDR

	Without TOU-PBDR	With TOU-PBDR
Cost ($)	247.8389062	249.5389315
Profit ($)	414.7210377	423.7334832
Revenue ($)	662.5599439	673.2724148
Charging Cost ($)	413.7412	413.1113

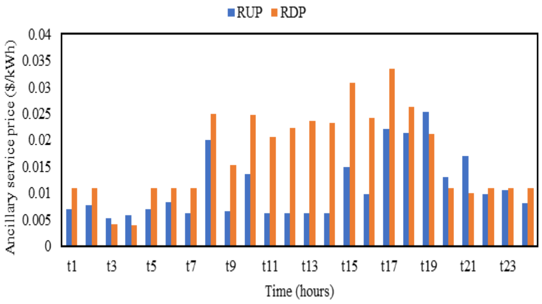


Fig.3 Prices of ancillary service from California Independent System Operator (CAISO) market

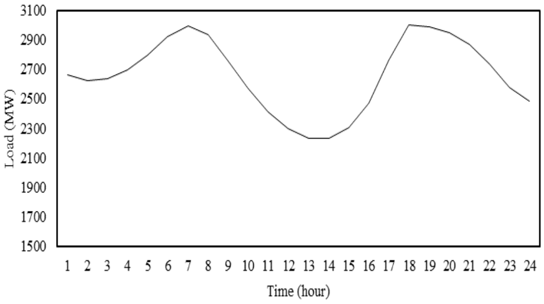


Fig.4. Base load profile from SO

Fig.3 depicts prices of ancillary service from California Independent System Operator (CAISO) market. Fig.4 is the forecasted base load profile from same market region CAISO. Output Power from PV based parking at workplace is shown in Fig. 5. Hourly energy prices and TOU prices designed from them are represented in Fig.6 and Fig.7 respectively. Table 2 represents performance metrics of EVA with and without TOU-PBDR. As it is clear that TOU-PBDR is more beneficial to EVA. EV owner's average charging cost reduces by 15%. EVA's profit increases by 2.173% which depends on variation of TOU (selling price) as compared to RTP (buying price). EVA earns more revenue from selling of regulation services.

EVA supports SO for maintaining grid stability and delays network reinforcement due to peak load management.

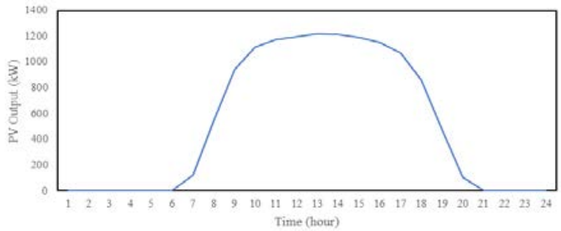


Fig. 5 Output Power from PV based parking at workplace

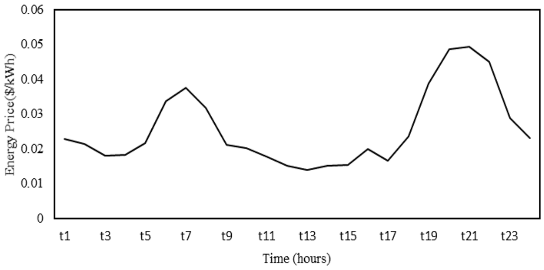


Fig.6 Hourly energy price in ($/kWh)

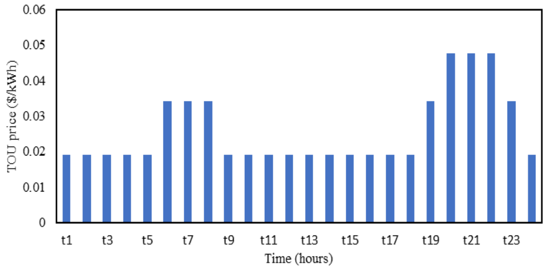


Fig.7 TOU price designed by EVA from hourly energy price in ($/kWh)

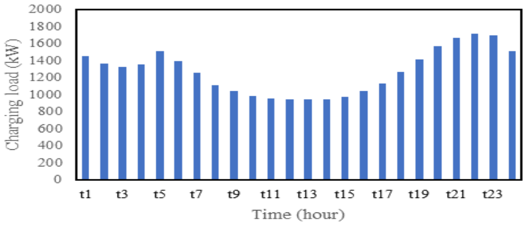


Fig.8 Charging load in kW

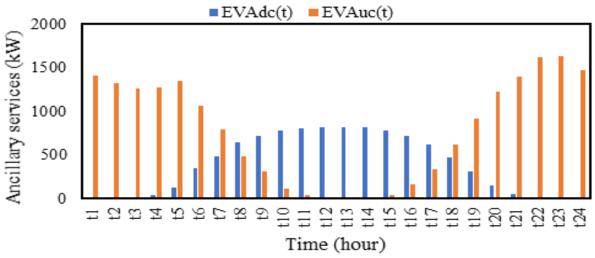


Fig.9 Ancillary services provided by EVA in kW

Fig. 8 illustrates aggregated EVs' charging load (kW) in response to offered TOU prices. Fig.9 depicts the regulation capacities provided by EVA. Fig. 10 represents performance metrics: revenue earned, cost incurred, and profit of EVA. It has potential to recover operational cost of V2G.

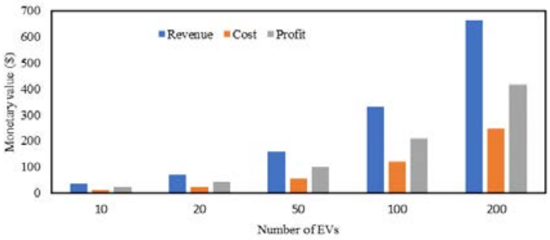


Fig.10 Performance metrics of EVA: Cost, Revenue, and Profit in $

VI. CONCLUSION

Proposed integrated TOU-PBDR V2G scheduling strategy has great potential to provide grid support regulation services by parked EVs. It recovers operational cost of EVA with self PVs generation, by the revenues generated from discharging EVs' stored energy to grid on peak hours. Simulation results validated the efficacy of proposed method in efficient utilization of PV output power to charge parked EVs and lessen the negative impacts on system. In addition, EV owners are satisfied with desired SOC at reduced charging tariff and battery health requirements. Thus, proposed work has capability to provide technoeconomic benefits to all involved entities: EVA, EV owners and SO.

As the future work, this paper can be extended by incorporating the effects of the satisfaction index of EV owners for charging EVs, mobility uncertainty, probability of unexpected trips, under dynamic V2G scheduling model. Further, EVA's financial risk due to uncertain market prices can be modelled to get trade-off among profit and risk.

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