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An Investigation into the Risk Assessment of Building-Integrated Photovoltaic Residential Project Development Utilizing the DEMATEL-ANP Methodology: A Chinese Case Study

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Abstract: Numerous countries are implementing building-integrated photovoltaic (BIPV) technology to enhance the energy performance of buildings, as new energy sources have attracted global interest. BIPV residential programs are an essential method to alleviate energy stress and promote energy transition in buildings; however, the high level of technology and capital investment required have hampered their marketization. Although certain obstacles have been examined by researchers, there remains a lack of studies concerning risk assessment in the context of the development of BIPV residential projects. Therefore, this study strives to develop a risk assessment model for the development of these projects. First, a risk evaluation index system is proposed by identifying and analyzing the risks associated with the development of BIPV residential projects, following the lines of risk identification–risk analysis–risk evaluation–risk management. Second, the DEMATEL-ANP-gray cluster analysis was utilized to construct the development risk assessment model. Finally, a case study demonstrates that the methodology proposed in this study can effectively solve the issues associated with correlating risk factors and the quantification of the magnitude of risks in the development of BIPV residential projects. This study will serve as a valuable reference for architect-urban developers and engineer contractors to formulate risk governance countermeasures for BIPV residential projects as it provides a framework for assessing the risk associated with their development.

Keywords: building-integrated photovoltaics; residential development; risk evaluation; grey clustering analysis

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1. Introduction

In light of the prevailing energy crisis, countries across the globe are facing certain challenges pertaining to energy scarcity and environmental pollution [1]. Over an extended duration in the past, when all countries were heavily developing and utilizing traditional energy sources, particularly fossil fuels, approximately 80% of global energy production depended on coal, oil, and gas [2]. The depletion of global fossil fuel reserves is anticipated to occur by 2083, unless renewable energy sources are implemented to replenish them [3]. The development of renewable energy is progressively becoming inevitable. In contrast to other alternative renewable energy sources, solar energy is favored by numerous countries due to its comparative accessibility, practicality, and affordability [4,5]. When considering the conversion of solar energy into electricity, photovoltaics is the most promising technology among others [6].

The potential application of photovoltaic technology In building-integrated photovoltaics (BIPV) is substantial [7]. BIPV integrates photovoltaic systems with buildings, allowing construction projects to mitigate environmental impact and resource consumption to a certain extent [8]. BIPV serves as an excellent complement to green energy development and is crucial for building energy retrofits. Therefore, it has an extremely promising future in the markets of all countries. While developed countries currently possess a large number of BIPV systems, numerous developing countries are gaining ground swiftly [9]. Current photovoltaic technology in BIPV systems has been applied to walls, roofs, and windows [10]. Despite the fact that BIPV is primarily employed in public structures, its potential for implementation in residential projects is still considerable [11]. BIPV residential programs are increasingly recognized as an effective way to facilitate energy transition within the construction industry. This is a significant impediment to the development of BIPV residential projects [11] due to the high level of technology and capital investment required, as well as the numerous building design, safety risk, and cost and benefit considerations that persist. Hence, assessing the development risk associated with BIPV residential projects receives elevated significance. Risk evaluation will be complicated, however, due to the interaction between various factors and the fact that the development of BIPV residential projects is still in its infancy, which will result in a shortage of information and considerable subjectivity.

This paper endeavors to eliminate the aforementioned shortcomings by conducting a literature review to identify 26 risk factors, followed by a questionnaire survey and Delphi method screening and optimization of the risk factors associated with the development of BIPV residential projects, resulting in the selection of 22 risk indicators. This article also establishes the WBS-RBS risk indicator system in accordance with the full life cycle theory and constructs a risk assessment model for the development of BIPV residential projects, which is used to assess the risk of Project A. Utilizing the DEMATEL-ANP-Gray cluster analysis model, the obtained evaluation results are compared with the actual situation. The comparison reveals that the evaluation results are consistent with the actual situation, which verifies the feasibility and effectiveness of the model. In conclusion, recommendations are provided as a reference for the improvement of subsequent BIPV residential projects based on the analysis of the evaluation's findings.

The following section will discuss each of the five components: literature review, methodology, case study, results and discussion, and conclusions.

2. Literature Review

2.1. Residential Project Development Risk Study

Although prior studies have extensively examined the effects of risk assessments for residential project development, the majority of them focused on examining them at the contractor and owner level [12,13], as well as the ability of risk identification [14,15]. Risks in early studies of residential programs can be broadly categorized into five classes: risk communication, risk responsibility, risk information management, and risk knowledge [16]. The causal relationship between risk factors can be addressed through the use of fuzzy cognitive mapping to model residential risk assessment [13]. Optimal risk identification can only be achieved through the examination and reflection of risk-forming factors [12]. Risk identification is conducted to improve the contractor's ability to recognize and manage risks throughout the construction process [14]. Furthermore, risk analysis in residential projects should not be confined to the contractor and owner levels. In reality, the design of building fire engineering for high-rise residential projects underestimated the safety of use risks, which was extremely concerning for the occupants [17]. Risks in real estate market projects [18] should also be focused on. The human element must also be taken into consideration when the risk model is established. In recent years, an expanding body of research has been devoted to identifying the risk factors associated with green projects. Hwang (2017) and others have identified and assessed a range of risks associated with the construction of green projects. They have also proposed corresponding mitigation measures to address these risks [19]. Nguyen (2022) et al. identified and categorized green building risks, providing industry practitioners and future researchers with a comprehensive list of green building risk factors that can be used [20]. The aforementioned analysis revealed that research concerning the identification and evaluation of risks in conventional and green residential construction projects is more developed.

2.2. Research on the Application of BIPV Technology

By substituting BIPV modules for conventional building modules as an integral component of the building envelope, a significant reduction in energy consumption can be achieved [21]. Satellites and the International Space Station were presumably the first locations to implement BIPV; photovoltaic power structures installed on satellites served as the initial prototypes of photovoltaic technology and structural integration [22]. Considering their significance in the realm of building energy retrofits, there is a growing body of exploration and research focusing on expanding their potential application to encompass additional aspects of buildings. Walls, roofs, and windows have been equipped with photovoltaic technologies of the first and second generations, and the potential applications of third-generation photovoltaic technologies are being explored [10]. BIPV is a viable technology that promotes the generation of renewable energy production and possesses the capacity to substantially reduce costs. In addition, projects utilizing BIPV technology can establish a building information system platform to manage and share data and information from design to completion [23]. Research has indicated that developed countries possess a considerable quantity of photovoltaic building-integrated systems, while developing countries, particularly those in the Middle East and North Africa, are advancing rapidly [9]. However, the development and application of BIPV in public buildings has been the subject of comparatively more research than its application in residential development projects.

2.3. A Study of Development Risks in BIPV Residential Projects

Risks associated with the development of BIPV residential projects have been studied across multiple levels: user acceptance [11,24,25], market development potential [26,27], economic benefit [27,28], environmental benefit [29], and technical barriers [30,31]. To encourage BIPV residential projects in the community, it is necessary to consider public acceptance of BIPV technology [24]. An examination of the public's response to the installation of BIPV systems in residential buildings revealed that intellectual, technological, economic, social, and political barriers impede the implementation and development of BIPV [11]. An investigation into the choices of Swiss homeowners for PV power generation suggested that homeowners prefer PV building-integrated roofs to roofs with PV mounts [25]. Economic and environmental benefits must be taken into consideration in the development of BIPV residential projects. Yatim, Y (2017) et al. determined the economic value of the PV modules selected for the project by calculating the life cycle cost, levelized cost of energy, and payback period to achieve the lowest payback period [27]. Furthermore, the potential of BIPV systems in urban building renovation projects is greater [26]. However, the application of BIPV technology in the development of residential projects faces a number of obstacles. Given the significant reliance of PV module performance on local climatic and environmental conditions, it is crucial to employ innovative BIPV modules and systems to mitigate shading stress (repeated or continuous shading) [31]. Despite the qualitative analyses conducted by experts and scholars regarding the development risk of BIPV residential projects, risk assessment throughout the entire life cycle of such BIPV residential projects is lacking.

3. Methodology

3.1. Research Framework

Firstly, the influencing factors of development risk for BIPV residential projects are derived from the literature on Web of Science and relevant code provisions (see Table S1). These risk factors are subsequently refined and filtered using the Delphi method. Following this, the indicator evaluation system is constructed utilizing the WBS-RBS methodology. On this basis, the weights of risk indicators are determined by the DEMATEL-ANP method, and the gray clustering model is developed to assess the risk associated with BIPV residential projects. The precise framework for the research is illustrated in Figure 1.

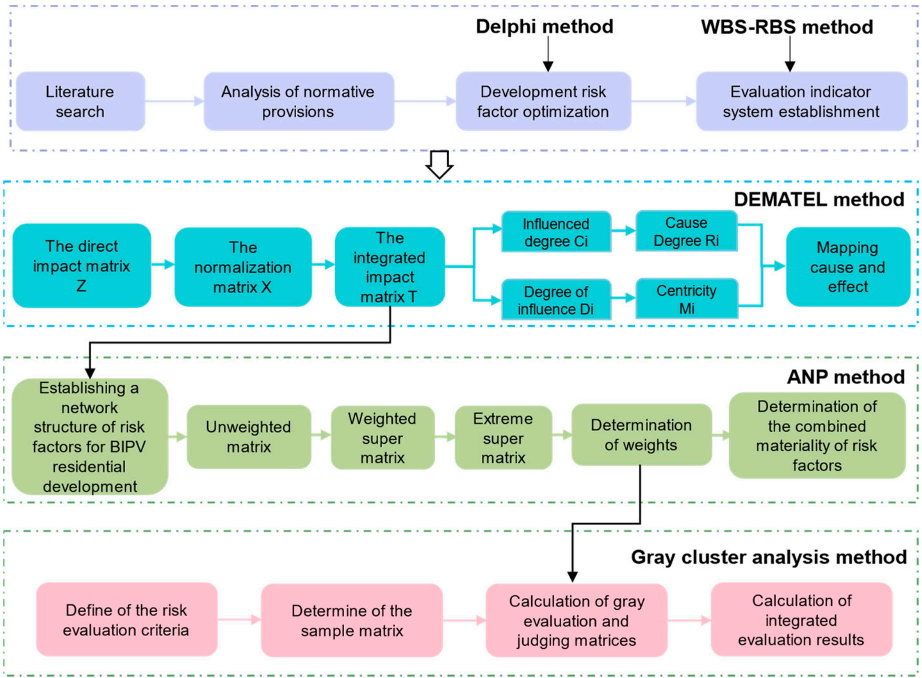


Figure 1. Research framework.

3.2. Construction of the Indicator System

3.2.1. Initial Identification of Risk Factors

Risk factors are initially identified through an analysis of the research findings on BIPV in public and residential buildings. We searched Web of Science using the search formulas TS = ("Building Integrated Photovoltaic (or BIPV)" and "risk") and TS = ("Residential Photovoltaic (or residential PV)" and "risk"), respectively. After sifting through the literature that exhibited a high degree of content similarity with the search results and this study, 19 articles were selected for further analysis. Following this, 23 risk factors were initially identified. The data on the relevant normative provisions in China were subsequently analyzed. Collecting 25 current technical specifications or documents that pertain to the risks associated with the development of BIPV, we conducted an article-by-article analysis of the specification and risk sources and factors pertaining to BIPV development. We then compared and categorized the risk factors identified based on the specification with those identified in the literature. The literature-identified risk of bidding and tendering, for instance, is expressed in overly general terms and is substituted with normative provisions that specify the risk associated with the bidding method and the contractor's qualification. In summary, the aforementioned two steps identified a preliminary list of 26 risk factors pertaining to the development of BIPV residential projects, as presented in Table 1.

3.2.2. Finalization of Risk Factors

The Delphi method is employed in the study of risk factor optimization to evaluate, refine, and screen preliminary risk factors for BIPV residential development. Given the imperative for integration in the design of BIPV residential development, this study enlisted the services of 15 relevant experts in areas encompassing overall planning, the integration of PV modules with the building, and structural and electrical considerations (see Table 2 for detailed information about the experts). Using an expert survey to conduct the first round of factor screening (the results are shown in Table S2), the experts evaluated the preliminary list of risks and proposed suitable improvements after being briefed on the study's context regarding the risks associated with BIPV residential development, its purpose, and other details. The results of the interviews were analyzed and corrected accordingly. A second round of interviews was conducted subsequently, during which experts were once again requested to assess and scrutinize the revised indicators again (the results are shown in Table S3). Following the retrieval of the assessment forms, the corresponding data processing and analysis were performed to validate the consistency and reliability of the experts' opinions, with the intention of ascertaining preliminary risk factors.

Table 1. The list of preliminary risk factors identified.

Risk Factors Based on Preliminary Information Obtained from the Literature Search			Normative Risk Factors Based on the Normative Provisions Identified		
Risk Number	**Risk Factors**	**Source Literature**	**Treatment**	**Outcome of the Process**	**Source Code Provisions**
1	Project finance risk	[32–35]	reservations	Project finance risk	
2	Incremental cost risk	[33,34,36]	reservations	Incremental cost risk	
3	Feed-in tariff risk	[36–39]	reservations	Feed-in tariff risk	
4	Construction management risk	[32,34–36]	variation	Progress management risk	[40,41]
5			add	Contract management risk	[40,41]
6			add	Cost management risk	[40,41]
7			add	Quality management risk	[40,41]
8	Bidding and tendering risks	[32]	variation	Tendering methods and contractor qualifications	[42]
9	Risk of changes in policies and regulations	[33,34,36,38,39,43,44]	reservations	Risk of changes in policies and regulations	
10	Program design risk	[45]	variation	Risk of poor program design	[46]
11	Integrated design risks	[36,45,47]	variation	Project integration design risk	[46,48]
12	Bidding and tendering risks	[32,35]	reservations	Bidding and tendering risks	
13	Geographical conditions of the project	[44,47]	reservations	Geographical conditions of the project	
14	Project location	[35,44,47,49]	reservations	Project location	
15	BIPV market supply risk	[11,35,50]	reservations	BIPV market supply risk	
16	Consumer awareness	[11,36,38,45]	reservations	Consumer acceptance risk	
17	Grid connection risk	[3,51]	reservations	Grid connection risk	[52]
18	Energy saving and environmental benefits	[33,34]	reservations	Energy saving and environmental benefits	
19	Security management risks	[53]	reservations	Security management risks	[54–56]
20	Master plan	[44,47]	variation	Master plan design risk	[57]
21	Operations management	[11,33,34,45,58]	reservations	Operations management	
22	Relay protection risks	[3,11]	variation	Risk of relay protection measures	[59]
23	Quality acceptance risk	[34]	variation	Risk of inadequate acceptance criteria	[60,61]
24	Load forecasting risk	[45]	reservations	Load forecasting risk	[62]
25	Inadequate design specification	[35,45]	variation	Risk of inadequate design codes and standards	[63]
26	Level of regional development	[44,47]	reservations	Level of regional development	

Table 2. Experts' information.

Expert Sources	Entry Requirement	Quorum
Photovoltaic plant managers	Staff engaged in PV plant management for more than 2 years	3
BIPV technicians	Staff engaged in the installation of photovoltaic modules	3
Specialist in the electrical field	Experts who are familiar with the conditions of PV power generation system equipment and technical requirements for grid connection and have the appropriate operational qualifications.	2
Specialist in the field of construction	Specialists engaged in the installation and production of buildings, structures and equipment, etc.	4
Photovoltaic building business specialist	Engaged in the design and development of photovoltaic curtain walls, materials, photovoltaic glass, etc.	3

Kendall's W coordination coefficient was employed to assess the consistency of expert opinions following two rounds of scoring. The coordination coefficient W rose from 0.185 in the first round to 0.291 in the second, indicating a greater degree of coordination among the experts' opinions. The *p*-value for both rounds of scoring remained below 0.05, indicating statistical significance and suggesting that the experts' viewpoints are consistent (See

Supplementary Material S4 for a detailed process). Therefore, the combined results of the expert assessment yielded a total of 22 risk factors, as presented in Table 3.

Table 3. List of initially identified risk factors.

Serial Number	Risk Factors	Serial Number	Risk Factors
1	Consumer acceptance risk	12	Tendering methods and contractor qualification risks
2	BIPV Market Supply Risk	13	Inadequate design codes and standards
3	Project finance risk	14	Security management risks
4	Project location risk	15	Risk of inadequate quality acceptance criteria
5	Incremental cost risk	16	Construction contract management risks
6	Feed-in tariff risk	17	Construction cost management risks
7	Risk of imperfect policies and regulations	18	Construction schedule management risks
8	Risk of poor project master plan design	19	Technical risk of PV equipment maintenance
9	Load forecasting risk	20	Grid acceptance and commissioning risks
10	Risk of poor program design	21	Risk of regular settlement of electricity bills
11	Project Integration Design Level	22	Risk of inoperability due to natural disasters

3.2.3. Establishment of the Evaluation Indicator System

From a full life cycle perspective, the main stages comprising the development process of a BIPV residential project can be categorized into four distinct stages: pre-decision, preparation and design, project implementation, and operation and maintenance. The decomposition of the WBS (work breakdown structure) is performed based on the four phases (as shown in Figure 2). The decomposition of work at each stage of the full life cycle facilitates a more efficient distribution of various types of risk to particular tasks. In accordance with the technical specificity and relevance of the BIPV residential project, the identified risk factors are then categorized by risk attributes into a risk breakdown structure (RBS) diagram (as shown in Figure 3). Finally, the WBS-RBS RBM (risk breakdown matrix) is constructed.

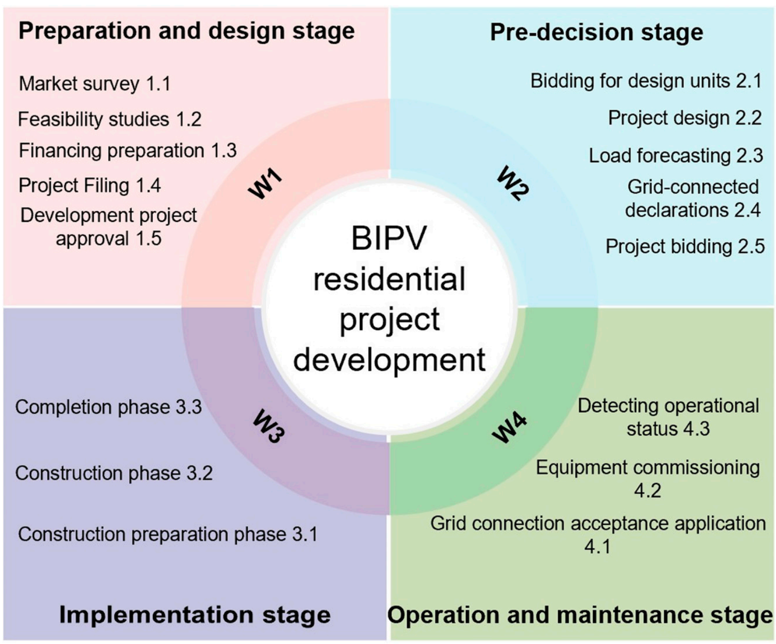


Figure 2. Work breakdown structure model of BIPV residential projects.

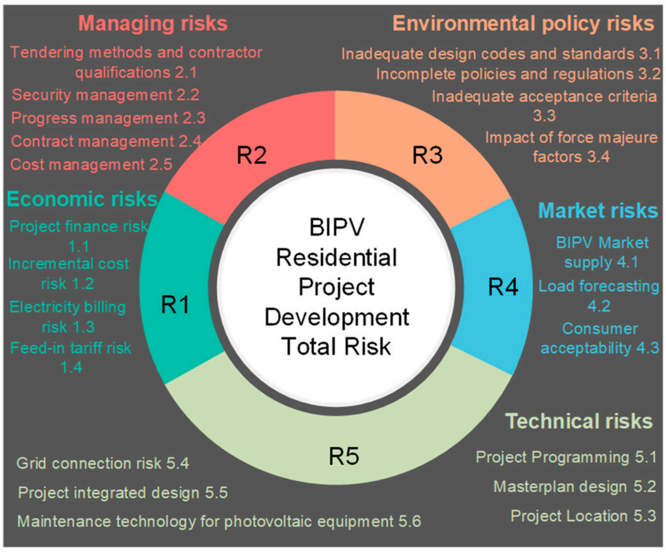


Figure 3. Risk breakdown structure model of BIPV residential projects.

The entire life cycle risk evaluation index system (Table 4) for BIPV residential development is derived by processing the risk coupling matrix and scoring results, which were obtained by soliciting the opinions of the fifteen previously presented experts as well as evaluating and scoring the constructed coupling matrix. Additionally, the system correlates the 22 risk indicators with each stage of the entire life cycle.

Table 4. Risk assessment index system of BIPV housing development.

Target Level	Standardized Layer	Indicator Layer
BIPV residential development Risk evaluation indicator system (I)	Pre-decision stage exposures (I1)	Risk of inadequate policies and regulations (I11) BIPV market supply risk (I12) Project finance risks (I13) Site selection risks (I14) Risk of consumer acceptance (I15) Feed-in tariff risk (I16) Incremental cost risk (I17)
	Preparation and design phase exposures (I2)	Risk of poor project master planning (I21) Risk of load forecasting accuracy (I22) Risk of poor project program design (I23) Risks to the level of integrated project design (I24) Tendering methods and contractor qualification risks (I25) Risk of not improving design codes, standards and related atlases (I26)
	Project implementation phase exposures (I3)	Construction safety risks (I31) Risk of inadequate quality acceptance criteria (I32) Risks in construction cost management (I33) Risks of construction schedule management (I34) Construction contract management risks (I35)
	Operation and maintenance phase exposures (I4)	Risk of not having well-established technical standards for PV equipment maintenance (I41) Grid acceptance and commissioning risks (I42) Risk of regular billing for electricity (I43) Risk of inoperability due to natural disasters (I44)

3.3. Establishment of a Risk Evaluation Model Based on the DEMATEL-ANP Method

3.3.1. DEMATEL Method

A systematic research methodology based on graph theory and matrix tools, DEMATEL (decision-making trial and evaluation laboratory) is an effective way of analyzing and evaluating influencing factors. DEMATEL has been implemented extensively across various fields to assess risk indicators. Since the development of BIPV residential projects in this study is influenced by multiple parties, risks exist throughout the entire life cycle. Furthermore, the risk indicators interact with each other, with certain qualitative ones relying on expert scoring, which brings a certain degree of ambiguity. The DEMATEL method possesses significant advantages when applied to complex system decision-making problems. In addition to simplifying the uncertainties associated with complex systems and synthesizing expert recommendations, it calculates the degree of influence between the evaluation indicators and takes into account the relationship between the factors. The precise procedures and formulas are illustrated in Figure 4.

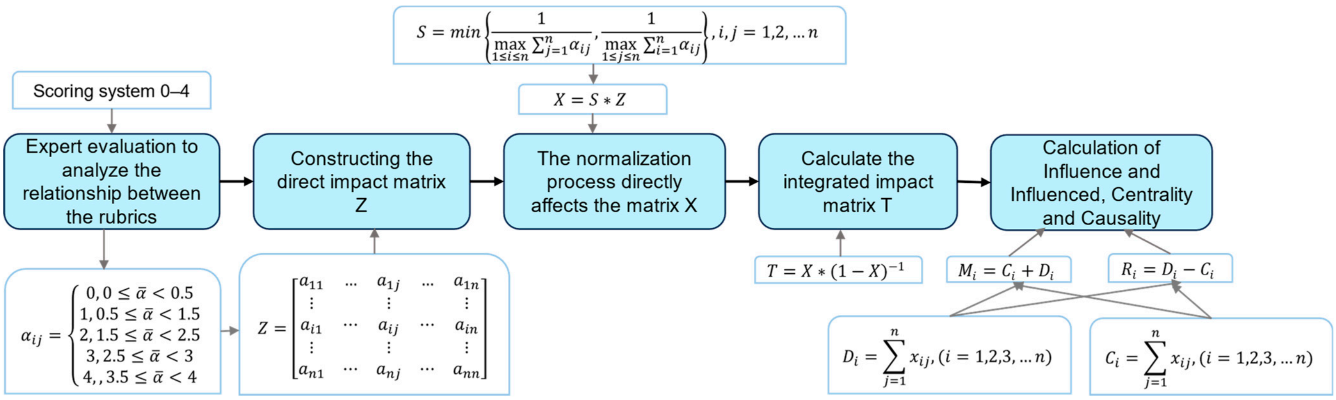


Figure 4. Determination of the level of impact of risk indicators based on the DEMATEL methodology.

The experts listed in Table 2 were requested to score the relationship between the risk factors on a scale of 0–4. The following scoring criteria were developed for the impact of factor α_i on α_j: 0 (no impact), 1 (a small impact), 2 (an average impact), 3 (a large impact), and 4 (a substantially large impact).

3.3.2. ANP Method

Incorporating a control layer and a network layer, the ANP (Analytic Network Process) methodology compares the degree of dominance of risk factors with each other by constructing a network relationship model, NRM (Net Relation Model), which takes into account the correlation that may exist between the indicators and differentiates the degree of importance between the indicators. The DEMATEL method was integrated into the ANP to exploit the ANP's strengths in addressing complex problems and nonlinear relationships between factors more effectively. Additionally, by utilizing the DEMATEL method's calculation results for risk indicator weight calculation, the ANP can mitigate the influence of subjective judgment errors to a certain extent, which enhances the standardization and efficacy of its application. The specific steps and formulas are illustrated in Figure 5.

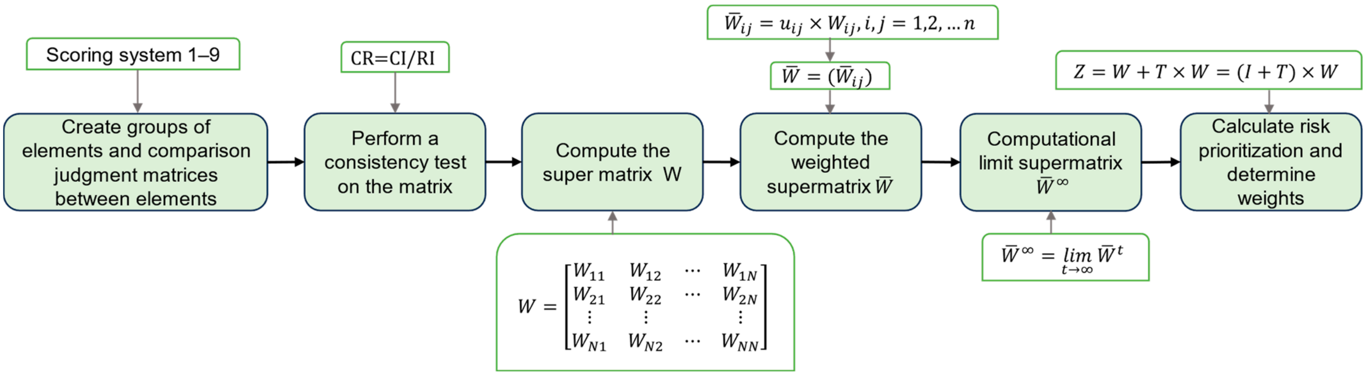


Figure 5. ANP-based risk indicator weight calculation.

3.3.3. Construction of a Gray Clustering Evaluation Matrix

(1) Determination of the collection of comments

To establish the evaluation table criteria and rubric set, this study categorizes the risk level of the development of BIPV residential projects into five grades. The range of values for the risk measure is expressed by the number of intervals [0, 1]. The evaluation criteria and rubric for this measure are presented in Table 5.

Table 5. Evaluation criterion.

Risk Level	Scope of Risk Measurement	Evaluation Criteria
low	[0, 0.2]	This risk has an exceedingly low probability of occurrence and exerts a nearly negligible impact on the project when it occurs.
relatively low	(0.2, 0.4)	This risk has a low probability of occurrence, exerts a low impact and loss on the project when it occurs, and does not impede the accomplishment of the project objectives.
moderate	(0.4, 0.6]	This risk has a moderate probability of occurrence and may cause a moderate amount of damage and financial loss to the project when it occurs, but measures can be taken to restore normalcy.
high	(0.6, 0.8]	This risk has a high probability of occurrence; it could result in significant loss and damage to the project when it occurs.
very high	(0.8, 1]	This risk has a high probability of occurrence. Its occurrence can have serious impacts and result in substantial repercussions for the project, ultimately impeding the achievement of its goals.

(2) Determination of the sample matrix

Supposing there are p experts on risk factor indicator Rj (j = 1,2...n), and the ith expert (i = 1,2...p) evaluates the observations on the Rj risk factor level as d_{ij}, the sample matrix D is computed.

(3) Determination of the whitening weight function and construction of the risk judgment matrix

The whitening weight function is the dynamic distribution relationship of the evaluation values, the distribution range of which is denoted by the gray number. Any value falling within this interval corresponds to the whitening number, thereby signifying the correlation with the gray scale. The specific steps and formulas for calculating the whitening weight function, which quantifies the degree to which an evaluation object belongs to a certain gray number, are shown in Figure 6.

The whitening weight function refers to the dynamic distribution relationship to the evaluation values, of which the distribution range is denoted by the gray number. Any value that falls within the range is called the whitening number, which signifies its correlation with the gray scale. The whitening function quantifies the degree to which an evaluation object belongs to a certain number. Detailed steps and formulas are shown in Figure 6.

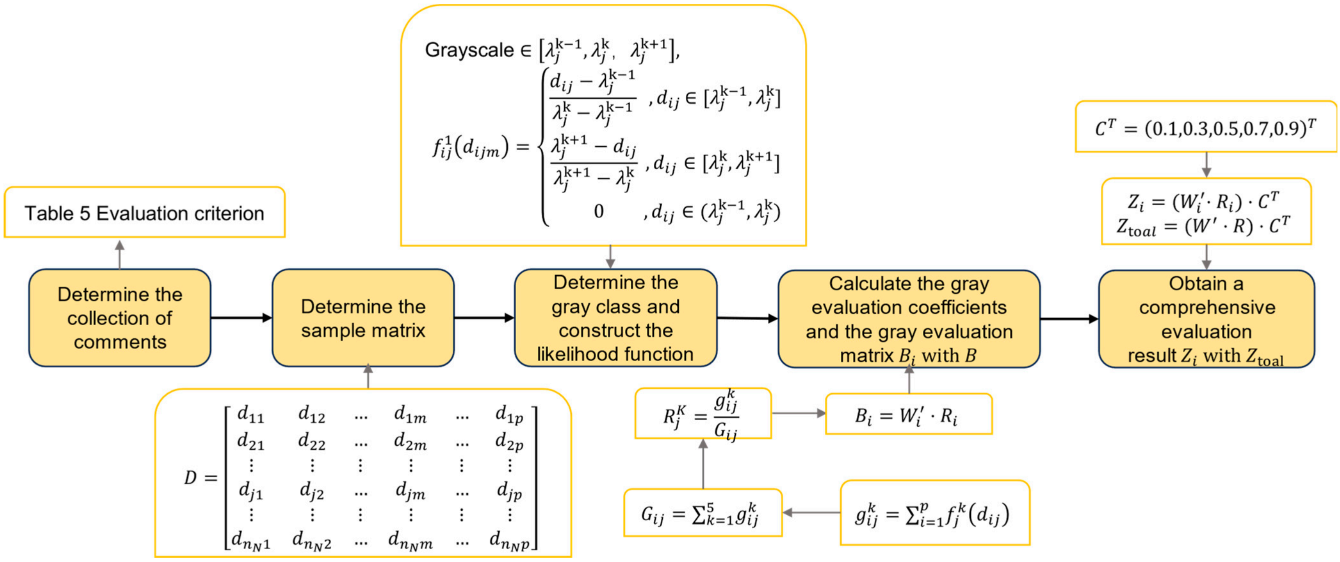


Figure 6. Constructing a gray clustering evaluation matrix.

4. Case Study

4.1. Project Overview

With a gross floor area of 178,819 m^2 and a total of 1936 residences, Project A is situated in East China, which consists of high-rise, small high-rise, and multi-story residences and townhouses. Project A comprises BIPV module products, which are incorporated into the residential design for roofing and shading. Additionally, the neighborhood kiosks have also implemented photovoltaic roofing. Additionally, PV modules are specifically designed for installation in the building's public area. The tilt angle of the roof photovoltaic panels was ultimately determined to be 42° during the design phase, taking into account several factors, including the geographic location of Project A and the continuity and uniformity of solar radiation. The area hosting Project A experiences an average of 2200~2300 h of annual sunshine, resulting in an average annual power generation of 60,165 Kwh. According to the power generation data, Project A demonstrates compliance with both the design and usage criteria. However, since the project is the first BIPV residential project in the city, there is a dearth of relevant experience to leverage, so the operation process may encounter certain unpredictability, the economic benefits being merely average, whereas the social demonstration benefits are obvious.

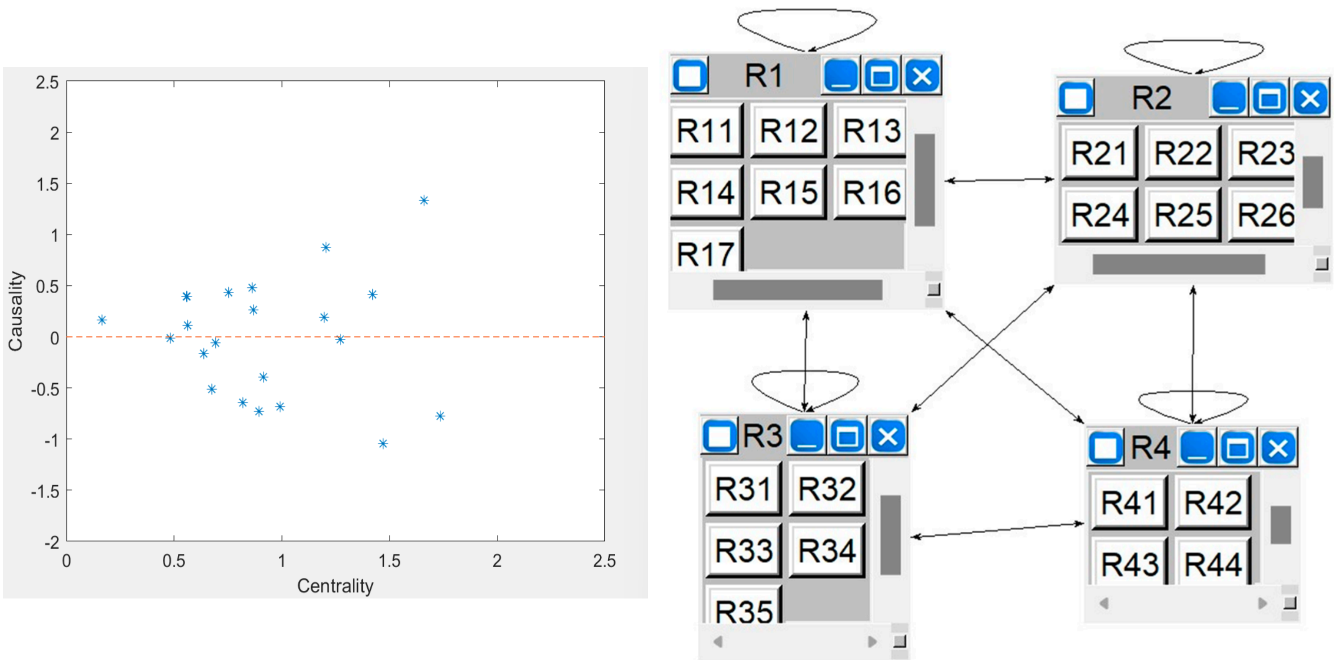
4.2. Evaluation of Project Development Risks

4.2.1. Impact Assessment of Risk Indicators Based on the DEMATEL Methodology

As illustrated in Table 4, the 22 risk indicators have been assigned an R value. The direct impact matrix Z, the normative impact matrix X, and the composite impact matrix T of the risk indicators are derived sequentially based on the methodological process described previously. The influenced, centered, and cause degrees were then calculated using the ANP method, as shown in Table 6. In order to provide a more precise delineation of the risk factors associated with the development of a BIPV residential project, the results of the matrix are utilized to generate a DEMATEL analytical causal diagram (Figure 7a). Positive values on the Y-axis of the causality–centrality diagram indicate that the influencing factors, which are the risks that directly affect the development of BIPV housing, are the causes. When values are negative, it implies that the influencing factors are outcomes, which are in turn impacted by causal factors that indirectly affect the risk of BIPV residential development. The further the factor is from the center of the image and the higher the ranking, the greater its centrality and significance. With the aid of risk indicators, BIPV residential development can be better comprehended with the aid of this chart, allowing for the development of more effective risk management strategies.

Table 6. Risk factor outcome analysis of DEMATEL.

Norm	Impact Di	Influenced Degree Ci	Centricity Mi	Order of Centrality	Cause Degree Ri
R11	0.480	1.257	1.74	1	−0.78
R12	0.476	0.083	0.56	19	0.39
R13	0.211	1.259	1.47	3	−1.05
R14	0.694	0.503	1.20	7	0.19
R15	0.337	0.225	0.56	18	0.11
R16	0.592	0.160	0.75	14	0.43
R17	1.498	0.161	1.66	2	1.34
R21	0.316	0.376	0.69	15	−0.06
R22	0.164	0.000	0.16	22	0.16
R23	0.623	0.650	1.27	5	−0.03
R24	0.917	0.505	1.42	4	0.41
R25	0.671	0.190	0.86	12	0.48
R26	1.040	0.166	1.21	6	0.87
R31	0.237	0.402	0.64	17	−0.16
R32	0.234	0.249	0.48	21	−0.02
R33	0.082	0.813	0.90	10	−0.73
R34	0.155	0.837	0.99	8	−0.68
R35	0.082	0.592	0.67	16	−0.51
R41	0.475	0.083	0.56	20	0.39
R42	0.090	0.731	0.82	13	−0.64
R43	0.260	0.655	0.91	9	−0.40
R44	0.565	0.303	0.87	11	0.26



(**a**) (**b**)

Figure 7. (**a**) The cause and effect diagram; (**b**) the network structure diagram of the ANP.

4.2.2. Determination of the Weights of the Risk Indicators for the Development of Project a Based on the ANP Methodology

The required ANP network structure was determined using the relationships between the development risk indicators in the DEMATEL model, as illustrated in Figure 7b. In order to compare risk indicators, a judgment matrix and an unweighted super matrix were constructed. The weighted super matrix, the limit super matrix, and the weights for each risk were then computed. From the collation of the limit super matrix and prioritization results, we obtained the total ranked weight vector *Wi* for the first level indicator *Ri*, the total ranked weight vector *Wini* for the second level risk indicator *Rij*, and the weight vector *Wini'* for risk indicator *Rij*. For the risk category *Ri* belongs to, see the summary in Table 7 below.

Table 7. Results of risk index weight.

Level 1 Indicators	Tier 1 Indicator Weights	Secondary Indicators	Localized Weights for Secondary Indicators	Total Weight
R1	0.630932	R11	0.38699	0.226
		R12	0.00421	0.002
		R13	0.28514	0.181
		R14	0.09187	0.050
		R15	0.14876	0.071
		R16	0.00484	0.003
		R17	0.07819	0.044
R2	0.215551	R21	0.58494	0.113
		R22	0.23201	0.045
		R23	0.09878	0.019
		R24	0.01671	0.003
		R25	0.00243	0.001
		R26	0.06513	0.013
R3	0.060968	R31	0.03545	0.003
		R32	0.06007	0.006
		R33	0.41844	0.039
		R34	0.42039	0.039
		R35	0.06565	0.006
R4	0.092548	R41	0.02233	0.003
		R42	0.55219	0.075
		R43	0.30905	0.042
		R44	0.11643	0.016

4.2.3. Risk Evaluation of Project A Development Based on the Gray Cluster Modeling

A determination of stake holders, comprising primarily the project developer, designers, construction technicians, responsible quality personnel, responsible government personnel, user representatives, and the individual in charge of the community property, was conducted through field research for Project A, which involved a visit to the project manager. A total of 15 questionnaires were distributed and 10 valid questionnaires were obtained (the results are shown in Table S13) after collation to obtain the risk evaluation results. The evaluator assigned scores and evaluated the project in accordance with the risk evaluation rating criteria outlined in the questionnaire. The gray clustering evaluation coefficients (the results are shown in Table S14) were computed to obtain the affiliation of the BIPV residential development risk level 2 indicator belonging to each gray category. Subsequently, the evaluation coefficients of the indicator belonging to each gray category were calculated. Taking the secondary indicators as an example, their gray assessment weight matrix was calculated. The gray assessment weights of R11 were calculated as follows:

$$r_{11}^{1} = \frac{g_{11}^{1}}{G_{11}} = 0 \tag{1}$$

The same reasoning leads to r_{11}^2, r_{11}^3, r_{11}^4, r_{11}^5, so the gray evaluation weight matrix for R_1 was derived as follows to obtain the gray evaluation weight matrices for R_2, R_3, and R_4.

$$R_1 = \begin{bmatrix} 0 & 0.083 & 0.330 & 0.330 & 0.257 \\ 0.284 & 0.303 & 0.182 & 0.130 & 0.101 \\ 0 & 0.082 & 0.336 & 0.328 & 0.255 \\ 0 & 0.310 & 0.304 & 0.217 & 0.169 \\ 0 & 0.227 & 0.341 & 0.243 & 0.189 \\ 0.284 & 0.303 & 0.182 & 0.130 & 0.101 \\ 0 & 0.355 & 0.284 & 0.203 & 0.158 \end{bmatrix}$$

Take R_1 as an example to calculate the risk composite evaluation value B_1 for R_1:

$$B_1 = W_{11}' \cdot R_1 = [0.0026 \quad 0.1482 \quad 0.3260 \quad 0.2944 \quad 0.2291] \tag{2}$$

$$\begin{aligned} B_2 &= [0.0397 \quad 0.2252 \quad 0.3131 \quad 0.2373 \quad 0.1845] \\ B_3 &= [0.0411 \quad 0.3578 \quad 0.2645 \quad 0.1895 \quad 0.1470] \\ B_4 &= [0.0589 \quad 0.2584 \quad 0.2909 \quad 0.2204 \quad 0.1714] \end{aligned}$$

Assign values to the gray levels of the risk indicators to calculate the final risk value:

$$Z_1 = B_1 \cdot C^T = B_1 \cdot \begin{bmatrix} 0.1 \\ 0.3 \\ 0.5 \\ 0.7 \\ 0.9 \end{bmatrix} = 0.6200 \tag{3}$$

$$Z_2 = 0.5603, \ Z_3 = 0.5086, \ Z_4 = 0.5375$$

Project A Total Risk Assessment Value:

$$Z = W' \cdot R \cdot C^T = 0.5883 \tag{4}$$

According to the Risk Rating Comparison Table, the risk level of Project A falls within the upper medium range.

5. Results and Discussion

It is critical to understand the level of risk and choose reasonable risk prevention and avoidance measures when assessing risk in residential project development [44]. The project plan must be modified and the risk must be transferred or avoided if the assessed level of risk exceeds the expectations of the decision makers. Projects can continue according to their original plans and under their control if the assessed level of risk is manageable.

According to the findings of the gray cluster analysis described in Section 4.2.3, the comprehensive evaluation value for the risk associated with Project A is 0.5883. It corresponds to the actual situation and places the project at the medium-high risk level. As the local government actively promotes the initiation of new energy projects in accordance with national policy, despite the moderately high risk assessment value of this project, it has provided the developer with taxation and financing assistance that enables them to manage the corresponding risks. The first-level indicator exhibits a risk value of 0.6220 at the pre-decision stage, indicating a high level of risk; 0.5603 at the design stage, indicating a medium level of risk; 0.5086 during project implementation, indicating a medium level of risk; and 0.5375 during operation and maintenance, indicating a medium level. Therefore, the pre-decision phase should be prioritized throughout the development of BIPV residential projects.

5.1. Pre-Decision Phase

The previous evaluation shows that Project A carries a relatively high risk in the pre-decision stage. Due to the nascent stage of BIPV residential development in China, policies and laws governing such projects are notably inadequate, and successful cases are scarce, with Project A serving as the sole BIPV residential project in a specific city. Consequently, the level of risk associated with this stage is comparatively elevated. Indicators with higher weights at this stage are the risk of imperfect policies and regulations (0.387), the risk of project financing (0.285), and the risk of consumer acceptance (0.149). Standards, specifications, and guidelines encompassing a wide range of aspects, including BIPV-related products, technologies, and engineering design examples, must be implemented immediately in order to further standardize the key technologies required for the development of BIPV residential projects [64]. To ensure that long-term, sustainable operational benefits can be realized and that BIPV residential projects are developed in compliance with industry standards and codes, these standards and codes should cover a wide range of aspects, including building design, electrical engineering, energy management, safety assessment, etc. The state provides financial subsidies for the investment and development of BIPV residential projects in order to attract banks and other forms of social capital. Nevertheless, financial institutions, including banks, exhibit a greater tendency to grant credit to state-owned enterprises, local government financing platforms, and large-scale enterprises. Consequently, this bias renders the financing of small and medium-sized projects more costly [65]. Therefore, financial services should be promoted, and third-party rating agencies should be introduced to join the insurance business. BIPV residential projects are rated to ensure the transparency and openness of project information. By providing insurance business coverage for PV module quality, O&M losses, and other situations, the project aims to bolster investor confidence through risk transfer. It is also imperative to increase publicity efforts to raise consumer awareness regarding BIPV housing projects and expand market demand.

5.2. Design Phase

The risk in the project design phase is medium. Indicators that carry greater weights at this stage are the project master plan risk (0.585), load forecast risk (0.232), and program design risk (0.099). In order for BIPV to function as an organic integration of PV and building, the PV system should be integrated with the building's functionality, safety, and information [66]. While meeting the building's power generation capacity, consideration should be given to the functional and aesthetic qualities of building materials [67]. In order to transform the BIPV residential project into a contemporary building that is smart, safe, green, and efficient, the design should incorporate an integrated building management system comprising a photovoltaic monitoring system, an intelligent control system, and an integrated energy management system. This allows for the collection of PV system operation data and environmental data, such as voltage, current, power generation, temperature, humidity, solar irradiation intensity, wind speed, and wind direction. This provides the basis for predicting PV power generation, providing information on operation and maintenance. Further research is required with regard to critical equipment products, methods for designing and analyzing PV systems, strategies for grid regulation, and response mechanisms. Therefore, further research is needed on control strategies and response mechanisms to regulate BIPV dwellings as flexible loads in the grid and to adapt to the development of the supply side of the grid. It is necessary to propose an effective model to realize a friendly interaction between the building and the grid.

5.3. Preparation and Implementation Phase

A medium level of risk exists during the implementation phase of the project. Indicators with higher weights at this stage are the risk of imperfect quality acceptance criteria (0.420) and the risk of construction cost management (0.418). The incompleteness of the quality acceptance criteria for the BITV project, which is still in its infancy, could potentially compromise the integrity and safety of the project and lead to substandard construction. Therefore, the process should be examined intensively during the installation phase, and the existing design specifications should be strictly adhered to. Project cost control is complex and cumbersome, especially for the initial BITV project. To facilitate workers' autonomous assumption of responsibility for cost control, it is essential to develop reasonable incentives and penalties and to raise their awareness of the importance of cost control. The construction budget should be formulated prior to the commencement of the project, with a reasonable estimation of the expenses to be invested in management fees, labor costs, machinery costs, and material costs. This will clarify the target of cost control. In the process of project implementation, a comparative analysis is conducted between the actual cost and target cost of each element. This enables the realization of an organic combination of cost risk prediction beforehand, control during the process, and effective treatment afterwards.

5.4. Operation and Maintenance Phase

Medium risk exists during the operation and maintenance phase of the project. Indicators with higher weights at this stage are the risk of inadequately established technical standards for the maintenance of PV equipment (0.552), the risk of acceptance and commissioning of grid connections (0.309), and the risk of inoperability as a result of natural disasters (0.099). Insufficiently defined and inconsistent technical criteria may lead to improper equipment maintenance, such as cleaning, inspection, and repair. Safety issues may arise as a result, in addition to the performance and sustainability of PV equipment. Furthermore, obstructions caused by natural disasters such as wind, rain, snow, and so forth may lead to reduced power generation efficiency or the inability to generate electricity. Therefore, strengthen the maintenance and upkeep of the equipment, conduct routine inspections of its operating condition, and identify and address malfunctions promptly. Establishing a data sharing system in collaboration with the local meteorological department would serve to mitigate the adverse effects of natural disasters by enabling early detection and prevention. In order to minimize the loss caused by the instability risk associated with the integration of excess power into the power grid, it is crucial to ensure that the power generated by the BIPV residential project equipment is operational prior to its integration into the power grid.

6. Conclusions

In the current situation of energy crisis, the development of BIPV residential projects plays a crucial role in promoting energy transition in the building sector. This paper begins with an introduction to the current state of development of BIPV residential projects from a developer's perspective. Secondly, risk factors were identified and a risk evaluation model for BIPV residential projects was established by combining the full life cycle theory. It concludes with further analysis and recommendations regarding critical risk factors that affect project development. The findings of this paper are presented as follows:

(1) The article firstly organizes and researches the related literature and norms to obtain the preliminary risk factor list. Secondly, it divides the development of BIPV residential projects into four stages, including establishing the WBS-RBS matrix structure, inviting experts to judge the matrix, analyzing the judgment results by combining with mathematical statistics to extract 22 key factors, and finally forming a risk evaluation index system for BIPV residential project development.

(2) A risk evaluation model was developed utilizing DEMATEL-ANP-Gray cluster analysis. DEMATEL was first introduced to obtain the center degree and cause degree ranking of each risk indicator, which were used to determine the degree of influence of risk indicators and to elucidate the causal relationship between indicators. Eventually, the relationship was demonstrated in a causal relationship diagram. The ANP was then used to construct a network structure diagram. A two-by-two dominance degree comparison of network relationships was performed to determine risk indicator

weights. Finally, based on the determination of the main risk factors and their weights, the risk level of the development of the case BIPV residential project was assessed using a gray cluster analysis.

(3) Program A was selected for the empirical study. By applying the previously created indicator system and evaluation model to evaluate the risk level of Project A's development, it was found that the risk value of the project fell into the medium-high range. Risks were found to be relatively high in the pre-decision and preparatory design phases. The findings align with the actual operation of the project, thereby confirming the feasibility and efficacy of the model.

In conclusion, examples confirm that the DEMATEL-ANP-Gray cluster analysis method selected in this paper is scientific and reasonable. By converting subjective assessments into numerical values for data analysis, it improves the accuracy of estimating the risk level of BIPV residential project development. Additionally, it monitors the risk level of the secondary indicators therein, which provides a scientific foundation for risk management of such projects, as well as novel ideas and approaches to the risk evaluation of subsequent BIPV residential developments. Moreover, the research in this paper is a good guide for BIPV real estate projects other than residential ones.

Despite achieving the intended research objectives, this paper has certain shortcomings: First, only one case was selected in this study to validate the evaluation model, which means it may not be highly representative. Therefore, subsequent studies can be conducted to compare and contrast the cases in various regions. Second, as risks are all subject to uncertainty, risks present in a project are inherently dynamic and evolving. As the project progresses, the corresponding risk evaluation indicator system should be updated accordingly.

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