

OPTIMAL ELECTRIC VEHICLE CHARGE SCHEDULING UNDER COLLABORATIVE FRAMEWORK

TUSHAR KUMAR¹ AND TRIPTA THAKUR²

ABSTRACT. Adoption of EVs for transportation in cities and suburban areas needs sound charging infrastructure. Planned scheduling and Charging can ensure benefits to both the customers as well as grid by efficiently managing the charging request. A day ahead scheduling scheme for EV charging is proposed by considering spatial-temporal properties of EVs. This framework is then tested on a 25-node transportation network for realistic traffic scenarios. Both inter aggregator collaboration and non-collaborative schemes are tested. Results for realistic traffic scenarios demonstrate that the proposed scheme for direct charging stations can increase the scheduling of EVs and profits for the aggregators.

1. INTRODUCTION

1.1. Background. Environmental concern and energy security are shifting world's attention towards renewable resources and electric mobility for sustainable development to finally curtail carbon emissions [1]. Uncontrolled charging which usually has been the norm till now, can impose significant impacts on the grid, especially increases the overall load in the power system if charging of EVs coincides with the peak demand of the system [2]. EV scheduling plays a significant role in mitigating issues related to power grid hence, scheduling must

¹*corresponding author*

2020 *Mathematics Subject Classification.* 74H15, 90C29.

Key words and phrases. Charging framework, Mobility Aware scheduling, Collaborative Charging.

be planned in a coordinated manner by service providers i.e. ‘aggregators’ in coordination with grid operator so as to suppress the negative impact of scheduling [3]. Relevant research from the perspective of collaboration is lagging and a robust charging framework is needed to take advantage of CS under collaborative scenarios. Many works are reported in the area of charge scheduling for EVs. Techniques such as First Available Scheduling (FAS), simulated annealing method, greedy local search that are employed to optimize the number of vehicles scheduled so as to minimize the peak charging activity along with the charging cost [4]. Many heuristic based algorithms are reported that analyses the charging pattern using customers behaviour [5]. In order to minimize the total charging cost of an EV owner, a decentralized algorithm is suggested [6] [7].

1.2. Objective of the present work. The objective of the research article is to present an idea of collaborative EV charging framework that is capable of solving various challenges for profit maximization of individual aggregator and mobility aware scheduling of vehicles requesting charging during peak load hours. Distributive charge scheduling scheme is compared against non-collaborative scheme so as to prove the efficacy of the proposed framework. All aggregators receive an incentive from other aggregators for their scheduled vehicle that increases the profit of all aggregator under collaboration scheme. The major contributions of this paper in scheduling framework are:

- (1) Analysis of direct charging and its effect on profits and percentage of EVs scheduled under collaboration and non-collaboration for realistic traffic scenarios.
- (2) Mobility aware scheduling for charging based on the travel route of the EV and its state of charge (SOC) limits

2. MATHEMATICAL FORMULATION FOR CHARGE SCHEDULING

In the 25 node transportation network [8] N_{agg} is considered for providing charge services with $N_{agg} = (Agg_1, Agg_2, Agg_3, \dots)$. Each Agg_i purchases a sum of total energy Enr_i^{pur} from the day ahead electricity market based on the number of scheduling requests received at the different station during a day a cost of $Pur_{E,i}^{cost}$. A list is prepared at subscribed $stn \in Stn_i$ for $b \in B_i$ in the form $(b, stn, a_{t,b}, d_{t,b}, En_{b,S}^{Min}, En_{b,S}^{Max}, Ch_{b,S}^{Min}, Ch_{b,s}^{max})$ based on the information

received before the start of journey to Agg_i . An EV may start charging at stn in the interval $a_{t,b} \leq s_{t,b} \leq d_{t,b} - Ch_{b,s}$ with an energy demand ($En_{b,S}^{Min} \leq En_{b,s} \leq En_{b,S}^{Max}$) are calculated as represented in the following equations :

$$(2.1) \quad En_{b,S}^{Max} = (FSOC_b - CSOC_{b,stn}) * Bat_m,$$

$$En_{b,S}^{Min} = (MSOC_b - CSOC_{b,stn}) * Bat_m.$$

The total profit Pr_{agg}^{total} is the sum of profit of all individual aggregators under non collaboration and collaboration scheme are written in Eq (2.2) and Eq (2.3):

$$(2.2) \quad Pr_{agg}^{total} = \sum_{i=1}^{N_{agg}} Pr_{i,NC}^{Agg},$$

$$(2.3) \quad Pr_{agg}^{total} = \sum_{i=1}^{N_{agg}} Pr_{i,C}^{Agg}.$$

Total revenue of an Agg_i is obtained in the form of total cost of charging imposed on $b \in B_i$ for its respective slot R_{st} of a charging outlet. Charging cost (Ch_{cost}^{max}) obtained from a vehicle for its $FSOC_b$ is estimated using Eq (2.4):

$$(2.4) \quad Ch_{cost}^{max} = \sum_{k=st_B}^{st_B + Ch_{B,S}^{Max}} En_{B,k}^{Slot} * slot_k^{cost}.$$

Total cost of purchased energy by an Agg_i under collaboration and non-collaboration scheme is calculated based on Eq (2.5) and Eq (2.6):

$$(2.5) \quad Pur_{E,i}^{cost, NC} = Enr_i^{NC} * E_{price},$$

$$(2.6) \quad Pur_{E,i}^{cost, C} = Enr_i^C * E_{price}.$$

If $EV b \in B_i$ is not still charged then Agg_i will check for another station ($stn_{chnng} \in Stn_i$) on the vehicle route with a discounted Charging cost ($Ch_{cost, stn_{chnng}}^{min}$) obtained from a $b \in B_i$ as shown in Eq (2.7):

$$(2.7) \quad Ch_{cost, stn_{chnng}}^{min} = \sum_{k=st_B}^{st_B + CH_{B,S}^{Min}} En_{B,k}^{Slot} * slot_k^{cost}.$$

Total cost of charging (Ch_{cost}^{mIn}) obtained from a EV $b \in B_i$ for charging up to $MSOC_b$ is estimated based on Eq(2.8).

$$(2.8) \quad Ch_{cost}^{mIn} = \sum_{k=st_B}^{st_B + CH_{B,S}^{Min}} En_{B,k}^{Slot} * slot_k^{cost}.$$

Total obtained profit of an aggregator (Agg_i) under non collaboration scheme is calculated using Eq(2.9):

$$(2.9) \quad \begin{aligned} Pr_{i, NC}^{Agg} = & \sum_{b \in B_i} \sum_{stn \in Stn_i} Ch_{cost}^{max} + \sum_{b \in B_i} \sum_{stn_{chnng} \in Stn_i} Ch_{cost, stn_{chnng}}^{mIn} \\ & + \sum_{b \in B_i} \sum_{stn \in Stn_i} Ch_{cost}^{min} - Enr_i^{NC} * E_{price}. \end{aligned}$$

Aggregator collaboration is employed to charge the EV that could not be charged at $stn \in Stn_i$. Total profit of Agg_i under collaboration scheme is estimated based on Eq (2.10):

$$(2.10) \quad \begin{aligned} Pr_{i, C}^{Agg} = & \sum_{b \in B_i} \sum_{stn \in Stn_i} Ch_{cost}^{max} + \sum_{b \in B_i} \sum_{stn_{chnng} \in Stn_i} Ch_{cost, stn_{chnng}}^{mIn} \\ & + \sum_{b \in B_i} \sum_{stn \in Stn_i} Ch_{cost}^{mIn} + \sum_{b \in B_j} \sum_{stn \in Stn_i} (Ch_{cost} + Prm_{cost}) \\ & - \sum_{b \in B_i} \sum_{stn \in \frac{Stn}{stn_i}} (Ch_{cost} + Prm_{cost}) - Enr_i^C * E_{price}. \end{aligned}$$

The main objective in the framework is to charge the maximum number of vehicles at different charging stations so as to maximize the total profit of aggregators using Eq (2.11) and Eq (2.12) :

$$(2.11) \quad \text{Maximize } P = \sum_{i=1}^{N_{agg}} Pr_i^{agg}$$

$$(2.12) \quad \text{Maximize } N_{sch} = \sum_{i=1}^{N_{agg}} N_i^B.$$

3. EV COLLABORATIVE HYBRID CHARGE SCHEDULING ALGORITHM

The algorithm inputs are (i) Number of charging outlets $C_{b, stn}$ at all $stn \in Stn_i$ along with their charging rate C_{rate} , (ii) price of energy for the day in 15 minute time intervals (iii) Rate for full charging, discounted rate for minimum charging and premium rate to be paid to other aggregators for collaborative charging, (iv) Request list for charging to every aggregator Agg_i in the form $[En_{b,S}^{Min}, En_{b,S}^{Max}, Ch_{b,S}^{Min}, Ch_{b,S}^{Max}, b, OD, a_{t,b}, d_{t,b}]$ from every subscribed EV $b \in B_i$. Time slots for charging are represented as a charging interval matrix $tslot_{stn}^i \subset \{0, 1\}^{s_{stn} \times T}$ Where, s_{stn} is the total number of charging slots in a station, T is the set of time interval. Before scheduling the EVs, the list L_i is sorted in descending order of their Average charging cost of an interval (ACCI)

$$(3.1) \quad ACCI = \sum_{s_{t,b}}^{s_{t,b} + Ch_{b,S}} cost / Ch_{b,S}.$$

The phase I consists of three stages as shown in fig.1. In stage 1 Agg_i receives the subscribed EV's travel information such as the origin location, destination, average speed of the EV and initial SOC ($ISOC_b$) at the start of the journey. The sorting of vehicle list is in descending order of their ACCI calculated from the Eq (3.1). EVs with higher ACCI are given higher priority. Based on the origin and destination of the EV, shortest path for the EV is calculated and a station under the Agg_i nearest to the origin location is assigned.

Then in the stage 2 Agg_i tries to schedule EV $b \in B_i$ for its maximum charging demand calculated by the Eq (2.1). Once the stage 2 is completed then for remaining unscheduled EVs in $minList_i$ stage 3 is operated. In this stage Agg_i tries to schedule the EV for the minimum charging demand calculated as $Ch_{b,S}^{Min} = \frac{En_{b,S}^{Min}}{C_{rate}}$. The remaining unscheduled EVs are then considered for the stage 4 in which the station nearest to the origin is checked for the availability of time slots for charging demand. If available then the main list L_i is updated with '1' and the EV b is removed from the $minList_i$. The charging cost for minimum charging demand is taken as per Eq (2.8).

In phase II $UsList_i$ consisting of the yet unscheduled EVs is sent to other aggregators. Once the EV list of Agg_i is received by Agg_j , stations under it that lie on the EV route are found out for each EV and time slots are checked for maximum charging demand. If the EV can be scheduled by the Agg_j then it

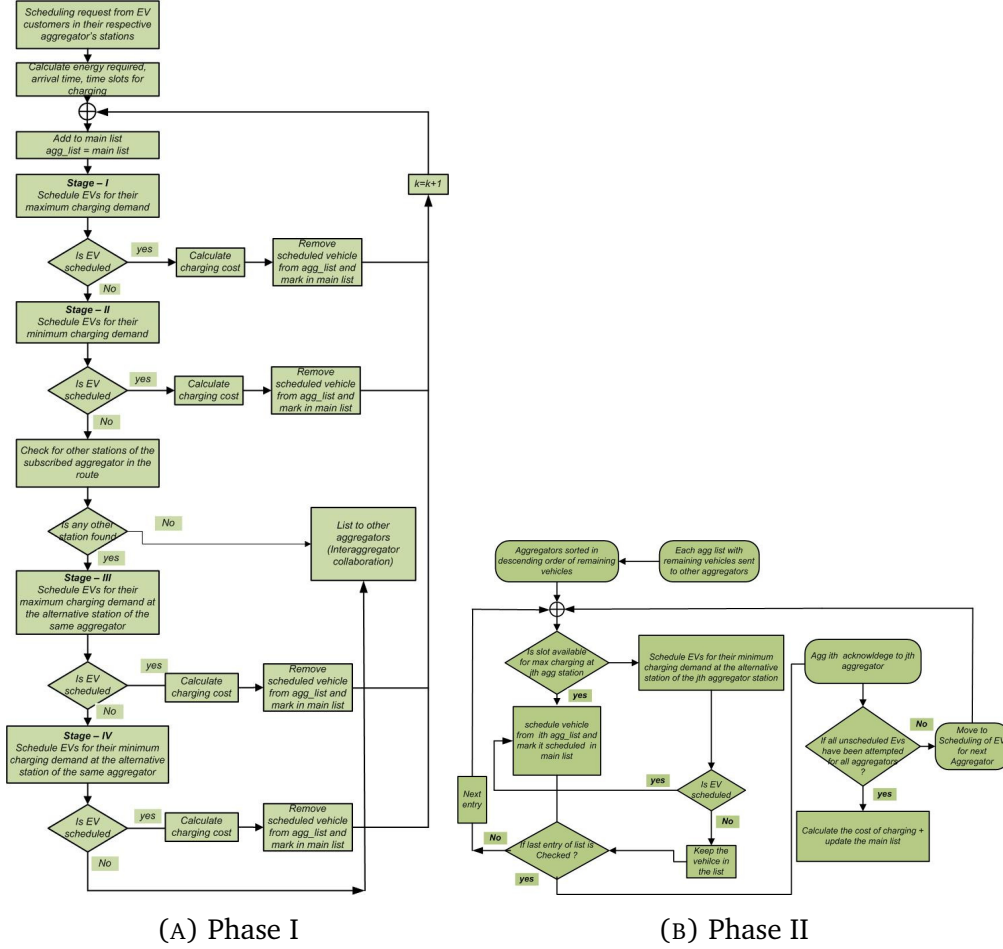


FIGURE 1. Flow chart of algorithm

sends '1' to Agg_i corresponding to scheduled EV and that EV id is removed from $UsList_i$ and Agg_j receives a premium value with the usual charging cost from the Agg_i .

4. RESULTS AND DISCUSSION

To model the spatial – temporal distribution of vehicles, origin-destination (OD) pairs are generated in a 25-node transportation network [8]. Each node has a weight assigned to it that relates to its tendency to attract traffic. The charging cost is based on the data acquired from Indian Energy Exchange [9]. For the simulation maximum battery capacity is taken to be 35 kWh and average speed between 30 to 50 km/hr. Initial SOC varies between 0.4 to 0.5. The

peak of vehicular traffic is observed to be occurring during mid-morning and evening hours [10]. A bimodal pattern for EV travel is generated as the EV users are more likely to charge their vehicles at public charging stations during the commute. Results for both collaborative and non-collaborative scheduling for the three traffic scenarios is presented. The total profit for the aggregators and percentage of scheduled vehicles is compared as the number of scheduling requests is varied from 5000 to 10000 per day.

4.1. Impact of collaboration on aggregator. The effect of the proposed framework on the profit of aggregators and percentage of vehicles scheduled for charging is analysed for two scenarios with both collaborative and Non-collaborative schemes. In Fig 2 for scenario 1 (non busy to busy traffic) the percentage of scheduled vehicles drops consistently for the non-collaborative scheme as the vehicle count on the network increases. Although the profit rises consistently for both schemes as shown in Fig 3, the margin of difference increases for the collaborative scheme as the vehicle count increases.

In Fig 4 for scenario 2 (busy to non-busy traffic) also the collaboration tends to improve the percentage of vehicles scheduled as well as the profits aggregators especially when the count of EVs to be scheduled is higher as in Fig 4.

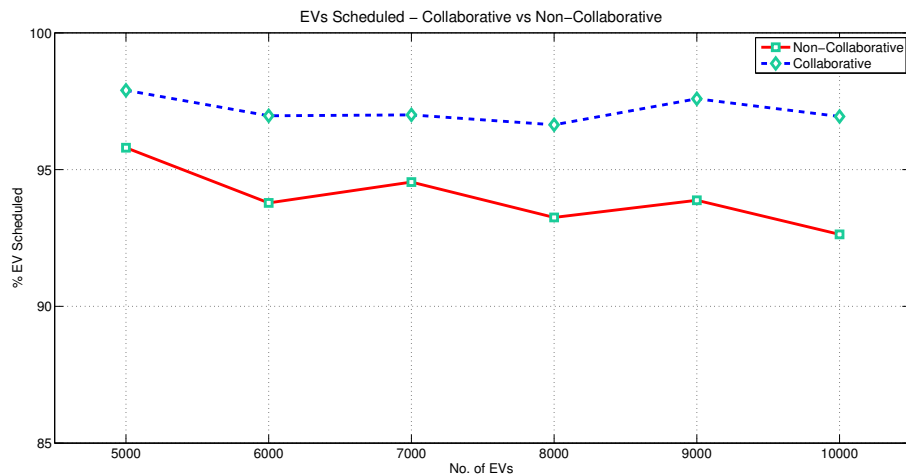


FIGURE 2. Percentage of EVs scheduled in non-busy to busy traffic scenario

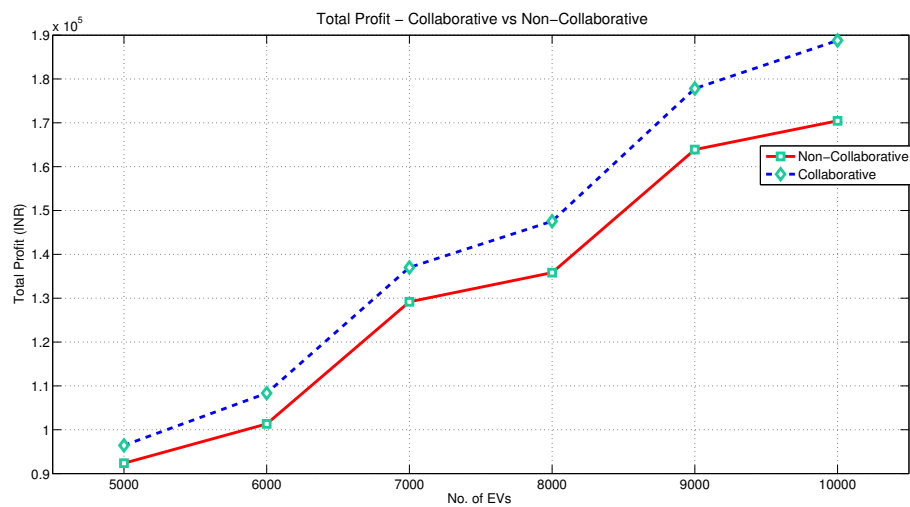


FIGURE 3. Total profit of Aggregators in non-busy to busy traffic scenario

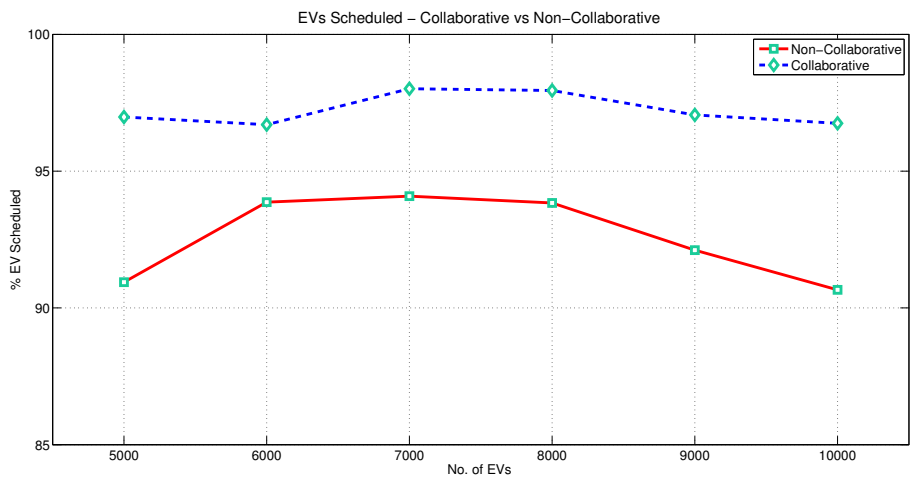


FIGURE 4. Percentage of EVs scheduled in busy to non-busy traffic scenario

4.2. Impact of EV count on aggregators. If a uniform random distribution of vehicle arrival is assumed then greater number of vehicles get scheduled as compared to a bimodal distribution. A bimodal distribution is a more realistic model of arrival of vehicles for charging as it considers the working hours in an

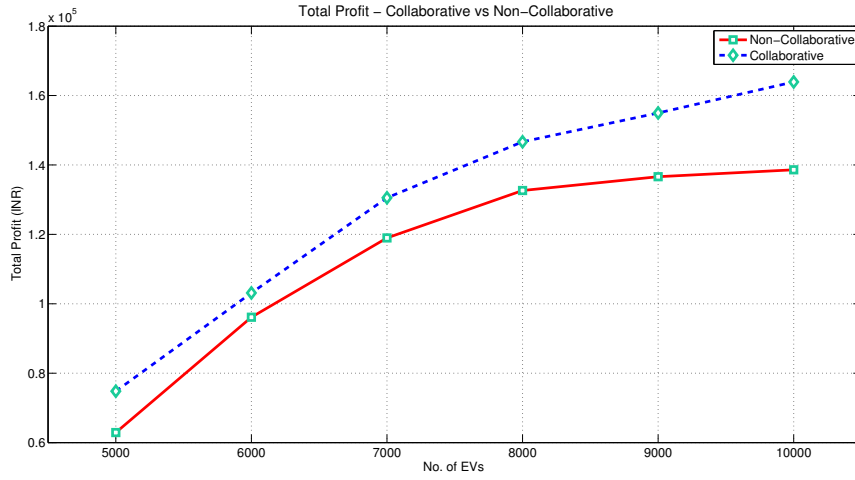


FIGURE 5. Total profit of Aggregators in busy to non-busy traffic scenario

industrial economy which starts in the morning and end at evening. Increase in number of scheduling requests results in an increased load on the service capability of the charging station. General pattern is that the increase in the EV count leads to a decrease in the percentage of scheduled EVs while the profit rises steadily. In case of the non-collaborative scheduling requests increases. Percentage of vehicles that get scheduled in case of the scenario 2 (busy to non-busy traffic) is lower since the number of busy nodes with weight above 50 is 9 which is less than the non-busy nodes. Hence when the origin destination pair combinations are considered in case of the busy to non-busy traffic scenario then more vehicles originate from fewer busy nodes may receive additional scheduling requests from the EVs during peak hours which can reduce the scheduling percentage.

5. CONCLUSION

A day ahead scheduling framework for charging EVs is proposed in this paper considering spatial and temporal properties of EVs. A 25-node transportation network is taken along with different traffic scenarios to test this process. Time slots considered for scheduling is based on the duration in which Indian energy exchange releases prices for particular areas. Non-collaborative scheme and collaborative scheme is compared and the effect on the number of scheduled

vehicles and overall profit of aggregators is demonstrated. Impact of increased vehicle count on the scheduling process is also analysed. Collaborative scheme performs better than non-collaborative scheme under every traffic scenario. The margin of improvement for collaborative scheme is even more when the vehicle count is high. Thus, effectiveness of the scheme is demonstrated under different traffic scenarios.

REFERENCES

- [1] M. PREMKUMAR, J.S.V. SIVAKUMAR, R.V. KRISHNA, R. SOWMYA: *Design, analysis and fabrication of solar pv powered bldc hub motor driven electric car*, Inter. J. Mecha. Produc. Engi. Res. Develop., **8**(1) (2018), 1255–1270.
- [2] R. SOWMYA AND V. SANKARANARAYANAN: *An Optimal Model for Electric Vehicle Battery Charging and Discharging Scheduling Strategy*, National Power Electronics Conference (NPEC) Tiruchirappalli, India, (2019), 1–6.
- [3] V.S. KADAM, R. SOWMYA, V. SANKARANARAYANAN: *Optimal Coordinated Charging Strategy for Electric Vehicles at Geographically Distributed Charging Stations*, National Power Electronics Conference (NPEC) Tiruchirappalli, India, (2019), 1–6.
- [4] N. JEWELL, L. BAI, J. NABER, M. L. MCINTYRE: *Analysis of electric vehicle charge scheduling and effects on electricity demand costs*, Energy Systems, **5**(4) (2014), 767–786.
- [5] M. ALONSO, H. AMARIS, J. GERMAIN, J. GALAN: *Optimal Charging Scheduling of Electric Vehicles in Smart Grids by Heuristic Algorithms*, Energies, **7**(4) (2014), 2449–2475.
- [6] C.K. WEN, J.C. CHEN, J.H. TENG, P. TING: *Decentralized Plug-in Electric Vehicle Charging Selection Algorithm in Power Systems*, IEEE Transactions on Smart Grid, **3**(4) (2012), 1779–1789.
- [7] L. YAO, W. H. LIM, T. S. TSAI: *A Real-Time Charging Scheme for Demand Response in Electric Vehicle Parking Station*, IEEE Transactions on Smart Grid, **8**(1) (2017), 52–62.
- [8] M. J. HODGSON: *A Flow-Capturing Location-Allocation Model*, Geographical Analysis, **22**(3) (1990), 270–279.
- [9] IEX: *Indian Energy Exchange Limited*, Day ahead prices Available: <https://www.ixindia.com/marketdata/areaprice.aspx>.
- [10] S. Á. FUNKE, T. GNANN, P. PLÖTZ: *Addressing the Different Needs for Charging Infrastructure: An Analysis of Some Criteria for Charging Infrastructure Set-up*, In: Leal Filho W., Kotter R. (eds) E-Mobility in Europe. Green Energy and Technology, Springer, Cham, (2015), 73–90.

^{1,2} ELECTRICAL ENGINEERING DEPARTMENT, MAULANA AZAD NATIONAL INSTITUTE OF TECHNOLOGY BHOPAL, BHOPAL, MADHYA PRADESH, INDIA

Email address: ¹tusharkumar1729@gmail.com

Email address: ²tripta_thakur@yahoo.in