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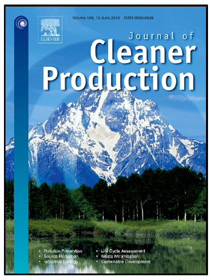

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Risk evaluation of electric vehicle charging infrastructure public-private partnership projects in China using fuzzy TOPSIS

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Abstract: With increasing worldwide attention on clean energy and sustainability of environment development, electric vehicle (EV) projects have been growing in number and scale all over the world. However, increasing demand-supply imbalance in charging infrastructure becomes the major obstacle of Chinese EV development. Governments are applying Public-Private Partnership (PPP) mode in this field to effectively make use of solid capital and advanced technological capability of private sector to improve charging performance and service. To ensure project success, risk evaluation, which has remained nebulous, has become a crucial step. This paper aims to explore risk factors through questionnaire survey and calculate the overall risk levels of EV charging infrastructure PPP projects with an integrated approach with Fuzzy Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS). Results of risk factors identification consisted of project/technical, political/legal, economic and social/environmental risk categories and four risk factors were selected for specific concern of charging infrastructure in China: inadequate PPP project experience, high battery cost, long charging period and power price rise. Overall risk levels of three alternative projects were evaluated and ranked with proposed approach whose feasibility and effectiveness were verified through a comparative analysis and a sensitivity analysis. Moreover, awareness of existing risks, suggestions were provided for private sectors of EV charging infrastructure PPP project. The detailed implications and limitations were presented in the suggestions and the conclusions.

Key words: electric vehicle; charging infrastructure; PPP; risk evaluation; fuzzy TOPSIS

1 Introduction

As global sustainable development, energy saving and emission reduction have become necessary and urgent issues. Electric vehicles (EVs), which play a key role in strategic development plans as a promising technology to promote environmental quality, livability, and sustainability without significantly reducing convenience or mobility (Stark Juliane et al., 2018; White and Sintov, 2017), has been given more attention for its outstanding performance in carbon emission reduction (Zhang and Han, 2017) and environment protection. Since transport sector has been one of the top contributors in greenhouse gas emissions (He and Zhan, 2018; S. Wang et al., 2017), significant efforts and series of measurements have been taken to satisfy China's sustainable development requirements. As a result, China has become the world's largest electric vehicle market and continues to maintain a high-speed growth (Lin and Wu, 2018) and its sales totaled 777,000 in 2017. Despite the EV development scale, it is noteworthy that demand-supply imbalance in electric vehicle charging infrastructure (EVCI) has become the major obstacle of EV development in China. To satisfy increasingly urgent charging demand, public-private partnership (PPP) mode has been introduced and supported to attract private sectors and make use of their advantages in financing, design, construction and operation for providing high quality, efficient and diverse charging services and creating social benefit (Ou, 2016).

PPP projects are always characterized by long construction period, large scale investment, complicated contract structure and various uncertain risk factors in the whole life-cycle of project construction, which arouse a fundamental concern in view of challenges from perspective of private sector, risk evaluation of a PPP project becomes increasingly important and necessary. However, research investigating the risk evaluation of EVCI PPP project is limited and China lacks certain experience in this field. It is therefore important to understand what risk factors might influence the projects and propose a method to evaluate the risk level of a potential project to ensure the continuous success.

There exist two kinds of research streams focused on EVCI projects. The firs stream studies innovation and improvement of key technologies of charging facilities, i.e., battery efficiency optimization and wireless charging technology (Ahmad et al., 2018; Laurischkat and Jandt, 2018; Yang et al., 2016) and charging service pattern and perfection, i.e., payment mechanisms and pricing model (Perez-Diaz et al., 2018; Zhang et al., 2017). The second stream considers PPP mode an effective path to activate charging infrastructure market for its advantages of attracting social capital, reducing financial burden, improving profitability and so on (Yang et al., 2016; Zhu Liping, 2017). The former research stream failed to discuss the operation and performance of charging infrastructure with PPP mode, the latter stream failed to consider comprehensive risk evaluation in life-cycle of a PPP project, and they both failed to identify risk factors and determine risk level of certain project from the perspective of private sectors. Comprehensive risk evaluation in EVCI PPP projects has not been completely investigated.

To fill this gap, we will discuss risk factors influencing EVCI PPP projects and calculate their occurrence probabilities (OPs), magnitudes of impact (MI) and integrated risk impacts (IRIs) and then investigate comprehensive risk evaluation of EVCI project with integrated fuzzy TOPSIS model from angle of private sector. PPP project risk evaluation takes numerous potential factors under uncertain conditions into consideration, such as political risks, economic risks, operating risks, environmental risks and so on (Osei-Kyei and Chan, 2017; Wu et al., 2017; Xing and Guan, 2017; Yang et al., 2017, 2016), and these make it a Multi-Criteria Decision Making (MCDM) problem which is considered a pertinent approach for overcoming great uncertainty and complexity of various risk factors (Govindan et al., 2013; P. U. Onu et al., 2017; Zhao and Li, 2016). Additionally, TOPSIS model has outstanding performance in solving a MCDM problem and is wildly used in performance and risk evaluation. For better dealing with risk factors and evaluating the risk level, we extend this model from three aspects, i.e., selecting risk factors with literature review and questionnaire survey, determining the criteria weight with normalized mean method, applying fuzzy theory in processing linguistic variables and evaluate overall risk level with fuzzy TOPSIS. In general, we propose a framework to identify risk factors and evaluate overall risk level of EVCI PPP project from the angle of private sector.

This paper makes following contributions on practically and academically. Firstly, we precisely identify risk factors and discuss OP, MI and IRI of each factor to shew new light on the understanding of underlying risks of EVCI PPP projects in China. Secondly, we propose a framework to evaluate overall risk level with fuzzy TOPSIS model to enrich the research on comprehensive risk evaluation of PPP project and better understand the risk level of corresponding project in China, which have not been fully investigated in previous research.

Finally, the proposed framework provides practical risk evaluation method and basis for upcoming boom of EVCI PPP projects in China.

The remainder of this paper is organized as follows. A review of risk analysis of EVCI PPP projects and fuzzy TOPSIS method is presented in Section 2. In Section 3, we present research framework of this work, identify and process risk factors, determine risk evaluation criteria and propose an integrated approach with fuzzy TOPSIS for risk evaluation of EVCI PPP project. The case study and results are presented in Section 4. Discussions and Suggestions are provided in Section 5 and Section 6. The Conclusions and further work are presented in Section7.

2 Literature review

2.1 EV charging infrastructure PPP projects in China

Electric vehicles (EVs) are defined as the vehicles that derive motive power exclusively from onboard electrical battery packs charged with a plug through an electric outlet (N. Wang et al., 2017; S. Wang et al., 2017) and recognized as an effective approach to reduce carbon emission and improve sustainability of environment development (Martínez-Lao et al., 2017; Stark Juliane et al., 2018; Xu et al., 2017; Zhang and Han, 2017).To further promote EV adoption and improve charging service, Chinese governments embark on PPP mode to satisfy charging requirements of increasing EV adoption numbers considering the advantages of this mode reflects, i.e. achieving win-win situation for public and social capital, improving the management and operation of the projects, improving the technology and the system innovation and so on (Ma et al., 2016; Yang et al., 2017, 2016; Zeng et al., 2016; Zhu Liping, 2017). Charging facilities construction has significant impacts on healthy development of EVs and the environmental sustainability, and China is taking series of measurements to guarantee the charging service (Chen Liangliang et al., 2011; N. Wang et al., 2017; S. Wang et al., 2017). Zhu (2017) believed that PPP mode was a new financing model and had the inherent driving force to lead the idea the technology and the system innovation and proposed that PPP mode would effectively improve the operation of EVCI operating efficiency. Yang et al. (2016) elaborated that introducing the PPP model into charging infrastructure can enhance project management and profitability and reduce construction and operation risks. What's more, a series of supportive policies have effectively attracted private sectors and increased its growth rate (MSTPRC, 2016; NDRC, 2015; Yang et al., 2016). Therefore, PPP mode will be gradually utilized in more and more EVCI projects.

However, China's EVCI PPP project development is still immature at the beginning stage. At present, only 14 related projects are selected by *China Public Private Partnerships Center* with a total investment of 5 billion yuan. It's noteworthy that none of them has been put into operation and all projects are in the preparatory or construction stage, China is in shortage of EVCI PPP project operation experience. Furthermore, previous literature analyzed its advantages and meanings and ignored in-depth discussion of potential risks. In this basis, it's important to launch the risk evaluation analysis for the smooth implementation of the project. This paper will conduct in-depth risk analysis of EVCI projects via PPP mode to ensure the project success and benefits.

2.2 Risk analysis with PPP mode

Giving priority to charging infrastructure construction is recognized one of the most important factors to keep EV market still present a perfect performance (N. Wang et al., 2017; S. Wang et al., 2017), and EVCI PPP projects are adopted for this purpose. At present, there is rare research on assessing risk factors and then comprehensively evaluating overall risk of the charging infrastructure PPP project. Existing studies focused on following aspects.

(1) PPP mode is a long-term partnership between public and private parties, the aim of which is to deliver infrastructure projects in a specific economic sector (Albalate et al., 2017; Bel et al., 2017), and this kind of project is accompanied with uncertainty with risk allocation (Maria Sastoque et al., 2016) and thus risk management is a key concern for PPP project success (Shrestha et al., 2018). Cheung and Chen (2012), Bel et al. (2017), Wu et al. (2017), Osei-Kyei and Chan (2017) selected major risk factors of PPP projects. A limitation of these studies is that they tried to analyze risk allocation and risk factors of infrastructure PPP projects instead of comprehensive risk evaluation of a PPP project.

(2) Risk analysis about EVCI PPP project deserves more attention. Current research in this field is limited while some others PPP projects have been studied. i) Road and highway sector: Kumar et al. (2018) investigated financial risk associated with highway infrastructure projects in India. ii) Power sector: Wu et al. (2017) identified and ranked critical risk factors of straw-based power generation PPP projects. Ameyaw and Chan (2015) investigated the risk factors of PPP water supply projects in developing countries.

Literature mentioned above shows that researchers have studied risk allocation, risk factors and risk management in PPP projects. However, most of them discuss and rank risk factors instead of assessing overall risk level. Therefore, it’s necessary to establish the risk evaluation criteria and launch a comprehensive risk evaluation focused on EVCI projects via PPP mode. Only in this way can private sector be informed of existing risk factors and the risk level of alternative project.

2.3 Applicable risk factors of infrastructure PPP projects

The important risk factors for risk evaluation in EVCI PPP project have been identified through wide-ranging literature resources in the first step and experts' judgements by questionnaire survey in the second step. In the first step, a primary list of 24 risk factors are obtained and identified with literature analysis (for details, see Table 1). In the second step, questionnaire survey is adopted to identify specific risk factors of EVCI PPP projects in China to obtain comprehensive and accurate risk factor system (for details, see Section 3.2).

2.4 Fuzzy TOPSIS method

MCDM techniques refer to methods provide ordering or grouping of alternatives and make a choice between them by evaluation of multiple decision criteria (Sengul et al., 2015). MCDM approach appears to be the most appropriate method to deal with complicated risk factors in various aspects, including political, economic, social and technical, and process the overall risk evaluation of feasible alternatives. In recent years, an increasing number of studies concerns the MCDM techniques, such as Elimination and Choice Expressing Reality (ELECTRE) (Zhou Huan et al., 2017), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) (Liang et al., 2017), grey approach (Liu et al., 2017; Su et al., 2016) and so on. These methods can effectively solve MCDM problems from different angles (Wang et al., 2018). TOPSIS as one of the most applicable MCDM methods assigns the best alternative among many feasible alternatives by calculating the distances from the positive ideal and the negative ideal (anti-ideal) solutions (Mahdevari et al., 2014) and it's commonly applied in solving MCDM problems (Lima Junior et al., 2014; P. U. Onu et al., 2017; Sengul et al., 2015).

Table 1 a 24 risk factor-list based on literature review

Categories	Risk factors \ Literature	(Tah and Carr, 2000)	(Li et al., 2005)	(Xu et al., 2011)	(Cheung and Chan, 2012)	(Amey-aw and Chen, 2013)	(Ma et al., 2016)	(Yang et al., 2016)	(Osei-K-yei and Chan, 2017)	(Xing and Guan, 2017)	(Wu et al., 2017)	(Bel et al., 2017)	(Kumar et al., 2018)	Referred frequency
Political/ legal risks	Legal risk		*	*			*	*			*			5
	Government credit			*			*	*			*			4
	Government intervention		*	*	*	*			*	*	*			7
	Corruption								*		*			2
	Policy		*				*	*		*				4
Economic risks	Financial risk						*				*	*		3
	Market		*	*		*	*	*		*		*	*	8
	Financing		*	*	*	*								4
	Inflation		*	*					*					3
	Exchange rate fluctuation		*						*		*			3
	Interest rate fluctuation		*						*		*		*	4
	Revenue		*					*		*			*	4
	Payment										*			1
Social/ Environm-ental risks	Shortage of supporting facility			*				*			*	*	*	5
	Public against		*							*	*			3
	Environmental risk		*								*			2
	Force majeure		*				*	*		*	*	*		6
Project/ technical risks	Construction						*	*	*		*	*	*	6
	Operation						*				*		*	3
	Completion		*		*						*			3
	Project operating		*			*		*	*					4
	Delay		*						*					2
	Contract change	*									*			2
	Project uniqueness		*							*		*		3

"*" represents the one was referred in the literature.

As the extension of TOPSIS method, fuzzy TOPSIS is usually introduced to efficiently handle and resolve the fuzziness of data involved in decision making (P. U. Onu et al., 2017) and deal with qualitative linguistic variables in various endeavors in the research. Estay-Ossandon et al. (2018) used a fuzzy TOPSIS-based scenario analysis to rank and support decision-making of the comparison of different potential alternative municipal solid waste treatments. P. U. Onu et al. (2017) applied the unique and exemplary features of fuzzy TOPSIS to aid the selection of sustainable acid rain control options intrinsic to society, under economic, environmental, social, technical, and institutional factors. Mahdevari et al. (2014) applied fuzzy TOPSIS to analyze risks associated with health and safety of coal miners for its capability and efficiency in handling uncertainties, simultaneous consideration of the positive and the negative ideal solutions, simple computations and logical concept. Rostamzadeh et al. (2018) evaluated sustainable supply chain risk management using an integrated fuzzy TOPSIS-based approach. Further studies with similar attributes include (Cayir Ervural et al., 2018; Hatami-Marbini and Kangi, 2017; Ic et al., 2017; Lima Junior et al., 2014; U. P. Onu et al., 2017; Sengul et al., 2015; Wang, 2014; Yong, 2006).

Despite the wide range of applications of fuzzy TOPSIS, it is rare in literature to assess the risk evaluation of EVCI PPP projects under uncertain and imprecise conditions and fuzzy TOPSIS, one of the most applicable MCDM methods, are an effective tool to handle this problem. This paper chooses fuzzy TOPSIS in risk evaluation of charging infrastructure PPP project for several advantages over other techniques within the study's concern:

i) Outstanding performance in changes in alternatives and criteria and agility in the decision process (Lima Junior et al., 2014) and it is identified to be better in group decision-making problem (Yong, 2006), and risk analysis of this paper includes group-making problem. ii) Capability of finding the best alternative of a decision problem by calculating the geometric distance between each alternative and the ideal alternative, which is the best score in each criterion (Estay-Ossandon et al., 2018) and the ability to compare and analyze the data simultaneously and faster compared with PROMETHEE (Vivekh et al., 2017). iii) It combines fuzzy theory with TOPSIS to handle both quantitative and qualitative data (P. U. Onu et al., 2017) and describe the evaluation result with accurate value and it is widely adopted in risk evaluation (Cavallaro et al., 2016; Chan et al., 2015) and performance evaluation (Cavallaro et al., 2016; Govindan et al., 2013; Tadic´ et al., 2014; Zhao and Li, 2016) for its ability in solving MCDM problems and risk evaluation (Islam et al., 2017). iv) Preferential ranking of alternatives with a numerical value that provides a better understanding of differences and similarities between alternatives, whereas other techniques (such as the grey approach and the ELECTRE) methods only determine the rank of each alternative (Govindan et al., 2013).

Based on literature reviewed above and within the span of our knowledge, no previous studies analyzing risk factors and simultaneously evaluating risk level of EVCI PPP projects adopting our approach has been reported and this study is a pioneer effort and a pacesetter.

3 Methodology and materials

3.1 Research framework

Figure 1 shows our research framework. The research design of this work includes: i) Identify and rank risk factors based on the 24 risk factor-list obtained above through two-round questionnaire survey and expert judgements. ii) Select evaluation criteria and determine criteria weight with normalized mean method. iii) Evaluate overall risk level and rank alternatives with proposed approach based on fuzzy TOPSIS. In this work, longitudinal and cross-wise designs were adopted to collect data on risk analysis of EVCI PPP projects with respect to evaluation criteria. Our purpose is to identify the most important risk factors influencing charging infrastructure PPP projects in China, effectively evaluate overall risk level of a PPP project and rank the alternatives with determined criteria.

The data adopted in this work was collected from archival records and expert interviews, all experts were selected purposively considering their profession and recommendations. Expert's eligibility criteria include two aspects: i) experts/researchers/managers with rich experience in PPP projects, power, EV and infrastructure construction sector at government or private sector; ii) having been involved in at least one PPP project with in-depth knowledge of risk management in PPP project (Wu et al., 2017). In this basis, 30 experts were invited for the interviews, see Table 2. Three sets of questionnaires were used for data collection, the first set was for identify risk factors, the second set was for updating risk factors and determining evaluation criteria, and the third was for ascertaining overall risk level of the alternative and ranking.

Collected data of qualitative criteria is always determined by linguistic variables whose values are natural language phrases such as very high, high, medium, low, etc. (Xu et al., 2017). To solve this situation, different data collected is processed with fuzzy theory and transferred into a fuzzy number with the triangle membership function. Furthermore, data analysis is launched with modeling approach composed by normalized mean method and fuzzy TOPSIS method to calculate risk level of a PPP project and rank the alternatives, as presented in Section 3.2 and 3.3.

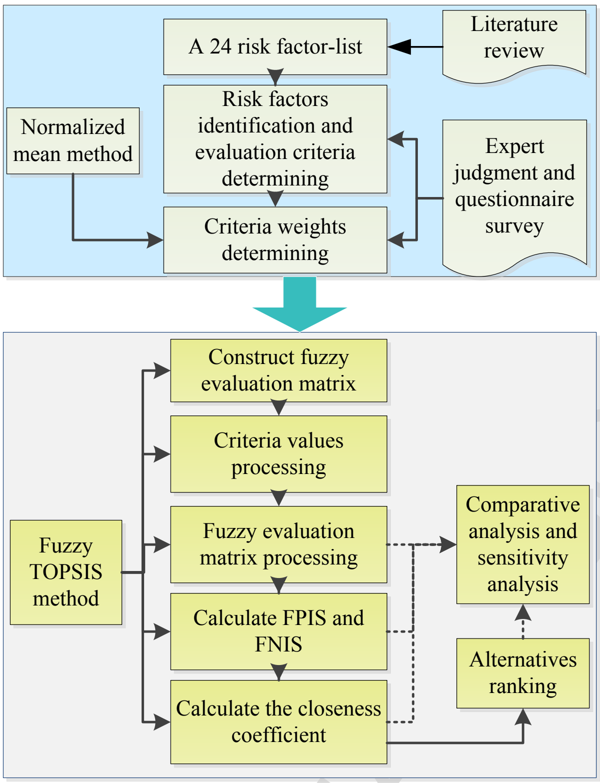


Figure 1 risk evaluation framework

Table 2 information of the respondents

Organization of respondents	No.	Percentage
Academic sector	10	33.3%
Government	6	20%
EV companies	2	6.8%
Infrastructure construction firms	4	13.3%
State Grid and China Southern Power Grid	4	13.3%
Private sector firms	4	13.3%

3.2 Risk evaluation criteria determination

Criteria determination includes two steps: risk factors identification and criteria determining.

3.2.1 Risk factors identification

Appropriate risk identification is important for project risk control and ensure project success (Khameneh et al., 2016). To identify risk factors and effectively determine evaluation criteria, a two-round questionnaire survey is conducted for data collection and this method has been used in similar PPP project risk analysis (Ameyaw and Chan, 2015; Ma et al., 2016; Osei-Kyei and Chan, 2017; Wu et al., 2017). In the first round, experts were required to give judgments about "OP" and "MI" of each risk factor in the 24 risk factor-list (see Table 1) with a 7-point system (1=extremely low, 2=very low, 3=low, 4=moderate, 5=good, 6=very good and 7=extremely good) and experts can add new risk factors based on their expertise and experience to obtain the updated risk factor list. The questionnaire consisted of two parts: i) risk factors were set as separate items and their OPs and MIs were scored; ii) definition of each risk factor. As a result, 30 experts were invited, and the new added risk factors were "Inadequate PPP project experience", "High battery cost", "Long charging period" and "Power price rise". In the second round, experts checked on updated risk factors and adjusted their adjustments about OP and MI of each risk factor. Therefore, data about scores of OPs and MIs was collected and the average score of OP and MI of each risk factor was calculated, see Table 3.

3.2.2 Risk factors ranking and criteria determining

Mean score ranking analysis is used to calculate the relative importance between risk factors and describe them with OPs and MIs (Ameyaw and Chan, 2015). We define "IRI" of each risk factor as $\sqrt{\mathrm{OP} \times \mathrm{MI}}$ (Wu et al., 2017) . According to data collected above, this section calculates each risk factor's mean scores of OP, MI and IRI, ranks them based on IRI values in descending order, and normalizing corresponding IRIs with Equation (1), results are showed in Table 3.

$$y_n = \frac{y_i - y_{\min}}{y_{\max} - y_{\min}} \tag{1}$$

Where, $y_{\max}$ and $y_{\min}$ are maximum and minimum of IRI of each risk factor respectively.

We defines the one as critical risk factor if its normalized value of IRI is equal to or greater than 0.50 (Chan et al., 2015). In this way, 17 critical risk factors are selected as evaluation criteria.

Table 3 evaluation result of the two-round questionnaire survey

Risk factors	OP	MI	IRI	Ranking	Normalized values
Operation	5.10	5.24	5.17	1	1.00
High battery cost	4.99	5.26	5.12	2	0.98
Policy	5.00	5.20	5.10	3	0.97
Government intervention	5.10	5.08	5.09	4	0.96
Long charging period	4.86	5.00	4.93	5	0.89
Construction	4.87	4.96	4.91	6	0.88
Inadequate PPP project experience	4.72	4.90	4.81	7	0.84
Market	4.38	4.85	4.61	8	0.75
Payment	4.20	4.98	4.57	9	0.73
Government credit	4.00	5.10	4.52	10	0.70
Project uniqueness	3.68	5.28	4.41	11	0.65
Interest rate fluctuation	4.20	4.62	4.40	12	0.65
Corruption	4.00	4.68	4.33	13	0.62
Power price rise	4.23	4.42	4.32	14	0.62
Shortage of supporting facility	4.30	4.25	4.27	15	0.59
Revenue	4.02	4.40	4.21	16	0.56
Project operating	3.86	4.53	4.18	17	0.55
Financing	4.08	3.98	4.03	18	0.48
Contract change	3.46	4.43	3.92	19	0.43
Financial risk	3.70	4.12	3.90	20	0.42
Legal risk	3.58	4.00	3.78	21	0.37
Environmental risk	3.76	3.80	3.78	22	0.37
Force majeure	2.58	5.43	3.74	23	0.35
Project completion	2.89	4.80	3.72	24	0.34
Delay	3.30	3.42	3.36	25	0.18
Exchange rate fluctuation	2.87	3.90	3.35	26	0.17
Inflation	3.24	3.35	3.29	27	0.15
Public against	2.98	2.96	2.97	28	0.00

Note: risk factor in bold font is newly added in the first round of questionnaire survey.

3.3 An integrated approach with fuzzy TOPSIS

The integrated approach proposed consists of fuzzy theory, normalized mean method and fuzzy TOPSIS and includes three phases as follows. Phase 1: Transfer the initial qualitative data into fuzzy numbers with triangle membership function in Section 3.3.1. Phase 2: Determine criteria weights with normalized mean method in Section 3.3.2. Phase 3: Evaluate and rank alternatives with fuzzy TOPSIS method in Section 3.3.3.

3.3.1 Criteria values processing with fuzzy theory

Linguistic variables based on experts' judgments, such as "High" and "Very low", cannot be directly used before processing. We transfer a linguistic variable into a fuzzy number with a triangle membership function $\mu_{\tilde{A}}(x)$ defined by 3 parameters (*a, b, c*). The shape and the calculating equation of the function are shown in Figure 2 and Equation (2). Linguistic variables are transferred into fuzzy numbers with rules in Table 4 (Wang, 2014).

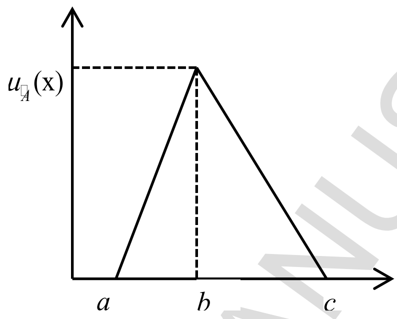


Figure 2 triangle membership function $\mu_{\tilde{A}}(x)$

$$\mu_{\tilde{A}}(x;a,b,c)=\begin{cases}0, & l\le a \text{ or } x\ge c\\ \dfrac{x-a}{b-a}, & a\le x\le b\\ \dfrac{c-x}{c-b}, & b\le x\le c\end{cases} \tag{2}$$

Table 4 transferring rules of linguistic variables into fuzzy numbers

Linguistic variables of OP/MI	Fuzzy numbers
Very High (VH)	(0.7,1,1)
High (H)	(0.5,0.7,1)
Moderate (M)	(0.3,0.5,0.7)
Low (L)	(0,0.3,0.5)
Very Low (VL)	(0,0,0.3)

3.3.2 Criteria weights determination with normalized mean method

Normalized mean method is adopted here to determine criteria weights, this method was put forward by Lo in 1999 and adopted in various studies (Ameyaw and Chan, 2015; Xu et al., 2011, 2010a, 2010b). We updated this method for criteria weight determining as Equation (3).

$$w_i=\frac{IRI_i}{\sum_{i=1}^{17} IRI_i},\ 0<w_i<1,\ \sum_{i=1}^{n} w_i=1 \tag{3}$$

Where $w_i(i=1,\ 2,\ \cdots,\ n)$ is the criteria weight, $IRI_i(i=1,\ 2,\ \cdots,\ n)$ is the integrated risk impact of criteria *i* and weighting function set is defined in Equation (4). Criteria weights of EVCI PPP project risk evaluation is determined in Table 5 with Equation (3).

$$\vec{W} = (w_1,\ w_2,\ \cdots,\ w_n) \tag{4}$$

Table 5 criteria weights of EVCI PPP project risk evaluation

Categories	Risk factors	IRI	Criteria weights	Category weights
C1	Policy (u1)	5.10	0.07	
	Government intervention (u2)	5.09	0.07	
	Government credit (u3)	4.52	0.05	
	Corruption (u4)	4.33	0.05	
	Political/legal risks (C1)	19.03		0.24
C2	Market (u5)	4.61	0.06	
	Interest rate fluctuation (u6)	4.57	0.06	
	Revenue (u7)	4.40	0.06	
	Payment (u8)	4.21	0.05	
	Economic risks (C2)	17.79		0.23
C3	Power price rise (u9)	4.32	0.06	
	Shortage of supporting facility (u10)	4.27	0.06	
	Social/environmental risks (C3)	8.60		0.11
C4	Operation (u11)	5.17	0.07	
	High battery cost (u12)	5.12	0.07	
	Long charging period (u13)	4.93	0.06	
	Construction (u14)	4.91	0.06	
	Inadequate PPP project experience	4.81	0.06	
	Project uniqueness (u16)	4.41	0.05	
	Operating (u17)	4.18	0.05	
	Project/technical risks (C4)	5.10	0.07	0.42

3.3.3 Risk evaluation with fuzzy TOPSIS

In this section, an integrated fuzzy TOPSIS approach is presented. Suppose that there are *m* alternative projects $A_i(i=1,2,\cdots,m)$ with *n* criteria $u_j(j=1,2,\cdots n)$. The initial evaluation values are noted by $\tilde{x}_{ij}$ and *p* decision makers are invited for evaluating qualitative variables. Before applying fuzzy TOPSIS in overall risk level evaluation and ranking of alternatives, data collection based on questionnaire survey is conducted to obtain initial evaluation data and then construct the fuzzy evaluation matrix. The interviews start with *p* decision makers being invited with eligibility criteria presented in Section 3.1, and questionnaires are updated with detail information about alternative projects $A_i(i=1,2,\cdots,m)$ and experts will give their judgements about integrated risk impacts of each alternative using linguistic variables in Table 4. Therefore, we obtain the archival evaluation data for further processing, see Table 6.

The following steps present data analysis process using the integrated fuzzy TOPSIS approach in risk evaluation.

Step 1: Determining criteria and criteria weights

17 criteria and criteria weights are determined by, see Table 5.

Step 2: Process expert judgment and construct the fuzzy evaluation matrix

First, process judgment of *j-th* criteria of *i-th* alternative from *s-th* (*s=1, 2, …, p*) expert

$\tilde{x}_{ij}^{s} = (u_{ij}^{s}, v_{ij}^{s}, \pi_{ij}^{s})$ with Equation (5) to obtain single judgment result of *j-th* criteria of *i-th* alternative. Second, construct the fuzzy evaluation matrix in Equation (6).

$$f_{ij} = (a_{ij}, b_{ij}, c_{ij}) = \lambda_1 x_{ij}^1 \oplus \lambda_2 x_{ij}^2 \oplus \cdots \oplus \lambda_s x_{ij}^s \oplus \cdots \oplus \lambda_p x_{ij}^p$$
$$= (1 - \prod_{s=1}^{p} (1 - u_{ij}^{s})^{\lambda_s}, \prod_{s=1}^{p} (v_{ij}^{s})^{\lambda_s}, \prod_{s=1}^{p} (\pi_{ij}^{s})^{\lambda_s}) \tag{5}$$

$$\tilde{D} = \begin{array}{c c} & \begin{array}{cccc} u_1 & u_2 & \cdots & u_n \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \end{array}, \ i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \tag{6}$$

Where, $\tilde{x}_{ij}$ is the initial value of criteria u_j of alternative A_i.

Step 3: Normalize the fuzzy evaluation matrix

Normalize the fuzzy evaluation matrix with Equations (7), (8) and (9).

$$\tilde{R} = [\tilde{r}_{ij}]_{m \times n}, \ i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \tag{7}$$

$$\tilde{r}_{ij} = (\frac{a_{ij}}{c_j^+}, \frac{b_{ij}}{c_j^+}, \frac{c_{ij}}{c_j^+}), \ \ c_j^+ = \max_i \{c_{ij}\}, \ \text{if } c_j^+ \text{ is benefit criteria;} \tag{8}$$

$$\tilde{r}_{ij} = (\frac{a_j^+}{a_{ij}}, \frac{a_j^+}{b_{ij}}, \frac{a_j^+}{c_{ij}}), \ \ a_j^+ = \min_i \{a_{ij}\}, \ \text{if } a_j^+ \text{ is cost criteria.} \tag{9}$$

Step 4: Construct weighted normalized fuzzy evaluation matrix.

$$\tilde{Z} = [\tilde{z}_{ij}]_{m \times n}, \ i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \tag{10}$$

$$\tilde{z}_{ij} = \tilde{r}_{ij} (\bullet) \tilde{w}_j \tag{11}$$

Step 5: Determine the fuzzy positive-ideal solution (FPIS) and the fuzzy negative-ideal solution (FNIS).

$$Q^+ = (\tilde{z}_1^+, \tilde{z}_2^+, \cdots, \tilde{z}_n^+), \ Q^- = (\tilde{z}_1^-, \tilde{z}_2^-, \cdots, \tilde{z}_n^-) \tag{12}$$

Where, $\tilde{z}_j^+ = \max_i (z_{ij})$, $\tilde{z}_j^- = \min_i (z_{ij})$; $i = 1, 2, \cdots, m, j = 1, 2, \cdots, n$.

Step 6: Calculate distance d_i^+ and d_i^- between each alternative from FPIS and FNIS.

$$d_i^+ = \sum_{j=1}^{n} d(z_{ij}, \tilde{z}_j^+), \ i = 1, 2, \cdots, m; \ j = 1, 2, \cdots, n \tag{13}$$

$$d_i^- = \sum_{j=1}^{n} d(z_{ij}, \tilde{z}_j^-), \ i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \tag{14}$$

Among which, $d(\tilde{a},\tilde{b})=\sqrt{\frac{1}{3}\sum_{i=1}^{3}(a_i-b_i)^2}$ represents the distance between two triangle fuzzy members $\tilde{a}$ and $\tilde{b}$.

Step 7: Obtain the closeness coefficient of alternative *i* and rank the alternatives.

$$CC_i=\frac{d_i^-}{d_i^+ + d_i^-}, i=1,\ 2,\ \cdots,\ m \tag{15}$$

Usually, the higher closeness coefficient means better performance of alternative, but alternatives in this paper are ranked in descending order, because high coefficient value means elevated risk level of EVCI PPP project. Hence, we choose the alternative with lowest closeness coefficient (Taylan et al., 2014).

4 Results

In this section, a case study is illustrated to evaluate and rank risk levels of three alternatives A1, A2 and A3 to verify the effectiveness and robustness of the proposed method. Meanwhile, construction demands of alternatives are respectively put forward by governments in *S*, *B* and *G* provinces of China and they all are strongly supported by national and local policies with different construction conditions. To help the private sector make an appropriate decision, overall risk conditions of alternatives are analyzed and ranked with proposed method. For accurate evaluation values of qualitative variables, we construct an expert group to collect the initial data and obtain the fuzzy evaluation matrix, including officer E1 of *China Public Private Partnerships Center*, project manager E2 in the EV company, professor E3 who has rich managerial experience on EV and a university student E4 who is the frequent user of EV in a long period (Xu et al., 2017). Weights of experts are defined as $\lambda=(0.27,0.25,0.25,0.23)$. The steps of fuzzy TOPSIS implementation is risk evaluation of a PPP project are as follows.

Step 1: Determine evaluation criteria and criteria weights, as showed in Table 5.

Step 2: Determine fuzzy evaluation results of expert judgments.

Experts E1, E2, E3 and E4 evaluate the integrated risk impacts of 17 criteria, see Table 6.

Step 3: Process expert judgment and construct the fuzzy evaluation matrix.

Transfer linguistic variables into fuzzy numbers with rules in Table 4, integrate judgments from 4 experts with Equation (5) and construct the fuzzy evaluation matrix with Equation (6).

Step 4: Normalize the fuzzy evaluation matrix and calculate weighted normalized fuzzy evaluation matrix with criteria weight with Equations (7) - (11). Results are shown in Table 7.

Step 5: Determine FPIS, FNIS, d_i^+, d_i^- and the closeness coefficient of each alternative and rank the alternatives.

Determine the fuzzy positive-ideal solution (FPIS) and the fuzzy negative-ideal solution (FNIS) with Equation (12), calculate distance d_i^+ and d_i^- between each alternative from FPIS and FNIS with Equations (13) and (14), obtain the closeness coefficient of each alternative with Equation (15) and rank the alternatives, as shown in Table 8.

Step 6: Obtain risk levels and rank alternatives.

Overall risk levels of alternatives A1, A2 and A3 is respectively 0.369, 0.411 and 0.421. According to descending closeness coefficients, the ranking order is A1>A2>A3, and that means risk level of A1 is the lowest, A2 is the moderate and A3 has highest risk level.

Table 6 fuzzy evaluation results of expert judgments

Indexes		A1				A2				A3			
		E1	E2	E3	E4	E1	E2	E3	E4	E1	E2	E3	E4
	u_1	H	M	H	H	VH	M	VH	H	VH	VH	H	H
C_1	u_2	H	VH	VH	H	VH	M	VH	VH	H	VH	H	H
	u_3	VH	VH	H	VH	L	H	VH	H	M	H	H	VH
	u_4	H	H	VH	H	L	VH	VH	VH	M	H	M	H
	u_5	M	H	M	VH	M	VH	H	H	M	M	H	H
C2	u_6	VH	VH	H	H	M	H	H	H	M	VH	H	H
	u_7	M	L	M	H	M	L	M	M	M	M	M	M
	u_8	H	M	M	M	M	L	M	M	L	M	L	M
C3	u_9	H	H	H	VH	L	VH	M	VH	H	VH	M	VH
	u_{10}	H	VH	H	M	H	VH	M	VH	H	M	VH	VH
	u_{11}	M	H	M	H	H	H	H	H	M	H	H	VH
	u_{12}	H	H	H	H	VH	VH	H	VH	H	H	VH	H
	u_{13}	H	H	H	M	H	H	H	VH	H	M	M	H
C4	u_{14}	H	H	VH	M	VH	M	H	H	VH	H	VH	H
	u_{15}	VH	VH	H	VH	VH	H	H	H	M	M	H	VH
	u_{16}	VH	VH	VH	VH	L	H	L	M	M	H	H	H
	u_{17}	H	H	VH	H	H	VH	VH	H	H	VH	H	H

Table 7 weighted normalized fuzzy evaluation matrix

	Criteria	A1	A2	A3
	u_1	(0.065,0.046,0.032)	(0.051,0.038,0.032)	(0.048,0.035,0.029)
C_1	u_2	(0.059,0.043,0.036	(0.057,0.043,0.039)	(0.064,0.047,0.036)
	u_3	(0.041,0.029,0.027)	(0.057,0.044,0.032)	(0.052,0.039,0.030)
	u_4	(0.040,0.029,0.022)	(0.038,0.031,0.027)	(0.055,0.038,0.027)
	u_5	(0.050,0.037,0.028)	(0.046,0.034,0.026)	(0.058,0.040,0.028)
C_2	u_6	(0.042,0.031,0.026)	(0.058,0.041,0.029)	(0.051,0.038,0.029)
	u_7	(0.045,0.028,0.019)	(0.056,0.030,0.020)	(0.044,0.026,0.019)
	u_8	(0.023,0.015,0.011)	(0.036,0.019,0.013)	(0.053,0.022,0.014)
C_3	u_9	(0.048,0.035,0.027)	(0.055,0.044,0.035)	(0.046,0.035,0.029)
	u_{10}	(0.054,0.040,0.031)	(0.049,0.037,0.031)	(0.049,0.037,0.031)
	u_{11}	(0.065,0.045,0.032)	(0.053,0.038,0.026)	(0.052,0.038,0.029)
	u_{12}	(0.065,0.046,0.032)	(0.049,0.035,0.032)	(0.058,0.042,0.032)
	u_{13}	(0.055,0.039,0.028)	(0.046,0.034,0.025)	(0.062,0.043,0.030)
C_4	u_{14}	(0.062,0.046,0.035)	(0.062,0.046,0.036)	(0.053,0.039,0.033)
	u_{15}	(0.043,0.031,0.029)	(0.051,0.037,0.029)	(0.061,0.045,0.034)
	u_{16}	(0.018,0.013,0.013)	(0.056,0.030,0.020)	(0.028,0.020,0.014)
	u_{17}	(0.053,0.039,0.030)	(0.048,0.035,0.030)	(0.053,0.039,0.030)

Table 8 distances between alternatives from FPIS and FNIS, closeness coefficient and ranking

Alternatives	d^+	d^-	CC	Ranking
A1	0.413	0.241	0.369	1
A2	0.385	0.268	0.411	2
A3	0.384	0.279	0.421	3

5 Discussions

To verify the feasibility and effectiveness of proposed method and risk factors of EVCI PPP projects, a comparative analysis based on different criteria weights and a sensitivity analysis based on proposed methods are illustrated as well. Then we reinterpret the results of this work.

5.1 Comparative analysis

The proposed method used above adopts IRI of risk factor for criteria weight determining, which is calculated by OP and MI. For a comparative analysis, this section will calculate criteria weights based on OPs and MIs of risk factors in Table 3 and applying them to determine criteria weights and evaluate risk levels of alternatives A1, A2 and A3 respectively (see Table 9).

Evaluation results of three criteria systems show that closeness coefficients of alternative A1 are 0.374, 0.364 and 0.369 and it ranks first based on all criteria systems. If OP or MI is used as calculating basis, the ranking priority is also A1>A2>A3. Which represent that A1 has best performance in risk conditions considering OP, MI and IRI of risk factors, followed by A2 and A3.

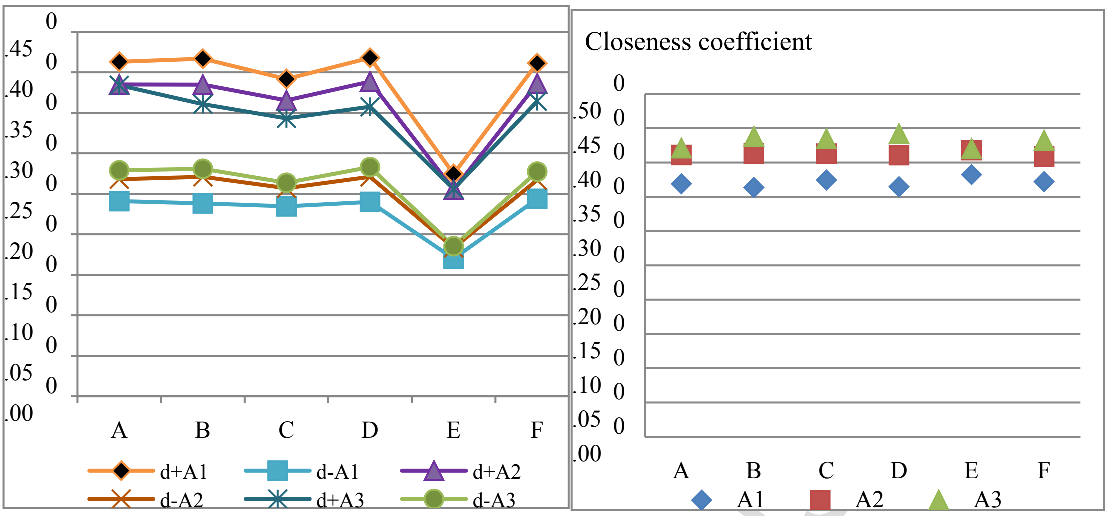
Table 9 evaluation results based on three criteria systems

Criteria systems	OP			MI			IRI		
	A1	A2	A3	A1	A2	A3	A1	A2	A3
d^+	0.409	0.384	0.382	0.417	0.385	0.387	0.413	0.385	0.384
d^-	0.244	0.266	0.279	0.239	0.271	0.279	0.241	0.268	0.279
CC	0.374	0.409	0.422	0.364	0.413	0.419	0.369	0.411	0.421

5.2 Sensitivity analysis

This section changes criteria weights and calculate corresponding risk levels of alternatives. The criteria weights are changed into 6 following groups: (1) Group A use criteria weights in Table 5; (2) 17 criteria of Group B have equal criteria weights; (3) Group C increases criteria weight of categories C1 (Political/legal risks) by 10%; (4) Group D increases criteria weight of categories C2 (Economic risks) by 10%; (5) Group E increases criteria weight of categories C3 (Social/environmental risks) by 10%; (6) Group F increases criteria weight of categories C4 (Project/technique risks) by 10%. What's more, rest of criteria weights are reduced with proportion structure in Table 5 in Groups C-F and the sum of criteria weights in every group is 1. In this basis, risk levels of alternatives are calculated and obtained as shown in Figure 3.

In Figure 3(a), "d+A1", "d-A1", "d+A2", "d-A2", "d+A3" and "d-A3" respectively represents d^+ and d^- of alternatives A1, A2 and A3. Curves in Figure 3(b) reflect that closeness coefficients of A1 is the minimum in Groups A-F, and that of A2 are lower than or equal to A3. Let criteria weights in Group B be the reference group and analyze evaluation results in Groups C-F as follows. Risk levels of A1 are ranked as: E>F>C>D>B, this result represents that social/environmental risks have largest impact on A1, followed by project/technique risks, political/legal risks and economic risks. Risk levels of A2 are ranked by: E>B>C>D>F, A2 are most sensitive with social/environmental risks, followed by political/legal risks, economic risks and project/technique risks. Risk levels of A3 are described with: D>B>C>F>E, and A3 are greatly influenced by economic risks, followed by political/legal risks, project/technique risks and social/environmental risks. In Figure 3(a), distances between alternatives from FPIS and FNIS are reduced greatly compared with other groups, and both FPIS and FNIS are influenced by social/environmental risks. Above all, three alternatives always keep the ranking in closeness coefficients no matter how the criteria weight changes. It can be verified that method we applied in EVCI PPP projects is robust and effective.



(a) (b)

Figure 3 evaluation results of Groups A-F of sensitivity analysis

5.3 Interpretation of results

With an integrated fuzzy TOPSIS approach, this study explores risk factors influencing charging infrastructure PPP projects and evaluates and ranks alternative projects to determine risk situation of the projects. We discuss our key findings as follows.

(1) IRI ranking of top 10 risk factors are determined, as presented in Figure 4 (series F1-F10 refer to risk factors operation, high battery cost, policy, government intervention, long charging period, construction, inadequate PPP project experience, market, payment and government credit). These factors were also identified as risk factors of PPP projects by previous studies: operation (Ameyaw and Chen, 2013; Xu et al., 2011), policy, government intervention and credit (Wu et al., 2017), market (Song et al., 2013), payment (Wu et al., 2017), construction (Bel et al., 2017). We contribute to adding new risk factors with this study's concern, namely high battery cost, long charging period, inadequate PPP project experience and power price rice.

(2) Risk categories are classified into political/legal criteria, economic criteria, social/environmental criteria and project/technical criteria, and they are consistent with classifications of existing studies (Ameyaw and Chan, 2015; Wu et al., 2017). The criteria weights are 24%, 23%, 11% and 42% respectively (see Figure 5), and all risk categories contribute to overall risk level of project.

(3) Different from literature reviewed about risk analysis of PPP projects, proposed method in this work conducted overall risk level evaluation of charging infrastructure PPP project, while other studies either identified risk factors and studied risk allocation between the public and private sectors or focused on PPP projects in other fields (Ameyaw and Chen, 2013; Ma et al., 2016; Shrestha et al., 2018; Yang et al., 2016). Proposed methods were verified through case study, comparative analysis and sensitivity analysis, thus the results can help to make literature on risk analysis and evaluation of infrastructure PPP project move forward. Under the light of literature in the field, the theoretical implications of this work include two aspects: i) we extend

the research on EVCI PPP projects with comprehensive risk analysis; ii) we extend the research on risk analysis of projects with PPP mode by providing overall risk level evaluation and ranking methods with an integrated fuzzy TOPSIS approach in charging infrastructure projects.

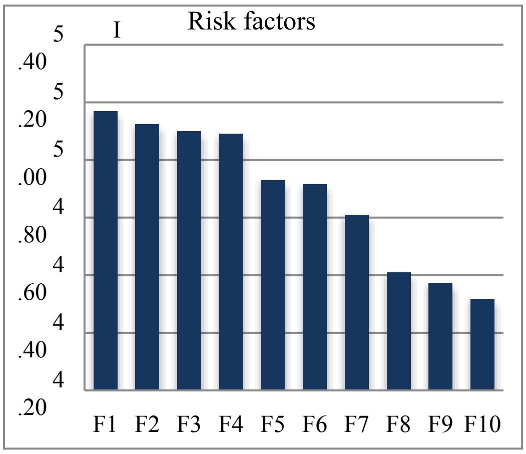


Figure 4 IRI ranking of top 10 risk factors

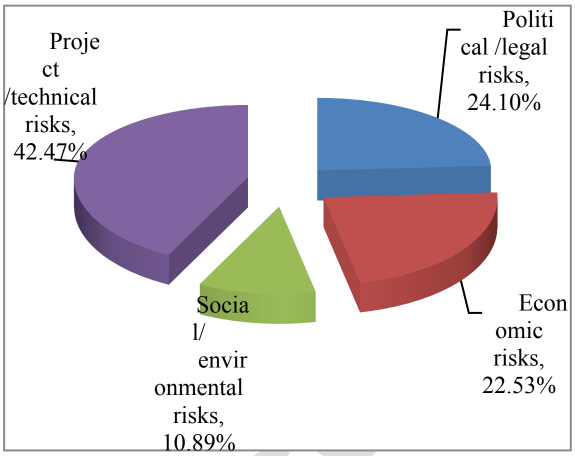


Figure 5 critical risk categories and criteria weights

6 Suggestions

Based on risk factors identified and the calculation results, we provide following suggestions to ensure project success. According to criteria determined, suggestions will be made from project/technical, political/legal, economic and social/environmental aspects.

(1) Project/technical aspect

Private sector should promote its construction and operation ability of charging infrastructure from: i) The entire process of the project operation should focus on efficiency improving and constructing standardized operation management. During the construction period, every detail should keep consistent with scientific construction steps and strictly control the quality. ii) Learn from relevant infrastructure PPP projects at home and abroad and take China's national conditions into account, such as charging demands in China is highly centralized in Beijing, Shanghai, Guangzhou and other highly developed cities with above 10 million people and limited land each one. iii) Reduce technical risks by strengthening battery development and research, mastering core technologies of charging and battery, constructing infrastructure and battery management system to realize intelligent charging services, and promoting charging efficiency.

(2) Political/legal aspect

Chinese EV industry benefits from political policies. Even though current political attitude is adventurous, industrial policies change and continuously standardized and unified domestic and foreign charging standards in the future might bring uncertain impacts on the projects considering that charging infrastructure construction and operation take a long time. For this concern, private sector should pay more attention to: i) Be detailed with partnership contract details to conform its corresponding rights; ii) Establish close corporation with governments, Land, Construction and relevant departments to ensure supports for the project from land acquisition, project approvals and permits, subsidy guarantee and so on.

(3) Economic aspect

Economic risks come from market, interest rate fluctuation, revenue and payment. Private sector should ensure maximum incomes and minimum cost during entire construction and operation periods: i) Establish reasonable and diversified charging services and modes to increase incomes and adjust charging habits with pricing measures based on peak and valley time price model of China. ii) Searching and making reasonable charging strategies combined with power sales firms, the Grid and EV firms to stabilize the EV market and stimulate EV demand to lay the foundation for charging infrastructure construction demands. iii) Precisely guarantee project fund, control construction and operation costs by promoting management and operating skills.

(4) Social/environmental aspect

Social/environmental risks include power price rise and shortage of supporting facility. As a response, i) Charging pricing system determination should anticipate the price increase risk after 2020 and develop a forward-looking pricing strategy considering that PPP project operation will last for a long time but current concession rate of power price for charging stations is guaranteed before 2020. ii) Scientifically and precisely select charging infrastructure placing sites in the basis of fast developing rate of urban extension and development and make the decision with corporation with long-term urban development plan, expressway construction plan, EV development plan and relevant sectors. Only by effective coordination and operation between public and private sectors can promote and ensure the success of EVCI PPP projects.

7 Conclusions

EV development can play a significant role in achieving clean environmental benefits and contribute to sustainability of the society. Introducing PPP mode into EV charging infrastructure construction to solve demand-supply imbalance is highly encouraged by the government as an effective mean to attract private capital and improve charging performances and services. Risk analysis of a PPP project is necessary for the private sector to ensure project success and it’s important to understand what risk factors might influence the project and how to calculate the overall risk level with scientific approach. To solve this problem, this paper constructed a risk identification and evaluation framework of EVCI PPP project with an integrated fuzzy TOPSIS approach. As the results, we selected 17 critical risk factors as evaluation criterion through literature review and questionnaire survey, determined criterion weights with normalized mean method and evaluated and ranked alternatives with proposed approach. A comparative analysis and a sensitivity analysis were constructed to verify feasibility and effectiveness of the model. Risk evaluation and analysis of PPP project are most critical issues and attract attentions from researchers all over the world. As part of main infrastructure construction, risk analysis of charging infrastructure plays a significant role though few literature has carefully identify its risk factors and conduct comprehensive evaluation in this field for the private sector. This paper intents to contribute to this section.

This paper also has limitations and shortcomings. Owing to inadequate PPP project experience in Chinese EV infrastructure PPP projects, risk factors identification cannot be perfect. The availability of information and data collection need to be more accurate with feasibility. In the meantime, only 4 experts were invited to determine criteria values, they might not be able to fully represent the actual conditions. In further study, risk factors identification methods should be updated, project managers should be encouraged to collect relevant data in the project, and a comparative study based on other decision-making methods, such as VIKOR, should be discussed.

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Author contributions

Jicheng Liu and Qiushuang Wei designed the proposed model in this paper. Qiushuang Wei wrote the paper.

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- Construct a risk identification and evaluation framework of EV charging infrastructure PPP project with an integrated fuzzy TOPSIS approach.
- Contribute to adding new risk factors in literature of PPP projects with this study's concern, namely high battery cost, long charging period, inadequate PPP project experience and power price rice.
- Extend the research on EV charging infrastructure PPP projects from private sector perspective with comprehensive risk analysis.
- Extend the research on risk analysis of projects with PPP mode by providing overall risk level evaluation and ranking methods in charging infrastructure projects.