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Coordinated Siting and Sizing of Electric Taxi Charging Stations Considering Traffic and Power Systems Conditions

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***Abstract*—Electric Vehicles (EVs) have gained increased attention courtesy their potential to mitigate environmental issues associated with transportation. To integrate EVs in transportation and power networks, it is essential to properly perform the siting and sizing of charging stations. In particular, this task is more challenging for users that have more rigid schedules such as taxi drivers. This paper proposes a coordinated siting and sizing methodology for electric taxi (ET) charging stations considering both transportation and power system constraints. The case of Quito, Ecuador has been analyzed. The results indicate the optimal placement of the ET charging stations and the number of charging spots to be installed.**

***Index Terms*—Charging Station, Electric Vehicle, Mixed-Integer Linear Programming (MILP), Power Distribution Systems, Siting and Sizing, Transportation Network**

NOMENCLATURE

Indices

i, j	Index for nodes in transportation network
k	Charging station index
s	Electrical substation index
v	Electric Taxi index

Parameters

β	Weighted resource leveling
$\Delta D_{k,k+1}$	Resource leveling term between consecutive charging stations
ΔT	Time Interval where taxi drivers are available to charge their ETs
η	Charging efficiency of the spot [%]
ω	Monetary value of travel time
$\overline{N_{ch}}$	Upper limits of number of charging spots in each charging station
$\overline{P_{ch}}$	Maximum charging power rate for charging station [kW]
$\underline{N_{ch}}$	Lower limits of number of charging spots in each charging station
DT_k	Mean travel distance of station k
E_{av}	Average daily electricity energy required by each ET v [kWh]
E_{req}	Total electricity energy required to supply to charge all the ETs [kWh]
N_V	Number of interest locations for ET charging stations
P_a^F	Feeder capacity at link a [kW]

Sets

$\mathcal{E}$	Set of edges
$\mathcal{K}$	Set of charging stations
$\mathcal{N}$	Set of nodes
$\mathcal{S}$	Set of electrical substations
$\mathcal{V}$	Set of electric taxis

Variables

C^{it}	Installation costs [\$]
C^{m}	Material costs [\$]
C^{w}	Workforce costs [\$]
C_k	Total investment cost for a charging station k [\$]
C_k^l	Land cost for each charging station k [\$]
C_k^{tr}	Travel cost for each charging station k [\$]
n_k	Number of charging spots at charging station k

I. INTRODUCTION

Electric Vehicles (EVs) have emerged as a promising solution to mitigate environmental issues in transportation, mainly the emission of GHG from fossil-fuel combustion. They are much more efficient than internal combustion vehicles (ICVs), do not pollute locally, and their global pollution is, in general, lower especially with a generation portfolio including renewable energies [1].

EVs present various challenges in the future that must be addressed. It has been demonstrated that a massive introduction of EVs generates grid issues such as power losses, voltage drops, voltage deviations, among others [2], [3]. Thus, power grid constraints must be taken into account while proposing charging strategies. Furthermore, EVs present a limited driving range compared with ICVs, which creates fear for EV users to do not have enough electrical energy in the battery to finish the trip, which is known as "range anxiety". In particular, range anxiety issues could be worse for taxi drivers, whose behavior in terms of charging must be much less flexible.

Various works have been conducted for investigating EV charging stations. In particular, various works have investigated the operation and scheduling of EV charging stations [4], charging navigation systems for EV charging stations [5], transportation and electric power networks [6], [7].

Several works have already studied the siting and sizing of EV charging stations. For example, in [8], the multistage placement of EV charging is studied considering incremental EV penetration rates. The authors of [9] propose a two-stage stochastic programming model for planning EV charging stations. In [10], an optimization model, based on the charging station coverage and the convenience of drivers is formulated. The authors of [11] assume a station in the EV charging station planning problem, which is an investor who intends to maximize its profit in a competitive environment. In [12], chicken swarm optimization is used for the charging station placement problem. However, these works have mainly considered Power System Conditions and not Traffic constraints.

Some other works have only considered mainly traffic constraints with no or few power grid constraints. For example, in [13], the optimal location of the EV charging station was obtained based on real vehicle travel patterns. The authors of [14] use pile assignment for the charging station placement problem.

So far, just a few works have investigated the coupled power and traffic siting and sizing for EV charging stations. For example, in [15], the siting and sizing problem includes power and traffic systems constraints; however, this work did not consider the land cost in the placement conditions. The authors of [16] study the optimal location and sizing of fast-charging stations. In [17], a graph automorphic approach is considered for the placement and sizing of charging stations. The authors of [18] propose a graph-computing based integrated location planning model, which maximizes PEV charging convenience while ensuring the power grid's reliability. In [19], the multi-objective synergistic planning of EV fast-charging stations is proposed in the distribution system.

Although these works and others have been proposed for the siting and sizing of EV charging stations, their attention has been devoted to private cars. In particular, many of these works consider the installation of fast-charging stations, which degrades the battery. However, less attention has been devoted to the siting and sizing of charging stations for electric taxis (ETs). In particular, their needs in terms of time and location are different from private users. For example, it is not technically correct to install only fast-charging stations for ETs, since the battery could be useless in less time. Thus, slow charging stations have to be planned considering the pauses of ETs and the requirements in terms of energy.

Furthermore, most of these works discuss theoretical rather than practical case studies, using limited and assumed data, rather than real data from real electrical companies and transportation conditions. Thus, this work proposes the coordinated siting and sizing of ET charging stations considering real traffic and power systems conditions.

The rest of the paper is organized as follows: Section II describes the methodology for siting and sizing ET charging stations. Section III presents the case study and assumptions. Section IV discusses the results. Finally, Section V highlights the main conclusions of this work.

II. METHODOLOGY FOR SIZING AND SITING CHARGING STATIONS

A. Transportation Modeling

In order to prototype a transportation system, two conditions are necessary: (i) an underlying structure, i.e. the city street network, usually modeled as a grid, and (ii) a traffic flow model. In this work, the street network of the city of Quito was extracted using the Python library Open Street Maps to network x (OSMnx) [20]. OSMnx returns a graph $\mathcal{G} = (\mathcal{N}, \mathcal{E})$ where interest points of the city represent the set of nodes $\mathcal{N}$ and the streets connecting such points are set of the edges $\mathcal{E}$, which are ordered pairs of elements of $\mathcal{N}$. The extracted network is trimmed using the edge length as a criterion. The graph $\mathcal{G}$ can be represented as the adjacency matrix D, where the elements $d_{ij} < p_{75th}$ become zero; in other words, only the top 25% of edge lengths were kept in the network. Here d_ij represent the driving distance (in Km) between nodes in a weighted adjacency matrix. From the trimmed network, an Origin-Destination ($\mathbf{OD}$) time matrix is obtained, where the traffic flow in driving time (minutes) between nodes f_{ij}, is extracted using the Google Distance API [21]. The $\mathbf{OD}$ matrix is summarized at node level, where the node degree:

$$x_a^{tot} = x_a^{in} + xk_a^{out} \tag{1}$$

with:

$$x_a^{in} = \sum_j f_{ij} \tag{2}$$

and:

$$x_a^{out} = \sum_j f_{ji} \tag{3}$$

That is x_a^{tot} measures the traffic flow of each point a which will be the candidates for charging stations.

B. Problem Formulation

A number of N_V of candidate charging stations is obtained. For each ET charging station k, a decision variable is defined for the number of charging spots n_k. Moreover, for each charging station, the search space for the number of charging spots is performed. The objective is to minimize the investment costs for installing public charging stations for ETs while. This work considers the travel cost of ETs in the total costs since it is a crucial incentive for taxi drivers to purchase EVs.

The total cost for the sizing of the charging stations includes a typical fixed installation cost, a land cost, and a trip cost, which is defined for each charging station k:

$$C_k = C^{it} + C_k^l + C_k^{tr} \tag{4}$$

The land cost is variable since each interest point is located in zones with different land prices.

The installation cost is defined:

$$C^{it} = C^m + C^w \tag{5}$$

The two terms are fixed costs. The first term corresponds to the material costs, which include the electric equipment and the charging spot costs. The second term is the workforce for building parking with charging spots.

The trip cost is a variable term defined for each charging station k:

$$C_k^{tr} = \omega \cdot DT_k \tag{6}$$

The objective is to minimize the sizing costs of the ET charging stations, as formulated:

$$minC = min \sum_{k \in \mathcal{K}} n_k \cdot C_k \tag{7}$$

Subject to:

$$n_k \cdot \overline{P_{ch}} \leq P_s^F \tag{8}$$

$$\underline{N_{ch}} \leq n_k \leq \overline{N_{ch}} \tag{9}$$

$$\sum_{k \in \mathcal{K}} n_k \cdot P_{ch} \cdot \eta \cdot \Delta T \geq E_{req} \tag{10}$$

$$n_{k+1} - n_k \leq \beta \cdot \Delta D_{k,k+1} \tag{11}$$

Constraint (8) imposes the electrical substation capacity limit of each charging station k belonging to a substation $s \in \mathcal{S}$. Constraint (9) defines the minimum and the maximum number of charging spots in each charging station. Constraint (10) guarantees that the total required energy by all the taxi drivers could be supplied by all the charging stations during the time horizon that the taxi drivers are free to stop and charge their EVs. Constraint (11) is a ramp-up limit between each charging station, which indicates that a maximum difference of charging stations should exist between the shortest driving distance, to avoid the taxi driver perform long distances if a charging station has all their spots in use. This problem can be solved by a mixed-integer linear optimization.

III. Case Study and Assumptions

The case study of Quito, Ecuador was selected, according to the willingness of the city Mayor to replace progressively internal combustion taxis with EVs. In particular, Quito is situated at 2,800 altitude meters, so due to the high altitude, the combustion in the vehicles is very inefficient resulting in major pollution concerns. Taxis are one of the main sources of traffic and noise, so it is crucial for the majors to propose cleaner transportation.

A. *Potential locations of ET charging stations*

In the previous work [22], the urban traffic flow mapping of Quito was performed, and various potential candidates for ET charging stations were selected. For this work, 10 candidate places are selected based on their minimum average time. Fig. 1 depicts the mean traffic times as a heatmap layer over the north-center of the city of Quito, and the potential locations of the 10 selected charging stations. A full connected graph for the 10 selected spots is build using driving traffic distances extracted from the Google API. A Hamiltonian cycle visits each node once while minimizing the total driving distance of the found cycle. Fig. 2 depicts the Hamiltonian cycle connecting the 10 selected charging stations. Each interest point has a different land cost. The interest points with minimum flow time selected are summarized in Table II with their respective land cost.

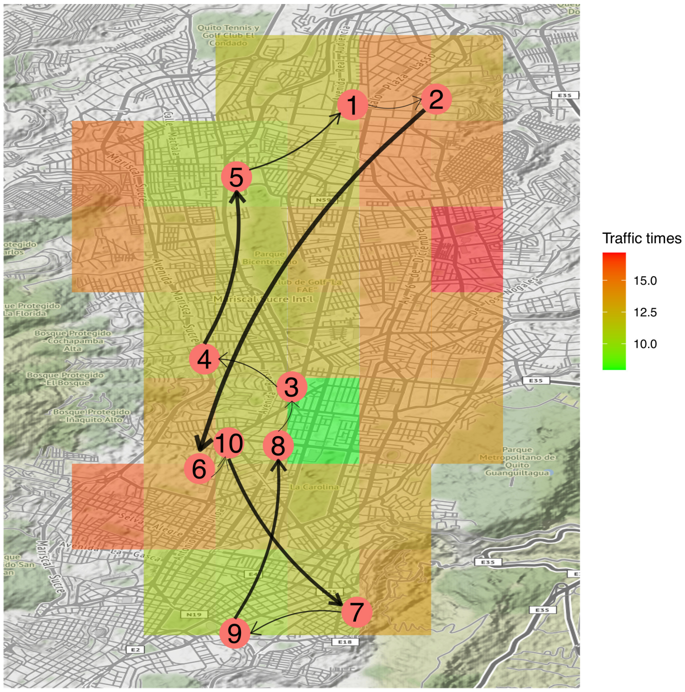

Fig. 1. Potential location of charging stations.

TABLE I

Interest points with minimum flow time selected as prefeasibility stations.

node	mean time [min]	land cost [\$/m^2]
1	6.45	1130
2	7.03	1400
3	8.48	780
4	10.42	600
5	9.07	1200
6	10.01	950
7	9.75	1300
8	7.94	780
9	8.41	2000
10	8.43	780

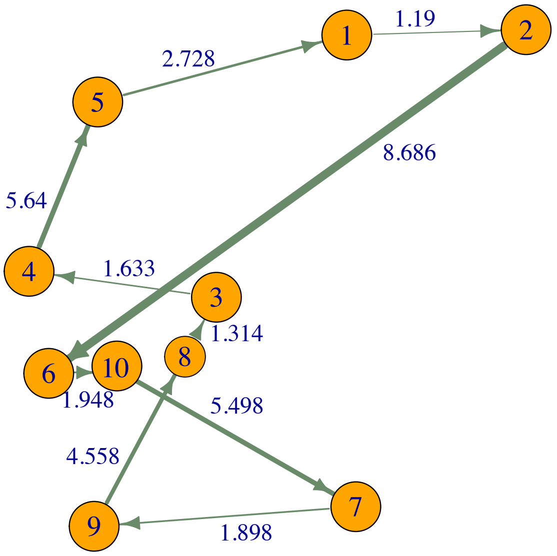

Fig. 2. Potential location of charging stations and Hamiltonian cycle connecting them.

B. ET Charging Parameters

In Quito, there are 8,633 taxis. There are very few ETs in Quito, so the charging behavior must be modeled to obtain a charging load curve for the optimal sizing of each charging station. To this end, real information from driving behavior based on GPS was obtained from taxi drivers in Quito [23]. A conversion rate from gasoline to electricity was used. The assumed required electricity energy by number of taxis resulted in an approximate Weibull curve with an average required energy 30 kWh of required energy per taxi. Moreover, it should be noted most of the taxi drivers make a pause from 3PM to 8PM after lunch and where there are few passengers. This implies based on the previous driven distance that 50% of the required energy should be supplied during this time, where the assumed peak load is observed. Thus, the energy required from eq. (10) results in:

$$E_{req} = \sum_{v \in \mathcal{V}} v \cdot E_{av} \tag{12}$$

The BYD e5 model was chosen to represent the taxi driver population since a few ETs have already purchased in Quito and in other cities in Ecuador [24]. This EV has a charging power of P_{ch}=22 kW and the charging efficiency η was assumed to be 90 % [25].

The fixed investment cost of each charging spot including the materials and the workforce is assumed to be \$ 3000, based on quotations [26]. The surface of the land used for each parking lot is assumed to be 20 m^2.

The minimum number of spots n_k in each charging station k is assumed to be 10 and the maximum 100.

C. Model Simulation

In this work, GAMS 33.1.0 with CPLEX were used to perform the simulations of the proposed MILP model, in an Intel Core i7-8700 with 32 GB of RAM [27].

IV. RESULTS AND DISCUSSION

Three different scenarios were studied, which consider different penetration levels of EVs (30%, 40%, and 50%).

A. Number of charging spots

In Table II, the total number of charging spots and their respective costs are summarized for an ET penetration of 30%.

The station with less charging spots is the 9, with 10 charging spots, since the land cost is the highest. The station with more charging spots is the 3, with 100 charging spots, since the land and travel costs are low.

TABLE II
NUMBER OF CHARGING SPOTS AND COSTS OF EACH CHARGING STATION FOR AN ET PENETRATION OF 30%.

Station	Number	Cost [k\$]
1	54	2252.48
2	14	679.98
3	100	3981.00
4	65	2667.93
5	38	1887.56
6	19	893.29
7	10	533.83
8	28	1076.46
9	10	640.15
10	55	2182.68
Total	393	16795.33

Fig. 3 depicts the number of charging spots in each charging station for three different scenarios with penetration levels of 30%, 40%, and 50%. Note that many charging stations reach their number limit or power limit since 30% of ET penetration level. An increase in ET penetration levels leads to an increase in the number of charging spots where the investment costs are higher. Moreover, 393, 524, and 654 charging spots must be installed in total for respectively ET penetration levels of 30%, 40%, and 50%.

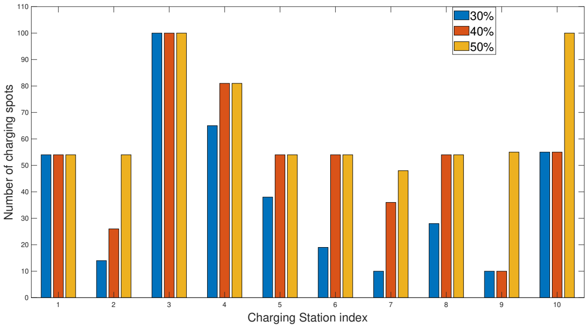

Fig. 3. Number of charging spots in each charging station for three different ET penetration levels.

In Fig. 4, the investment costs for each of the three scenarios (ET penetration level of 30%, 40%, and 50%) are illustrated, considering each component of the investment cost.

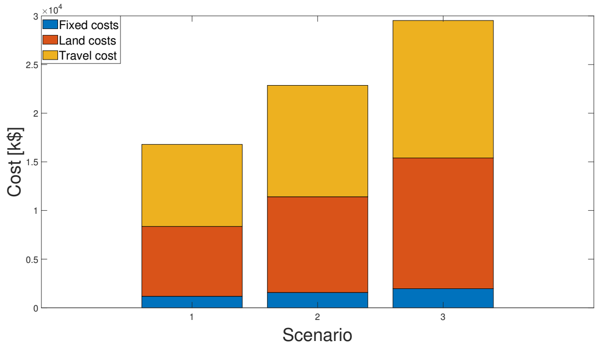

Fig. 4. Potential location of charging stations.

B. Sensitivity Analysis

To address the uncertainties considering the possible travel costs and constraints, a sensitivity analysis was performed for the parameters ω and β. Thus, the parameter β is adjusted from 5 to 15 by increments of 1. The parameter ω is adjusted from 500 to 5,000 by increments of 500. The results of this sensitivity analysis is illustrated in the surface plot in Fig. 5 for an ET penetration level of 30%. Note that the parameter β has a stronger influence in the investment costs than the parameter ω.

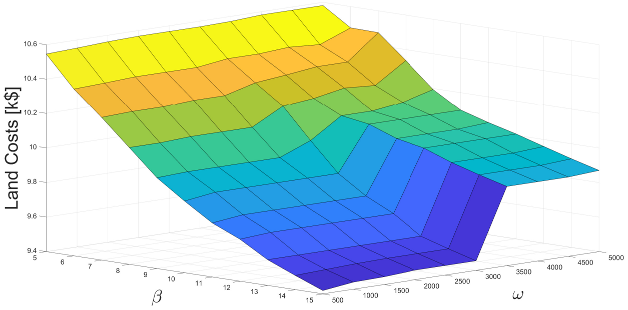

Fig. 5. Investment costs depending on β and ω.

C. Discussion

Since existing input data is available such as traffic flows, land costs, charging station costs, one can assume good results for the sizing and siting problem of ET charging stations. The primary source of uncertainty is the number of ETs on Quito's roads, which will create some investment concerns while implementing ET charging stations.

It is also essential to consider government policies for purchasing ET charging stations, which influence the success of installing charging stations [28]. Some of the policies include financial and fiscal, regulatory, and education and awareness [29]. Furthermore, consumer preferences have to be highly taken into account since it has a positive effect on the promotion of EV infrastructures [30].

Another point that should be considered is the accuracy of the modeling of the electric power systems. Equation (8) provides valuable information for not creating grid issues; however, it does not provide enough information concerning observability over congestion and voltage problems [31]. Thus, this should be clearly addressed in future work.

V. CONCLUSIONS

This paper presents the coordinated siting and sizing of ET charging stations considering traffic and power systems conditions. The case study of Quito, Ecuador is considered.

Ten charging stations are selected based on a transportation network, which are classified based on the meantime. For each charging station, various traffic and power grid constraints are taking into account to minimize the total investment costs. The results indicate the optimal number of charging spots to be installed in each station. A sensitivity analysis was also carried out to address the uncertainties of travel costs and constraints.

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