Impact Assessment of Large Scale Integration of Electric Vehicle Charging Infrastructure on Distribution System

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***Abstract*— Energy requirements of power sector in India continue to rise due to urbanization, improvement in energy access, the growing transportation sector and industrialization. In light of the growing pollution problem, the Government of India (GoI), over the last few years, has been increasingly promoting alternative mobility solutions, chief among which are Electric Vehicles (EVs). The paper analyses the impact of large scale integration of electric vehicles on the distribution network by analyzing the sample feeders with different consumer mix in Delhi city. The number of electric vehicles at Delhi level, DISCOM (Distribution Company) level and sample feeders level are projected till the year 2030. The estimation of future projections are based on the available vehicle registration data, average kilometres run by each segment of vehicles, battery capacities and various electric vehicle policies by Government of India and other regulatory bodies at State and central level. Dynamic simulations are carried out considering various stochastic scenarios generated based on the characteristics of EV charging, roof top PV (Photo Voltaic) generation and Battery characteristics along with load variations over a period 24 hours period with time resolution of minutes. The following factors are analysed to find the impact of EV penetration levels on distribution grid: the effect on load pattern, system losses, transformer loading, voltage profile, network infrastructure and voltage regulation. The results and conclusions obtained from the sample feeders are extrapolated to the entire distribution grid system to assess the impact of large scale integration of EV charging infrastructure in terms of additional grid infrastructure and energy requirements etc.**

Keywords- Battery Storage, Dynamic simulation, Electric vehicles, , EV charging infrastructure, Grid infrastructure, Grid impact studies.

I. INTRODUCTION

Global warming is one of the environmental reasons for leveraging the large scale adoption of EVs as means of mitigation measure. The transport sector accounts for about 23% of global energy-related Green-House Gas (GHG) emissions [1]. The ambitious GHG emissions reduction required to limit global warming to less than 2°C is unlikely to be achievable without a major contribution from the transport sector. However, replacement of ICE (Internal Combustion Engine) vehicles by EVs is not sufficient to effectively reduce GHG emissions, if the electricity used to charge EVs is generated through power plants using fossil fuels instead of renewable generation. It will only shift fossil fuel consumption from the transportation sector to the electricity sector, hardly reducing the global emissions of GHG.

The integration of small quantities of EVs into the distribution grid will not impact the grid. However moderate to high penetration of EVs into distribution grid would most likely create some challenges in grid operation and management. The simulations studies are performed by referring the pilot EV studies reported in the literature. Impact assessment of varying penetrations of electric vehicles on low voltage distribution systems is assessed in literature [2]. A Monte Carlo method to evaluate electric vehicles impacts in distribution networks is discussed in [3]. EV charging stations consist of power electronic converters which generate harmonics, impact of Electric Vehicle Charging on power quality is addressed in [4][5]. Residential EV chargers or home charging devices are single phase chargers, voltage dependent charging strategies for single-phase electric vehicles in a distribution grid is addressed in [6]. Various barriers in incorporating EV to the distribution network are assessed [7]. Various policies in EV established countries have allowed the growth of EVs keeping the security of grid at a high level [8], [9], [10].

This paper analyses the impact of large scale integration of electric vehicles on the distribution network. The modeling of EV charging infrastructure is considered by building scenarios of charging station with combinations of slow, fast, rapid and high-power chargers. Each scenario further shall build network models to include solar rooftop and storage. Impact of EV load on existing feeder load over a period of time, energy consumed by EVs and losses due to EVs are assessed. The number of electric vehicles in the sample feeders are projected for the year 2030 based on the available vehicle registration data, average distance covered by each segment of vehicles in a day, battery capacities and various electric vehicle policies by Government of India, Government of NCT Delhi, Ministry of Power, Niti Ayog reports & FAME schemes. Projection of EVs under selected feeder for FY2030 is discussed. Impact of the EV charging infrastructure based on the charging pattern and number of charges in the selected feeder is presented.

II. METHODOLOGY

A. *Projection of EVs under selected feeder*

BYPL is one of the five Distribution Companies (DISCOMs) in Delhi, capital city of India. BYPL has shortlisted about 12 feeders emanating from different grid substations under its jurisdiction with the objective to assess the impact of EVs on the grid. Of the shortlisted feeders one feeder has been selected for simulation studies. Feeder selection is assessed by considering various aspects like existing EV charging stations in the feeder, solar rooftop penetration in the feeder, feeder loading, feeder voltage profile, priority for public charging stations, DT loading, consumer mix monthly energy consumption. Simulation studies are performed for various scenarios to understand the impact. Based on historical data available for vehicles in Delhi [11] from FY2014 to FY2018, CAGR growth of each vehicle category (IC+EV) are calculated and projected for future years up to FY2030. Cumulative EVs in the selected feeder for FY2030 is calculated in three stages.

Stage I: Considering various EV policies [12][13], percentage of sales of vehicles for every future year for each vehicle category is projected.
Stage II: Cumulative EVs in BYPL for FY2030 is projected corresponding to the ratio of number of electrical connections in BYPL to number of electrical connections in Delhi.
Stage III: Cumulative EVs in the selected feeder for FY2030 is projected corresponding to the ratio of number of electrical connections in the selected feeder to number of electrical connections in BYPL.
It is considered that for future years when the load increases in the feeder area, the additional load coming on to the feeder is shifted to a nearby feeder or a new feeder will be commissioned to accommodate the additional load. Hence the present peak demand on the feeder is maintained for the future years as present 11 kV feeder network cannot accommodate all future year load growth.

Based on the location, chargers are categorized as home charging, office/work charging, mall/parking charging, public charging station, dedicated charging and battery swapping. Rate of charge varies based on the location of the charger. However in the selected feeder only home charging, office/work charging, mall/parking charging and public charging station are considered for all the cases.

B. *Approximation of number of charges per day for projected EVs under selected feeder*

Based on vehicle category, battery size, efficiency, vehicle range, charging pattern of each vehicle category, initial SoC of EV, number of charges required per day for all the EVs under the selected feeder is calculated.

C. *Impact of EVs load on selected feeder*

For dynamic simulation of the selected feeder, annual peak load of the selected feeder is chosen to simulate for 24 hour simulation with minute wise resolution. Three phase unbalanced loads are modeled at poles of the selected feeder considering the HT and LT network. Three phase dynamic analysis is used to solve the simulated network using MiPower [14]. Based on the number of EVs projected and number of charges per day under the selected feeder, the EVs are distributed across the feeder under various distribution transformers for different time slots in a day by using stochastic distribution.

C.1. *Base case*

The distribution network is modeled with the selected load curve without EVs in the system and the feeder flows and transformer loadings are matched with the existing system condition observed from SCADA system. Fig.1 shows the network diagram of the sample feeder developed using MiPower [14], simulation tool used to solve power system networks both transmission and distribution.

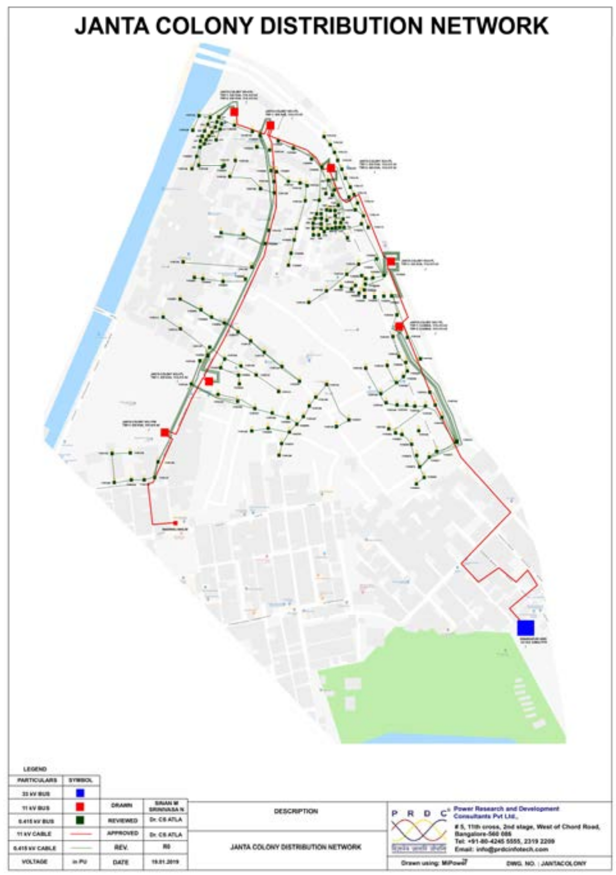

Figure 1: Network diagram of sample feeder

For the selected feeder, a peak load of 4.32 MW is observed for FY2019. Fig.2 shows the feeder loading under base case.

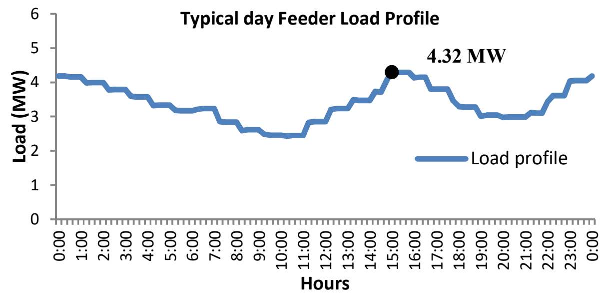

Figure 2: Feeder loading under base case

C.2. *Selected feeder with EV Penetration*

EVs are modeled on top of base case system and dynamic analysis is performed for a period of 24 hours. Considering the EV pilot experiences of western countries, it is found that EVs will get connected to charger with State of Charge (SoC) varies from 15% to 55%. However to find the maximum impact on distribution network, initial SoC of 25% is presented in the paper. TABLE I shows the EV battery sizes for FY2030 under various vehicle categories. Fig.3 depicts the number of EVs projected in the selected feeder and number of charges per day for each vehicle category. Fig.4 presents the EVs projected for various charging locations. TABLE II presents the stochastic distribution of EVs under each DT. Fig.5 shows the feeder load profile with EV loads.

From Fig.5, it is observed that EV peak load of 257.02 kW is observed at 20:30 hours and corresponding feeder loading is 2.99MW (8.6% of feeder load). Total energy consumed by feeder is 86.97 MWh with the contribution of 3.24 MWh by the connected EV loads, which corresponds to 3.73% of feeder daily energy consumption. Energy loss of 2.99% (with reference to feeder energy of 86.97 MWh) is observed.

TABLE I: EV BATTERY CAPACITIES CONSIDERED FOR YEAR 2030

Vehicle Category	*Battery Capacity (kWh)*	*No. of charges per year per vehicle*
2W	4	65
3W - PV	7	487
3W - CV	9	389
4W - PV	80	48
4W - CV	80	292
Bus	250	389

***Note**: 2W: two wheeler; 3W: three wheeler; 4W: four wheeler; PV: Private Vehicles; CV: Commercial vehicles*

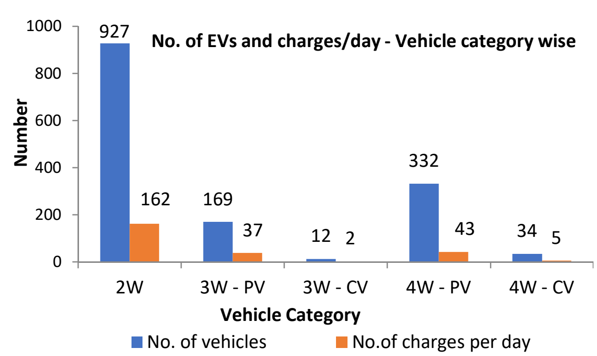

Figure 3: Number of EVs and charges per day - Vehicle category wise

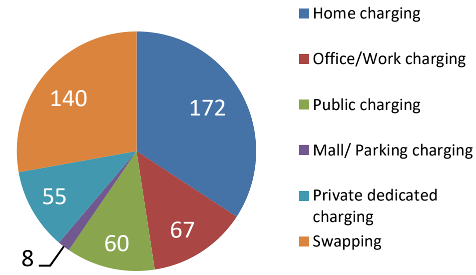

Figure 4: EVs projected under various charging locations

TABLE II: STOCHASTIC DISTRIBUTION OF EVS FOR EACH DT IN SELECTED FEEDER FOR FY2030

Random distribution of EVs under each DT		
Name of the Distribution Transformer (DT)	*No. of EVs plugged in a day*	*Cumulative battery capacity (kWh)*
DT 1	50	1176
DT 2	42	740
DT 3	32	822
DT 4	40	655
DT 5	34	763
DT 6	49	839
Total		4995

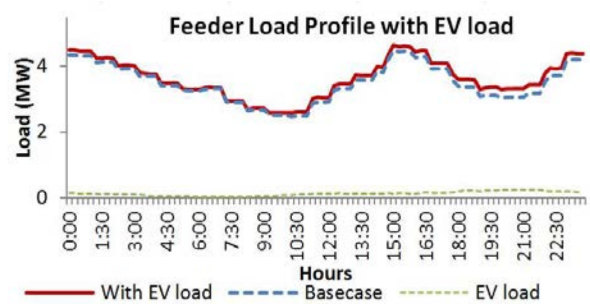

Figure 5: Selected feeder load profile with EV loads (with 25% initial SoC)

C.3. *EV Penetration and Typical Solar Rooftop Generation Profile*

This case is performed on top of base case with EV penetration and solar roof top generation. FY2030 solar rooftop penetration of 40% [15] is considered under each DT. Number of EVs, initial SoC and charges per day is same as considered in C.1. Fig.6 presents selected feeder load profile with EV loads and solar penetration.

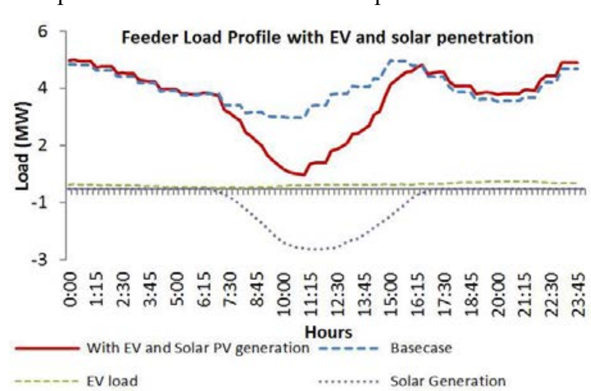

Figure 6: Selected feeder load profile with EV loads and solar penetration

From Fig.6, it is observed that peak load of the feeder is 4.5 MW at 00:15 hours and corresponding EV load is 152.71 kW. EV peak load of 257.02 kW is observed at 20:30 hours and corresponding feeder loading is 2.99MW (EV load is 8.6% of feeder load). Total energy consumed by feeder is 86.73 MWh with the contribution of 3.24 MWh by the connected EV loads, which corresponds to 3.74% of feeder daily energy consumption. Solar generation contributes to 12.75 MWh, as compared with feeder daily energy consumption of 86.73 MWh. Energy loss of 2.73% (with reference to feeder energy of 86.73 MWh) is observed in this case.

It is observed from the simulation study that the impact of EV charging during rooftop PV generation is minimum or nil. Feeder can take up more EV charging penetration during PV generation. The additional EV load can be taken up with PV generation by implementation of Time of Usage (ToU) tariff.

It may happen that solar generation at a particular DT may be greater than the regular load of the DT. At this point there may be reverse power flow through the specific DT. Similarly, if reverse power flow occurs in majority of DTs in the feeder, there may be reverse power flow at the grid transformer. Hence in case, DISCOM wants to control the reverse power flow at 33/11 kV grid transformer, the maximum solar PV penetration can be limited to minimum loading of 33/11 kV grid transformer during maximum rooftop generation time period. In other way, by enhancing protection settings and maintain harmonics within the limit, PV roof top penetration can be increased further. DISCOM can take a call on case-to-case basis.

C.4. *EV penetration with public charging*

The projected EVs under the category of public charging are considered in the simulation study. Considering the current regulations by MOP [16], it is considered that EVs in a public charging station with various capacities to accommodate the projected EVs (1x15 kW, 9x50 kW, 1x250 kW). The simulation is performed with total of 96 EVs of different vehicle segments charge at the public charger over a period of 24 hours. Fig.7 presents selected feeder load profile with EV loads and a public charger in the system.

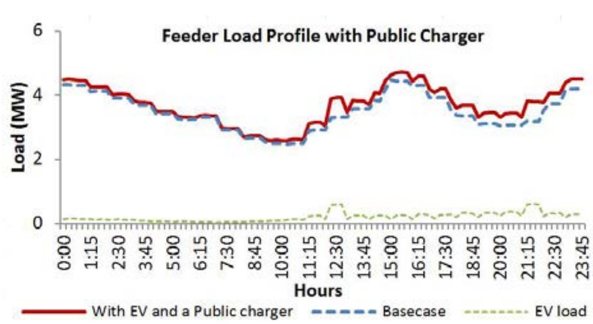

Figure 7: Selected feeder load profile with EV loads and a public charger

From Fig.7, it can be observed that peak load of the feeder is 4.72 MW at 15:30 hours and corresponding EV load of 264.12 kW. EV peak load of 611.5 kW is observed at 21:30 hours and corresponding feeder loading is 3.1MW (19.72% of feeder load). Total energy consumed by feeder is 88.55 MWh with the contribution of 4.8 MWh by the connected EV loads, which corresponds to 5.42% of feeder daily energy consumption. Energy loss of 2.97% (with reference to feeder energy of 88.55 MWh) is observed in this case.

C.5. *EV Penetration with Public Charger with ToU (Time of Usage) Tariff*

In order to assess the system with more aggressive adoption of EV by the year FY2030, total EVs in the selected feeder is considered with 100% more than projected. To evaluate the impact of EV plugins during PV generation, ToU is incorporated in this case. Vehicles charging at all places including public charger are made to plug-in during the time when solar is high. It is assumed that 80% of EVs will be connected to the grid during high solar period. Fig.8 presents selected feeder load profile with EV loads, ToU and solar penetration.

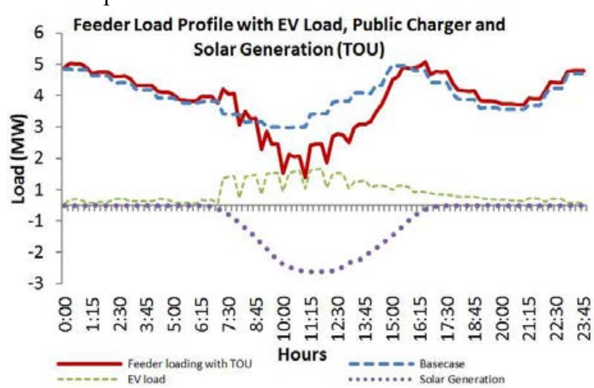

Figure 8: Selected feeder load profile with EV loads, ToU and solar penetration

From Fig.8, it is observed that most of the EVs are charging during high solar period and the stress on the system can be reduced during peak time. Peak load of the feeder is 4.58 MW at 16:30 hours and corresponding EV load of 403.26 kW is observed. EV peak load of 1173.4 kW is observed at 11:45 hours and corresponding feeder loading is 2.85MW (41.13% of feeder load).

Total energy consumed by feeder is 93.49 MWh with the contribution of 9.82 MWh by the connected EV loads, which corresponds to 10.5% of feeder daily energy consumption. Energy loss of 2.73% (with reference to feeder energy of 93.49 MWh) is observed in this case.

C.6. *EV penetration with solar generation, one public charger and grid storage element in the feeder*

To evaluate the need of storage system in the network, a battery storage system of 1MWh (200kW capacity) with 0.2C (5 hours of charging or discharging cycle) is considered. Fig.9 presents selected feeder load profile with EV loads, solar penetration and grid storage.

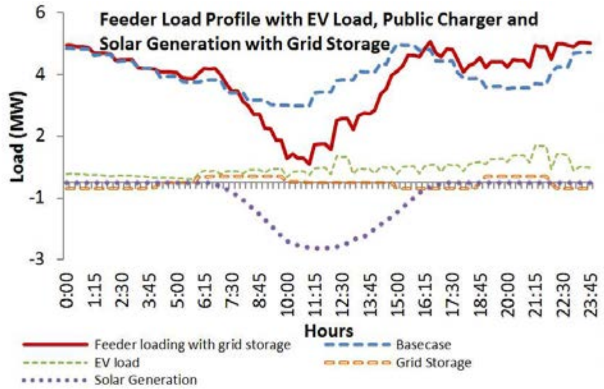

Figure 9: Selected feeder load profile with EV loads, solar penetration and grid storage

Peak load of the feeder is 4.56 MW at 16:30 hours and corresponding EV load of 573.55 kW is observed. EV peak load of 1206.1 kW is observed at 21:15 hours and corresponding feeder loading is 3.11MW (38.73% of feeder load). Total energy consumed by feeder is 92.65 MWh with the contribution of 10.82 MWh by the connected EV loads, which corresponds to 11.68% of feeder daily energy consumption. Energy loss of 2.76% (with reference to feeder energy of 92.65 MWh) is observed in this case.

Grid storage element can be utilized to store energy during high solar generation and discharge during peak time, reducing the load on the grid transformer and peak shaving. However, the economic feasibility of battery storage placement at feeder level needs to be looked into.

D. *Impact of EV penetration at DISCOM Level for 2030*

With the projected EVs in the DISCOM, overall impact on the DISCOM's energy requirement and peak load requirements are analyzed. Initial SoC of EVs is considered to be 25%. TABLE III presents the peak power consumed by EVs under each DT for one of sample feeders. Load factor of the same feeder for FY19 is observed as 52.6% (load factor = total energy consumption/maximum demand over a period of 1 year). From the simulation studies, peak power and energy requirement per day for EV charging is observed as 173.9 kW and 2348 kWh and same is presented in TABLE III.

TABLE III: Peak power by EV under each DT in sample feeder

DT Name	*Peak power with EV charging in kW*	*Energy consumption per day in kWh*
DT 1	21.79	100
DT 2	23.45	194
DT 3	24.16	275
DT 4	28.8	160
DT 5	3.55	45
DT 6	32.83	351
DT 7	24.04	234
DT 8	39.92	524
DT 9	31.88	246
DT 10	38.86	219
Total	269.28	2348

EV charging Load factor (for 24 hours) = average demand/maximum demand

$$= 2348/ (173.9*24) = 0.56$$

Hence, by comparing the load factor of EV charging behaviour (56%) and consumer regular load factor (52.6%), the charging behaviour of EVs is similar to the behaviour of regular loads used by consumers. Based on these observations, energy requirements at Distribution level are projected and same are presented in TABLE IV.

TABLE IV: ENERGY REQUIREMENT FOR EV CHARGING FOR DISCOM FOR THE YEAR 2030

EV type	*Battery Capacity (kWh)*	*Energy per charge (kWh)*	*No of EVs*	*No of Charges per EV per year*	*EV charging Energy in MU*
2W	4	3	509281	65	99
3W - PV	7	5.25	93083	594	290
3W - CV	9	6.75	6571	441	20
4W - PV	80	60	182467	48	526
4W - CV	80	60	18478	292	324
Bus	250	187.5	3547	389	259
Total					1517

Energy sales projected for DISCOM for FY2030 without EVs, considering a growth rate of 4.76% is 11022 MU. Additional energy requirement estimated with EV penetration for FY2030 is 1517 MU. Energy consumption by EV for FY2030 with reference to energy sales without EVs is 13.8%. Projected peak demand for the year FY2030 is 2943 MW (CAGR of 6% without EVs). Peak demand contribution of EVs considering current load factor (of DISCOM) of 0.48 is 361 MW. Demand contribution by EV for the year 2030 with reference to peak demand without EVs is 12.3%. During the planning for the network strengthening and energy sales, DISCOM has to consider the additional demand and energy imposed by EVs in future years. However the peak demand contribution can be reduced from 12.3% to below 5% by implementing ToU tariff or controlled charging mechanisms which has been observed from the simulation results.

III. CONCLUSIONS

From simulation studies and methodology proposed the following conclusions and recommendations are drawn for Distribution companies.

- Peak load due EV charging may not pose a significant toll on the existing business-as-usual infrastructure upgradation plan. The load factor from EV charging closely matches with DISCOM's other loads and hence can be planned on as is basis rather than a drastic change or investments.
- Irrespective of EVs growth rate, DISCOM shall be able to manage the load with right balance of network addition, ToU and strong backend for controlled/managed EV charging options.
- Bulk Grid Energy Storage for absorbing any impact from EVs or solar is not recommended and will not be viable in current economics. It should have a stand-alone business case for specific commercial application and when integrated into the grid.
- DISCOM should build and integrate strong back-end for its Grid to receive and send communication and control signals to EVs and their multiple

charging or energy operators to achieve the necessary grid balance.

- Devising separate EV tariff is a new trend to have price distinction on basis of type of loads within a single premise. This shall require the use of separate meters for EVs.
- As per the EV projections and EV charging patterns considered in the methodology, un-controlled EV charging will contribute around 13.8% of energy sales for the year 2030. Similarly, un-controlled EV charging will contribute around 12.3% of peak demand for the year 2030 for the DISCOM. Hence, it is recommended to adopt controlled charging and/or Time of day or Time of Usage tariff to minimize the impact on peak load. This will minimize the grid infrastructure cost considerably.
- From the simulation studies, it is observed that addition of solar roof top PV generation in the system and moving the EV charging preferences to day time will minimize the grid impacts and grid infrastructure.

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