Optimal Siting and Sizing of Public Charging Stations in Urban Area

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Abstract

Electric Vehicles (EVs) have achieved a significant development because of the continuous technology revolution and policy supports in recent years, which leads to a larger demand of EV charging stations (EVCSs). Strategies about optimal siting and sizing of public EVCSs are urgently needed in order to further assist the development of EVs. This paper focus on the return of investments on EVCSs and proposes a Mixed Integer Linear Programming (MILP) model based on Geographic Information System (GIS) to identify the optimal location and size of EVCS in cities. Traffic flow data, aggregated charging profiles and land-use classifications are used as important inputs together with important constraints, are included in the MILP model with the objective function of maximizing the total profits of new charging stations. The effectiveness of the proposed method is then demonstrated by implementing a case study in Västerås, Sweden.

Keywords: electricity vehicle, GIS, charging station, traffic flow, MILP

Nomenclature

Abbreviation
EV Electric Vehicle
EVCS Electric Vehicle Charging Station
GIS Geographic Information System
ICE Internal Combustion Engine
SOC State of Charge
MILP Mixed Integer Linear Programming
OSM Open street maps
NHTS National Household Travel Survey

1. Introduction

Electric vehicles (EVs), as a kind of sustainable means of transportation, have shown benefits of reducing fossil fuel consumption, low emission to environment, energy efficiency and noise mitigation. Thus, developing EVs is regarded as a promising way to tackle the issues related to the fossil resource depletion and global climate change [1]. With continuous technology revolution and government policy supports, EVs have achieved a significant development during recent years. Global cumulative sales of EVs reached one million in September 2015 and this number was doubled by the end of 2016 [2]. Moreover, various regulations and financial incentives have been proposed by governments and related organizations to promote the development of EVs. Ten leading EV countries, including Canada, China, France, Germany, Japan, the Netherlands, Norway, Sweden, the U.K and the U.S had set a collective goal of 30% market share for EVs in 2030 [3].

EVs have become the most popular mode of new energy automobiles, and they are expected to become substitutes for internal combustion engine (ICE) vehicles. However, EVs depends on batteries of which the technology of capacities and charging speed evolve slowly. The lack of EV charging stations (EVCSs) has become one of the most crucial obstacles faced by EVs when they compare with regular motor vehicles in an analogical range and safety awareness. Thus, to promote the penetration of EVs, how to appropriately deploy charging infrastructures, particularly public EVCSs in cities, becomes an important issue.

Many studies are emerged in the deployment of public charging stations. Most of the existing literatures are network design problems [4-8] and usually using traffic flow volume or vehicle ownership density to estimate charging demand, which is quite similar to the refueling station planning. However, fully recharging the battery
on an EV can take a much longer time than refueling liquid fuels, from 30 min to several hours depending on the charger power, battery size, and the state of charge (SOC) of the battery. EV charging is more likely to happen at the end of a trip instead of in the middle of a trip, which indicates the importance of travel patterns in EVCS usage. In addition, some EV owners can charge their vehicles at home during the night, the charging behavior of EVs varies at different types of locations and different periods. Thus, the charging demand, especially out-home demand, of EVs should be considered with the land-use of the public EVCS coverage area and the types of chargers, i.e. slow or fast charging. The EVCSs deployment with charging demand that integrated with travel data was implied in [9], where the focus was on taxis travelling, as well as [10], where the model just considered home arrival time of travel patterns. As a result, the EV charging profiles which related to real-world travel patterns and charging behaviors is essential for the optimal siting and sizing of public EVCSs.

Unique constraints and objectives have been included in the optimization models regarding the allocation of charging infrastructures. Driving range of EV batteries [11], range anxiety and distance convenience of users [12], and the distribution system and renewable sources [13, 14] are considered as decision making criteria for EVCS planning. Most studies focus on the service ability of the charging infrastructures, and the purpose of these models is to meet as much as charging demands, i.e. a maximum coverage problem, in the study area [5, 15, 16] or to achieve highest utilization rate of the chargers [17, 18]. Although there are also some studies exploring the economics of the EVCSs, most of these focus on the construction costs of stations [4, 19, 20] and the access cost of drivers [8, 10, 12, 21], rather than the return of operations of the charging stations. However, studies on how to allocate charging stations geographically in order to gain maximal profits is also important, because higher returns on investment could encourage more investments, which indirectly might lead to higher adoption rates of EVs.

The aim of this paper is to optimal siting and sizing the public EVCSs while maximizing the total return of investments on the charging stations, and both demand coverage and investment costs of the station are considered in the model. To better model the charging demand of potential EVCSs, charging profiles considering real-world travel patterns and charging behaviors are integrated with the traffic flow and land-use classification of Geographic Information System (GIS). With the aggregated charging profiles, a GIS-based Mixed Integer Linear Programming (MILP) approach is proposed in order to find the optimal deployment of charging stations, which is followed by a case study in Västerås, Sweden.

2. Methodology

In this study, MILP is adopted to obtain the optimal location and size of charging stations with the objective of maximizing the overall profits. Fig.1 shows the process steps of the study, which consists of mainly two steps, the charging profile generation step and MILP optimization step. The model employs GIS data to extract the locations of parking lots and to cluster different land-use type, which can be employed using open source data such as open street maps (OSM) data or other proprietary map data.

2.1 Charging demand generation

With the objective of maximizing overall profits, the optimal locations of charging stations are highly influenced by the distribution and amount of EV charging demands. So, calculating charging demand is one of the most important steps in the model. The charging profiles of EVs at multi-locations with different charging strategies and supply equipment have been studied in our previous research [22]. With the innovative agent-based trip chain method, the aggregated charging profile of EVs are generated based on the real-world travel data in National Household Travel Survey (NHTS) [23] and charging behaviors [24]. The daily charging profile, CP, of each types of locations is represented by 24 hourly charging demands, Dt, as can be seen in formula (1).

\[ CP = \{D_1, D_2 \ldots D_{24} \}, \quad t = 1, 2, \ldots, 24. \]  \hspace{1cm} (1)

The charging profile of each node in the map is calculated based on the daily traffic flow in different measurement points and land-use information of different demand nodes, so GIS is employed to calculate the charging demand in different locations. The measurement point of traffic flow is not evenly distributed and may be missing in some area, a grid network is constructed to make effective use of traffic flow data. The target district could be divided into I identical small grids with the side of L meters, and take the centroid of every grid as the demand node, on which average traffic flow could be calculated by formula (2). For those grids that do not include any measurement...
points, the traffic flow would be the average of the surrounding grid.

\[ f_i = \frac{1}{K_i} \sum_{k=1}^{K_i} f_{ki}, \quad i = 1, 2, \ldots, l. \]  

(2)

Where \( f_i \) is the average traffic flow in grid \( i \); \( K_i \) represents the number of traffic flow measurement points in grid \( i \); and \( f_{ki} \) is the daily traffic flow in measurement point \( k_i \).

Different land-use classifications including residential with villa, residential with apartment, working, commercial, mixed land-use and natural area are identified using GIS to diversify types of charger and to calculate the charging demands of EVs in different locations. The traffic flow of each kinds of location in node \( i \), \( t_i \), is related to their area, as shown in formula (3).

\[ f_{xi} = f_i \cdot \frac{A_{xi}}{A_{xi} + A_{rv} + A_{rw} + A_{mi}}, \quad x \in \{ ra, rv, w, c, m \} \]  

(3)

Where \( A \) is the area of the land and \( rv \), \( ra \), \( c \) and \( m \) represent residential with villa, residential with apartment, working, commercial, mixed land-use.

The charging profile of node \( i \) is calculated based on formula (4). It is noted that in this study the commercial and mixed land use are assumed to be public land, the calculation process can be applied to other EVCSs programming even with more detailed information. In addition, the public EVCSs at residential area assumes to satisfy apartment users since villa users can access to home charge easily.

\[ CP_i = CP_{rarv} \cdot \frac{f_{rai}}{\sum_{i=1}^{l} f_{rai}} + CP_{rw} \cdot \frac{f_{wri}}{\sum_{i=1}^{l} f_{wri}} + CP_{cm} \cdot \frac{f_{cri} + f_{mi}}{\sum_{i=1}^{l} (f_{cri} + f_{mi})}, \quad i = 1, 2, \ldots, l \]  

(4)

2.2 MILP optimization

2.2.1 Parking lot location and aggregated demands

Parking lot is a reasonable and convenient location to install charging piles owing to its accessibility. So, the alternative locations of charging station in this model are defined as the parking lots in the study area. A buffer distance is assumed around the parking lots obtained from the map data representing the walking distance between the parking lot and the demand nodes visited by the EV driver. Reasonable buffer distance is equal to the acceptable walking distance from the parking lot to the destination. It is assumed that a charging station could only serve the demands in that buffer area. In this paper, the service radius of a station is set as \( L \) meter, which is similar with length of side of the grid. The demand nodes within the buffer distance are considered to be covered by the charging station located in this specific parking lot. A binary variable \( r_{ij} \) is adopted to describe the demand coverage level of station \( j \) on demand node \( i \), whose value is 1 when demand node \( i \) could be covered by station \( j \), otherwise the value is 0, that is,

\[ r_{ij} = \begin{cases} 1 & s_{ij} \leq L, \ i = 1, 2, \ldots, l; \ j = 1, 2, \ldots, f \ \
0 & s_{ij} > L \end{cases} \]  

(5)

Where \( r_{ij} \) represents the demand coverage level of station \( j \) on demand node \( i \), and \( s_{ij} \) is the Euclidean distance between station \( j \) and demand node \( i \).

The charging profile of station \( j \) is,

\[ CP_j = \sum_{i=1}^{l} CP_i \cdot r_{ij}, \quad j = 1, 2, \ldots, f. \]  

(6)

2.2.2 Costs of the EV charging station

It is assumed that fast chargers and slow chargers are chosen according to the function of the land-use, and the costs and charging price are different for two types of chargers. The costs of a station consist of rent costs, equipment costs, installation costs, maintenance and operation costs, and electricity costs, which vary with the number and the type of chargers. Therefore, the total cost of building one station is calculated by formula (7).

\[ c_j = c_{j1} + c_{j2} + c_{j3} + c_{j4} \]  

(7)

Where \( c_j \) stands for the total costs for station \( j \); \( c_{j1} \) is the unit rent cost per day of parking lot \( j \); \( c_{j2} \) and \( c_{j4} \) represents the purchase cost of a charger and the installing cost of one charger in station \( j \) respectively; \( c_{j3} \) stands for the operating costs; and \( c_{j4} \) is the costs for purchasing electricity from the power grid. And all the costs should be transformed into daily costs.

The rent costs for places to install the chargers and to park cars are calculated based on the opportunity costs of the spot, which is the parking fee the owner should have if it is used for charged parking. It is also assumed that the maintenance and operating costs are 10% of the equipment costs and installing costs. That is,

\[ c_{j1} = c_{j1}^* \cdot n_j, j = 1, 2, 3, \ldots, f. \]  

(8)

\[ c_{j2} = c_{j2}^* \cdot n_j, j = 1, 2, 3, \ldots, f. \]  

(9)

\[ c_{j3} = c_{j3}^* \cdot n_j, j = 1, 2, 3, \ldots, f. \]  

(10)

\[ c_{j4} = 10% \cdot c_{j4}^* \cdot n_j, j = 1, 2, 3, \ldots, f. \]  

(11)

Where \( n_j \) is the number of chargers in station \( j \); \( c_{j1}^* \) represents the parking fee per day of parking lot \( j \); \( c_{j2}^* \) represents the price of one charger; \( c_{j3}^* \) is the costs of installing one charger; and \( c_{j4}^* \) stands for the operating costs.

And the electricity costs are the total costs spent to buy the electricity needed to charger EVs, which is

\[ c_{j4} = p_e \cdot TD_j, j = 1, 2, 3, \ldots, f. \]  

(12)

Where \( p_e \) is the price of purchasing electricity from the power grid; and \( TD_j \) is the total charging demand covered by station \( j \).

2.2.3 The objective function

To achieve better returns of investment on the charging stations, an objective function of maximizing the total profits of all the new stations is adopted in the MILP model. The decision variables in this model are the locations of the charging stations; the number of fast or slow chargers needed to be installed in each station;
and the charging demands met by each station. The profits of deploying the new stations are the revenues of charging EVs subtracted by the costs of building and maintaining the station, which gives the objective function

\[ \text{Maximize } Pr(y_j, n_j, TD_j) = \sum_{i=1}^{J} [p_j \cdot y_j \cdot TD_j / pw_j - c_j], j = 1,2,...,J. \]  

(13)

Where \( Pr \) is total profits of new stations in the study area; \( p_j \) is the charging price in station \( j \); \( TD_j \) is charging demand covered by each station \( j \); \( pw_j \) is the power of the charger in station \( i \); \( c_j \) is the total cost of charging station \( j \); and \( y_j \) represents the binary decision variable, which is defined as

\[ y_j = \begin{cases} 
1 & \text{if there is a station in parking lot } j, \ j = 1,2,...,J. \\
0 & \text{otherwise.} 
\end{cases} \]

(14)

2.2.4 The constraints

With the purpose of achieving the maximum profits, there are some constraints need to be satisfied in the model, including demand constraint assignment constraint, limitation of number of chargers in each station and the total number of stations. In addition, the non-negative and integer requirements of the decision variables are also necessary. The formulas of the constraints are shown below:

(1) Demand constraint

Constraint (15) referring to the hourly charging demand which could be actually met by station \( j \). Equation (16) refers to the total daily charging demand met by station \( j \).

\[ AD_{jt} = \min\{D_{jt}, n_j \cdot pw_j\} \]  

(15)

\[ TD_j = \sum_{t=1}^{24} AD_{jt} \quad t=1,2,...,24; j=1,2,...,J. \]  

(16)

Where \( n_j \) is the number of chargers in station \( j \); \( AD_{jt} \) is the charging demand met by station \( j \) at \( t^{th} \) hour of the day. \( D_{jt} \) is the charging demand of station \( j \) at \( t^{th} \) hour of the day. \( TD_j \) is the daily total charging demand met by station \( j \).

(2) Assignment constraint

Constraint (17) means that the remaining demands in demand node \( i \) are only in the service area of one station, which ensures that different demand nodes are distributed to different charging stations.

\[ \sum_{j=1}^{J} y_j \cdot r_{ij} \leq 1, \ i = 1,2,\ldots,L, j = 1,2,\ldots,J. \]  

(17)

(3) Limitation of number of chargers in a station

Formula (18) and (19) ensure that each station would have at least one charger and at most \( l_j \) chargers, determined by the loads of the power grid. And the constraints also have the logical implication that if there is no station, there is no charger, vice versa.

\[ n_j \geq y_j, j = 1,2,...,J. \]  

(18)

\[ n_j \leq l_j \cdot y_j, j = 1,2,...,J. \]  

(19)

Where \( l_j \) stands for the upper bound of chargers in station \( j \).

(4) The total number of charging stations

Also, the budget of allocating charging equipment may be limited, so at most \( N \) stations would be allocated in the city according to formula (20).

\[ \sum_{j=1}^{J} y_j \leq N, j = 1,2,...,J. \]  

(20)

Where \( N \) is the number of the total stations which will be installed in the study area.

(5) Non-negative and integer requirements of the decision variables

Constraint (21) makes sure all the important decision variables should be integers and non-negative.

\[ y_j, n_j \geq 0 \text{ and are integers}, j = 1,2,...,J. \]  

(21)

3. Case study

3.1 Description of study area and parameters

The selected study area is the central part of Västerås, Sweden and its overall area is 67 km². The population of Västerås is reported as 119,372 and there were 44,192 personal cars in 2016, and 324 of them are plug-in EVs. The map of the parking lots was obtained from OpenStreetMap [25]. As shown in Fig. 2, 532 parking lots in this area are regarded as the alternative locations of charging stations (J=532). And the authors assumed that there were enough parking spaces in every location.

**Figure 2** The parking lots in the study area

The daily traffic flow data derived from the website of traffic administration of Västerås [26] is used to calculate the charging demand in each grid, including data from 245 traffic flow measurement points, range from 253 to...
18,458 vehicles per day. The measurement points is given in Fig. 3.

Figure 3 The measurement points of traffic flow

Table 1 presents the assumed parameters used in the case study. The charging price is derived from the current price charged by the existing charging station. And the price of equipment is studied by [27] and commonly cited by other literature. The demand nodes and small grid are shown in Fig. 4. The land-use classifications and corresponding area in the nodes are extracted by ARCGIS.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price of electricity ( p_e )</td>
<td>0.5 SEK/kWh</td>
</tr>
<tr>
<td>Upper bound of chargers in a station ( l_i )</td>
<td>20</td>
</tr>
<tr>
<td>EV adoption rate</td>
<td>5%</td>
</tr>
<tr>
<td>Buffer distance (L)</td>
<td>500 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Fast charger</th>
<th>Slow charger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>44 kW</td>
<td>6.6 kW</td>
</tr>
<tr>
<td>Price of charging ( p )</td>
<td>2 SEK/min</td>
<td>0.2 SEK/min</td>
</tr>
<tr>
<td>Price of equipment (including installation)</td>
<td>$54,525</td>
<td>$5,525</td>
</tr>
</tbody>
</table>

Table 1 Assumption of input parameters in the model

Figure 4 The demand nodes in the study area

3.2 The results

The aggregated charging profiles of different types of locations in the case is given in Fig. 5. The charging demands at different types of locations have different patterns, especially regarding the peak load and peak time.

Figure 5 Aggregated charging profiles of different locations.

The results of optimal location of the charging stations are presented in four cases. It is defined to install 3, 5, 10 and 15 new stations in the study area from case I to IV respectively. The optimal locations of new stations and type of chargers are shown in Fig. 6 and the summary results of different cases are given in Table 2.

It is shown in case I and II that to maximize the profits, fast charging stations in commercial area are considered first, and as the stations to be built increase as in case III and IV, slow chargers in the working and residential area are adopted, and all the stations scatter in the city to cover more charging demands. The Max case indicates the maximum profits situation without station number limits, from which the number of fast charging stations reaches peak at 8. In addition to the station numbers in each case, another important issue is the charger numbers of each station, which highlights the service ability of fast chargers.

Table 2 Summary results of different cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Fast charge (Number)</th>
<th>Slow charge (Number)</th>
<th>Profit (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>3 5</td>
<td>0 0</td>
<td>3307</td>
</tr>
<tr>
<td>II</td>
<td>5 7</td>
<td>0 0</td>
<td>4673</td>
</tr>
<tr>
<td>III</td>
<td>7 9</td>
<td>3 15</td>
<td>6862</td>
</tr>
<tr>
<td>IV</td>
<td>8 10</td>
<td>7 33</td>
<td>7910</td>
</tr>
<tr>
<td>Max</td>
<td>8 10</td>
<td>32 62</td>
<td>9420</td>
</tr>
</tbody>
</table>

4. Conclusions

The results of the case study demonstrate the effectiveness of the deployment model built in this paper, and the framework could be easily applicable in
different cities as long as the data of geographical information, traffic flow and other related information could be accessible for the target city. The optimal locations in the result ensure optimal profits of the charging stations, which could encourage more initiative investments and therefore a better EV penetration.

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Reference


