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Research Article

Optimal Siting of Electric Vehicle Charging Stations Using Pythagorean Fuzzy VIKOR Approach

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Site selection for electric vehicle charging stations (EVCSs) is the process of determining the most suitable location among alternatives for the construction of charging facilities for electric vehicles. It can be regarded as a complex multicriteria decision-making (MCDM) problem requiring consideration of multiple conflicting criteria. In the real world, it is often hard or impossible for decision makers to estimate their preferences with exact numerical values. Therefore, Pythagorean fuzzy set theory has been frequently used to handle imprecise data and vague expressions in practical decision-making problems. In this paper, a Pythagorean fuzzy VIKOR (PF-VIKOR) approach is developed for solving the EVCS site selection problems, in which the evaluations of alternatives are given as linguistic terms characterized by Pythagorean fuzzy values (PFVs). Particularly, the generalized Pythagorean fuzzy ordered weighted standardized distance (GPFOWSD) operator is proposed to calculate the utility and regret measures for ranking alternative sites. Finally, a practical example in Shanghai, China, is included to demonstrate the proposed EVCS sitting model, and the advantages are highlighted by comparing the results with other relevant methods.

1. Introduction

Due to the rapid economic development and the acceleration of urbanization, energy shortage and environment pollution have become severe issues for the sustainable development of China. Automobiles contribute 20–30% of the total production of greenhouse gases (GHGs) in China, and thus the reduction of GHGs is a very pressing problem for the transportation sector [1]. As a kind of environmentally friendly transportation, electric vehicles are considered as a promising solution for the problems of energy consumption and carbon emission [2]. The central government is strongly motivated to promote the adoption of electric vehicles to maintain a healthy balance of urban mobility and energy consumption and has set a goal of putting 5 million hybrid and electric vehicles on the road by 2020 [3, 4]. In recent years, many strategies have been launched by local governments to accelerate electric vehicle marketization by, for example, subsidizing manufacturers and buyers, building charging facilities, and offering tax breaks [5, 6].

One of the factors that significantly influence the popularization and market acceptance of electric vehicles is access to public charging infrastructure. Because of the range limitation and resulting anxiety over the available range, convenient and economic charging facilities can enhance the willingness of consumers to buy electric vehicles. The deployment of public charging facilities is very important with regard to harmonious and sustainable development of electric vehicle systems. Site selection for electric vehicle charging stations (EVCSs) is the process of determining the most suitable location among alternatives for the construction of charging facilities for electric vehicles. As a preliminary work, it plays an important role in the transport planning and has substantial impact on the service quality and operational efficiency of EVCSs [7]. Therefore, in recent years, a great deal of attention has been given for the determination of the optimal location for EVCSs [3, 7–10].

In practical EVCS site selection processes, it is generally hard to find an alternative that satisfies all criteria at the same time; so, a good compromise solution is preferred. This problem may become more complex when multiple decision makers are involved, each having a different perception on the alternatives. Therefore, the optimal siting of EVCSs has always been a problem which can be effectively solved by multicriteria decision-making (MCDM) methods. The VIKOR (VIsekriterijumska optimizacija i KOmpromisno Resenje) method initially proposed by Opricovic and Tzeng [11] is an efficient tool to solve group decision-making problems with contradictory and noncommensurable criteria. It assumes that compromising is adequate for conflict resolution, the decision maker wants a solution which is the closest to the ideal, and the alternatives are ordered based on all predefined criteria [12, 13]. This technique is a helpful tool in the situations where a decision maker is not able to indicate preferences among alternatives that may result in varied consequences. Because of its characteristics and competencies, the VIKOR method is a promising tool to find the optimal location of EVCSs.

Normally, the techniques such as initial interview, field investigation, and programming (optimization) models were used for the optimal location of EVCSs [7]. However, with the increasing complexity of EVCS site selection problems, decision makers often need to consider multiple criteria, such as the effect on ecological environment, the investment payoff period, and the attitude of local residents, to make decisions. There are also some situations when the assessments of alternatives must cope with the vagueness of established criteria, and the development of a fuzzy MCDM method is needed to handle either qualitative or incomplete data [2, 7, 8]. As a generalization of intuitionistic fuzzy sets [14], the Pythagorean fuzzy sets (PFSs) were introduced by Yager and Abbasov [15]. The PFSs are also characterized by a membership degree and a nonmembership degree, whose square sum is less than or equal to 1 but the sum is not required to be less than one. Consequently, the theory of PFSs can depict more imprecise and ambiguous information in solving MCDM problems [16–18]. In many real circumstances, particularly in the process of group decision-making under uncertainty, the judgments or preferences provided by decision makers may be appropriately expressed in Pythagorean fuzzy values (PFVs) [19]. Thus, PFSs can be very useful to manage the subjective evaluations of domain experts in the EVCS site selection.

Based on above discussions, this paper presents a Pythagorean fuzzy VIKOR (PF-VIKOR) method to select the optimal site of EVCSs under Pythagorean fuzzy environment. Specifically, the evaluations of alternatives against each criterion are treated as linguistic terms which can be denoted by PFVs. The Pythagorean fuzzy weighted averaging (PFWA) operator [20] emphasizing the individual influence is employed to aggregate all decision makers' opinions into group assessments. Particularly, the generalized Pythagorean fuzzy ordered weighted standardized distance (GPFOWSD) operator is proposed to calculate the utility and regret measures of the PF-VIKOR. The new model can not only include the attitudinal character of a decision maker for the site selection of EVCSs but also parameterize the results from the minimum to the maximum according to the decision maker's interests. Thus, it is able to provide a wide range of situations according to the attitude taken by a decision maker in the particular application considered.

The rest of this paper is outlined as follows: in Section 2, a review of the existing literature related to this study is included. In Section 3, some basic concepts related to PFSs are reviewed and the GPFOWSD operator is developed. Section 4 provides the PF-VIKOR method to group EVCS site selection. A numerical example is provided in Section 5 to illustrate the proposed approach, and a comparative analysis is conducted to display the advantages of the new EVCS site selection model. Finally, conclusions of this article are presented in Section 6.

2. Literature Review

2.1. Application of VIKOR Method. Recently, the VIKOR method has been successfully utilized by scholars to handle various decision-making problems. For example, Yalçın and Ünlü [21] used VIKOR and CRiteria Importance Through Intercriteria Correlation (CRITIC) methods for the multicriteria performance evaluation of initial public offering firms. Wang et al. [22] presented an integrated model based on VIKOR and entropy weight methods for the risk evaluation of construction project under picture fuzzy environment. Tavana et al. [23] constructed an extended VIKOR approach that accounts for differences in the risk attitudes of decision makers when ranking stochastic alternatives. Sennaroglu and Varlik Celebi [24] solved the location selection problem for a military airport by combining analytic hierarchy process (AHP) and VIKOR methods. Gul et al. [25] proposed a modeling framework incorporating fuzzy AHP with fuzzy VIKOR for occupational health and safety risk assessment. Shojaei et al. [26] proposed an integration method using Taguchi loss function, best-worst method and VIKOR technique to evaluate and rank airports, and Gupta [27] evaluated the service quality of airline industry using a hybrid approach consisting of best-worst method and VIKOR method. In [28], an environmentally friendly decision-making model using decision-making trial and evaluation laboratory- (DEMATEL-) based analytical network process (ANP) (DANP), interval uncertainty, and VIKOR method was presented for the reliability-based product optimization. In [29], a compromising decision-making method based on interval-valued Pythagorean fuzzy sets and VIKOR method was developed and applied to decision analysis for hospital-based post-acute care. In [30], the authors employed an integrated fuzzy AHP-VIKOR framework for multi-tier sustainable global supplier selection. Besides, a systematic review of the literature on the VIKOR method and its applications can be found in [31, 32].

2.2. Application of PFSs. The PFSs have received wide attention in recent years and many researchers have applied it to address a variety of real-world decision-making problems.

For instance, Xue et al. [33] proposed a Pythagorean fuzzy linear programming technique for multidimensional analysis of preference (LINMAP) method based on entropy theory for railway project investment decision-making. Liang et al. [34] reported a method of three-way decisions-based ideal solutions in the Pythagorean fuzzy information system and used the technique for order preference by similarity to ideal solution (TOPSIS) method to estimate the conditional probability. Ilbahar et al. [35] constructed an integrated risk assessment approach for occupational health and safety using Fine Kinney, Pythagorean fuzzy AHP, and fuzzy inference system. Chen [36] suggested a remoteness index-based VIKOR method for multiple criteria decision analysis involving Pythagorean fuzzy information. An agent-based Pythagorean fuzzy model was developed by Baloglu and Demir [37] for demand analysis in environments with incomplete information. A closeness index-based QUALIFLEX method was proposed by Zhang [38] to address hierarchical multicriteria decision-making problems within the Pythagorean fuzzy context. Ren et al. [39] introduced a modified TODIM (an acronym in Portuguese of interactive and multiple criteria decision-making) method and Zhang and Xu [19] proposed an extended TOPSIS approach to deal with the Pythagorean fuzzy MCDM problems. In addition, a variety of aggregation operators, such as the Pythagorean fuzzy induced ordered weighted averaging weighted average operator [40], the Pythagorean fuzzy Maclaurin symmetric mean operators [41], the Pythagorean fuzzy power aggregation operators [42], the Pythagorean fuzzy Bonferroni mean aggregation operator [43], and the probabilistic Pythagorean fuzzy aggregation operators [44] were developed for complex decision-making in the Pythagorean fuzzy environment.

2.3. EVCS Site Selection. The optimal location of EVCSs is a hot topic which has received much more attention in recent years. To maximize the demand coverage, Yang [45] developed a user-choice model for locating congested fast charging stations and deploying chargers in a stochastic environment. He et al. [46] presented a bi-level programming model to location planning of charging stations with the consideration of EVs' driving range. Guo et al. [47] established a bi-level integer programming model to solve the battery charging station location problem considering impact of users' range anxiety and distance convenience. Tu et al. [9] addressed the location problem of electric taxi charging stations by presenting a spatial–temporal demand coverage method. Shahraki et al. [3] selected the optimal locations of electric public charging stations by formulating an optimization model based on vehicle travel behaviors. On the other hand, Liu et al. [48] proposed an integrated MCDM approach using grey decision-making trial and evaluation laboratory (DEMATEL) and uncertain linguistic MULTIMOORA (multiobjective optimization by a ratio analysis plus the full multiplicative form) for finding the best location of EVCSs. Zhao and Li [2] employed a fuzzy grey relation analysis- (GRA-) VIKOR method and Guo and Zhao [7] utilized a fuzzy TOPSIS method for optimal siting of EVCSs from a sustainability perspective. Wu et al. [49] built an EVCS site selection approach for residential communities based on triangular intuitionistic fuzzy numbers and VIKOR method.

After analyzing the literature, it can be concluded that the majority of existing studies related to the site selection of EVCSs are concentrated on multiobjective decision-making (MODM) methods, and only limited research has dealt with the problems using MCDM methods. However, the MODM methods can only account for quantitative factors, and are not capable of modeling important qualitative factors [2, 7]. In addition, the VIKOR method has been successfully employed in sitting EVCSs and has demonstrated satisfactory results [2, 49], but no study has dealt with the EVCS site selection in the Pythagorean fuzzy environment. Therefore, we intend to develop a new MCDM model in this study to perform the EVCS site selection by combining Pythagorean fuzzy sets and VIKOR method, in order to capture both quantitative and qualitative criteria and model imprecision and vagueness of assessment information given by decision makers.

3. Preliminaries

3.1. Pythagorean Fuzzy Sets. The concept of PFSs was initially introduced by Yager [35] by extending intuitionistic fuzzy sets [14], and the general mathematical form of PFSs was proposed by Zhang and Xu [19]. Next, the basic definitions and concepts related to PFSs are given.

Definition 1. Let X be a fixed nonempty set. A PFS P in X is defined as

$$P = \{\langle x, \mu_P(x), \nu_P(x)\rangle \mid x \in X\}, \tag{1}$$

which is characterized by a membership function $\mu_P : X \to [0,1]$ and a nonmembership function $\nu_P : X \to [0,1]$ and satisfies the condition that $0 \le (\mu_P(x))^2 + (\nu_P(x))^2 \le 1$, for all $x \in X$. The numbers μ_P and ν_P are the membership degree and the nonmembership degree of the element x to the set P, respectively.

For each PFS P in X, the function $\pi_P(x) = \sqrt{1-(\mu_P(x))^2-(\nu_P(x))^2}$ is called the hesitation degree (or Pythagorean index [38]) of the element $x \in X$ to the set P. For a PFS P in X, the pair $\tilde{p} = (\mu_p(x), \nu_p(x))$ is referred to as a Pythagorean fuzzy value (PFV) [19], and each PFV can be denoted by $\tilde{p} = (\mu_p, \nu_p)$ for convenience.

Definition 2. For any two PFVs $\tilde{p}_1 = (\mu_{p_1}, \nu_{p_1})$ and $\tilde{p}_2 = (\mu_{p_2}, \nu_{p_2})$, the basic mathematical operations of PFVs are defined as follows [19]:

(1) $\tilde{p}_1 \oplus \tilde{p}_2 = (\sqrt{(\mu_{p_1})^2 + (\mu_{p_2})^2 - (\mu_{p_1})^2(\mu_{p_2})^2}, \nu_{p_1}\nu_{p_2})$;

(2) $\tilde{p}_1 \otimes \tilde{p}_2 = (\mu_{p_1}\mu_{p_2}, \sqrt{(\nu_{p_1})^2 + (\nu_{p_2})^2 - (\nu_{p_1})^2(\nu_{p_2})^2})$;

(3) $\lambda\tilde{p}_1 = (\sqrt{1-(1-(\mu_{p_1})^2)^{\lambda}}, (\nu_{p_1})^{\lambda})$, $\lambda > 0$;

(4) $\tilde{p}_1^{\lambda} = ((\mu_{p_1})^{\lambda}, \sqrt{1-(1-(\nu_{p_1})^2)^{\lambda}})$, $\lambda > 0$.

Definition 3. Let Φ be the set of all PFVs in X. The score function of a PFV $\tilde{p} = (\mu_p, \nu_p)$ is represented as follows [50]:

$$S(\tilde{p}) = \frac{1}{2}\left(1 + (\mu_p)^2 - (\nu_p)^2\right), \tag{2}$$

and the accuracy function of a PFV $\tilde{p} = (\mu_p, \nu_p)$ is defined by the following [51]:

$$H(\tilde{p}) = (\mu_p)^2 + (\nu_p)^2, \tag{3}$$

where $S(\tilde{p}) \in [0,1]$ and $H(\tilde{p}) \in [0,1]$.

In line with the score function S and the accuracy function H, Wu and Wei [50] gave the following comparison laws of PFVs.

Definition 4. Supposing there are two PFVs $\tilde{p}_1 = (\mu_{p_1}, \nu_{p_1})$ and $\tilde{p}_2 = (\mu_{p_2}, \nu_{p_2})$, then

(1) if $S(\tilde{p}_1) > S(\tilde{p}_2)$, then $\tilde{p}_1 > \tilde{p}_2$;

(2) if $S(\tilde{p}_1) = S(\tilde{p}_2)$ and $H(\tilde{p}_1) > H(\tilde{p}_2)$, then $\tilde{p}_1 > \tilde{p}_2$;

(3) if $S(\tilde{p}_1) = S(\tilde{p}_2)$ and $H(\tilde{p}_1) = H(\tilde{p}_2)$, then $\tilde{p}_1 = \tilde{p}_2$.

Zhang and Xu [19] further proposed the Hamming distance measure for Pythagorean fuzzy decision-making.

Definition 5 (see [19]). Let $\tilde{p}_1 = (\mu_{p_1}, \nu_{p_1})$ and $\tilde{p}_2 = (\mu_{p_2}, \nu_{p_2})$ be two PFVs in Φ. The Hamming distance between them is computed by

$$\begin{aligned} d_H(\tilde{p}_1, \tilde{p}_2) = \frac{1}{2}\Big(&\left|(\mu_{p_1})^2 - (\mu_{p_2})^2\right| + \left|(\nu_{p_1})^2 - (\nu_{p_2})^2\right| \\ &+ \left|(\pi_{p_1})^2 - (\pi_{p_2})^2\right|\Big). \end{aligned} \tag{4}$$

Based on the basic operational rules of PFVs, Zhang [20] developed the Pythagorean fuzzy weighted averaging (PFWA) operator as follows.

Definition 6 (see [20]). Suppose $\tilde{p}_i = (\mu_{p_i}, \nu_{p_i})$ $(i = 1, 2, \ldots, n)$ is a collection of PFVs in Φ. Then the PFWA operator is defined as follows:

$$\begin{aligned} PFWA(\tilde{p}_1, \tilde{p}_2, \ldots, \tilde{p}_n) &= \bigoplus_{i=1}^{n} w_i \tilde{p}_i \\ &= \left(\sqrt{1 - \prod_{i=1}^{n}\left(1 - (\mu_{p_i})^2\right)^{w_i}}, \prod_{i=1}^{n}(\nu_{\tilde{p}_i})^{w_i}\right), \end{aligned} \tag{5}$$

where $w = (w_1, w_2, \ldots, w_n)^T$ is the associated weights of $\tilde{p}_i$ $(i = 1, 2, \ldots, n)$, satisfying $w_i \in [0,1]$ $(i = 1, 2, \ldots, n)$ and $\sum_{i=1}^{n} w_i = 1$.

3.2. The GPFOWSD Operator. Motivated by the generalized ordered weighted averaging standardized distance (GOWASD) operator [52], we develop a generalized Pythagorean fuzzy ordered weighted standardized distance (GPFOWSD) operator for the VIKOR method. Let $\tilde{P}^* = \{\tilde{p}_1^*, \tilde{p}_2^*, \ldots, \tilde{p}_n^*\}$, $\tilde{P}^- = \{\tilde{p}_1^-, \tilde{p}_2^-, \ldots, \tilde{p}_n^-\}$ and $\tilde{R}_i = \{\tilde{r}_{i1}, \tilde{r}_{i2}, \ldots, \tilde{r}_{in}\}$ be three sets of PFVs, then we can define the GPFOWSD as follows.

Definition 7. An GPFOWSD operator of dimension n is a mapping GPFOWSD: $\Phi^n \times \Phi^n \times \Phi^n \rightarrow R$ that has an associated weighting vector $\omega = (\omega_1, \omega_2, \ldots, \omega_n)^T$, with $\omega_k \in [0,1]$ and $\Sigma_{k=1}^{n}\omega_k = 1$, such that

$$\begin{aligned} &\mathrm{GPFOWSD}(\langle \tilde{p}_1^*, \tilde{p}_1^-, \tilde{r}_{i1}\rangle, \ldots, \langle \tilde{p}_1^*, \tilde{p}_1^-, \tilde{r}_{in}\rangle) \\ &\quad = \left(\sum_{k=1}^{n}\omega_k \overline{d}_k^{\lambda}\right)^{1/\lambda}, \quad \lambda \neq 0, \end{aligned} \tag{6}$$

where $\overline{d}_k$ represents the kth largest of the standardized Pythagorean fuzzy distance $d(\tilde{p}_j^*, \tilde{r}_{ij})/d(\tilde{p}_j^*, \tilde{p}_j^-)$ and $\tilde{p}_j^*$ and $\tilde{p}_j^-$ are the Pythagorean fuzzy positive ideal solution (PFPIS) and the Pythagorean fuzzy negative ideal solution (PFNIS) of the jth criterion, $\tilde{r}_{ij}$ is the assessment of ith alternative with regard to C_j, $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n$.

Note that the GPFOWSD operator is commutative, monotonic, idempotent, and bounded, which can be proven easily and omitted here. In addition, by analyzing the weighting vector$\omega$and the parameter λ in the GPFOWSD operator, different types of Pythagorean fuzzy distance operators can be acquired.

Remark 8. If $\lambda = 1$, then the GPFOWSD operator is reduced to the Pythagorean fuzzy ordered weighted Hamming standardized distance (PFOWHSD) operator:

$$\begin{aligned} &\mathrm{PFOWHSD}(\langle \tilde{p}_1^*, \tilde{p}_1^-, \tilde{r}_{i1}\rangle, \ldots, \langle \tilde{p}_1^*, \tilde{p}_1^-, \tilde{r}_{in}\rangle) \\ &\quad = \sum_{k=1}^{n}\omega_k \overline{d}_k, \end{aligned} \tag{7}$$

where $\overline{d}_k$ represents the kth largest of the standardized Pythagorean fuzzy distance $d(\tilde{p}_j^*, \tilde{r}_{ij})/d(\tilde{p}_j^*, \tilde{p}_j^-)$. Note that if $\omega_k = 1/n$ for all k, we get the Pythagorean fuzzy normalized Hamming standardized distance (PFNHSD). The Pythagorean fuzzy weighted Hamming standardized distance (PFWHSD) is obtained if the position of j is the same as the ordered position of k.

Remark 9. If $\lambda = 2$, the GPFOWSD operator is reduced to the Pythagorean fuzzy ordered weighted Euclidean standardized distance (IFOWESD) operator:

$$\begin{aligned} &\mathrm{PFOWESD}(\langle \tilde{p}_1^*, \tilde{p}_1^-, \tilde{r}_{i1}\rangle, \ldots, \langle \tilde{p}_1^*, \tilde{p}_1^-, \tilde{r}_{in}\rangle) \\ &\quad = \left(\sum_{k=1}^{n}\omega_k \overline{d}_k^{2}\right)^{1/2}, \end{aligned} \tag{8}$$

where $\overline{d}_k$ represents the kth largest of the standardized Pythagorean fuzzy distance $d(\widetilde{p}_j^*, \widetilde{r}_{ij})/d(\widetilde{p}_j^*, \widetilde{p}_j^-)$. Note that if $\omega_k = 1/n$ for all k, we get the Pythagorean fuzzy normalized Euclidean standardized distance (PFNESD). The Pythagorean fuzzy weighted Euclidean standardized distance (PFWESD) is obtained if the position of j is the same as the ordered position of k.

Remark 10. If $\lambda \to 0$, then the GPFOWSD operator is reduced to the Pythagorean fuzzy ordered weighted geometric standardized distance (PFOWGSD) operator:

$$\text{PFOWGSD}\left(\left\langle \widetilde{p}_1^*, \widetilde{p}_1^-, \widetilde{r}_{i1} \right\rangle, \ldots, \left\langle \widetilde{p}_1^*, \widetilde{p}_1^-, \widetilde{r}_{in} \right\rangle\right) = \prod_{k=1}^{n} \overline{d}_k^{\,\omega_k}, \quad (9)$$

where $\overline{d}_k$ represents the kth largest of the standardized Pythagorean fuzzy distance $d(\widetilde{p}_j^*, \widetilde{r}_{ij})/d(\widetilde{p}_j^*, \widetilde{p}_j^-)$. Note that if $\omega_k = 1/n$ for all k, we get the Pythagorean fuzzy normalized geometric standardized distance (PFNGSD). The Pythagorean fuzzy weighted geometric standardized distance (PFWGD) is obtained if the position of j is the same as the ordered position of k. Note also that the PFOWGSD can only be used when all the individual standardized distances are different from 0. That is, when $d(f_j^*, r_{ij})/d(f_j^*, f_j^-) \neq 0$, for all j.

Using a similar methodology as for the GOWASD [52] operator, numerous other families of GPFOWSD operators can be proposed. For instance, we could define the step-PFOWSD operator, the window-PFOWSD, the Olympic-PFOWSD, the median-PFOWSD, the centered-PFOWSD, and the non-monotonic-PFOWSD.

4. The Proposed EVCS Site Selection Method

In this section, we extend the VIKOR method to the Pythagorean fuzzy environment for finding the optimal location of EVCSs. In many practical situations, the criteria of alternative sites are not easy to be precisely evaluated because of the increasing complexity and the lack of knowledge or data. As such, in this paper, linguistic terms are used by decision makers to express their subjective judgments on EVCS locations and the individual evaluation grade is defined as a PFV. Similar to [36], the linguistic terms can be represented by PFVs as presented in Table 1. In practice, the membership functions for linguistic terms can be estimated according to historical data or the questionnaire answered by decision makers.

Assuming that an EVCS site selection problem has l decision makers DM_k $(k = 1, 2, \ldots, l)$, m alternatives A_i $(i = 1, 2, \ldots, m)$, and n evaluation criteria C_j $(j = 1, 2, \ldots, n)$. Each decision maker DM_k is given a weight $w_k > 0$ $(k = 1, 2, \ldots, l)$ satisfying $\sum_{k=1}^{l} w_k = 1$ to reflect his/her relative importance in the EVCS site selection process. Based upon these assumptions, the detailed steps of the Pythagorean fuzzy VIKOR (PF-VIKOR) are described as follows.

Table 1: Linguistic terms for rating alternatives.

Linguistic terms	PFVs
Very Low (VL)	(0.15, 0.85)
Low (L)	(0.25, 0.75)
Moderately Low (ML)	(0.35, 0.65)
Medium (M)	(0.50, 0.45)
Moderately High (MH)	(0.65, 0.35)
High (H)	(0.75, 0.25)
Very High (VH)	(0.85, 0.15)

Step 1. Pull the decision makers' opinions to construct a Pythagorean fuzzy assessment matrix.

In the EVCS site selection process, all the participated experts' judgments need to be merged into group assessments to construct an aggregated Pythagorean fuzzy assessment matrix. Let $\widetilde{r}_{ij}^k = (\mu_{ij}^k, v_{ij}^k)$ be the PFV provided by DM_k on the assessment of A_i in relation to C_j. Then, the aggregated Pythagorean fuzzy ratings $(\widetilde{r}_{ij})$ of alternatives with respect to each criterion are calculated by using the PFWA operator.

$$\begin{aligned}\widetilde{r}_{ij} &= \text{PFWA}\left(\widetilde{r}_{ij}^1, \widetilde{r}_{ij}^2, \ldots, \widetilde{r}_{ij}^l\right) = \bigoplus_{k=1}^{l} \lambda_k \widetilde{r}_{ij}^k, \\ &= \left(\sqrt{1 - \prod_{k=1}^{l}\left(1 - \left(\mu_{ij}^k\right)^2\right)^{w_k}}, \prod_{k=1}^{l}\left(v_{ij}^k\right)^{w_k}\right), \\ & \qquad i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots, n.\end{aligned} \quad (10)$$

Hence, an EVCS site selection problem can be concisely represented in a matrix format as follows:

$$\widetilde{R} = \begin{bmatrix} \widetilde{r}_{11} & \widetilde{r}_{12} & \cdots & \widetilde{r}_{1n} \\ \widetilde{r}_{21} & \widetilde{r}_{22} & \cdots & \widetilde{r}_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \widetilde{r}_{m1} & \widetilde{r}_{m2} & \cdots & \widetilde{r}_{mn} \end{bmatrix}, \quad (11)$$

where $\widetilde{r}_{ij} = (\mu_{ij}, v_{ij})$ is an element of the aggregated Pythagorean fuzzy assessment matrix $\widetilde{R}$.

Step 2. Determine the PFPIS $\widetilde{p}_j^* = (\mu_j^*, v_j^*)$ and the PFNIS $\widetilde{p}_j^- = (\mu_j^-, v_j^-)$ of all criteria ratings by

$$\widetilde{p}_j^* = \begin{cases} \max\limits_i \widetilde{r}_{ij}, & \text{for benefit criteria} \\ \min\limits_i \widetilde{r}_{ij}, & \text{for cost criteria,} \end{cases} \quad (12)$$
$$j = 1, 2, \ldots, n,$$

$$\widetilde{p}_j^- = \begin{cases} \min\limits_i \widetilde{r}_{ij}, & \text{for benefit criteria} \\ \max\limits_i \widetilde{r}_{ij}, & \text{for cost criteria,} \end{cases} \qquad j = 1, 2, \ldots, n. \tag{13}$$

Step 3. Compute the values of S_i and R_i as follows:

$$S_i = \text{GPFOWSD}\left(\langle \widetilde{p}_1^*, \widetilde{p}_1^-, \widetilde{r}_{i1}\rangle, \ldots, \langle \widetilde{p}_1^*, \widetilde{p}_1^-, \widetilde{r}_{in}\rangle\right) = \left(\sum_{k=1}^{n} \omega_k \overline{d}_k^{\lambda}\right)^{1/\lambda}, \quad i = 1, 2, \ldots, m \tag{14}$$

$$R_i = \left(\max_k \left(\omega_k \overline{d}_k^{\lambda}\right)\right)^{1/\lambda}, \quad i = 1, 2, \ldots, m, \tag{15}$$

where ω_k are the ordered weights of criteria, representing the relative importance of their ordered positions. Many different methods have been proposed in the literature for determining the ordered weighted average (OWA) weights [53] that can also be implemented for the GIFOWSD operator. It is worth noting that it is possible to consider a wide range of GPFOWSD operators such as those presented in Section 3.2.

Step 4. Compute the values Q_i by the relation

$$Q_i = v \frac{S_i - S^*}{S^- - S^*} + (1 - v) \frac{R_i - R^*}{R^- - R^*}, \quad i = 1, 2, \ldots, m, \tag{16}$$

where $S^* = \min_i S_i$, $S^- = \max_i S_i$, $R^* = \min_i R_i$, $R^- = \max_i R_i$; v is introduced as a weight of the maximum group utility, whereas 1-v is the weight of the individual regret. In this paper, the value of v is taken as 0.5.

Step 5. Rank the alternative sites based on the values of S, R, and Q in increasing order. The results are three ranking lists.

Step 6. Propose a compromise solution. The alternative $A^{(1)}$ with the minimum Q value is considered to be a compromise solution for the given criteria weights, if the following two conditions are satisfied:

(**C1**) Acceptable advantage: $Q(A^{(2)}) - Q(A^{(1)}) \geq 1/(m-1)$, where $A^{(2)}$ is in the second place of the alternatives ranked by Q.

(**C2**) Acceptable stability: the alternative $A^{(1)}$ must also be the best according to S or/and R. This compromise solution is stable within the EVCS site selection process, which could be "voting by majority rule" ($v > 0.5$), or "by consensus" $v \approx 0.5$, or "with veto" ($v < 0.5$).

When only one of the two conditions is not satisfied, a set of compromise solutions can be proposed, which are composed of

(i) alternatives $A^{(1)}$ and $A^{(2)}$ if the condition (C2) is not satisfied;

(ii) alternatives $A^{(1)}, A^{(2)}, \ldots, A^{(M)}$ if the condition (C1) is not satisfied; $A^{(M)}$ is calculated using the relation $Q(A^{(M)}) - Q(A^{(1)}) < 1/(m-1)$ for maximum M.

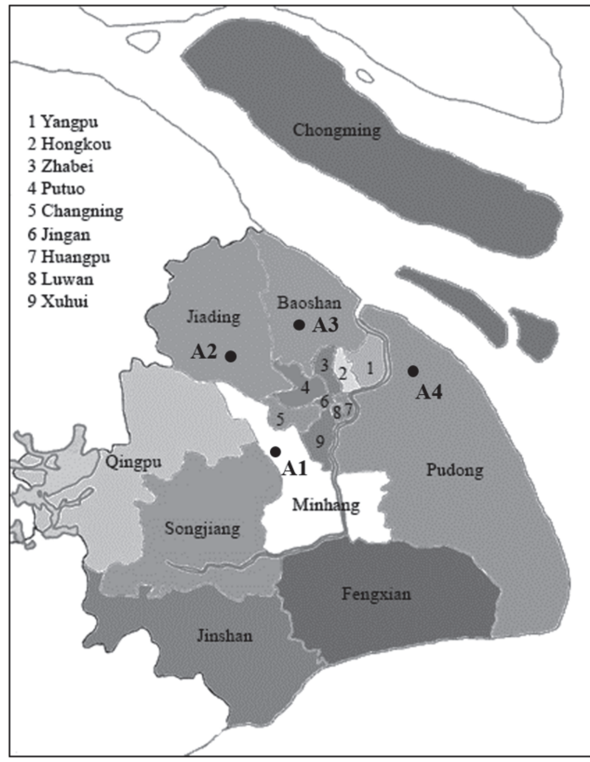

Figure 1: Geographical locations of the alternative sites.

5. Illustrative Example

In this section, an empirical study conducted in Shanghai, China [48], is provided to illustrate the applicability and efficacy of the proposed EVCS site selection model.

5.1. Background Description. Shanghai is one of the fastest developing cities in China and because of rapidly economy development, vehicle demand is rising dramatically. In 2016, the number of cars in Shanghai reached 3.22 million, ranking the fourth in China. Similar to others cities in China, air pollution is a growing problem in Shanghai. Hence, Shanghai government is endeavoring to promote sustainable development of the EV industry. Currently, a Chinese electricity company needs to construct a charging station for EVs in Shanghai based on the company's development strategy and market requirements. After initial screening, four sites located in Minghang district (A_1), Jiading district (A_2), Baoshan district (A_3), and Pudong district (A_4) are determined as the alternative sites as shown in Figure 1. An expert committee consisting of five decision makers (denoted as $DM_1, DM_2, \ldots, DM_5$) has been formed to conduct the assessment and select the most suitable site for the EVCS. These experts are authorities in the areas of engineering, economy, environment, electrical power system, and transportation system.

Generally, it is needed to consider various criteria to determine the optimal siting of EVCSs. According to a literature review and expert interviews, four dimensions together with their criteria are taken into account for

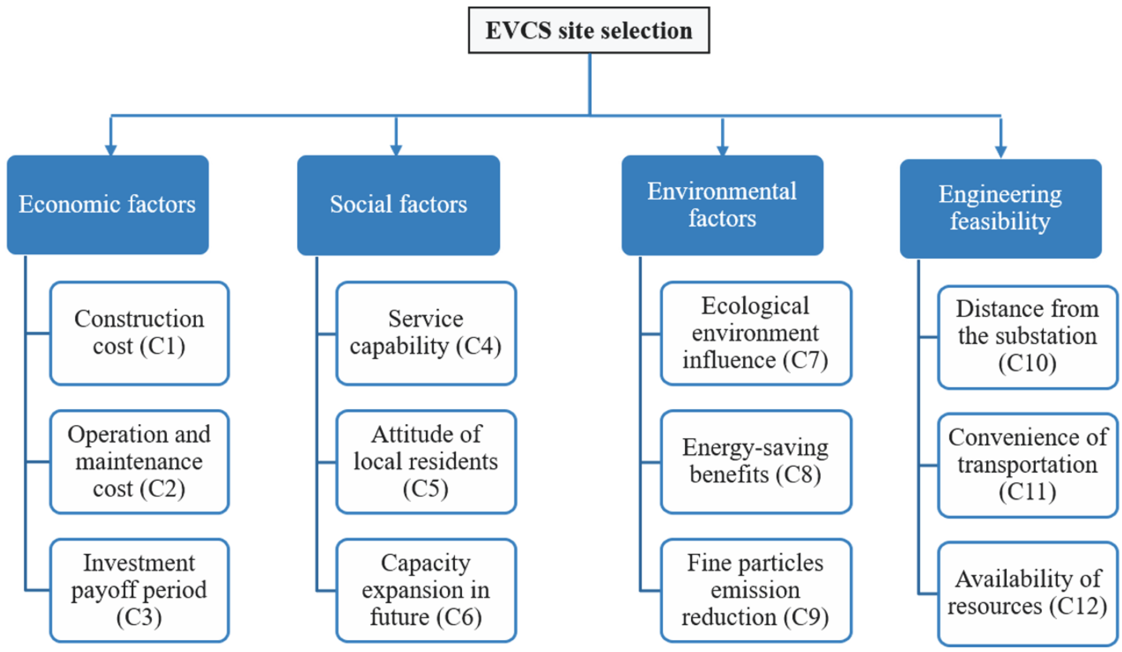

Figure 2: Dimensions and related criteria for EVCS site selection.

Table 2: Linguistic assessed information of the alternative sites.

Decision makers	Alternatives	Criteria											
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
DM_1	A_1	H	H	H	H	H	H	M	H	H	L	M	MH
	A_2	H	MH	H	VH	M	H	M	MH	M	ML	ML	M
	A_3	MH	MH	VH	H	M	VH	M	H	VH	L	MH	H
	A_4	VH	H	VH	H	H	M	MH	H	M	VL	M	MH
DM_2	A_1	VH	H	H	H	H	H	MH	H	MH	L	M	MH
	A_2	VH	H	H	VH	MH	H	M	MH	M	ML	ML	M
	A_3	H	MH	VH	VH	M	VH	M	VH	MH	L	MH	H
	A_4	VH	MH	VH	H	VH	M	M	H	M	VL	M	MH
DM_3	A_1	H	MH	H	H	H	MH	M	H	H	ML	M	M
	A_2	H	MH	VH	VH	M	H	M	M	ML	L	M	M
	A_3	H	MH	VH	VH	MH	VH	MH	H	VH	L	MH	VH
	A_4	VH	H	H	H	H	MH	M	H	M	VL	MH	H
DM_4	A_1	VH	H	H	MH	MH	H	M	H	H	L	M	H
	A_2	VH	MH	MH	VH	M	H	MH	MH	M	ML	ML	M
	A_3	MH	MH	H	VH	MH	VH	M	H	VH	VL	M	M
	A_4	VH	H	VH	VH	H	M	M	H	M	VL	M	MH
DM_5	A_1	VH	MH	H	H	H	H	M	H	MH	L	M	MH
	A_2	H	H	H	VH	MH	H	M	M	M	ML	ML	M
	A_3	H	MH	VH	H	M	VH	M	VH	VH	L	MH	H
	A_4	VH	H	VH	H	MH	M	MH	VH	M	VL	M	H

evaluating the alternative sites comprehensively (see Figure 2). Given the difficulty in precisely assessing these criteria, the five experts are assumed to evaluate them by using the linguistic terms defined in Table 1. Afterwards, the linguistic evaluations of the decision makers for the four alternatives are obtained as shown in Table 2. The five decision makers from different organizations are supposed to be of different importance considering their different academic backgrounds and domain knowledge. Hence, they are assigned the following relative weights: 0.15, 0.20, 0.25, 0.25, and 0.15 in the EVCS site selection process.

Table 3: Aggregated Pythagorean fuzzy assessment matrix $\widetilde{R}$.

	C_1	C_2	C_3	C_4	C_5	C_6
A_1	(0.817, 0.184)	(0.715, 0.286)	(0.750, 0.250)	(0.729, 0.272)	(0.729, 0.272)	(0.729, 0.272)
A_2	(0.802, 0.199)	(0.690, 0.311)	(0.763, 0.239)	(0.850, 0.150)	(0.562, 0.412)	(0.750, 0.250)
A_3	(0.715, 0.286)	(0.650, 0.350)	(0.830, 0.170)	(0.826, 0.175)	(0.585, 0.397)	(0.850, 0.150)
A_4	(0.850, 0.150)	(0.733, 0.267)	(0.830, 0.170)	(0.781, 0.220)	(0.764, 0.237)	(0.545, 0.423)
	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
A_1	(0.537, 0.428)	(0.750, 0.250)	(0.720, 0.281)	(0.279, 0.724)	(0.500, 0.450)	(0.652, 0.343)
A_2	(0.545, 0.423)	(0.599, 0.387)	(0.469, 0.493)	(0.328, 0.674)	(0.395, 0.593)	(0.500, 0.450)
A_3	(0.545, 0.423)	(0.792, 0.209)	(0.824, 0.178)	(0.229, 0.774)	(0.619, 0.373)	(0.744, 0.255)
A_4	(0.554, 0.417)	(0.769, 0.232)	(0.500, 0.450)	(0.150, 0.850)	(0.545, 0.423)	(0.695, 0.306)

5.2. Application and Results. Next, we use the PF-VIKOR approach to select the optimal site for the EVCS, which involves the following steps.

Step 1. After converting the linguistic evaluations of decision makers into PFVs according to Table 1, the aggregated Pythagorean fuzzy assessment matrix $\widetilde{R} = [\widetilde{r}_{ij}]_{4\times 12}$ is formed by utilizing (10). The calculated results are presented in Table 3.

Step 2. The benefit criteria are C_3, C_4, C_6, C_8, C_9, C_{11}, C_{12} and the cost criteria are C_1, C_2, C_5, C_7, C_{10}. Thus, the PFPIS and the PFNIS of the twelve criteria ratings are determined as follows:

$$
\begin{aligned}
f_1^* &= (0.715, 0.286), \\
f_2^* &= (0.650, 0.350), \\
f_3^* &= (0.830, 0.170), \\
f_4^* &= (0.850, 0.150), \\
f_5^* &= (0.562, 0.412), \\
f_6^* &= (0.850, 0.150), \\
f_7^* &= (0.537, 0.428), \\
f_8^* &= (0.792, 0.209), \\
f_9^* &= (0.824, 0.178), \\
f_{10}^* &= (0.150, 0.850), \\
f_{11}^* &= (0.619, 0.373), \\
f_{12}^* &= (0.744, 0.255); \\
f_1^- &= (0.850, 0.150), \\
f_2^- &= (0.733, 0.267), \\
f_3^- &= (0.750, 0.250), \\
f_4^- &= (0.729, 0.272), \\
f_5^- &= (0.764, 0.237), \\
f_6^- &= (0.545, 0.423), \\
f_7^- &= (0.554, 0.417), \\
f_8^- &= (0.599, 0.387), \\
f_9^- &= (0.469, 0.493), \\
f_{10}^- &= (0.328, 0.674), \\
f_{11}^- &= (0.395, 0.593), \\
f_{12}^- &= (0.500, 0.450).
\end{aligned} \tag{17}
$$

Steps 3 and 4. In this example, we use the PFNHSD, the PFWHSD, the PFOWHSD, the PFNESD, the PFWESD, and the PFOWESD operators in the PF-VIKOR method while assuming that the OWA weights are $\omega = (0.0353, 0.0538, 0.0752, 0.0968, 0.1144, 0.1245, 0.1245, 0.1144, 0.0968, 0.0752, 0.0538, 0.0353)$ [53]. According to (14)-(16), the results obtained are listed in Table 4.

Step 5. Based on the values of S, R, and Q, the rankings of the four alternatives are obtained as shown in Table 5. It is clear that A_3 is the most appropriate alternative for all the cases, followed by A_1, A_2, and A_4.

It should be noted that depending on the particular type of the distance operator used, the ordering of the alternatives may be dissimilar, thus leading to different decisions. Therefore, the electricity company can properly select the desirable EVCS site according to actual needs. But in this example, it seems clear that A_3 is the optimal choice. Therefore, the EVCS site in Baoshan district should be selected as the best EVCS site in this case study.

5.3. Comparative Study. To demonstrate the effectiveness of the proposed PF-VIKOR approach, we use the data in the above example to analyze some existing EVCS site selection methods, such as the fuzzy GRA-VIKOR [2] and the fuzzy TOPSIS [7] methods. In addition, we extend the TOPSIS method with PFSs and use the Pythagorean Fuzzy TOPSIS (PF-TOPSIS) for solving the same case study. The ranking results of the four alternative sites derived by using these methods are summarized in Table 6. From the results in

Table 4: Aggregated results.

Distance operator		A_1	A_2	A_3	A_4
PFNHSD	S	0.592	0.652	0.106	0.606
	R	0.083	0.083	0.042	0.083
	Q	0.945	1.000	0.000	0.958
PFNESD	S	0.661	0.749	0.208	0.732
	R	0.289	0.289	0.145	0.289
	Q	0.919	1.000	0.000	0.985
PFWHSD	S	0.551	0.596	0.129	0.644
	R	0.097	0.114	0.063	0.125
	Q	0.686	0.872	0.000	1.000
PFWESD	S	0.638	0.710	0.230	0.763
	R	0.311	0.338	0.178	0.353
	Q	0.764	0.909	0.000	1.000
PFOWHSD	S	0.606	0.690	0.068	0.641
	R	0.092	0.114	0.025	0.116
	Q	0.798	0.989	0.000	0.960
PFOWESD	S	0.649	0.758	0.157	0.742
	R	0.260	0.338	0.107	0.338
	Q	0.741	1.000	0.000	0.986

Table 5: Rankings of the alternatives by the PF-VIKOR method.

Distance operator	Ranking	Distance operator	Ranking
PFNHSD	$A_3 \succ A_1 \succ A_4 \succ A_2$	PFNESD	$A_3 \succ A_1 \succ A_4 \succ A_2$
PFWHSD	$A_3 \succ A_1 \succ A_2 \succ A_4$	PFWESD	$A_3 \succ A_1 \succ A_2 \succ A_4$
PFOWHSD	$A_3 \succ A_1 \succ A_4 \succ A_2$	PFOWESD	$A_3 \succ A_1 \succ A_4 \succ A_2$

Table 6: Ranking comparison.

Alternatives	Fuzzy GRA-VIKOR				Fuzzy TOPSIS		PF-TOPSIS	
	S	R	Q	Ranking	CC	Ranking	CC	Ranking
A_1	0.519	1.000	0.897	2	0.523	2	0.452	2
A_2	0.539	1.000	0.914	3	0.384	3	0.370	3
A_3	0.059	0.376	0.000	1	0.955	1	0.929	1
A_4	0.638	1.000	1.000	4	0.345	4	0.344	4

Table 6, the advantages of the proposed PF-VIKOR model over other EVCS site selection methods can be identified.

As we can see, the top two alternatives obtained from the proposed approach and the three compared methods are exactly the same, i.e., A_3 and A_1. Particularly, when the PFWHSD and the PFWESD operators are used, our prioritization of the alternatives is in accordance with the rankings yielded by the fuzzy GRA-VIKOR, the fuzzy TOPSIS, and the PF-TPOSIS methods. Besides, the same EVCS site selection example has been investigated by Liu et al. [48] and the result showed that the site in Baoshan district (A_3) is the most suitable location. These demonstrate the validity of the proposed EVCS siting approach.

On the other hand, there are some differences in the priority orders of alternatives if other types of distance operators are adopted in the proposed approach. The divergences mainly result from different characteristics between the listed methods and the presented PF-VIKOR approach. First, both the fuzzy GRA-VIKOR and the fuzzy TOPSIS methods adopt fuzzy sets to depict the performance assessments of alternatives provided by the decision makers. However, the fuzzy set theory considering only a membership function is not able to model imprecision and vagueness of assessment information in detail and comprehensively. Second, the rankings of alternative sites are determined based on the GRA-VIKOR and the TOPSIS in the three compared methods. But the TOPSIS method introduces two reference points without considering the relative importance of the distances from these points. Moreover, the calculation complexity of the GRA-VIKOR method is relatively higher than the VIKOR method used in this study. That is, the proposed approach is able to generate identical results in less time complexity.

Therefore, from the comparative analysis, it can be concluded that the proposed approach is more flexible and useful to deal with EVCS site selection problems and can provide more information for the sitting decision-making. Compared with other EVCS location models, the PF-VIKOR approach provided in this study has the following attractions:

(i) Based on PFSs, the vagueness and complex uncertainty of performance assessments can be effectively handled. The proposed method gives experts the additional ability to represent imprecise knowledge and can address EVCS site selection problems in a more flexible way.

(ii) The attitudinal character of a decision maker can be reflected by using the GPFOWSD operator in the selection process of EVCSs. As a result, we are able to underestimate or overestimate the results according to the desired degree of optimism.

(iii) We can get a complete picture of an EVCS site selection problem by considering a wide range of distance operators. Hence, the decision maker is able to make decisions taking different scenarios into consideration and select the one that better fits his or her interests.

(iv) The PF-VIKOR method introduced a ranking index based on the particular measure of closeness to the ideal solution, which is an aggregation of all criteria and their importance, and a balance between total and individual satisfaction. Therefore, a more reasonable and reliable ranking of alternatives can be derived according to the basic principle of the VIKOR method.

6. Conclusions

Vehicle electrification is a promising approach to address peak oil and air pollution problems. As the energy provider of electric vehicles, the construction of EVCSs is picking up speed to ensure the synergetic development of the technology. The selection of the best site for EVCSs, which considers multiple criteria exhibiting vagueness and imprecision, can be regarded as a complicated MCDM problem. In this research, an extended VIKOR method called PF-VILOR is proposed for the optimal siting of EVCSs under Pythagorean fuzzy setting. This model is easy to implement and consistent with human recognition. In the performance evaluation process, the rating values of alternatives are treated as linguistic terms expressed by PFVs. The PFWA operator is employed to fuse individual opinions of decision makers into collective assessments. Then the rank orders of alternatives are obtained by utilizing an improved VILOR method, in which the S, R, and Q values of each alternative are calculated based on the GIFOWSD operator. Finally, the effectiveness and advantages of our proposed EVCS site selection approach are demonstrated by a case study conducted in Shanghai, China.

In future research, it is a meaningful topic to extend our approach to the interval-valued Pythagorean Flow [54] and the Pythagorean uncertain linguistic [55] environments. Also, as we can see, with the development of cloud model theory and hesitant fuzzy linguistic term sets, in the future, our work should be well attached with such new technologies to explore new application areas in other decision-making problems.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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