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Research Article

Constructing a Risk Assessment Framework for Building Integrated Photovoltaic (BIPV) Projects from the Perspective of Four-Dimensional Risk

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Building photovoltaic integration (BIPV) technology can effectively solve the urban energy shortage, environmental damage, and other environmental problems, which is of great significance to the sustainable development of the urban. However, the practical application of BIPV technology has been very slow, and BIPV projects have encountered numerous obstacles and risks in the process of promotion and construction. Although some researchers have conducted qualitative studies on these obstacles and risks, systematic risk assessment methods for BIPV projects are missing. This study aims to systematically develop a framework to assess the risk of BIPV projects to address this gap. First, a comprehensive risk indicator system is established using literature analysis and expert interview methods. Second, DEMATEL (decision-making trial and evaluation laboratory) is used to calculate constant rights. Then, the risk assessment is carried out from the perspective of four-dimensional risk including severity, possibility, urgency, and uncontrollability. The variable weight theory is used to calculate variable weight. The data fusion and risk level determination are realized by the matter-element extension model. Finally, a case study is conducted to verify the feasibility and applicability of the BIPV project risk assessment framework. The results show that the comprehensive risk grade of the BIPV project in Qingdao is III, which belongs to medium risk. In addition, some suggestions are made based on the evaluation results. This study can enrich the methods in the field of risk assessment, and the results can provide a valuable reference for BIPV project investors and decision-makers.

1. Introduction

With the rapid development of society and the economy, the excessive consumption of fossil fuels has brought great challenges, such as energy shortage, environmental damage, and climate change [1]. According to statistics, about 80% of the world's energy production depends on fossil fuels [2]. To avoid future energy and environmental crisis, renewable energy as alternative energy has attracted wide attention in the world [1]. At present, solar energy is considered a natural, abundant, pollution-free, and free renewable energy source in the world [3]. Only 1% of solar energy needs to be converted to meet global energy needs [4]. Not only that but solar photovoltaics (SPV) can also solve the world's shortage of freshwater resources. Although composite membrane technology has been widely used in the field of seawater desalination, its performance is still affected by many factors [5–7], and PV integration technology is expected to improve the efficiency of reverse osmosis desalination [8]. Clearly, SPV is starting to play an important role in various industries. Even more remarkably, the construction industry accounts for about 36% of global energy consumption and generates approximately 39% of global CO2 emissions [4]. The advent of the low-carbon era has put forward higher requirements for energy conservation and environmental protection in the construction industry. In the face of this challenge, some claim that SPV will eventually be able to provide all the energy needed for residential and nonresidential buildings. Shortly, the photovoltaic industry will be primarily focused on the built environment [9]. Therefore, building photovoltaic integration (BIPV), an application form of SPV in the construction industry, has unprecedented development opportunities.

BIPV is an intelligent energy production system that uses SPV as part of roof, window, facade, and sun shading equipment, providing significant advantages in environmental improvement [9, 10]. BIPV brings the excellent potential to modern buildings in regarding onsite power generation and has been recognized as a critical approach to solving energy and environmental problems in urban environments [1]. However, the development of BIPV still faces challenges, such as lack of government support, high capital requirements, and low efficiency [11]. Higher integration also leads to higher initial investment, including design, installation, and shipping costs. Although many countries and regions have adopted a series of corresponding policies and measures to improve this situation [4], the risk is accompanied by the whole life cycle of BIPV. Many uncertain risk factors still greatly affect the normal operation of BIPV, which makes the risks more complex and special. Therefore, comprehensive identification of risk factors and scientific assessment is essential for the development of BIPV. However, the comprehensive evaluation of BIPV focuses more on cost-effectiveness [12], energy efficiency [13], feasibility analysis [4], sustainable performance assessment [14], technical and economic assessment [15], and environmental assessment [16]. Little research has been done on BIPV risk assessment. Existing researches mainly use qualitative analysis to systematically sort out and summarize the technical obstacles, economic obstacles, institutional obstacles, cost-benefit, and risk of BIPV projects and propose possible solutions [9, 17, 18]. Only Zeng et al. [19] and Liu et al. [20] used the TOPSIS (technique for order preference by similarity to an ideal solution) and fuzzy comprehensive evaluation, respectively, to conduct empirical studies on BIPV project risks. The above research brings some reference significance to the risk assessment of BIPV project, but fails to solve three key problems well: (1) Most existing researches use the qualitative analysis method to analyze the risk of BIPV project without systematic identification of risk factors and the formation of an evaluation system. (2) The determination of the weight of risk indicators usually adopts the constant weight mode of single weighting or combination weighting. It is not easy to reflect the influence of changes in evaluation data on indicator weight. (3) Risk quantification usually only considers the probability and severity of risk occurrence while ignoring uncertainty and urgency.

To fill the above gaps, this study constructed a BIPV project risk assessment framework from the perspective of four-dimensional risk. Firstly, the risk assessment indicator system suitable for the BIPV project is constructed by literature analysis and expert interviews. Secondly, we propose a weight assignment method based on the DEMATEL method and variable weight theory, which fully considers the dynamic change of indicator weight with the change of evaluation data. Finally, based on the matter-element extension model, a four-dimensional risk assessment framework for the BIPV project is constructed, which considers the severity, possibility, urgency, and uncertainty of risks, and is verified by a specific case. The remainder of this study is organized as follows. The literature review is provided in Section 2. A detailed framework of the risk assessment is presented in Section 3. In Section 4, a case analysis is conducted. Discussion is conducted based on the case result obtained in Section 5 and finally in Section 6.

2. Literature Review

2.1. Concept and Application of BIPV. The trend of turning buildings from energy users to energy producers is not new. Since photovoltaics first entered the market, architectural, structural, and aesthetic solutions have been sought to integrate photovoltaics into building envelopes. BAPV (building applied photovoltaic) and BIPV (building integrated photovoltaic) are two approaches for incorporating photovoltaics into the building envelope. BAPV refers to the integration of photovoltaic systems into a building upon completion. However, in the BIPV system, photovoltaic modules are part of the building envelope [10]. Currently, more than 90% of the world's PV systems are connected to the grid, and many of them are BIPV projects. BIPV technology uses of photovoltaic cells to integrate traditional building materials into the building envelope, such as roofs, windows, facades, balconies, and skylights [1]. BIPV was first installed in 1991 in Aachen, Germany [17]. After years of application and practice, BIPV has shown its potential as a multifunctional, efficient building energy technology that can bring many advantages to buildings. First, solar radiation is free and unlimited and can be obtained almost anywhere. Solar energy has no polluting waste or side effects nor harms the global climate. Second, solar panels are not relatively difficult or expensive to install, operate, and maintain, nor do they require the construction of more transmission lines [18]. Another distinguishing feature of BIPV compared to traditional building materials is its appearance. Until now, BIPV has been considered a compromise between building energy consumption and building aesthetics. Various photovoltaic modules can be integrated into the building envelope, providing great opportunities for innovative architectural design to make future buildings more aesthetically appealing [1]. In addition, BIPV systems offer insulation, noise protection, wind and rain protection, privacy protection, and onsite power generation, making them the most promising energy system in the future urban environment [1, 21]. To promote the research and development of BIPV technology, countries have also developed many incentives. While research into the application of BIPV systems of performance and optimization is fairly new, and many national incentives have been introduced in the past few years, their practical adoption has been slow [10]. Some scholars have concluded that the reasons are institutional barriers (lack of government support), public acceptance (lack of public understanding), economic barriers (high cost of photovoltaic modules and high cost of design and construction), and technical barriers (lack of standards, lack of professional personnel, low power efficiency, and poor power reliability) [9, 17, 18]. To sum up, under the global sustainable development strategy, BIPV technology has great development potential in the future, but it also faces many challenges and risks. Accurate identification and scientific assessment of project challenges and risks are required to promote better promotion and application of BIPV.

2.2. Risk Assessment Method. Risk assessment methods include the construction of a risk indicator system, the determination of indicator weight, and the risk assessment model. However, few studies have conducted risk assessments for BIPV projects. Liu et al. divided the risk of the BIPV project into environmental, policy, operational, effective, and credit risk, and constructed a fuzzy comprehensive evaluation method [20]. Zeng et al. constructed investment risk indicators for BIPV projects from policy, economic, technological, and natural environment dimensions, and conducted risk analysis for eight BIPV projects in China using the entropy-TOPSIS method [19]. In addition, some risk assessment studies related to photovoltaic and other new energy construction projects also provide a good reference for this paper. Regarding the construction of a risk indicator system, Jianwei Gao et al. summarized the construction risks of offshore photovoltaic projects as economic, technical, environmental, and market risks [22]. Yunna Wu et al. found that financing difficulties, unclear division of responsibilities and obligations, lack of operational experience, and material supply and installation defects are the most critical risk factors for photovoltaic poverty alleviation projects [23]. They also identified 38 risk factors for urban rooftop distributed photovoltaic project construction and screened out 11 critical risk factors [24]. In addition, Yunna Wu et al. collected 72 risk factors of wind-photovoltaic-hydrogen storage projects through a literature review and further screened them into four categories: economic risk, technical risk, environmental risk, and safety risk [25]. Jie Zhou et al. divided the risks of offshore photovoltaic power generation projects into economic, technical, environmental, and management risks, and identified 16 specific risk factors [26]. The above research provides a theoretical basis for subsequent BIPV project risk identification.

In terms of the determination of indicator weight, in addition to the entropy weight method and AHP (analytic hierarchy process), the DEMATEL method is widely used because it can determine indicator weight by analyzing the interaction between indicators [23, 24]. However, the determination of weight is established in a relatively static environment, without considering the impact of the change of evaluation data on weight. The variable weight theory can fully solve this issue. Professor Peizhuang Wang first proposed the variable weight theory in 1985. This method takes into account the attribute values of various factors and highlights the significant differences among them by increasing the weight of factors [27], which has been widely applied in many fields. In terms of the dimension of risk analysis, many of studies rank risks from the possibility and severity of risk occurrence. However, project management should not only pay attention to the probability of risk occurrence and loss caused by risk [28] but also pay more attention to the uncontrollability and urgency of risk [29]. Therefore, BIPV projects should be evaluated in more risk dimensions. In terms of risk assessment models, in addition to the cloud model [25], fuzzy comprehensive evaluation method [24], TODIM (TOmada de Decisao Interativa Multicriterio) [30], VIKOR(VIse Kriterijumska Optimizacija I Kompromisno Resenje) [29], and D-S evidence theory [26], a matter-element extension model composed of matter-element theory and extension set has gradually attracted attention. Compared with the above risk assessment models, the matter-element extension model is a method that considers both quantitative and qualitative changes and can transform the contradictions in the objective world into the contradictions between matter elements. In addition, the model supports multiattribute risk analysis and is well integrated with the indicator system, taking into account the differences and inaccuracies of indicators at different risk levels [31]. Matter-element extension model is suitable for the evaluation and analysis of complex systems and has been widely applied in investment risk assessment [32], service quality assessment [33], environmental performance assessment [34], and many other fields. Based on the above issues, we will comprehensively identify the construction risks of BIPV project in the subsequent research and construct a risk assessment framework of BIPV project integrated by DEMATEL-variable weight and matter-element extension model from the perspective of four-dimensional risk.

3. Methodology

This study takes the BIPV project as the research object, and the research method is divided into three stages (see Figure 1). Firstly, the critical factors of the BIPV project are identified and analyzed by literature analysis, expert investigation, and field interviews. Then, DEMATEL is used to analyze the mechanism of interaction between risk indicators and preliminarily determine the weight of indicators. Finally, from the perspective of four-dimensional risk, the matter-element extension model is used to assess the risk of the BIPV project. It must be emphasized that the constant weight determined by the DEMATEL method may neutralize the influence of some poor indicators by other indicators. So variable weight theory is introduced in the evaluation process, and variable weight is determined by using the evaluation data based on constant weight.

3.1. BIPV Project Risk Assessment Indicator System. Establishing of a risk indicator system directly affects the accuracy and efficiency of evaluation results. The research should consider all risk factors from as many angles as possible. Literature analysis and expert interviews are the main methods to identify risk factors [35]. Therefore, this study firstly mines risk factors in BIPV-related literature, invites relevant experts to conduct interviews, and finally determines the risk assessment indicator system suitable for BIPV projects.

3.1.1. Literature Analysis. Scopus was used as the retrieval database in this study. Currently, few researchers have assessed the risk of BIPV projects. Therefore, the retrieval scope is extended to rooftop distributed PV, energy Retrofits,

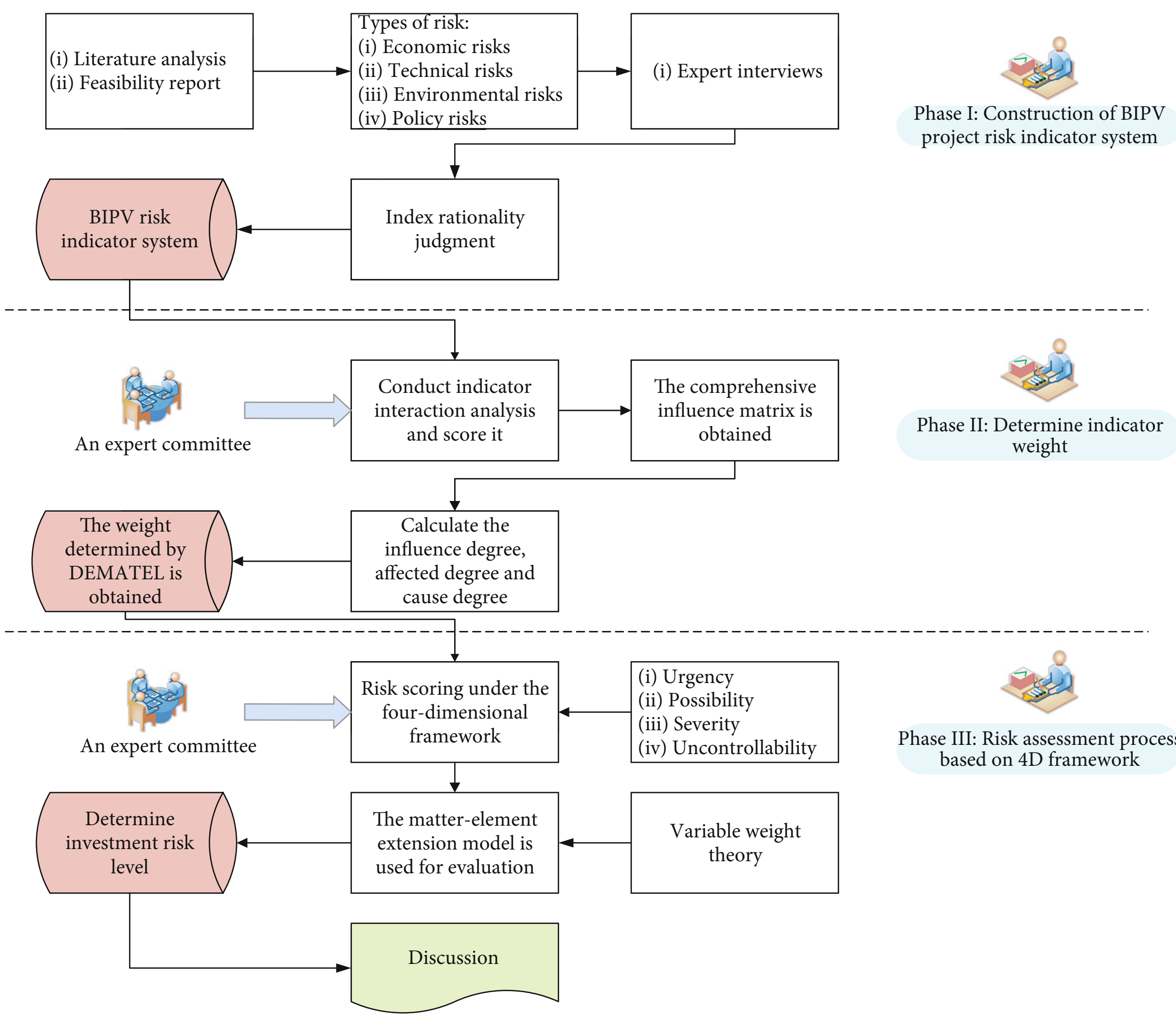

Figure 1: Research framework.

PV power generation projects, energy-saving building projects, and other new energy construction projects. This is because the risks faced by such projects in the construction process are more similar to those of BIPV projects, which has certain reference significance for establishing the risk assessment indicator system of BIPV projects. Therefore, this study first conducted a literature survey to identify nineteen risk indicators (Table 1) and categorized them into four groups: environmental risk, economic risk, technological risk, and policy risk. Table 1 shows all the risk indicators initially identified. According to the list of indicators, an interview outline was designed, and experts were interviewed.

3.1.2. Expert Interview. Ten experts with rich knowledge and experience are selected as the interviewees. The specific information of the experts is shown in Table 2. It must be emphasized that the risks of BIPV projects involve laws, policies, technology, the economy, and the natural environment. The comprehensive information of risk indicators cannot be obtained only from the employees of enterprises engaged in photovoltaic construction. Therefore, we invited two representatives from government departments who have been involved in photovoltaic construction project planning, three enterprise experts with rich experience in BIPV construction and R&D (research and development), three academic professionals who have carried out scientific research in the field of PV construction, and two professional consultants with rich experience in risk management consulting. The comprehensiveness of the interview experts ensures the rationality of the risk indicator system.

In the expert interview, the opinion is put forward that an "imperfect bidding mechanism" can be ruled out from the initial risk list because the BIPV technology combined with EPC (engineering procurement construction) and other contracting methods has a mature bidding mechanism. In addition, "component missing risk" and "material supply and installation risk" both refer to material supply risk and should be combined into "material supply and installation risk". "Lack of construction experience" is the root cause of "construction operation risk," so just keep the former. Based on this, experts say "public acceptance" should be added to the list of risks. Because the public is unaware of the

Table 1: List of risk indicators preliminarily identified.

First-level risk indicators	Second-level risk indicators	References
Economic risks		
1	On grid price fluctuation risk	[30, 36–38]
2	Financial risk	[37, 39, 40]
3	High capital requirements	[11, 23, 41]
Technical risks		
4	Design risk	[9, 10, 40]
5	Operation and maintenance risk	[30, 37, 40]
6	Grid connection risk	[9, 10, 42]
7	Power supply reliability risk	[30, 37, 43]
8	Material supply and installation risk	[9, 30, 44]
9	Lack of construction experience	[9, 10, 45]
10	Construction operation risk	[30, 37]
11	Component missing risk	[18]
Natural environment risks		
12	Solar energy resource	[30, 37, 46]
13	Harsh climatic conditions	[10, 18, 47]
14	Visual damage of buildings	[11, 46, 48]
15	Noise pollution	[9, 48]
Policy risk		
16	Power generation subsidy	[37]
17	Government approval lag risk	[10, 49]
18	Government support	[11, 37]
19	Imperfect bidding mechanism	[23]

importance of renewable energy, it may not be easy to accept. The final risk list is discussed again by experts and reached a consensus.

3.1.3. Establish a Risk Indicator System. Based on the final results of literature analysis and expert interviews, this study constructed the risk assessment indicator system for the BIPV project (see Figure 2).

(1) Economic risk (V1) mainly comes from debt, cost, profit, and some other factors related to income or expenditure. It directly or indirectly affects the ultimate benefit of the project and includes three subrisks. Price fluctuation risk (V11) is affected by the decrease in photovoltaic power price and the increase in civil electricity price. Financing risk (V12) represents the uncertainty of the financing process, including financing mode, financing structure, and macroeconomic uncertainty. Because there are still many challenges in BIPV technology, future revenue is unpredictable, and there may be various financing risks; high capital investment (V13) refers to the high initial cost of BIPV projects, including design, installation, transportation, and maintenance costs

Table 2: Information of the experts.

Interviewee NO.	Position	Years of working experience
1	Government representative	5
2	Government representative	8
3	BIPV project engineer	7
4	BIPV R&D manager	10
5	BIPV project manager	9
6	Professor	15
7	Professor	20
8	Associate professor	8
9	Risk management consultant	8
10	Risk management consultant	5

(2) Technical risk (V2) refers to the threat from design method, construction technology, operation, and maintenance technology, including six subrisks. Among them, design risk (V21) refers to the design defects of the BIPV project that may be caused by experience, ability, and other problems in the design stage, and the benefits cannot be guaranteed. Operation and maintenance risk (V22) refers to a series of potential risks during operation and maintenance caused by external forces or insufficient cognition of the subject. For grid connection risk (V23), the project contractor and power grid company are the main body to reduce this risk. BIPV projects have brought huge challenges and security risks to power supply networks, with power supply reliability becoming an important source of risk (24). Material supply and installation risk (V25) refers to the possibility of problems such as "late delivery" and "nonconforming PV components" due to an unreasonable manufacturing process or backward construction technology. Due to the high technical requirements of BIPV projects, the lack of sufficient construction experience (V26) will lead to many unpredictable risks in the construction process, increasing the difficulty of construction

(3) Environmental risk (V3) refers to the external risk caused by the natural environment and internal risk caused by environmental pollution or damage, including four subrisks. Solar energy resource (V31) is an unchangeable risk factor, and the appropriate construction area must be selected to reduce this risk before the BIPV project investment. Severe weather conditions (V32) will directly lead to the service life of some batteries being greatly reduced and other problems. The destruction of the visual integrity of the building (V33) refers to the fact that the BIPV project requires a variety of photovoltaic modules to meet the technical requirements of the building and the aesthetic requirements of the visual effect. Noise pollution (V34) refers to the noise

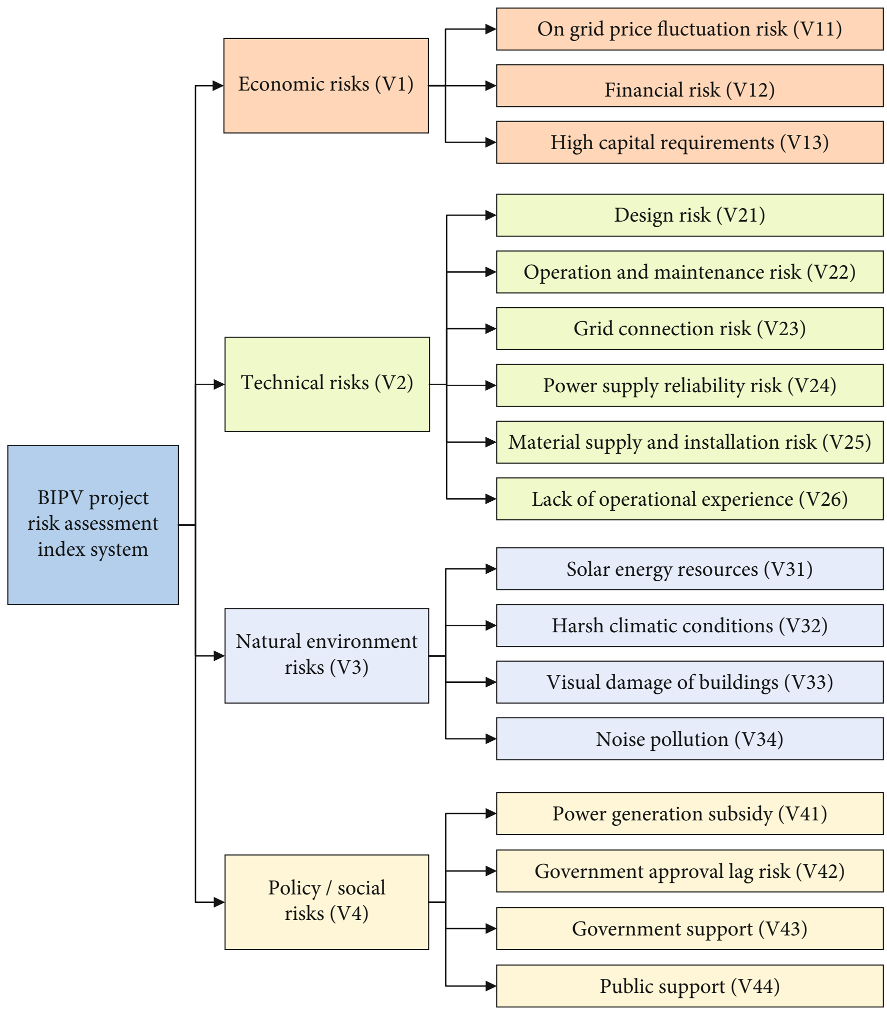

Figure 2: BIPV project risk assessment indicator system.

generated during the construction and operation of BIPV projects, which affects the environment and users

(4) Policy/social risk (V4) is caused by imperfect policies or low public acceptance, which determines whether the project can be started and implemented commonly, mainly including four subrisks. Power generation subsidy policy (V41) refers to the possibility that the government will reduce the subsidy as BIPV projects spread and PV module production technology matures, affecting income and weakening investment enthusiasm. Government approval lag risk (V42) refers to the complex BIPV approval process involving multiple departments and application materials, which poses a threat to regular operation. Government support (V43) is critical to successfully implementing BIPV projects, a risk often associated with policy instability and unsustainability. Public support (V44) refers to humble awareness of the importance of renewable energy and low acceptance of BIPV technology in buildings

These risks are common to other cities worldwide because we combed, identified, and confirmed these risk factors from the worldwide literature. Cities in different countries are faced with these risk factors in common. Still, the risk level of the same factor in different cities is different, which requires specific assessment of specific cities through the risk assessment framework we proposed.

3.2. DEMATEL Method. DEMATEL is a systems engineering model for factor analysis. The core idea is to use the matrix tool and graph group method to analyze the mutual influence degree of the BIPV project risk indicator. In other words, DEMATEL can simplify the problem and determine the importance of indicators by analyzing and stripping out the interaction between two indicators [23]. The steps to use the DEMATEL method are as follows:

(1) Experts score the degree of mutual influence among risk indicators and summarize the final evaluation data by the arithmetical average method as the initial direct influence matrix F:

$$F = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{n1} & f_{n2} & \cdots & f_{nn} \end{bmatrix}, \quad (1)$$

where f_{ij} represents the degree of direct influence of the risk indicator v_i on v_j.

(2) Determine the normalization direct influence matrix E:

$$E = (e_{ij})_{n\times n} = F\left(\max_{0\le i\le n}\sum_{j=1}^{n} f_{ij}\right)^{-1}. \quad (2)$$

(3) Determine the comprehensive influence matrix T:

$$T = (t_{ij})_{n\times n} = \lim_{h\longrightarrow\infty}\left(E^1 + E^2 + \cdots + E^h\right). \quad (3)$$

When h is large enough, $E^h = 0$.

(4) Determine the indicator weight ω_j^0:

$$\omega_j^0 = \frac{\sqrt{(M_i)^2 + (U_i)^2}}{\sum_{i=1}^{n}\sqrt{(M_i)^2 + (U_i)^2}}, \quad (4)$$

$$M_i = A_i + B_i = \sum_{j=1}^{n} t_{ij} + \sum_{i=1}^{n} t_{ij}, \quad (5)$$

$$U_i = A_i - B_i = \sum_{j=1}^{n} t_{ij} - \sum_{i=1}^{n} t_{ij}. \quad (6)$$

The influence degree (A_i) and being influenced degree (B_i) are calculated by summing the rows and columns in the comprehensive impact matrix T, respectively. M_i and U_i represent center degree and cause degree, respectively. When $U_i > 0$, the indicator is the causal factor, indicating that it has a great influence on other indicators. Otherwise, it is a result factor, indicating that this indicator is greatly influenced by other indicators.

3.3. Variable Weight Method. The constant weight obtained by the DEMATEL method can well reflect the relative importance of each risk indicator, but its weight value will not change with different states of affairs. The essence of the variable weight method is to introduce a state variable weight vector based on a constant weight vector. This method ensures that the weight value can be changed according to the state value of the indicator or the diversification of specific circumstances. Therefore, this study uses the following variable weight formula to modify the constant weight [50].

$$\omega_j(x_1, x_2, \cdots, x_m) = \frac{\omega_j^0 x_j^{\alpha-1}}{\sum_{j=1}^{m}\omega_j^0 x_j^{\alpha-1}}, \quad (7)$$

Where ω_j, ω_j^0, and x_j indicate the variable weight, constant weight, and state value of the indicator j $(j = 1, 2, \cdots, m)$, respectively. $\alpha(0 \le \alpha \le 1)$ is the equilibrium coefficient. When the value of α is greater than 0.5, it indicates that experts have high requirements on indicator balance. If the value of α is less than 0.5, it indicates that experts have low requirements on indicator balance. When $\alpha = 1$, the result represents constant weight. The value of α in this paper is 0.5 to reflect the equality of all risk indicators.

3.4. Four-Dimensional Risk Analysis Framework. Seventeen risk factors were identified after a comprehensive literature review analysis. Based on the four-dimensional risk analysis method proposed in the literature [20], this study intends to evaluate the BIPV project from the four dimensions of risk indicators (severity, possibility, urgency, and uncontrollability). S represents the comprehensive evaluation value of each indicator. The four-dimensional risk analysis framework is shown in Figure 3.

$$S = \sqrt[4]{Se * P * \mathrm{Ur} * \mathrm{Un}}. \quad (8)$$

3.5. Matter-Element Extension Model. The matter-element extension model proposed by Cai et al. in 1983 combines matter-element theory with extension set theory. The model determines the comprehensive evaluation level according to the correlation degree between the research object and the different evaluation levels preset in the model [51, 52]. However, the traditional model adopts approximate processing when determining the evaluation grade through the correlation degree, which may ignore the information of some matter elements to be evaluated and affect the accuracy of evaluation results. Therefore, an improved matter-element extension model is used to solve this problem. First, the classical domain and the matter element to be evaluated are normalized. Secondly, the variable weight method is used to determine the weight of each BIPV project risk indicator. Finally, the criterion of closeness is used to replace the criterion of maximum membership to determine the risk level of BIPV project [53]. The specific steps are as follows:

(1) Experts evaluate risk indicators according to the four dimensions shown in Figure 2 and calculate comprehensive evaluation values according to Formula (8).

(2) Determine the matter element to be evaluated:

$$R_0 = (Q_0, V_i, C_i) = \begin{bmatrix} Q_0 & v_1 & c_1 \\ & v_2 & c_2 \\ & \vdots & \vdots \\ & v_n & c_n \end{bmatrix}. \quad (9)$$

The risks of the BIPV project are divided into j evaluation grades, which are represented by Q_j. The risk indicator set is represented by $V\ (v_1, v_2, \cdots, v_n)$. $C\ (c_1, c_2, \cdots, c_n)$ represents the evaluation status value of the matter element to be evaluated under different indicators.

(3) Determine the matter-element matrix of the classical domain as

$$R_j = \left(Q_j, V_i, C_{\text{ij}}\right) = \begin{bmatrix} Q_j & v_1 & c_{1j} \\ & v_2 & c_{2j} \\ & \vdots & \vdots \\ & v_n & c_{\text{nj}} \end{bmatrix} = \begin{bmatrix} Q_j & v_1 & \left(a_{1j}, b_{1j}\right) \\ & v_2 & \left(a_{2j}, b_{2j}\right) \\ & \vdots & \vdots \\ & v_n & \left(a_{\text{nj}}, b_{\text{nj}}\right) \end{bmatrix}, \quad (10)$$

where Q_j represents the j_{th} risk evaluation grade. v_i is the i_{th} risk indicator of the j_{th} risk grade. C_j is the value range of risk grade j. a_{ij} and b_{ij} indicate the upper limit and lower limit of the value range.

(4) Determine the nodal domain matter-element matrix as

$$R_Q = \left(Q, V_i, C_{\text{ip}}\right) = \begin{bmatrix} Q & v_1 & c_{1p} \\ & v_2 & c_{2p} \\ & \vdots & \vdots \\ & v_n & c_{\text{np}} \end{bmatrix} = \begin{bmatrix} Q & v_1 & \left(a_{1q}, b_{1q}\right) \\ & v_2 & \left(a_{2q}, b_{2q}\right) \\ & \vdots & \vdots \\ & v_n & \left(a_{\text{nq}}, b_{\text{nq}}\right) \end{bmatrix}, \quad (11)$$

where Q is all the risk evaluation grades, and C_{ip} is the value range of Q about v_i. a_{ij} and b_{ij} indicate the upper limit and lower limit of the C_{ip}.

(5) Determine the proximity degrees of the matter element to be evaluated for different evaluation grades

$$K_j(R_0) = 1 - \frac{1}{n(n+1)} \sum_{i=1}^{n} D_j(v_i)\omega_i(X), \quad (12)$$

$$D_j(v_i) = \left| v_i - \frac{a_{\text{ij}} + b_{\text{ij}}}{2} \right| - \frac{1}{2}\left(b_{\text{ij}} - a_{\text{ij}}\right), \quad (13)$$

where $K_j(R_0)$ is the proximity degree, $D_j(v_i)$ is the distance, and $\omega_i(X)$ is the weights of the i_{th} indicator, which can be obtained using the DEMATEL and variable weight method.

(6) Determine the BIPV project risk grade. If $K_{j'}(Q_0) = \max\{K_j(Q_0)\}(j = 1, 2, 3, 4, 5)$ exists, it can be determined that the matter element to be evaluated belongs to the grade j'

$$\bar{K}_j(R_0) = \frac{K_j(R_0) - \min\left[K_j(R_0)\right]}{\max\left[K_j(R_0)\right] - \min\left[K_j(R_0)\right]}, \quad (14)$$

$$j^* = \frac{\sum_{j=1}^{m} j\bar{K}_j(R_0)}{\sum_{j=1}^{m} \bar{K}_j(R_0)}, \quad (15)$$

where j^* is the characteristic value of the grade variable of the matter element (R_0) to be evaluated, which is used to judge the degree to which the R_0 deviates to adjacent grades.

4. Application of the Proposed Framework

This study takes Qingdao city as an example to implement the risk assessment of the BIPV project. Qingdao is located in the south of the Shandong Peninsula, at 119°30′~121°00′ east longitude, 35°35′~37°09′ north latitude. Qingdao is located in the north temperate monsoon region, belonging to the temperate monsoon climate. The Qingdao area belongs to the second-class area of solar energy resources, with an average annual horizontal total radiation of 5,282.3 MJ/m^2. It is rich in solar energy resources, with uniform distribution of light energy and good lighting conditions. It is a good area for the development of solar energy resources and has good lighting conditions for the construction of BIPV projects. In recent years, Qingdao has actively issued a series of policies to promote the organic integration of photovoltaic and other industries. Figure 4 clearly shows the geographical location of Qingdao.

4.1. Determination of Constant Weight. Firstly, the risk assessment expert group of the Qingdao BIPV project was established, which was composed of 10 experts (see Table 2). Then, each expert scored the mutual influence of risk indicators by their rich professional knowledge and work experience. The score ranges from 0 to 4, namely, "0 — no influence, 1 — low influence, 2 — medium influence, 3 — high influence, and 4 — very high influence." Finally, the final evaluation values are summarized through the method of statistics as the direct impact matrix (see Table 3), and the constant weights of each risk indicator are calculated by Formulas (1)–(4) in the DEMATEL method (see Table 4).

According to the center and cause degree, the cause-effect diagram was drawn (see Table 5) to identify the attributes of each risk factor and how they interact with each other. As shown in Figure 5, the horizontal axis represents the center degree. The higher the value, the more important the risk factor. The vertical axis represents the degree of cause, the points above the horizontal axis belong to the

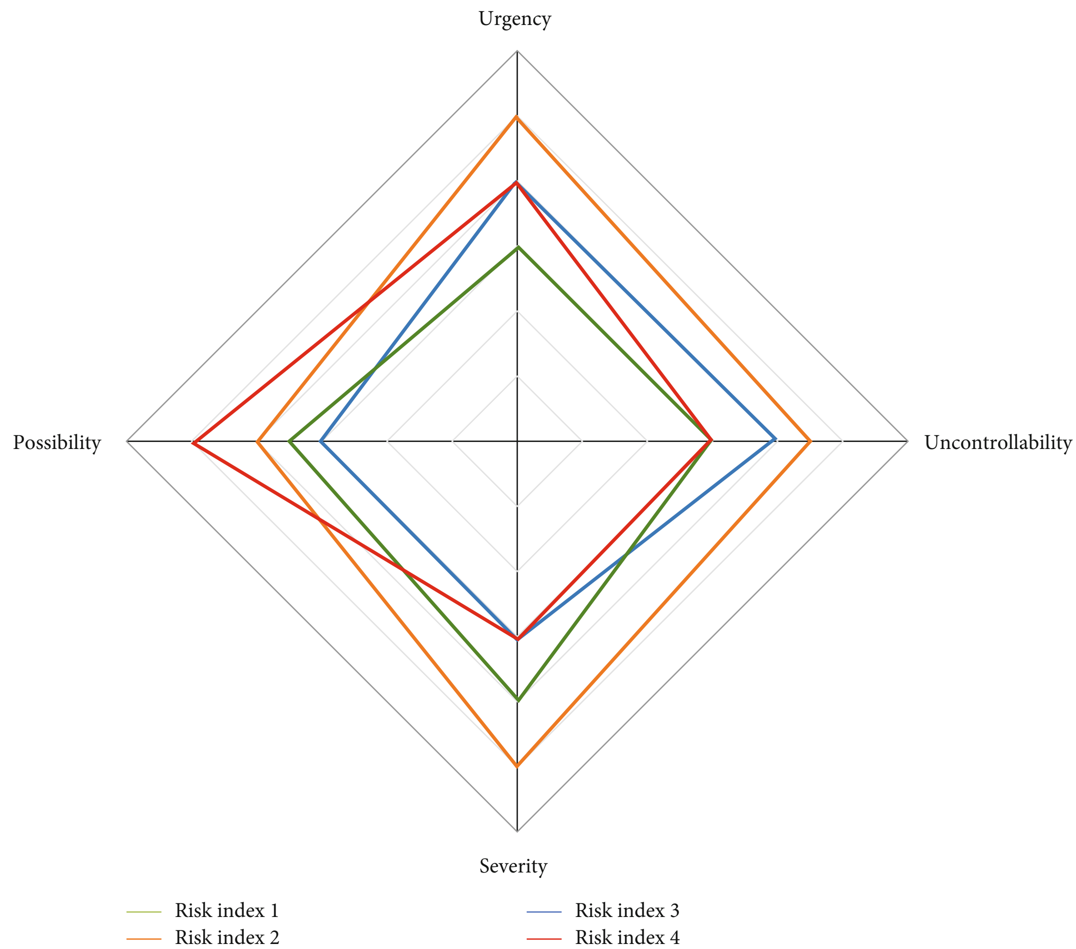

Figure 3: Four-dimensional risk analysis framework.

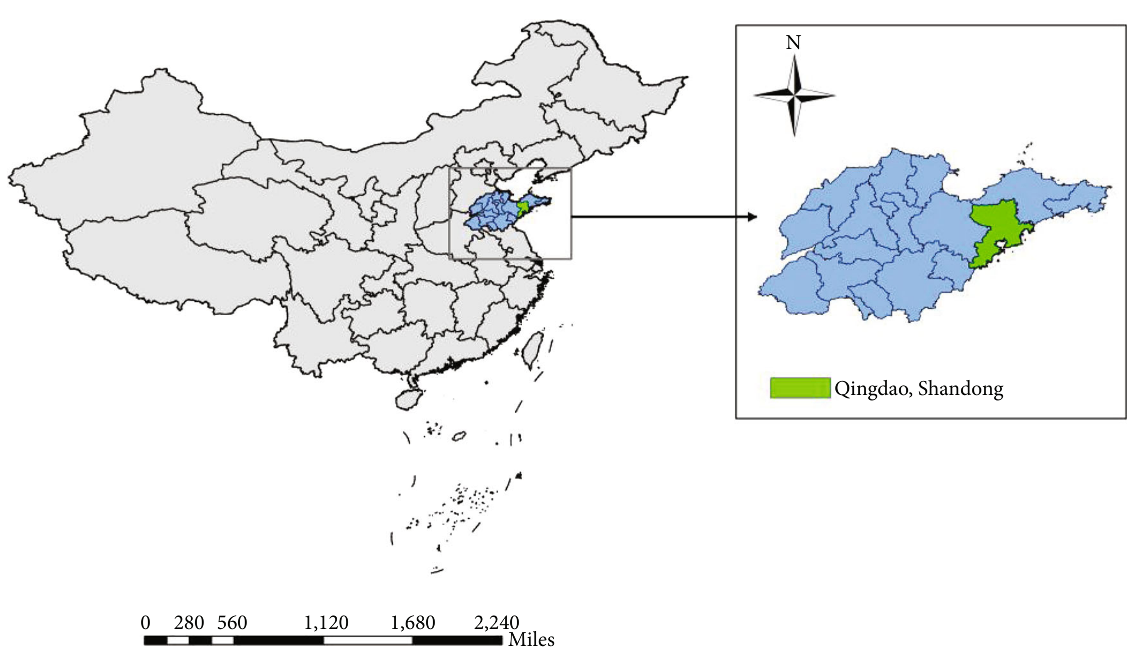

Figure 4: Map of Qingdao city, Shandong Province, China.

Table 3: The direct influence matrix.

Indicator	V11	V12	V13	V21	V22	V23	V24	V25	V26	V31	V32	V33	V34	V41	V42	V43	V44
V11	0	1	3	1	0	0	0	0	0	0	0	0	0	2	0	3	2
V12	0	0	0	0	0	0	0	3	0	0	0	0	0	0	3	2	1
V13	0	3	0	2	3	3	0	2	0	0	0	0	0	0	0	1	1
V21	0	0	2	0	3	3	2	0	2	0	0	4	3	0	0	0	2
V22	0	0	3	0	0	0	3	0	0	0	0	0	3	0	0	0	0
V23	0	1	2	2	1	0	3	0	0	0	0	0	1	0	2	0	1
V24	0	0	0	0	1	3	0	0	0	0	0	0	0	0	1	1	3
V25	0	0	3	1	0	2	2	0	0	0	0	0	0	0	0	0	0
V26	0	3	3	2	3	4	3	0	0	0	0	3	1	0	0	1	1
V31	2	3	4	1	1	2	4	0	0	0	0	0	0	1	0	1	3
V32	0	3	1	3	4	4	2	1	0	3	0	0	0	0	0	2	2
V33	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	4
V34	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	4
V41	3	4	4	0	0	0	0	0	0	0	0	0	0	0	2	0	2
V42	0	0	0	2	0	0	0	3	0	0	0	0	0	0	0	0	0
V43	0	3	2	0	0	0	0	0	0	0	0	0	0	4	3	0	2
V44	0	3	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0

Table 4: Summary of the constant weight of each risk indicator.

Indicator	A_i	B_i	M_i	U_i	Constant weight
V11	1.923	1.264	3.187	0.659	0.049
V12	1.577	2.695	4.271	-1.118	0.066
V13	2.072	2.875	4.947	-0.803	0.075
V21	2.442	1.992	4.435	0.450	0.067
V22	1.608	2.233	3.841	-0.625	0.058
V23	1.905	2.441	4.346	-0.536	0.065
V24	1.599	2.268	3.867	-0.669	0.059
V25	1.627	1.870	3.496	-0.243	0.052
V26	2.687	1.159	3.846	1.528	0.062
V31	2.577	1.120	3.697	1.457	0.059
V32	2.901	1.000	3.901	1.901	0.065
V33	1.437	1.458	2.895	-0.021	0.043
V34	1.395	1.651	3.046	-0.256	0.046
V41	2.041	1.453	3.493	0.588	0.053
V42	1.391	2.301	3.692	-0.911	0.057
V43	1.963	1.918	3.881	0.045	0.058
V44	1.435	2.881	4.316	-1.446	0.068

cause factor, and the factors below the horizontal axis belong to the result factor. Figure 5 shows that the center degree of high capital investment (V13), design risk (V21), grid connection risk (V23), public support (V44), and financing risk (V12) are high, which are the key risk factors. Risks such as severe weather conditions (V32), the lack of sufficient construction experience (V26), and solar energy resources (V31) are cause factors, which will have a great impact on other risk factors. Risks such as public support (V44) and financing risk (V12) are result factors, which are easily affected by other risk factors. The weights of risk factors are calculated by Formula (4) considering the center and cause degree.

4.2. Grade Standard of each Criterion. Based on BIPV industry standards, literature [32, 54], and expert discussion, the comprehensive risk of the BIPV project in Qingdao is divided into five grades: I, II, III, IV, and V. I represents "very low," II represents "low," III represents "medium," and IV represents" high." V indicates "very high." These grades and their corresponding scores are shown in Table 5.

4.3. Implement Risk Assessment. The expert panel scores from the four risk dimensions (urgency, possibility, severity, and uncontrollability) of each indicator. The scoring criteria are shown in Table 4. The arithmetic mean method is adopted to obtain the average score of each indicator under each risk dimension, as shown in Table 6. The comprehensive risk value (S) was calculated according to Formula (8). Traditional risk assessment methods only from a single dimension of risk assessment cannot fully express the evaluation information, resulting in high uncertainty and incompleteness in the evaluation process. The method proposed in this study evaluates related risks from four dimensions. The evaluation process integrates the four dimensions of risks, gathers more information, and can reflect the characteristics of risks more comprehensively.

4.4. Determination of Variable Weights. According to Formula (7), the variable weight of each index can be calculated (see Table 6).

4.5. Operation of the Matter-Element Extension Model. Formulas (9)–(11) in the matter-element extension model are used to determine the classical domain matrix (R_j), the

Table 5: Risk grades and corresponding scores for expert assessment.

Risk grades	I	II	III	IV	V	Joint domain
Scores	(0, 2]	(2, 4]	(4, 6]	(6, 8]	(8, 10]	[1, 10]
Linguistic variables	Very low	Low	Medium	High	Very high	——

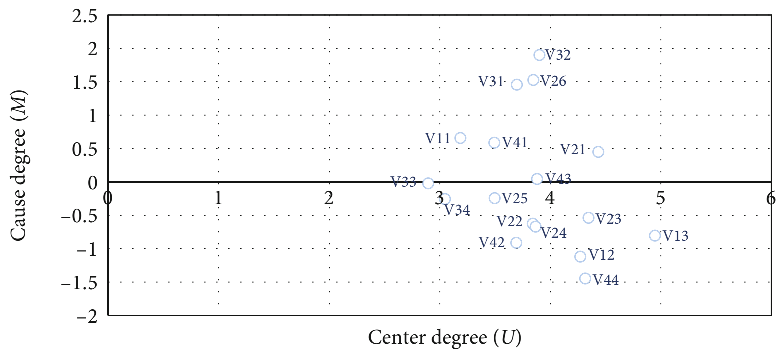

Figure 5: Cause-effect diagram.

node-domain matrix (R_Q), and the matter element to be evaluated (R_0):

$$R_j = (Q_j, V_i, C_{ij}) = \begin{bmatrix} Q_j & V_i & j=\mathrm{I} & j=\mathrm{II} & j=\mathrm{III} & j=\mathrm{IV} & j=\mathrm{V} \\ & v_1 & (0,2) & (2,4) & (4,6) & (6,8) & (8,10) \\ & v_2 & (0,2) & (2,4) & (4,6) & (6,8) & (8,10) \\ & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ & v_{17} & (0,2) & (2,4) & (4,6) & (6,8) & (8,10) \end{bmatrix},$$

$$R_Q = (Q, V_i, C_{ip}) = \begin{bmatrix} Q & v_1 & (1,10) \\ & v_2 & (1,10) \\ & \vdots & \vdots \\ & v_{17} & (1,10) \end{bmatrix},$$

$$R_0 = (Q_0, V_i, C_i) = \begin{bmatrix} Q_0 & v_1 & 4.240 \\ & v_2 & 6.236 \\ & \vdots & \vdots \\ & v_{17} & 5.686 \end{bmatrix}. \quad (16)$$

According to Formula (13), the distance between 17 risk indicators and corresponding risk grades can be obtained. The results are shown in Table 7.

4.6. Risk Assessment Results. Formula (11) can be used to calculate the proximity degree of each risk indicator and different risk grades. The risk grade of each indicator and the comprehensive risk grade are determined (see Table 8). According to Formulas (14) and (15), the eigenvalue (j^*) of the comprehensive risk level is 3.188<3.5. It can be seen that the comprehensive risk grade is III (medium risk), but it is more inclined to II (low risk). Power supply reliability risk, solar energy resources, and visual damage of buildings are at a low level, belonging to the grade II. On grid price fluctuation risk, high capital requirements, operation and maintenance risk, grid connection risk, material supply and installation risk, harsh climatic conditions, noise pollution, power generation subsidy, government approval lag risk, and public support are at the medium level of risk, belonging to the grade III. Financing risk, design risk, lack of construction experience, and government support are at the high level of risk, belonging to the grade IV.

5. Discussion

5.1. Comparative Analysis. This study makes a comparative analysis from weight and risk dimensions, respectively, to better explain the advantages of the proposed risk assessment framework.

5.1.1. Comparative Analysis of Weight. The constant weight calculated by DEMATEL method was substituted into Formula (7) to calculate the final variable weight. The results show that the comprehensive risk grade and the risk grades of each risk indicator were consistent with the original result. By comparing constant weights and variable weights, it is found that the weight of individual indicators varies greatly (such as V21, V24, V26, V31, and V33). This is because the indicator weights obtained by the variable weight method are not invariable due to the influence of indicator state value (see Figure 6). It must be emphasized that variable weights are calculated based on constant weights, which can mine indicator data information and reflect the horizontal distribution of indicator data. In addition, this method can effectively reduce the influence of subjective factors on the evaluation results and reflect the active participation of the matter element to be evaluated in the evaluation system.

Table 6: Indicator evaluation status values under different risk dimensions.

Indicator	Urgency	Possibility	Severity	Uncontrollability	S
V11	5.3	2.1	3.5	8.3	4.240
V12	6.2	3.6	8.8	7.7	6.236
V13	3.8	5.7	5.4	6.1	5.168
V21	6.5	7.9	8.5	4.4	6.620
V22	2.4	8.7	7.3	4.6	5.146
V23	4.8	4.5	7.2	3.6	4.864
V24	3.2	2.8	7.6	3.1	3.812
V25	5.9	5.8	5.6	4.2	5.326
V26	6.3	8.6	8.5	5.6	7.126
V31	6.9	1.8	7.8	1.5	3.472
V32	6.5	2.9	8.2	2.5	4.434
V33	2.2	6.8	2.4	3.8	3.418
V34	2.7	6.4	6.9	3.6	4.552
V41	6.8	5.3	3.1	7.6	5.398
V42	5.6	6.2	3.8	6.3	5.369
V43	6.3	4.5	7.2	6.6	6.058
V44	6.7	6.5	7.5	3.2	5.686

Table 7: The distance between 17 risk indicators and corresponding risk grades and variable weights.

Risk indicator	I	II	III	IV	V	Variable weights
V11	2.240	0.240	-0.240	1.760	3.760	0.053
V12	4.236	2.236	0.236	-0.236	1.764	0.059
V13	3.168	1.168	-0.832	0.832	2.832	0.074
V21	4.620	2.620	0.620	-0.620	1.380	0.058
V22	3.146	1.146	-0.854	0.854	2.854	0.057
V23	2.864	0.864	-0.864	1.136	3.136	0.066
V24	1.812	-0.188	0.188	2.188	4.188	0.067
V25	3.326	1.326	-0.674	0.674	2.674	0.051
V26	5.126	3.126	1.126	-0.874	0.874	0.052
V31	1.472	-0.528	0.528	2.528	4.528	0.071
V32	2.434	0.434	-0.434	1.566	3.566	0.069
V33	1.418	-0.582	0.582	2.582	4.582	0.052
V34	2.552	0.552	-0.552	1.448	3.448	0.048
V41	3.398	1.398	-0.602	0.602	2.602	0.051
V42	3.369	1.369	-0.631	0.631	2.631	0.055
V43	4.058	2.058	0.058	-0.058	1.942	0.053
V44	3.686	1.686	-0.314	0.314	2.314	0.064

5.1.2. Comparative Analysis of Risk Dimensions. This study puts forward a risk assessment framework from the perspective of four-dimensional risk (urgency, possibility, severity, and uncontrollability). The four-dimensional risk perspective can help to get the scientific comprehensive risk assessment results and the different situations under urgency, possibility, severity, and uncontrollability, respectively. The results will help decision-makers and managers to understand and control risks from all dimensions. To further reflect the role of the four-dimensional risk perspective, this section compares the comprehensive assessment results and the different situations under different risk dimensions. As shown in Figure 7, there is a big gap between the indicator risk grade in a single dimension and the comprehensive risk grade. For example, the risk grades of lack of construction experience (V26) under the dimensions of urgency, possibility, severity, and uncontrollability are IV, IV, V, and III, respectively, and the comprehensive risk grade is IV. The results show that the consequences caused by the risk are very serious, and the urgency of risk response and the

Table 8: The proximity degree of each risk indicator and risk grades of each risk indicator.

Code	Risk indicator	I	II	III	IV	V	Risk grades
V11	On grid price fluctuation risk	0.9408	0.9936	*1.0064*	0.9535	0.9006	III
V12	Financial risk	0.8747	0.9339	0.9930	*1.0070*	0.9478	IV
V13	High capital requirements	0.8832	0.9569	*1.0307*	0.9693	0.8956	III
V21	Design risk	0.8661	0.9241	0.9820	*1.0180*	0.9600	IV
V22	Operation and maintenance risk	0.9097	0.9671	*1.0245*	0.9755	0.9181	III
V23	Grid connection risk	0.9049	0.9713	*1.0287*	0.9623	0.8959	III
V24	Power supply reliability risk	0.9391	*1.0063*	0.9937	0.9264	0.8592	II
V25	Material supply and installation risk	0.9155	0.9663	*1.0171*	0.9829	0.9321	III
V26	Lack of construction experience	0.8671	0.9189	0.9708	*1.0227*	0.9773	IV
V31	Solar energy resource	0.9475	*1.0188*	0.9812	0.9098	0.8385	II
V32	Harsh climatic conditions	0.9161	0.9850	*1.0150*	0.9460	0.8770	III
V33	Visual damage of buildings	0.9629	*1.0153*	0.9847	0.9324	0.8800	II
V34	Noise pollution	0.9388	0.9868	*1.0132*	0.9653	0.9173	III
V41	Power generation subsidy	0.9133	0.9643	*1.0154*	0.9846	0.9336	III
V42	Government approval lag risk	0.9075	0.9624	*1.0173*	0.9827	0.9278	III
V43	Government support	0.8930	0.9457	0.9985	*1.0015*	0.9488	IV
V44	Public support	0.8823	0.9462	*1.0100*	0.9900	0.9261	III
Comprehensive risk		0.9900	0.9965	*1.0005*	0.9969	0.9904	III

possibility of risk occurrence are relatively high, but the risk is under control as a whole. It is worth noting that if risk status is considered from only one dimension and other risk attributes are ignored, the risk assessment will be irrational. Understanding risk levels from multiple dimensions is more conducive to project risk management and BIPV project delivery.

5.2. Applications Enlightenment and Risk Control. The risk assessment framework has the following useful applications:

(1) The risk index system can help decision-makers fully grasp the potential risks in BIPV-related fields. (2) Managers can use the DEMATEL method to analyze the interaction between risks and clarify the importance of risk factors. (3) Under the guidance of the four-dimensional risk perspective, the manager can use the matter-element extension model to carry out the risk evaluation of the BIPV project and obtain the comprehensive risk level and the risk level of each risk factor

According to the output results of the risk assessment framework, risk control methods are used to manage and control the related risks. The four basic methods of risk control include risk avoidance, loss control, risk transfer, and risk retention. According to the risk attribute of this study, the loss control method is mainly used to put forward the corresponding suggestions. Loss control is not the abandonment of risk, but the development of plans and measures to reduce the likelihood of loss or reduce the actual loss. The stage of control includes three stages: before, during, and after. The purpose of control in advance is mainly to reduce the probability of loss, and the control in the event and after the event is mainly to reduce the actual loss. The results showed that financing risk, design risk, lack of construction experience, and government support are rated as risk grades IV (high risk). This means that these four risk indicators urgently require relevant departments to adopt loss control methods to control risks.

First, many studies have explored BIPV technology's theoretical advantages in-depth, and it is attractive enough to some conservative investors. But some advantages are not guaranteed, such as uncertainty over investment returns such as energy production and investment returns. Therefore, few solar contractors are willing, and even fewer can credibly deliver system performance warranties covering the typical term of energy project financing, i.e., 10 years [9]. Facing this challenge, on the one hand, relevant enterprises should strengthen their professional ability and financial strength. On the other hand, the relevant specifications and standards of BIPV technology should also be continuously improved under the guidance of relevant government departments. In addition, it is necessary to continuously improve investors' awareness of BIPV projects and reduce investors' concerns about the uncertainty of BIPV projects, to achieve the purpose of expanding financing channels.

Second, the design integration of the BIPV system is the first stage of the full life cycle of the BIPV project. The BIPV system involves the integration of PV and architectural design to integrate the BIPV module into the building envelope. Due to the limited number of design professionals with BIPV experience, architectural designers often lack knowledge on how to ensure the selection of the most effective design for BIPV systems, resulting in mismatches between individual PV modules. The professionalism of this design

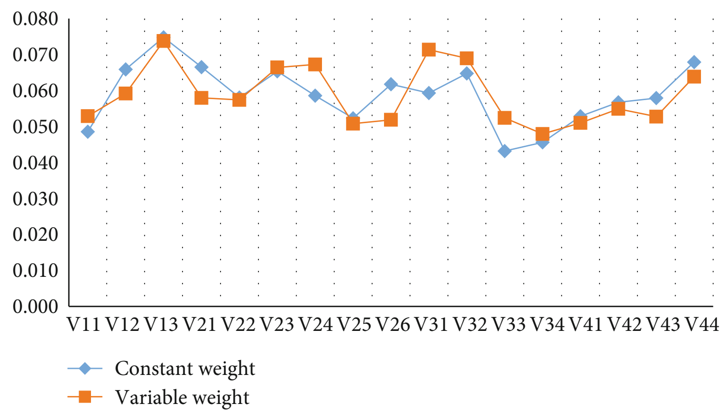

FIGURE 6: The change of weight obtained by different methods.

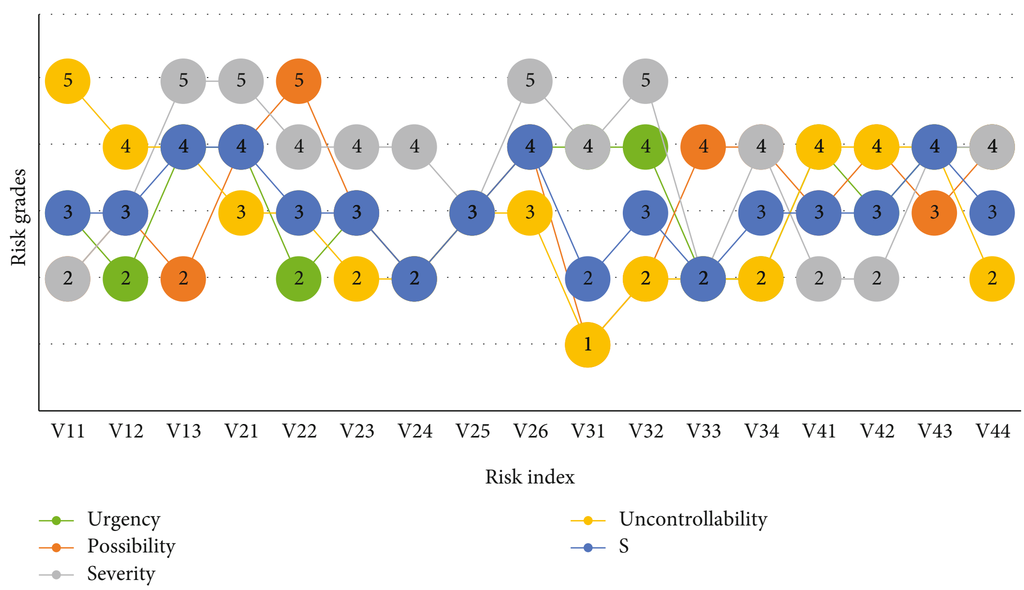

FIGURE 7: Risk grades in different dimensions.

leads to higher design risks. In addition, BIPV technology has not yet developed complete construction codes, standards, or guidelines, and staff training and practice opportunities are limited. Therefore, most of the local contractors' architects and engineers have insufficient knowledge of the characteristics of various photovoltaic systems and products and lack the necessary capabilities and construction experience to handle BIPV projects. Moreover, photovoltaic modules also need to be combined with buildings, and structural and aesthetic problems need to be considered comprehensively. Lack of construction experience is inevitable as one of the biggest risk sources. Therefore, designers need to improve their design skills, and installers and field engineers need to improve their construction skills. Photovoltaic workers and technicians need to be skilled in the maintenance, repair, and replacement of photovoltaic systems. The cooperation between stakeholders is an effective means to further promote knowledge sharing and technological innovation in design, installation, and maintenance. It is also critical to note that these professionals and related companies should seek educational and practical opportunities to improve their skills and knowledge in BIPV design and construction techniques.

Finally, national and local governments have issued many guiding policies, but a large part of these policies are not specifically designed for BIPV, but PV systems. Moreover, BIPV-related policies have not put forward more specific measures in education, R&D, finance, incentives, and other aspects. These uncertainty and insufficiently specific policies greatly increase the overall risk of the project. Therefore, the government should give full play to its role, not only to provide guidance but also to formulate specific policies such as subsidies to stimulate industrial development. Meanwhile, relevant government departments must provide substantial support in BIPV technology education, training, and R&D.

6. Conclusion

BIPV technology has been widely concerned because it can promote the sustainable development of the environment. Scientific and effective risk assessment is conducive to the implementation and construction of BIPV projects. Therefore, this study established a conceptual risk assessment framework for BIPV projects from a four-dimensional risk perspective. The results provided valuable guidance for investors and decision-makers to take action to mitigate the risks of BIPV projects. This study advances previous studies as follows.

First, this study systematically reviewed literature related to BIPV risk and identified 17 risk indicators through expert interviews. These indicators are divided into four categories, including economic risk, technological risk, natural environment risk, and policy-social risk. Second, variable weight theory is introduced. Based on the constant weight determined by DEMATEL, the variable weight method is adopted to calculate the variable weight of the indicator, to ensure that the weight value can be changed according to the state value of the indicator. Thirdly, based on the four-dimensional risk perspective, this study carries out risk assessment from four perspectives: possibility, severity, uncontrollability, and urgency. Finally, the results of the case study show that the comprehensive risk grade of the BIPV project in Qingdao is III, belonging to the medium risk. According to various risk indicators, the risk grades of financing risk, design risk, lack of construction experience, and government support are IV, which are the most critical potential risk and should be focused on. In addition, this study verifies the effectiveness and applicability of the proposed framework through model comparison and puts forward corresponding suggestions through risk control methods.

The assessment framework is verified to be feasible and suitable for BIPV project risk assessment. However, considering the complexity and uncertainty of BIPV technology promotion and implementation, the BIPV project risk assessment indicator system needs to be improved in the future. Meanwhile, the framework proposed in this study is not limited to the BIPV project but can be transplanted to more complex and uncertain risk assessments, to realize the broad application of the method, such as offshore photovoltaic power generation projects. In addition, the risk assessment framework can help the researchers to develop the risk assessment software and realize the intelligent application of the method.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflict of interest.

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