TWO STAGE OPTIMIZATION APPROACH FOR SITING WIND-POWERED CHARGING STATIONS

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ABSTRACT

Recently, wind power has become an economically viable clean energy resource without requiring state subsidies. This paper addresses the siting problem of wind-powered charging stations for the electric vehicles. The objective of the study is to find the best locations for the wind-powered charging stations from a set of given potential candidate locations. In order to solve the problem, a two stage optimization approach is introduced. The first stage of the solution methodology ranks the candidate locations by using a fuzzy multi-criteria decision making approach. Then the locations of the charging stations are identified based on a set covering model. The proposed solution approach is tested on a problem that is formed by using real life data. As a result of the computations, the best locations for siting the wind-powered charging stations are identified from a given set of alternatives.

1. INTRODUCTION

Since greenhouse gas emissions and air pollution from vehicles using fossil fuel-based engines have been increasing, electric vehicles are considered a promising alternative to reduce the environmental effects of transportation activities [1]. However, the limited cruising range and long charging times of the electric vehicles hinder their wide adoption. In this context, the site selection of the charging stations is one of the essential research areas to increase the usage of electric vehicles. Selecting the most suitable locations for the charging stations plays an important role in urban areas.

In order to solve the site selection problem for charging stations, different solution approaches are introduced in the literature. Based on the mathematical modelling, Baouche et al. [2] present a taxonomy of discrete location models regarding the three foundational discrete families of locations models: coverage, median and dispersion models. Another formulation for the problem is given by Lam et al. [3]. The authors also introduced four solution methods to solve the problem. Cavadas et al. [4] proposed an improved mathematical model formulation for the slow-charging stations in urban areas. Xi et al. [5] developed a simulation-optimization model to maximize the usage of charging stations by privately owned electric vehicles. Cai et al. [6] used big-data informed travel patterns of the taxi fleet in a city for siting the public electric vehicle charging stations.

Alternative and more recent solution methodologies for the charging station siting problem are introduced in the literature based on multi-criteria decision making approaches. These methods allow decision makers to take into account multiple criteria for siting the charging stations, such as, environmental, economical, social, technological, service availability, geographical, etc. Guo and Zhao [7] used a fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) based on a sustainability perspective. The authors considered environmental, economical and social effects of the charging stations to rank the alternative locations. Similarly, Wu et al. [8] proposed a PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) integrated cloud model. Wu et al. [9] introduced a fuzzy VIKOR (Vlsekriterijumska Optimizacija I Kompromisno Resenje) method to site electric vehicle charging stations for residential communities. However, these studies utilize multi-criteria decision making methods only to rank the alternatives with respect to their weights and select only the best location for a charging station instead of allocation of a set of charging stations. In addition to these studies, Xu et al. [10] developed a multi-criteria group decision making framework with linguistic information to rank the alternatives and select a specified number of locations for a charging station with respect to ranking result.

This study considers the site selection problem of relatively recently introduced wind-powered charging stations. To solve the problem, a new two stage optimization approach based on the fuzzy TOPSIS (F-TOPSIS) and set covering model is proposed. To the best of our knowledge, there exists only one paper that considers siting wind-powered charging stations, i.e. introduced by Xydis and Nanaki [11]. The authors used a Geographic Information System (GIS) based approach to identify the ideal locations of the charging stations. However, their study is limited to the geographical analysis for siting the wind turbines instead of identifying the locations for a set of wind-powered charging stations. Therefore, this study has the potential to contribute to the literature by considering the siting problem of charging stations with new concept wind-powered re-charging technology. Moreover, this paper contributes to the literature by introducing a two stage optimization methodology for siting the charging stations, in which the F-TOPSIS and a set covering model are employed, consecutively. This method allocates a set of wind-powered charging stations to the potential locations taking into account multiple criteria.

The rest of the paper is organized as follows. Section 2 defines the wind-powered charging station siting problem with the considered assumptions. The proposed two stage solution approach for the considered problem is introduced in Section 3. Section 4 presents the numerical application for the proposed solution approach. Finally, conclusions with future research perspectives are given in Section 5.

2. PROBLEM DEFINITION

The wind-powered charging station siting problem consists of selecting several locations to construct wind-powered charging stations for electric vehicles from a set of predetermined alternatives. Existing studies on charging station siting problems only take into account the charging stations that use the public electricity network. Distinct from these studies, the charging stations which use wind power as an energy source are taken into account in this study. In order to identify the suitability of a candidate location, a set of criteria is taken into account, which are average wind speed ($C1$) at the location, geographic conditions ($C2$), energy demand ($C3$), and closeness to the main roads ($C4$). The problem aims to find the best locations for the wind-powered charging stations which have to cover all demand locations while minimizing the number of constructed wind-powered charging stations regarding the suitability of the locations.

The foundations of the site selection problem are described as follows:

- A set of demand locations, which are also described as potential charging station location, are known.
- A wind-powered charging station can be constructed at any demand location.
- Each demand location has to be covered at least by one wind-powered charging station within a specific distance.
- Each constructed wind-powered charging station has to be covered at least by one other wind-powered charging station within a specific distance.
- The wind-powered charging stations to be constructed are identical and only one wind-powered charging station can be constructed at any alternative location.

3. SOLUTION METHODOLOGY

In order to solve the wind-powered charging station siting problem, a two stage optimization approach is proposed. In the first stage, the F-TOPSIS method is used to rank the alternative candidate locations by taking into account the identified criteria. After the priorities of the candidates are observed in the first stage, the location of the charging stations to be constructed are determined by a set covering model.

3.1. Stage 1: F-TOPSIS Method

The first stage of the solution methodology evaluates the suitability of the alternative locations for the wind-powered charging stations by using the F-TOPSIS method. F-TOPSIS method combines the traditional TOPSIS method with the fuzzy set theory to deal with the ambiguity and uncertainty in decision making issues [12]. The traditional TOPSIS method identifies the best alternative with respect to the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution [13]. In addition to the TOPSIS method, the F-TOPSIS method allows the decision makers to incorporate unquantifiable information, incomplete information, and non-obtainable information to cope with the uncertainty. The weights of the criteria and the ratings of the alternatives are formed by using linguistic variables [14, 15]. In this study, the F-TOPSIS method introduced by Chen [16] is used to evaluate the ratings of the alternative locations. The linguistic terms described by Chen [16] are shown in Table 1 and Table 2, respectively.

Table 1. Linguistic scale to evaluate the weight of the criteria

Linguistic Definition	Fuzzy Triangular Number
Very Low (VL)	(0.0, 0.0, 0.1)
Low (L)	(0.0, 0.1, 0.3)
Medium Low (ML)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
Medium High (MH)	(0.5, 0.7, 0.9)
High (H)	(0.7, 0.9, 1.0)
Very High (VH)	(0.9, 1.0, 1.0)

Table 2. Linguistic scale to evaluate the ratings of the alternatives

Linguistic Definition	Fuzzy Triangular Number
Very Poor (VP)	(0, 0, 1)
Poor (P)	(0, 1, 3)
Medium Poor (MP)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Medium Good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very Good (VG)	(9, 10, 10)

3.2. Stage 2: Set Covering Model

Following the first stage of the proposed solution methodology, a set covering model is employed to identify the best locations of the wind-powered charging stations in a set of alternative locations. The traditional set covering problem, which is first introduced by Toregas et al. [17], aims to minimize the total number of locations needed to cover all demand points. Distinct from the traditional objective function, the F-TOPSIS scores determined in the first stage for the alternatives are used in this study to identify the weights of the alternatives. The notations and model formulation are given as follows:

Parameters

- N Set of alternative locations
- d_{ij} distance from location i to location j; $\forall i, j \in N$
- w_i weight of the alternative i; $\forall i \in N$
- α maximum covering distance of the wind-powered charging stations
- β maximum allowed distance between a wind-powered charging station and its nearest stations
- c'_{ij} binary data matrix and identifies the location pairs where the $d_{ij} \leq \alpha$; $\forall i, j \in N$
- c''_{ij} binary data matrix and identifies the location pairs where the $d_{ij} \leq \beta$; $\forall i, j \in N$

Decision Variables

- x_i is a binary variable and equal to 1 if a wind-powered charging station is constructed at location i, otherwise 0; $\forall i \in N$

Model

$$Min\ z = \sum_{i \in N} x_i / w_i \tag{1}$$

Subject to

$$\sum_{j \in N} c'_{ij} x_j \geq 1 \qquad \forall i \in N \tag{2}$$

$$\sum_{\substack{j \in N \\ i \neq j}} c''_{ij} x_j \geq x_i \qquad \forall i \in N \tag{3}$$

$$x_i \in \{0,1\} \qquad \forall i \in N \tag{4}$$

Equation (1) describes the objective function which aims to minimize the total weight of the selected alternative locations. The term x_i/w_i in this equation favours the locations which have higher weights. Equation (2) ensures that each location is covered at least by one wind-powered charging station. Equation (3) guarantees that if a wind-powered charging station is constructed at location i, the distance of the nearest wind-powered charging station to location i has to be less than β. Finally, equation (4) describes the binary decision variable.

4. NUMERICAL APPLICATION

The proposed two stage optimization approach is tested on a problem which is formed by using geographic, environmental, and demography information of Bursa, a city in Turkey. With more than 1.5 million people and more than 0.5 million registered vehicles, Bursa has a potential to widely adopt electric vehicle technology. Considering the geographical structure and average wind speed of the region, which is shown in Fig. 1, Bursa is also suitable for wind-powered charging station technology.

For the input data of the problem, first, 30 different points/alternatives $(A1, A2, \ldots, A30)$, which are located in the central districts of Bursa and used as a fuel station or have a potential to construct a wind-powered charging station, are specified by using the Google Maps® web service. Fig. 2 represents the specified points on the map of Bursa. Subsequently, these alternative points are evaluated for the four different criteria described above by using linguistic variables.

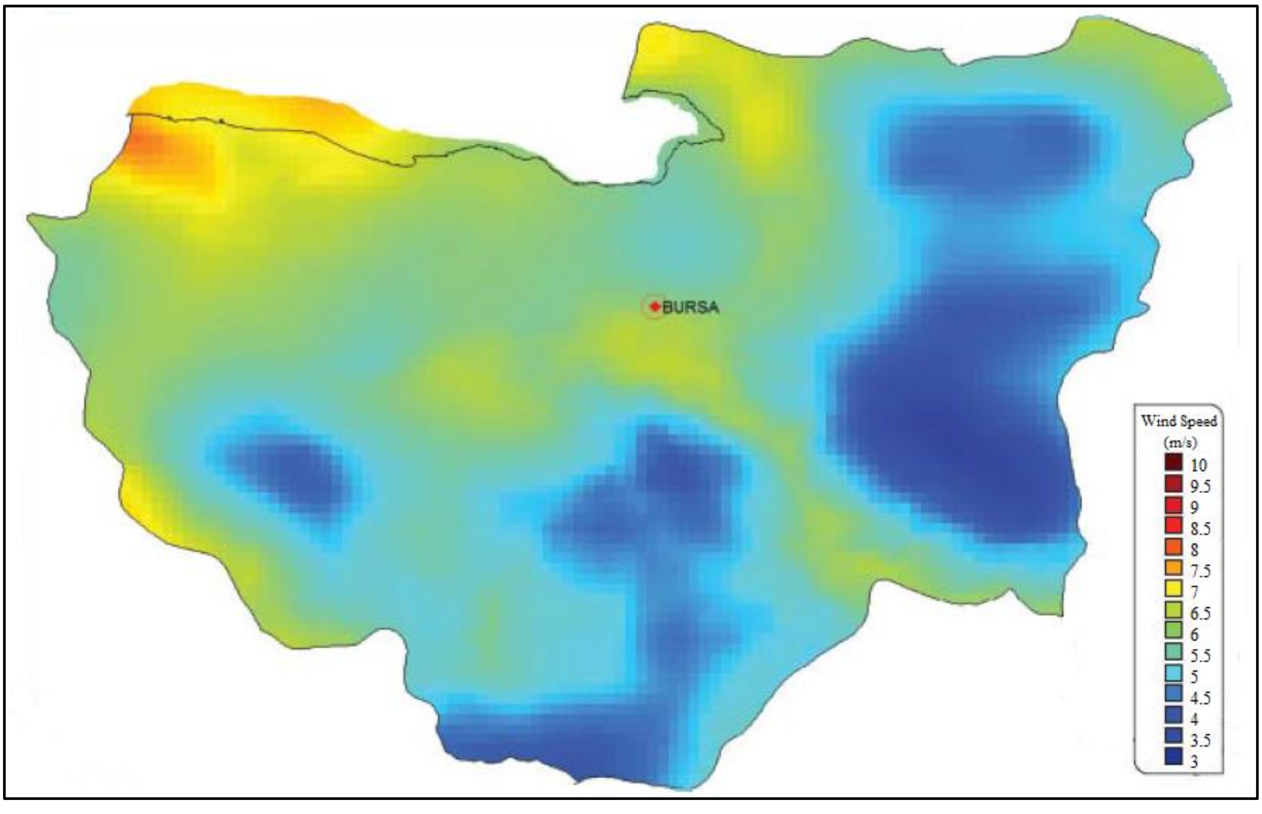

Fig. 1. Average wind speed map of Bursa (http://www.eie.gov.tr)

Fig. 2. Locations of the specified alternative wind-powered charging station points

In order to evaluate the alternatives for $C1$, the average wind-speed map of the Bursa is used. For $C2$ and $C4$, the geographic and road map of Bursa are taken into account. For $C3$, the population dispersion of the city with respect to the districts is considered. Table 3 and Table 4 show the input data of the F-TOPSIS method. Table 4 additionally contains the latitudes and longitudes of the alternative points to determine distances between the locations by using the Google Maps® web service. As a result of the first stage computations, the F-TOPSIS preference scores for the alternatives are observed as shown in Table 5. The ranking performance of the alternative locations are shown in Fig. 3.

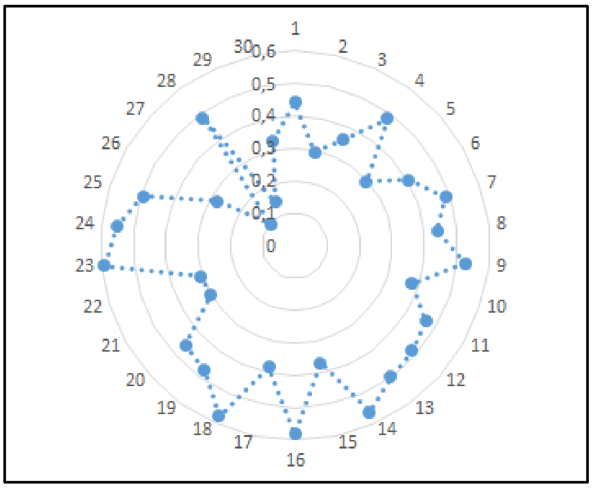

Fig. 3. Ranking performance of the alternative locations

Table 3. Weight of the criteria

Criteria	CR_1	CR_2	CR_3	CR_4
Weight	VH	M	MH	H

Table 4. Location information and their ratings

Location Information			**Ratings of the Locations**			
#	**Latitude**	**Longitude**	$\boldsymbol{CR_1}$	$\boldsymbol{CR_2}$	$\boldsymbol{CR_3}$	$\boldsymbol{CR_4}$
1	40.215943	28.627350	MP	VG	P	VG
2	40.293288	28.648823	F	G	VP	P
3	40.347395	28.688750	G	MG	VP	P
4	40.214227	28.731837	F	VG	P	VG
5	40.181187	28.796695	F	G	VP	P
6	40.315056	28.799177	VG	MG	MP	VP
7	40.391272	28.795369	VG	VG	F	P
8	40.223117	28.815068	MP	VG	P	VG
9	40.217022	28.871085	MG	VG	P	VG
10	40.177456	28.903127	F	G	F	P
11	40.355349	28.916583	F	MG	MG	F
12	40.300179	28.938731	F	MP	MG	G
13	40.258831	28.952176	MP	F	VG	G
14	40.211191	28.970480	MG	P	VG	VG
15	40.361042	29.022873	MP	G	F	MP
16	40.214804	29.012552	G	P	G	VG
17	40.253855	29.017852	F	MP	VG	P
18	40.200011	29.041286	G	P	VG	G
19	40.234104	29.062957	P	MG	G	G
20	40.292634	29.057262	P	G	F	VG
21	40.245826	29.089156	MP	F	MP	MP
22	40.271546	29.090485	F	F	MP	P
23	40.332043	29.086931	MG	MG	MG	VG
24	40.396564	29.132658	G	F	F	G
25	40.195164	29.158648	P	MG	G	VG
26	40.246865	29.163564	F	MG	P	VP
27	40.324503	29.195823	P	P	VP	VP
28	40.211921	29.258080	P	G	MG	VG
29	40.301721	29.275452	VP	MP	P	P
30	40.196909	29.353402	VP	G	VP	G

Table 5. Preference scores of the locations

#	Score	#	Score	#	Score
1	0.44154	11	0.46480	21	0.30019
2	0.29591	12	0.48600	21	0.30838
3	0.35739	13	0.50231	23	0.58996
4	0.48421	14	0.56162	24	0.55410
5	0.29591	15	0.37089	25	0.49360
6	0.40528	16	0.58250	26	0.27596
7	0.48653	17	0.38360	27	0.10048
8	0.44154	18	0.57731	28	0.48691
9	0.52647	19	0.47575	29	0.14783
10	0.37929	20	0.45669	30	0.33061

Following the first stage of the solution methodology, the set covering model is solved by using the F-TOPSIS preference scores in the objective function. For this stage, the parameter values for α and β are set to 15. The set covering model is solved within one second by using the GUROBI 7.5.1 solver. According to the GUROBI result, the locations $A1$, $A4$, $A6$, $A7$, $A16$, $A23$, $A24$, $A25$, $A27$, and $A28$ are selected to construct a wind-powered charging station, which are identified with red pins in Fig. 4. It can be seen from the obtained result that the selected alternatives consist of not only locations which have higher F-TOPSIS preference scores, but also locations with lower F-TOPSIS preference scores to cover all demand points while minimizing the $\sum_{i \in N} x_i / w_i$.

Fig. 4. Result of the proposed two stage optimization approach

5. CONCLUSION

With increasing environmental awareness, it is becoming clear that an efficient methodology to select suitable locations for wind-powered charging stations is required and this can be based on the proposed methodology. This study proposes a two stage optimization methodology to siting the wind-powered charging stations. The first stage evaluates the suitability of the alternative locations for the stations using the F-TOPSIS method while the second stage identifies the best locations of the stations on the basis of an extended form of the traditional set covering problem. The proposed methodology is tested on a problem which is formed by using real life data of a city in Turkey. As a result of the numerical application, best locations of the wind-powered charging stations for 30 demand locations are found.

This study can be extended as a future research as follows: The GIS can be integrated to collect more realistic geographic information for the wind-powered charging stations. Moreover, the criteria used in the F-TOPSIS method can be investigated in more detail. The mathematical model used in the second stage can be extended regarding the different wind-powered charging technologies, capacities of the stations, budget limit for the wind-powered charging stations, operational costs of the stations, etc. In addition to the allocation decision of the wind-powered charging stations, routing of the electric vehicles can be considered simultaneously in the second stage. Finally, the computational performance of the proposed solution methodology can be analysed. In this study, the results of the set covering model could be found within one second for 30 alternative locations. In this context, the proposed two stage optimization method can be tested on large sized and different cases formed by using different region's information.

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