INTRODUCTION

Cities around the world have added the development of sustainable transport to their agenda owing to escalating energy and environmental issues. Electric vehicles (EVs) are a promising solution to greenhouse gas (GHG) emissions and the energy crisis. As of 2018, China had sold a total of 1.256 million new energy vehicles, consisting of 984,000 blade electric vehicles (BEV), 271,000 plug-in hybrid electric vehicles (PHEV), and 1527 fuel cell vehicles (FCV). Blade electric vehicles and PHEVs are driven by electricity and require charging using a power converter at home or in...
public. Although EV users, especially PHEV and BEV users, prefer to charge at home in the evening, doing so may not be practical and economic, especially in heavily populated areas. Thus, public charging infrastructure has become the most important secondary charging point after private charging piles. The efficient supply of electric vehicle charging infrastructure (EVCI) is therefore an important step in popularizing the application of EVs. As of December 2018, there were 300 thousand charging piles, including 190 thousand alternating current (AC) charging piles and 110 thousand direct current (DC) charging piles. Although charging facilities are supported by the government, they are still experiencing an issue. In China, the increasing charging needs are up against the low participation of social sectors in the construction of charge facilities, which hinders the sustainable development of EVCI and EVs.

To encourage the participation of social sectors and increase charging service efficiency, China’s EVCI projects began to take a public-private partnership (PPP) approach in 2015. The use of PPPs to operate charging infrastructure combines the complementary advantages and resources of the government and the private sector, thus mitigating the government’s financial burden, and accelerating the growth of charging facilities and the sustainable development of EVs and EVCI. By December 2018, 13 PPP projects were involved in charging infrastructure to provide charging services for BEVs and PHEVs. However, few EVCI-PPPs are in specific implementation stages, partly because charging facilities are still in an initial stage in China, and the related policies and standards are not yet complete. The inherent complexities and long-term nature of PPP projects increase the difficulty of applying PPPs to EVCI projects.

One of the major challenges of EVCI-PPPs is choosing the right private partner. Awarded long-term concession right, the private sector shoulders the responsibility for the finance, design, construction, and operation of the EVCI project. The private-sector partner fulfills these responsibilities and provides charging services in return. A sound private partner is required to maintain a stable relationship and provide effective operations. Poor private partners create difficulties in providing daily charge services or may even fail to deliver projects to the government. Thus, the private-sector partner is a critical success factor of EVCI-PPP projects, and a reasonable scientific evaluation system is the key to partner selection. However, research investigating private-sector partner selection in the context of EVCI-PPP projects is limited. Thus, it is necessary and important to understand the selection factors that influence PPP projects and to propose a technique to assess potential private-sector partners to ensure project success.

Some previous studies focus on EVCI-PPP projects. For example, ref pointed out that the PPP model is an effective supply path for charging infrastructure. Based on a case study of Shenzhen, China, argued that a government-enterprise cooperation model can encourage private participation and investment in charging infrastructure. stated that the PPP model is a new financing model that can improve the efficiency of EVCI operations. All three studies viewed the PPP model as a promising way to accelerate the development of EVCI, but they only discussed strategic measures from a macroperspective and neglected practical concerns, such as construction, operation, risk management, and concessionaire selection. conducted a case study to provide a closer look at some key elements of a sound deal structure in the context of EVCI PPP projects. focused on tax policy for improving the scale of EVCI-PPP projects. proposed a system dynamic model to set a reasonable charge price. explored risk factors and developed an evaluation model to assess the risk levels of different EVCI-PPP projects. Based on this model, proposed a risk management framework. Taken together, these studies show that the PPP model has attracted the attention of scholars, as a valuable model to stimulate private participations, and the research stream gradually shifted from a macroperspective to practical applications. However, none of these studies deals with the issue of private-sector partner selection, which is a crucial step in conducting an EVCI-PPP project. This study fills this research gap by focusing on selecting appropriate private-sector partners for EVCI-PPP projects.

Concessionaire selection is a key issue for the success of PPP projects, and various important selection criteria, such as financial, technical, managerial, safety, health, and environmental aspects, to assess the performance of private partners have been identified by other PPP projects. Some earlier studies focused on the importance of the lowest tender price to win a contract. Studies have also acknowledged that a long-term relationship and partnership is one of the main success criteria for infrastructure development. examined factors such as profitability and project experience in the context of the Chinese PPP experience. For the inconsistency of market necessities, nonfinancial aspects, and sustainabil-
in experts’ experience. Thus, multicriteria decision-making (MCDM) methods have been developed and used to deal with this issue. The most common methods are Analytic Hierarchy Process (AHP), Overall Evaluation Score, Elimination and Choice Translating Reality (ELECTRE), Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), and vlekriterijumska optimizacija I kompromisno resenje (VIKOR).

A number of studies have applied these methods in various contexts. Zhong and Yao29 used an extended-ELECTRE ranking method to conduct supplier selection. Lima Junior et al30 presented a comparative analysis of fuzzy AHP and fuzzy TOPSIS for supplier selection, and the results showed that the fuzzy TOPSIS method is a more suitable approach, considering changing alternatives and criteria. Hamdan and Cheaitou31 criteria decision making combined the AHP and fuzzy TOPSIS methods to investigate supplier selection. Liu et al32 evaluated social capital based on an improved TOPSIS method.

The TOPSIS and VIKOR methods are effective multicriteria tools for selecting among various alternatives considering multiple criteria. The TOPSIS approach determines the best solution based on the shortest distance to the ideal solution and the greatest distance from the least ideal solution,33 but it does not consider the relative importance of these distances. The VIKOR method overcomes this drawback and determines a compromise solution that is closest to the ideal. These comparative findings were discussed in several studies, such as those of Opricovic34, Xu et al35 and Valipour Parkouhi and Safaei Ghadikolaei.36 These studies showed that the VIKOR method is an effective MCDM method. Thus, the VIKOR...
| No  | Criteria                                                                 | References |
|-----|---------------------------------------------------------------------------|------------|
|     |                                                                           | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Total |
|-----|---------------------------------------------------------------------------|------------|
| 1   | **General ability**                                                       | √ | √ | √ | √ | √ | 5 |
| 2   | **Total assets**                                                          | √ | √ | √ | √ | 5 |
| 3   | **Equity/debt ratio**                                                     | √ | √ | √ | √ | 5 |
| 4   | **Qualification**                                                         | √ | √ | 3 |
| 5   | **Payment and drawdown schedules**                                        | √ | √ | 2 |
| 6   | **Staff status**                                                          | √ | √ | √ | 4 |
| 7   | **Plants and equipment**                                                  | √ | √ | √ | 4 |
| 8   | **Main place of business**                                                | √ | √ | 3 |
| 9   | **Competencies of designer/subdesigners and contractor/subcontractors**   | √ | √ | 4 |
| 10  | **Reputation and social influence**                                       | √ | √ | 2 |
| 11  | **Tariff/toll setup and adjustment mechanism**                           | √ | √ | 3 |
| 12  | **Government's control on tariffs/tolls**                                 | √ | √ | 3 |
| 13  | **Investment schedule**                                                   | √ | √ | 4 |
| 14  | **Financial analysis**                                                    | √ | √ | 4 |
| 15  | **Financing schedule**                                                    | √ | √ | 3 |
| 16  | **Financing capability**                                                  | √ | √ | 5 |
| 17  | **Financing channel**                                                     | √ | √ | 3 |
| 18  | **Currencies of loans and equity finance**                               | √ | √ | 3 |
| 19  | **Currencies of revenues and payments**                                  | √ | √ | 3 |
| 20  | **Comprehensive capital cost rate of financing**                         | √ | √ | 1 |
| 21  | **Interest rate financing**                                               | √ | √ | 4 |
| 22  | **Ability to deal with fluctuations in interest/exchange rates**          | √ | √ | 3 |
| 23  | **Financial institution guarantees**                                      | √ | √ | 3 |
| 24  | **Insurance cover**                                                       | √ | √ | 4 |
| 25  | **Cohesive consortium**                                                   | √ | √ | 3 |
| 26  | **Main/standby loan agreement**                                           | √ | √ | 2 |
| 27  | **Internal rate of return**                                               | √ | √ | 3 |
| 28  | **Net present value**                                                     | √ | √ | 4 |
| 29  | **Revenues schedule**                                                     | √ | √ | 3 |
| 30  | **Bidding price**                                                        | √ | √ | 5 |
| 31  | **Sharing of revenues and profits with governments**                     | √ | √ | 6 |
| 32  | **Design/organization plan**                                              | √ | √ | 6 |
| 33  | **Construction/organization scheme**                                      | √ | √ | 5 |
| 34  | **Cost control**                                                          | √ | √ | 4 |
| 35  | **Construction/concession period**                                       | √ | √ | 6 |
| 36  | **Technical ability**                                                     | √ | √ | 7 |
| 37  | **Structural aspects**                                                    | √ | √ | 3 |

(Continues)
TABLE 1 (Continued)

| No | Criteria                                  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Total |
|----|-------------------------------------------|---|---|---|---|---|---|---|---|---|-------|
| 38 | Innovative solution                       | ✓ | ✓ | ✓ |   | ✓ | 4 |   |   |   |       |
| 39 | Value engineering potential               | ✓ | ✓ | ✓ |   |   | 3 |   |   |   |       |
| 40 | Use of local equipment and materials       | ✓ |   |   |   |   | 1 |   |   |   |       |
| 41 | Operational specification document        |   | ✓ | ✓ |   |   | 2 |   |   |   |       |
| 42 | Operational management ability            |   | ✓ | ✓ |   |   | 1 |   |   |   |       |
| 43 | Operation and maintenance policy          | ✓ | ✓ | ✓ |   |   | 3 |   |   |   |       |
| 44 | Organizational culture and structure       | ✓ | ✓ | ✓ |   |   | 3 |   |   |   |       |
| 45 | Maintenance management                    | ✓ | ✓ |   |   | 2 |   |   |   |   |       |
| 46 | Transfer plan                             | ✓ |   |   |   |   | 1 |   |   |   |       |

Relevant experience

| 47 | Project experience                        | ✓ | ✓ | ✓ | ✓ | ✓ | 5 |   |   |   |       |

Management

| 48 | Management structure                      | ✓ | ✓ | ✓ |   |   | 4 |   |   |   |       |
| 49 | Management system                         | ✓ | ✓ | ✓ |   |   | 4 |   |   |   |       |
| 50 | Management safety accountability          | ✓ | ✓ | ✓ |   |   | 4 |   |   |   |       |
| 51 | Quality management                        | ✓ | ✓ | ✓ | ✓ | ✓ | 5 |   |   |   |       |

Relationship

| 52 | Leadership and allocation of responsibilities | ✓ | ✓ | ✓ | ✓ | ✓ | 4 |   |   |   |       |
| 53 | Relationship management                    | ✓ | ✓ | ✓ | ✓ | ✓ | 5 |   |   |   |       |
| 54 | Coordination and communication skills       | ✓ | ✓ | ✓ | ✓ | ✓ | 5 |   |   |   |       |
| 55 | Dispute resolution system                   | ✓ | ✓ | ✓ |   |   | 3 |   |   |   |       |

Health, safety, and environment

| 56 | Trade union record                         | ✓ | ✓ | ✓ |   |   | 3 |   |   |   |       |
| 57 | Training regime                            | ✓ | ✓ | ✓ |   |   | 3 |   |   |   |       |
| 58 | Safety production scheme                   | ✓ |   |   |   |   | 1 |   |   |   |       |
| 59 | Safety and health record/accident rate      | ✓ | ✓ | ✓ | ✓ | ✓ | 5 |   |   |   |       |
| 60 | Safety and health policy and management system | ✓ | ✓ | ✓ | ✓ | ✓ | 4 |   |   |   |       |
| 61 | Environmental policy and management plan    | ✓ | ✓ | ✓ | ✓ | ✓ | 5 |   |   |   |       |
| 62 | Conformance to laws and regulations        | ✓ | ✓ | ✓ | ✓ | ✓ | 4 |   |   |   |       |
| 63 | Public safety, health, and environment     | ✓ | ✓ | ✓ | ✓ | ✓ | 6 |   |   |   |       |
| 64 | Environment conservation/protection plan    | ✓ | ✓ | ✓ | ✓ | ✓ | 5 |   |   |   |       |
| 65 | Environmental improvement                  | ✓ | ✓ | ✓ |   |   | 2 |   |   |   |       |
| 66 | Waste management                           | ✓ |   |   |   |   | 1 |   |   |   |       |
| 67 | Recycling and safe disposable systems       | ✓ | ✓ | ✓ |   |   | 3 |   |   |   |       |
| 68 | Resource utilization                       | ✓ |   |   |   |   | 1 |   |   |   |       |

Risk system

| 69 | Risk management                           | ✓ | ✓ | ✓ |   |   | 4 |   |   |   |       |
| 70 | Risk response                             | ✓ | ✓ | ✓ |   |   | 2 |   |   |   |       |
| 71 | Risk sharing                              | ✓ | ✓ | ✓ |   |   | 2 |   |   |   |       |
| 72 | Emergency response                        | ✓ |   |   |   |   | 1 |   |   |   |       |

Note: 1 = Zhang8; 2 = Zhang17b; 3 = Ouenniche et al48; 4 = Kumaraswamy & Anvuur32; 5 = Tang et al56; 6 = Zhang8; 7 = Zhang17b; 8 = Zhang et al42; 9 = Liu et al52.
method is used to evaluate and rank private-sector partners to satisfy both the maximum group utility and the minimum individual regret. In general, the score of each criterion used by this method is determined subjectively by decision makers, adding to the uncertainty of the results. To deal with this issue, an intuitionistic fuzzy set (IFS) is introduced to extend the VIKOR method. Furthermore, the information entropy method is used to obtain an objective weight, which can reduce the subjectivity of the performance evaluations, especially for qualitative indicators.

Thus, it can be seen that studies rarely evaluate private-sector partners in EVCI-PPP projects, and VIKOR is an effective method to tackle this problem. Thus, this study aimed to investigate selection criteria and, then, establish an evaluation index system for private-sector partners in EVCI-PPP projects. An extended VIKOR-based model is proposed to obtain the optimal solution in an uncertain environment to help the government make decisions.

The remainder of the paper is structured as follows. Section 2 outlines the research framework, establishes an indicator system for selection, and presents the extended VIKOR method. This method is empirically applied in Section 3. Section 4 provides analysis and findings, including sensitivity and comparative analysis. Finally, Section 5 presents conclusions and directions for future study.

| Table 2 | Evaluation indicator system for private-sector partner selection for EVCI-PPPs |
|---------|--------------------------------------------------------------------------------|
| **Goal** | **Criteria** | **Subcriteria** | **Description** | **Criteria type** | **Value type** |
| Selection criteria of private-sector partner in EVCI-PPP projects | Basic ability (I1) | Total assets (C1) | A larger amount of assets can burden large financial investments | A1 | B1 |
| | | Equity/debt ratio (C2) | Equal to total liabilities/total assets | A1 | B1 |
| | | Technical level in the charging infrastructure industry (C3) | The core technique ahead of the competition | A1 | B2 |
| | | Charging technical staff (C4) | The total number of professional charging technical staff | A1 | B1 |
| | Management ability (I2) | Management structure (C5) | A suitable and efficient management structure can release the enterprise's energy to the maximum extent | A1 | B2 |
| | | Risk response capability (C6) | Refers to the emergency management and risk sharing plan | A1 | B2 |
| | | Operational management capability (C7) | Refers to the planning, organization, implementation, and control of the operation process | A1 | B2 |
| | | Coordination and communication skill (C8) | Refers to the ability to properly handle various relations between superiors, peers, and subordinates in daily work, so as to reduce friction and mobilize enthusiasm for all aspects of work | A1 | B2 |
| | Quality management system (C9) | Quality of goods and charge services provided by private partners | A1 | B2 |
| | Relevant charging infrastructure project experience (C10) | Similar construction or/and operation experience with charging infrastructure projects | A1 | B2 |
| Previous performance and credit performance (I3) | Contract fulfillment rate (C11) | The ratio of actually delivered projects to contracted projects | A1 | B1 |
| | | Social influence in charging business (C12) | Comprehensive social influence in the charging business field | A1 | B2 |
| | | Insurance (C13) | Indispensable security and insurance measures | A1 | B2 |
| | | Client satisfaction (C14) | Client satisfaction regarding goods and services | A1 | B2 |
| (Continues) |
This section presents the research framework, as shown in Figure 1. The framework includes selection criteria based on previous literature and experts’ judgment, establishing a 22-item evaluation indicator system for the selection of private-sector partners, evaluating and ranking alternatives using a VIKOR-based method. The collected data include experts’ reviews to determine selection criteria, as described in Section 2, and linguistic variables to evaluate the qualitative criteria, as shown in Section 3.1. The data analysis and findings are performed in Section 4.

### 2.1 Research framework

Private partner selection is an important part of project procurement, and an appropriate partner directly affects the quality of the product and service. The first requirement of this process is a reasonable, scientific, and standard system to evaluate candidates comprehensively. Although selection criteria vary from project to project, they have some common characteristics. For example, the concessionaire should have a certain economic strength, good financing ability, advanced technology, and outstanding operational management capacity, and EVCI. PPP projects are no exception. In this case, private-sector partner selection is divided into three steps, as shown in Figure 2. First, a list of partner selection and assessment criteria based on reviewing various PPP project cases is developed, as shown in Table 1. Then, the list of selection criteria is adjusted by experts to combine the government’s requirements for the development of EV industry and the construction and operations management of charging facilities. Finally, the final selection criteria are defined, as shown in Table 2.

### Phase 1: Identifying partner selection criteria through various PPP infrastructure projects.

The PPP model has been widely used in many countries for different public infrastructure projects, such as highway projects, waste-to-energy programs, pension community construction projects, and wastewater treatment projects. Although different projects have different characteristics, they have some basic indicators for selecting partners in common. In this phase, the selection indicators are listed with references to other types of PPP items, leading to the 72 indicators shown in Table 1.

### Phase 2: Adjust the list of selection criteria.

The government’s strategic determination to develop EVs and the requirements for construction of charging facilities
should be clarified when adjusting selection criteria. The Chinese government has three aims in introducing private investor participation in charging infrastructure projects: (a) expand the total number of charging facilities to match the growing demand for EVs and eliminate the anxiety of EV users; (b) provide users with professional, high-quality charging service to consumers’ enthusiasm around purchasing EVs; and (c) relieve the government’s financial and management burden.

Thus, in this phase, the list of indicators in Table 1 is revised by experts in the charging facility industry and PPP project areas. All experts are purposely selected considering their profession and recommendations. The standards for choosing the experts include two aspects: (a) They must have more than eight years of experience in PPP projects in either the EV and infrastructure construction sector at a public utility or the private sector; and (b) they must be involved in at least one PPP project with in-depth knowledge of concessionaire for such projects. Based on these criteria, 15 experts are selected and organized as a panel. The experts were asked to select 30% of the indicators based on Table 1, and they could add other important factors based on their knowledge. They used two principles in choosing selection indicators: (a) The selected indicators should investigate the comprehensive ability of private partners; and (b) the selected criteria should highlight the candidate’s experience and uniqueness in EVCI-PPP projects.

To ensure independence in decision-making, the experts were interviewed in separate rooms with no discussion. Interviews were conducted in two rounds, the first was for identifying the selection criteria, and the second was for adjusting and determining the final selection indicators. The organizer collected and computed the selection criteria, and the top 18 general indicators that experts considered important to PPP projects were determined. These 18 indicators are also high-frequency indicators highlighted in italics in Table 1. Based on the characteristics of charging infrastructure projects, some indicators are revised slightly, such as “staff status” to “charging technical staff,” “technical ability” to “technical level in the charging infrastructure industry,” and “bidding price” to “charge price.”

Some additional selection criteria are added. First, the contract fulfillment rate and client satisfaction are important indicators for assessing the previous performance and credit performance of bidders. China’s charging facilities are still in the market cultivation stage, and the current business model is ambiguous. The government encourages stakeholders to improve customer stickiness by expanding the charging service scope to include vehicle-to-grid systems, demand side responses, and various service packages, which are classified as value-added services. New energy generation provides a new energy supply method for charging stations, which can further improve the clean advantages of EV by avoiding the use of coal-fired power generation. Thus, the contract performance rate, client satisfaction, value-added services, and the use of new energy power system are included as well, for a total of 22 selection indicators, as shown in Table 2.

**Phase 3:** Define the final selection criteria.

Combining the classification of PPP project partner selection indicators of 9,17 and,42 this study divides the indicator system into five group of factors: basic ability, management ability, previous performance and credit performance, performance of project, and sustainable development, which include 22 subindicators. The selection system is composed...
of two types of indicators: benefit-type (A1) and cost-type indicators (A2). The index value types are divided into quantitative indicators (B1) and qualitative indicators (B2), as shown in Table 2. The specific meaning of each criterion is also given in Table 2.

2.3 | An extended approach with VIKOR

This section presents the methodological background for this study. Specifically, IFS is shown in Section 2.3.1, the information entropy method is illustrated in Section 2.3.2, and the VIKOR method is described in Section 2.3.3. The specific phases are transforming the evaluation language given by decision makers into an intuitionistic fuzzy number (IFN), calculating the weight of each decision maker using information entropy, and ranking the alternatives using the VIKOR method (see Figure 1). Suppose that there are m alternatives $A_i$ ($i = 1, 2, \ldots, m$) and n criteria $C_j$ ($j = 1, 2, \ldots, n$).

### 2.3.1 | Process the criteria values using IFS

To evaluate the potential candidates efficiently, an evaluation indicator system is established, as shown in Table 2. Suppose that there are m alternatives and n criteria. To obtain accurate decision results, a normalization process must be performed to eliminate the dimensions of the criteria. The criteria are divided into numerical values $N_1$ and linguistic variables $N_2$, and the numerical criteria are further divided into benefit criteria, and cost criteria, for which smaller values are better. The normalization processes for the two types of criteria values are as follows:

1. Numerical values

   $$ r_{ij} = \frac{x_{ij}}{\max_j x_{ij}}. $$
For cost criteria, the normalization process is performed as in Equation 2.

\[
    r_{ij} = \frac{\min_j x_{ij}}{x_{ij}} \tag{2}
\]

where \(1 \leq i \leq m, 1 \leq j \leq n\).

(2) Linguistic variables

Performance on qualitative criteria is always described by natural phrases, such as good, medium, poor, and others. To obtain normalized values of the linguistic variables, the IFS is used to measure these terms. The related concepts and definitions are as follows:

**Definition 1** Let the universe of discourse IFS on \(X\) be defined as:

\[
    A = \{ (x, \mu_A(x), \gamma_A(x)) \mid x \in X \}
\]

where \(\mu_A(x)\) is the membership degree, \(\mu_A(x) \colon X \to [0,1], x \in X \to \mu_A(x) \in [0,1]\); \(\gamma_A(x)\) is the nonmembership degree, \(\gamma_A(x) \colon X \to [0,1], x \in X \to \gamma_A(x) \in [0,1]\). For an arbitrary \(x \in X\), \(0 \leq \mu_A(x) + \gamma_A(x)\) is satisfied.

**Definition 2** The intuitionistic fuzzy hesitation degree of \(x\) is defined as:

\[
    \pi_A(x) = 1 - \mu_A(x) - \gamma_A(x)
\]

where \(0 \leq \pi_A(x) \leq 1\).
Definition 3  $\alpha = (\mu_\alpha, \gamma_\alpha, \pi_\alpha)$ is the specific IFN that satisfies $\mu_\alpha \in [0,1], \gamma_\alpha(x) \in [0,1], \mu_\alpha(x) + \gamma_\alpha(x) \leq 1$. and $\pi_\alpha(x) = 1 - \mu_\alpha(x) - \gamma_\alpha(x)$. Among them, $\alpha^+ = (1,0,0)$ and $\alpha^- = (0,1,0)$ are the maximum and minimum IFNs.

Definition 4  Suppose $\alpha = (\mu_\alpha, \gamma_\alpha, \pi_\alpha)$ and $\beta = (\mu_\beta, \gamma_\beta, \pi_\beta)$ are two IFNs. The distance between them is defined as:

$$d(\alpha, \beta) = \sqrt{\frac{1}{2} \left\{ (\mu_\alpha - \mu_\beta)^2 + (\gamma_\alpha - \gamma_\beta)^2 + (\pi_\alpha - \pi_\beta)^2 \right\}}$$  (3)

The linguistic evaluation is transformed into fuzzy values through the following transformation process.

Step 1. Quantify the linguistic variables by IFNs.
For qualitative criteria, a linguistic variable is used to present the value of each criterion provided by decision makers according to their knowledge and experience. This study uses nine-level transformation rules, as shown in Table 3.

Step 2. Determine the weights of decision makers.
The hesitancy degree represents the uncertainty inherent in the evaluation information given by decision makers. In general, a larger hesitancy degree implies a lower confidence level. Decision makers with a larger degree of hesitancy should be given lower weights. Based on information entropy, the confidence function $H_s(\pi)$ is established to obtain the objective weights of the decision makers. Let $\lambda_s$ be the weight of the s-th decision maker. The calculation functions are defined by Equations 6 and 7.

$$H_s(\pi) = - \frac{1}{\ln n} \left( \sum_{i=1}^{n} \sum_{j=1}^{m} \pi_{ij}^s \right) \ln \left( \sum_{i=1}^{n} \sum_{j=1}^{m} \pi_{ij}^s \right)$$  (4)

$$\lambda_s = \frac{H_s(\pi)}{\sum_{s=1}^{p} H_s(\pi)}$$  (5)

where $s = 1, 2, ..., p$.

Step 3. Aggregate the criteria values determined by the decision makers.
The performance of the criteria assessed by linguistic variables can be obtained by aggregating the weights of decision makers and by using subjective evaluation information. Let $r_{ij} = (\mu_{ij}^s, \gamma_{ij}^s, \pi_{ij}^s)$ be the IFN of $A_i$ with respect to criterion $C_j$ given by decision maker $D_s$. The aggregate values are represented by Equation 8.

$$r_{ij} = \lambda_1 r_{ij}^1 \otimes \lambda_2 r_{ij}^2 \otimes \cdots \otimes \lambda_p r_{ij}^p$$  (6)

2.3.2 Determine the criteria weights using the information entropy method

This study adopts the information entropy method, which was proposed by Claude Shannon in 1948, to obtain the objective weights of criteria. On principle, criteria with larger information entropies should be given larger weights. The steps of the entropy method are as follows:

Step 1. Determine the mean values of the normalized criteria weights, as described by Equation 9.

$$r_i = \frac{1}{\sum_{i=1}^{p} \mu_i} \sum_{i=1}^{p} \gamma_i^{1/2} \prod_{j=1}^{m} (1-\gamma_j^{1/2}) \prod_{j=1}^{m} (1-\gamma_j^{1/2})$$  (7)

Step 2. Compute the information entropy of $C_j$, defined by Equation 10.
\[ e_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} \left[ \frac{d(r_{ij}, \bar{r}_j)}{\sum_{i=1}^{n} d(r_{ij}, \bar{r}_j)} \ln \left( \frac{d(r_{ij}, \bar{r}_j)}{\sum_{i=1}^{n} d(r_{ij}, \bar{r}_j)} \right) \right] \] 

Step 3. Calculate the objective weights of the criteria according to Equation 11.

\[ w_j = \frac{1 - e_j}{\sum_{j=1}^{m} (1 - e_j)}. \] (9)

### 2.3.3 Evaluate and rank alternatives using the VIKOR method

Opricovic proposed the VIKOR method as a means of solving MCDM problems. Based on maximum group utility and minimum individual regret, the VIKOR method is a compromised ranking technique that chooses an appropriate partner (alternative) from a given set of partners under contradictory criteria. The fundamental principles of the VIKOR method are based on the \( L_p \) metric measure function, which can be written as follows.

\[ L_{pj} = \left\{ \sum_{j=1}^{n} \left[ w_j (f_j^* - f_{ij}) / (f_j^* - f_{ij}) \right]^p \right\}^{1/p} \]

where \( 1 \leq p \leq \infty; j = 1, 2, \ldots, n \).

The specific steps of the VIKOR method are as follows:

1. Establish the normalized decision matrix.
2. Obtain the positive and negative ideal solutions.
3. Compute the values of \( S_i, R_i \), and \( Q_i \) using Equations 12 and 15.

\[ S_i = \sum_{j=1}^{m} w_j \left[ f_j^* - f_{ij} \right] / \left( f_j^* - f_{ij} \right) \] (13)

\[ R_i = \max_j \left[ w_j \left( f_j^* - f_{ij} \right) / \left( f_j^* - f_{ij} \right) \right] \] (14)

\[ Q_i = \frac{S_i - S^*}{S^* - S^*} + (1 - \nu) \frac{R_i - R^*}{R^* - R^*} \] (15)

where \( S_i \) is the maximum group utility and measure of \( L_{1,i} \); \( R_i \) is the minimum individual regret and measure of \( L_{\infty,i} \); \( S^* = \min_i (S_i), R^* = \max_i (R_i), R^* = \max_i (R_i) \); \( \nu \in [0, 1] \) is the coefficient of the decision mechanism. This study takes \( \nu = 0.5 \), which provides a means of balancing and finding a compromise between all alternatives.

Step 4. Rank the alternatives and obtain the assessment results based on the values of \( S_i, R_i \), and \( Q_i \).

Rank the partners according to \( S_i, R_i \), and \( Q_i \) in increasing order. Let \( \{ A^1, A^2, \ldots, A^m \} \) be the new set of alternatives. The optimal alternative \( A^{(1)} \) is selected as the best partner if it satisfies conditions \( C_1 \) and \( C_2 \) with the minimal \( Q_i \).

\[ C_1: \text{Acceptable advantage} \]

\[ Q (A^{(2)}) - Q (A^{(1)}) \geq 1 / (m - 1) \]

\[ C_2: \text{The partner } A^{(1)} \text{ is also considered optimal according to the values of } S_i \text{ and/or } R_i. \]

### 3 CASE STUDY

To support the development of EVs, many regions in China have adopted laws and incentive measures for EVCI-PPP projects. This case study investigates a charging infrastructure PPP project in Anhui province, which is the largest EVCI‐PPP project executed in China, using the proposed framework. This project was sponsored by the local government in 2015, to provide sound public charging facilities and charging services that can meet the mobility and diversity requirements of EVs. It is planned to be implemented in two phases and will build 10 bus charging stations, six taxi charging stations, and 3000 charging piles. The first phase of the project is dominated by the main city, whereas the second phase is dominated by one town and six rural suburbs. The project is estimated to have a total investment of 818 million yuan.

According to the project plan, the selection of private-sector partners is to be conducted through competitive negotiation and performed using regional concession (RC) operational model, meaning that it covers the entire defined region with a promise of not building any charging facilities. The government and the selected private partner will form a joint venture to establish a special purpose vehicle (SPV). During the concession period, the selected concessionaire is offered exclusive concession rights and is responsible for construction and operations and providing charging services (ie, buses, taxis, sanitation, logistics, and passenger vehicles) within the defined area. According to the provision, viability gap funding is applied, meaning that the profits of the project mainly come from user charges, and municipal and county finances shall pay a feasibility gap subsidy according to performance appraisal results when the revenues cannot recover the investment and provide a reasonable income. After expiration, the charging infrastructure project will be transferred...
to the government without compensation. The SPV shall have an exclusive service obligation in accordance with the planning and government instructions and will receive exclusive management rights in return.

3.1 | Data collection

A panel of five experts is responsible for evaluating the submitted tender documents. The expert group consists of five experts from project management, industry (D1), engineering (D2), finance (D3), and the legal field (D4; see in Table 4). The project management expert is appointed as the leader to collect and summarize the linguistic evaluations of the other experts.

After the bidding, documents were received one by one, only three private candidates, represented as P1, P2, and P3, were deemed eligible to enter the final assessment. The quantitative indicator values of the three candidate partners are shown in Table 5. The subjective evaluation values (as shown in Table 6) were obtained from the four experts based on reviewing the tender documents and social surveys.

3.2 | Calculation process and results

Step 1: Process the criteria

In this step, the data in Tables 5 and 6 are processed according to Section 2.3.1; the weights of the decision makers are given by \( e_k = (0.2653, 0.2396, 0.2599, 0.2351) \).

The values for each criterion resulting from the data processing are listed in Table 7.

Step 2: Calculate the weights of all criteria

Based on Equations, objective criteria weights could be obtained, as shown in Table 8. Criteria C10, project experience, is the most important factor for selecting an appropriate private partner in an EVCI-PPP.

Step 3: Evaluate potential partners based on the VIKOR approach.

First, based on the value of each criterion shown in Table 6, and Equations and, the PIS and NIS of each criterion can be determined. According to Equations, the values of \( S_j, R_j, \) and \( Q_j \) can be calculated, as shown in Table 9.

Step 4: Rank the potential partners

Because \( Q_1 \) is the minimum value and \( P_1 \) satisfies conditions \( C_1 \) and \( C_2 \) presented in Section 2.3.3, \( P_1 \) is the best partner for this EVCI-PPP project. Furthermore, the public sector can negotiate with potential private partners one by one according to the ranking order: \( P_1 > P_2 > P_3 \).

4 | ANALYSIS AND FINDINGS

4.1 | Sensitivity analysis

In this section, a sensitivity analysis of all criteria is conducted to verify the robustness of the extended VIKOR method. The sensitivity analysis includes a perturbation method, in which the values of alternatives are recalculated, and the order of alternatives is changed when criteria scores change somewhat.

Assume that the initial weight of \( C_j, \) \( \omega_j \) is changed into \( \omega'_j = \xi \omega_j \) where \( 0 \leq \xi \) \leq 1. Thus, the variation range of \( \xi \) is between \( [0, 1] \). Correspondingly, the weights of other criteria also vary within \( \omega'_k = \phi \omega_k, \phi = (1 - \xi \omega_j) / (1 - \omega_j) \), \( k \neq j, k = 1, 2, \ldots, n \), and satisfied the following equation.

\[
\omega'_j + \sum_{k \neq j} \omega'_k = 1 \Rightarrow \xi \omega_j + \phi \sum_{k \neq j} \omega_k = 1.
\] (16)

Then, the weights of the other criteria can be obtained. For all 22 criteria, 88 sensitivity analysis experiments are conducted for the values of \( \xi \) with variations of 10% or 20% more than the initial weights and 10% or 20% less than the base weights, as shown in Figure 3.

The evaluation results are more sensitive to criteria C1, C3, C10, C12, C13, and C15. Potential partner P1 is the optimal choice in all 88 experiments (100%). Further, the most common order of alternatives is P1 > P2 > P3, which is the result of 86 experiments (98%), whereas the order P1 > P3 > P2 is the result of merely 2% of experiments. Thus, the evaluation results are robust.

In this case, the charging infrastructure project experience of partners ranked as the first criterion, followed by technical level in the charging infrastructure industry and the financing plan. In China, charging facilities are still in an early stage, and the charging business model has remained nebulous. An experienced private partner with a high technical level in the charging infrastructure industry and a sound financing plan is expected to operate the charging project, as these characteristics are important to the success of EVCI-PPPs.

4.2 | Comparative analysis

In this section, a comparative analysis with two widely used MCDM methods, including TOPSIS and simple additive weighting (SAW), is conducted to verify the effective of this proposed method. The TOPSIS method was proposed by Hwang and Yoon44 and selected the best solution by relative closeness coefficient \( r \). The simple additive weighting (SAW) technique generates an overall performance index value for each alternative across product of all attributes and their weights. The output ranking results are computed and shown as follows:

By TOPSIS method: P1 (0.6068) > P3 (0.5539) > P2 (0.4033)
By SAW method: P1 (−0.8253) > P3 (−1.2399) > P2 (−1.4136)

It can be seen that ranking the candidates by the TOPSIS and SAW method give P1 as a solution, as does the VIKOR
method, indicating the effectiveness of the proposed method. However, the ranking of P2 and P3 according to TOPSIS and SAW (P3 > P2) and VIKOR (P2 > P3) differ. The criteria weights indicate that the evaluation index of P2 is better than P3 for C10, C14, and C1, and thus, P2 is more likely to be better than P3. The result using the VIKOR method is therefore more reasonable. Under the proposed extended VIKOR approach, the best alternative is always closest to the ideal solution. However, under the TOPSIS method, the ranking order is determined by the relative closeness coefficient, which does not ensure that the highest ranked alternative is always closest to the ideal solution. Thus, the proposed VIKOR-based method shows an advantage over the TOPSIS and SAW method and is more suitable for the selection of an optimal private-sector partner for EVCI-PPP projects.

5 | CONCLUSIONS

Suitable private partners are essential to the viability of EVCI-PPP projects, as they determine the service level of performance, commercial viability, and profitability of the projects. Selecting an appropriate private-sector partner plays a significant role in the creation of a PPP model to promote the sustainable development of EV charging facilities, but it is rarely studied. Thus, this study established an evaluation index system for the performance of potential alternatives and proposed an extended VIKOR method. This evaluation index system consists of 22 subcriteria, classified into five factor packages: basic ability, management ability, previous performance and credit performance, performance of project, and sustainable development. An empirical case study demonstrated the robustness and validity of the proposed method, which can guarantee quantitative objectivity and reduce the prejudice of individual experts. The findings of this study provide a workable and efficient selection framework for the government to select an appropriate private partner.

The results show that, among 22 subcriteria, relevant charging infrastructure project experience (C10), technical level in the charging infrastructure industry (C3), management structure (C15), client satisfaction (C14), design and construction plan for charging points (C16), and charge price (C18) are the top six criteria according to their weights, which demonstrates that these criteria should be given special attention in selecting the right private-sector partner. Additionally, the evaluation indicator system consists of sixteen qualitative and six quantitative indicators. To guarantee the objectivity of scoring in actual practice, including richly experienced experts is very important to obtain objective language evaluation, and the level of transparency in tendering processes should be increased.

The findings of this study provide make a solid foundation for future sustainable development of EVCI-PPPs. The strength of the extended VIKOR method is its practical applicability under uncertain and limited conditions. For further study of the effective selection of private partners of PPP programs, more fuzzy methods should be applied to deal with the qualitative variables and obtain comparative results.

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AUTHOR CONTRIBUTIONS

For this work, Lihui Zhang provided professional guidance, Zhenli Zhao designed the proposed model and wrote the paper; and Zhinan Kan investigated PPP projects.

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