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Comprehensive Benefit Evaluation of SZ Distributed Photovoltaic Power Generation Project Based on AHP-Matter-Element Extension Model

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Abstract: With the introduction of the "dual carbon goals," there has been a robust development of distributed photovoltaic power generation projects in the promotion of their construction. As part of this initiative, a comprehensive and systematic analysis has been conducted to study the overall benefits of photovoltaic power generation projects. The evaluation process encompasses economic, technical, environmental, and social aspects, providing corresponding analysis methods and data references. Furthermore, targeted countermeasures and suggestions are proposed, signifying the research's importance for the construction and development of subsequent distributed photovoltaic power generation projects.

Keywords: Distributed photovoltaic power generation; Comprehensive benefits; Evaluation

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1. Introduction

The comprehensive evaluation of distributed photovoltaic power generation projects enables a systematic assessment of their economic, technical, environmental, and social benefits. By summarizing the experiences and practices derived from completed projects, potential issues and shortcomings in ongoing project constructions can be promptly identified. This article focuses on the SZ distributed photovoltaic power generation project, examining its economic, technical, environmental, and social benefits. A more scientifically structured comprehensive benefit evaluation index system is introduced, utilizing the AHP-matter-element extension model for in-depth analysis. This approach not only provides insights into the project's overall benefits but also serves as a reference for future photovoltaic power generation initiatives. The study concludes by offering targeted countermeasures and suggestions to enhance the comprehensive benefits of distributed photovoltaic power generation projects.

2. Overview of SZ distributed photovoltaic power generation project

The focus of this research is the SZ distributed photovoltaic power generation project. The project utilizes a building roof area of 410 m^2, and to ensure both roof safety and user capacity, the planned investment and construction scale for the photovoltaic power station is 47.4 kWp. This involves a 50 kW photovoltaic inverter, a grid-connected cabinet, and integration into the user-side power distribution system at a 400 V voltage level.

The estimated total power generation over 25 years is 1.6 million kWh, averaging an annual production of 64,000 kWh. The grid-connected approach emphasizes self-consumption, with the excess electricity (30%) being fed back into the grid. The project follows the EPC general contracting method, excluding photovoltaic components, inverters, photovoltaic grid cabinets, photovoltaic project cables, and photovoltaic brackets. The expected investment return rate stands at 7.69%.

3. Construction of a comprehensive benefit evaluation index system for SZ distributed photovoltaic power generation projects

3.1. Principles of index system construction

Constructing a comprehensive benefit evaluation index system for distributed photovoltaic power generation projects necessitates consideration of the project's economic, technical, environmental, and social benefits. Simultaneously, adherence to principles of scientificity, systematicness, operability, and the integration of quantitative and qualitative evaluation is essential. This ensures the accuracy and objectivity of the evaluation results [1].

3.2. Determination of evaluation indicators

The selection of evaluation objects should be based on the specific conditions of the distributed photovoltaic power generation project and the evaluation objectives. The evaluation object could be the entire project, a specific project component, or a particular indicator. In choosing the evaluation object, its representativeness and importance must be thoroughly considered to ensure the evaluation results reflect the overall comprehensive benefits of the project [2]. By collating and analyzing current research results, considering the actual situation of the SZ distributed photovoltaic power generation project, and consulting expert opinions, economic benefits and technical benefits are determined. Evaluation indicators are then selected from four aspects: economic benefits, technical benefits, environmental benefits, and social benefits, resulting in the construction of a comprehensive benefit evaluation index system for SZ distributed photovoltaic power generation projects, as depicted in **Table 1**.

3.2.1. Economic benefits

In distributed photovoltaic power generation projects, economic benefits take precedence. The project's successful operation must ensure that the generated income is sufficient to repay short-term and long-term debts [3]. Primary indicators are derived from two aspects: profitability and solvency. Profitability indicators encompass three secondary indicators: investment payback period, net capital profit rate, and total investment return rate. Solvency indicators include two secondary indicators: the asset-liability ratio and the liquidity ratio.

3.2.2. Technical benefits

The quality of the selected project site significantly influences the size and efficiency of the solar energy resources that the project can effectively harness. Simultaneously, the hardware's performance and stability directly impact the project's final operational effectiveness [4]. First-level indicators are predominantly determined by project site selection and system performance. Site selection indicators encompass two secondary indicators: site selection conditions as well as solar radiation and climate conditions. System performance indicators include two secondary indicators: photovoltaic array design as well as photovoltaic system efficiency and reliability [5].

Table 1. Comprehensive benefit evaluation index system for SZ distributed photovoltaic power generation projects

Target	Criterion layer	First level indicator	Secondary indicators
SZ distributed photovoltaic power generation project comprehensive benefit Z	Economic benefit A_1	Profitability B_1	Payback period C_1
			Net profit margin on capital C_2
			Total investment return C_3
		Solvency B_2	Asset-liability ratio C_4
			Current ratio C_5
	Technical benefit A_2	Project site selection B_3	Site selection condition C_6
			Solar radiation and climate conditions C_7
		System performance B_4	Photovoltaic array design C_8
			Photovoltaic system efficiency and reliability C_9
	Environmental benefits A_3	Energy saving and emission reduction B_5	Average annual coal emission reduction C_{10}
			Average annual carbon dioxide emission reduction C_{11}
			Average annual sulfur dioxide emission reduction C_{12}
			Average annual carbon and nitrogen emission reduction C_{13}
		Impact on regional environment B_6	Land occupation reduction C_{14}
			Ecological environment improvement C_{15}
	Social benefit A_4	Socioeconomic B_7	Economic development promotion C_{16}
			Increased jobs C_{17}
		Social environment B_8	Energy structure improvement C_{18}
			Public awareness C_{19}

3.2.3. Environmental benefits

Photovoltaic power generation, as a clean energy source, contributes substantially to environmental benefits. Distributed photovoltaic power generation projects play a crucial role in reshaping the current energy structure, reducing reliance on traditional energy sources, and curbing toxic and harmful gas emissions. First-level indicators are primarily determined by energy conservation, emission reduction, and their impact on the regional environment. Energy conservation and emission reduction indicators include average annual coal emission reduction, annual carbon dioxide emission reduction, annual sulfur emission reduction, and annual average carbon and nitrogen reduction, totaling four secondary indicators. The impact on the regional environment includes two secondary indicators: reducing land occupation and improving the ecological environment.

3.2.4. Social benefits

Lastly, social benefits encompass a broad spectrum. Distributed photovoltaic power generation projects not only create employment opportunities, alleviating employment pressure to some extent, but also stimulate the development of related local industries. First-level indicators are mainly determined by two aspects: socioeconomic and the social environment. Socioeconomic indicators include two facets: promoting economic development and increasing job opportunities. Social environment indicators encompass two aspects: improving the energy structure and enhancing social public awareness.

4. Comprehensive benefit evaluation of SZ distributed photovoltaic power generation project

According to the constructed comprehensive benefit evaluation index system, the analytic hierarchy process (AHP) is utilized to calculate the weight of the indicators. Additionally, a matter-element extension model of the comprehensive benefit of the SZ distributed photovoltaic power generation project is developed to evaluate the overall project benefits.

4.1. Determination of indicator weight based on the AHP method

4.1.1. Construct a judgment matrix

Referring to the indicator system outlined in **Table 1**, indicators at the same level are systematically compared in pairs. Expert scoring, combined with the scale values from **Table 2**, determines the degree and importance of their impact on the upper-layer indicators. This information is expressed in matrix form to generate a judgment matrix.

Table 2. The scale and meaning of each element in the judgment matrix

Scale value	Judgment of pairwise comparison results
1	The i element and the j element are equally important.
3	The i element is slightly more important than the j element.
5	The i element is significantly more important than the j element.
7	The i element is strongly more important than the j element.
9	The i element is more important than the j element.
2, 4, 6, 8	Indicates the intermediate degree of the above adjacent judgments
The reciprocal of the above scale value	The importance coefficient of element j relative to element i

4.1.2. Calculation of index weight and consistency test

The evaluation index system and the constructed judgment matrix undergo a consistency test using MATLAB software. Once the test is successfully passed, the results for the index weights are calculated, as presented in **Table 3**.

Table 3. Weight table of comprehensive benefit evaluation index system for SZ distributed photovoltaic power generation projects

Target	Criterion layer	Weight	First level indicator	Weight	Secondary indicators	Weight
SZ distributed photovoltaic power generation project comprehensive benefit Z	Economic benefit A_1	0.5638	Profitability B_1	0.7500	Payback period C_1	0.0516
					Net profit margin on capital C_2	0.1351
					Total investment return C_3	0.2361
			Solvency B_2	0.2500	Asset-liability ratio C_4	0.1175
					Current ratio C_5	0.0235
	Technical benefit A_2	0.2634	Project site selection B_3	0.2000	Site selection condition C_6	0.0395
					Solar radiation and climate conditions C_7	0.0132
			System performance B_4	0.8000	Photovoltaic array design C_8	0.0702
					Photovoltaic system efficiency and reliability C_9	0.1405
	Environmental benefits A_3	0.1178	Energy saving and emission reduction B_5	0.8000	Average annual coal emission reduction C_{10}	0.0371
					Average annual carbon dioxide emission reduction C_{11}	0.0220
					Average annual sulfur dioxide emission reduction C_{12}	0.0220
					Average annual carbon and nitrogen emission reduction C_{13}	0.0131
			Impact on regional environment B_6	0.2000	Land occupation reduction C_{14}	0.0059
					Ecological environment improvement C_{15}	0.0177
	Social benefit A_4	0.0550	Socioeconomic B_7	0.7500	Economic development promotion C_{16}	0.0330
					Increased jobs C_{17}	0.0083
			Social environment B_8	0.2500	Energy structure improvement C_{18}	0.0115
					Public awareness C_{19}	0.023

4.2. Comprehensive benefit evaluation of SZ distributed photovoltaic power generation project based on matter-element extension model

The matter-element analysis method, initially proposed by Professor Cai Wen, provides a solution to the incompatibility problem from both qualitative and quantitative perspectives. Comprehensive benefits analysis of distributed photovoltaic power generation projects encompasses multiple dimensions including economy, technology, environment, and society. The influence of evaluation indicators on the results varies. The matter-element extension model adeptly combines qualitative and quantitative indicators, accurately describing the comprehensive benefits and the mutual influence and interaction among various evaluation indicators in the evaluation index system [6]. The model-building steps are as follows:

4.2.1. Determine the classical domain, nodal domain, and matter elements to be evaluated

$$R_j = (N_j, C_i, V_{ji}) = \begin{bmatrix} N_j & C_1 & V_{j1} \\ & C_2 & V_{j2} \\ & \vdots & \vdots \\ & C_n & V_{jn} \end{bmatrix} = \begin{bmatrix} N_j & C_1 & [a_{j1}, b_{j1}] \\ & C_2 & [a_{j2}, b_{j2}] \\ & \vdots & \vdots \\ & C_n & [a_{jn}, b_{jn}] \end{bmatrix} \quad (1)$$

In **Formula (1)**, N_j represents the j-th evaluation level of the rating object, C_i represents the i-th evaluation index of N_j, V_{ji} represents the value range of N_j with respect to C_i, and $[a_{ji,} \ b_{ji}]$ is the classic domain.

$$R_p = (N_p, C_i, V_{pi}) = \begin{bmatrix} N_p & C_1 & V_{p1} \\ & C_2 & V_{p2} \\ & \vdots & \vdots \\ & C_n & V_{pn} \end{bmatrix} = \begin{bmatrix} N_p & C_1 & [a_{p1}, b_{p1}] \\ & C_2 & [a_{p2}, b_{p2}] \\ & \vdots & \vdots \\ & C_n & [a_{pn}, b_{pn}] \end{bmatrix} \quad (2)$$

In **Formula (2)**, N_p represents all levels of the index to be evaluated, V_{pi} represents the set of value ranges of N_p with respect to all levels of ,C_i and $[a_{pi,} \ b_{pi}]$ is the node domain.

$$R_0 = (N_0, C_i, V_i) = \begin{bmatrix} N_0 & C_1 & V_1 \\ & C_2 & V_2 \\ & \vdots & \vdots \\ & C_n & V_n \end{bmatrix} \quad (3)$$

In **Formula (3)**, R_0 represents the matter element to be evaluated, N_0 represents the evaluation index, and V_i represents the measured data of the characteristic value of N_0 with respect to C_i.

Evaluation indicators are classified into five levels: “poor, relatively poor, average, good, and excellent.” Quantitative indicators’ classical and sectional domains are determined by referring to relevant industry standards, existing research results, and consulting expert opinions. Qualitative indicators are categorized into five levels based on project characteristics and converted into numerical values, with the value range being [0, 100]. The classical and nodal domains are then determined based on the project conditions.

Table 4. Evaluation indicators classic domain and section domain

Index	Poor	Relatively poor	Average	Good	Excellent	Joint domain
C_1	[16, 25]	[13, 16]	[10, 13]	[7, 10]	[0, 7]	[0, 25]
C_2	[0, 1]	[1, 6]	[6, 12]	[12, 18]	[18, 27]	[0, 27]
C_3	[0, 2]	[2, 3.9]	[3.9, 4.6]	[4.6, 5.7]	[5.7, 8]	[0, 8]
C_4	[73.1, 77.7]	[66.1, 73.1]	[61, 66.1]	[55.1, 61]	[0, 55.1]	[0, 77.7]
C_5	[0, 0.5]	[0.5, 1]	[1, 1.5]	[1.5, 2]	[2, 3]	[0, 3]
C_6	[0, 20]	[20, 40]	[40, 60]	[60, 80]	[80, 100]	[0, 100]
C_7	[0, 20]	[20, 40]	[40, 60]	[60, 80]	[80, 100]	[0, 100]
C_8	[0, 20]	[20, 40]	[40, 60]	[60, 80]	[80, 100]	[0, 100]
C_9	[0, 20]	[20, 40]	[40, 60]	[60, 80]	[80, 100]	[0, 100]
C_{10}	[0, 5]	[5, 10]	[10, 15]	[15, 20]	[20, 25]	[0, 25]
C_{11}	[0, 15]	[15, 30]	[30, 45]	[45, 60]	[60, 75]	[0, 75]
C_{12}	[0, 0.05]	[0.05, 0.1]	[0.1, 0.15]	[0.15, 0.2]	[0.2, 0.25]	[0, 0.25]
C_{13}	[0, 0.04]	[0.04, 0.08]	[0.08, 0.12]	[0.12, 0.16]	[0.16, 0.2]	[0, 0.2]
C_{14}	[0, 20]	[20, 40]	[40, 60]	[60, 80]	[80, 100]	[0, 100]
C_{15}	[0, 20]	[20, 40]	[40, 60]	[60, 80]	[80, 100]	[0, 100]
C_{16}	[0, 20]	[20, 40]	[40, 60]	[60, 80]	[80, 100]	[0, 100]
C_{17}	[0, 4]	[4, 7]	[7, 10]	[10, 13]	[13, 15]	[0, 15]
C_{18}	[0, 20]	[20, 40]	[40, 60]	[60, 80]	[80, 100]	[0, 100]
C_{19}	[0, 20]	[20, 40]	[40, 60]	[60, 80]	[80, 100]	[0, 100]

4.2.2. Calculate correlation degree

$$K_j(V_i) = \begin{cases} -\dfrac{\rho(v_i, v_{ji})}{|v_{ji}|} & v_i \in v_{ji} \\ \dfrac{\rho(v_i, v_{ji})}{\rho(v_i, v_{pi}) - \rho(v_i, v_{ji})} & v_i \notin v_{ji}; \rho(v_i, v_{ji}) \neq 0 \\ -\rho(v_i, v_{ji}) - 1 & v_i \notin v_{ji}; \rho(v_i, v_{ji}) = 0 \end{cases} \quad (4)$$

$$\rho(v_i, v_{ji}) = \left|v_i - \frac{1}{2}(a_{ji} + b_{ji})\right| - \frac{1}{2}(b_{ji} - a_{ji}) \quad (i = 1,2,\cdots,n, j = 1,2,\cdots,k) \quad (5)$$

$$\rho(v_i, v_{pi}) = \left|v_i - \frac{1}{2}(a_{pi} + b_{pi})\right| - \frac{1}{2}(b_{pi} - a_{pi}) \quad (i = 1,2,\cdots,n) \quad (6)$$

Equation (4) represents the correlation between the i-th indicator and the j-th level, **Equation (5)** represents the distance between V_i and the classical domain, and **Equation (6)** represents the distance between V_i and the nodal domain. The larger the value of $K_j(V_i)$, the greater the degree of membership of the indicator relative to this level. If $K_j(V_i) = maxK_j(V_i)$, V_i's evaluation object belongs to level j.

Quantitative indicators were analyzed and calculated based on the actual data of the project, and qualitative indicators were scored by experts based on the project's actual situation. The eigenvalue matrix of each indicator of the SZ distributed photovoltaic power generation project was obtained as p = (10.97, 25.99, 7.69, 66.7, 1.7, 77, 62, 85, 90, 20.90, 54.80, 0.18, 0.15, 69, 71, 73, 8, 57, 66)^T. Through correlation calculation, the evaluation level of each indicator is p = (average, excellent, excellent, poor, good, good, good, excellent, excellent, excellent, good, good, good, good, good, good, average, average, good)^T.

4.2.3. Calculate the comprehensive correlation and determine the evaluation level

$$K_j(N_0) = \sum_{i=1}^{n} \omega_i K_j(V_i) \quad (i = 1,2,\cdots,n) \tag{7}$$

In **Formula (7)**, ω_i represents the weight of each evaluation index, and $K_j(N_0)$ is the comprehensive correlation degree. If the comprehensive correlation is less than -1, it means that the evaluation index does not belong to this level; if the comprehensive correlation is greater than -1 and less than 0, it means that although the evaluation index does not belong to this level, it tends to reach this level. The closer the value is to 0, the stronger the trend toward this level; if the comprehensive correlation is greater than 0, the evaluation index belongs to this level. The evaluation grade correlation of each indicator and comprehensive benefit at the criterion level based on the indicator weight calculation are shown in **Table 5**.

Table 5. Evaluation grade correlation of each indicator and comprehensive benefit at the criterion level

Evaluation index	Poor	Relatively poor	Average	Good	Excellent	Evaluation results
Economic benefits	-0.2900	-0.2573	-0.2503	-0.2588	0.0062	Excellent
Technical benefits	-0.1510	-0.1416	-0.1229	-0.0688	0.0685	Excellent
Environmental benefits	-0.0569	-0.0492	-0.0337	0.0125	-0.0051	Good
Social benefit	-0.0203	-0.0155	-0.0057	0.0072	-0.0089	Good
Overall benefit	-0.2111	-0.1890	-0.1778	-0.1622	0.0204	Excellent

4.3. Result analysis

Through the above analysis, it is evident that indicators such as the project's investment payback period, job creation, and improvement of the energy structure are rated as "average," while the asset-liability ratio indicator is rated as "relatively poor." This suggests that the project is contributing to the transformation of the energy structure and job creation, but the impact is somewhat modest. The investment recovery time could be improved, and there are certain operational risks.

Simultaneously, the comprehensive benefit evaluation grade is "excellent," indicating that the project demonstrates strong overall benefits. Specifically, the economic and technical benefit evaluation grades are "excellent," highlighting the project's robust economic benefits and advanced, reliable technology. On the other hand, the environmental and social benefit evaluation grades are "good," signaling effective energy conservation, emission reduction, and developmental promotion. However, it is acknowledged that further efforts are still required in these areas.

5. Countermeasures and suggestions for improving efficiency

5.1. Promote technological innovation and reduce project costs

To ensure that projects yield optimal comprehensive benefits, it is crucial to promote innovation in photovoltaic technology and exercise stringent cost control. This involves enhancing technological innovation in photovoltaic power generation, developing photovoltaic modules with higher conversion efficiency, improving the overall efficiency of photovoltaic systems, and gradually achieving the integration of photovoltaic power generation projects with buildings. Such measures will help reduce installation costs and enhance comprehensive benefits by optimizing the layout of photovoltaic components and making informed choices in inverter selection [7].

5.2. Strengthen policy support and expand market presence

In-depth investigations into the operational status of existing distributed photovoltaic power generation projects are essential. A comprehensive understanding of the benefits and challenges arising from the current promotion of these projects should inform an analysis of existing policies. The introduction of Chinese "dual carbon goal" policies can further bolster the healthy development of distributed photovoltaic power generation projects. Additionally, reinforcing market research on these projects will enable a nuanced grasp of policy orientation, market demand, and competition dynamics. Armed with this insight, targeted market expansion strategies can be formulated, and directional adjustments made [8].

5.3. Strengthen the implementation of responsibilities and promote win-win development

Promoting photovoltaic power generation enterprises to align with national policies and guidelines while actively embracing social responsibilities is essential. This involves heightened exploration and research effects, increased investment in research and development, and the ongoing enhancement of China's photovoltaic industry competitiveness [9]. Encouraging the widespread application of clean energy contributes to better environmental and social benefits, fostering the stable development of distributed photovoltaic power generation projects. This, in turn, provides robust support for China's aspirations to build a clean, low-carbon, safe, and efficient energy system, expediting the nation's energy transformation.

6. Conclusion

This article has established a comprehensive benefit evaluation index system focusing on economic, technical, environmental, and social aspects of distributed photovoltaic power generation projects. Through the evaluation and analysis of the SZ distributed photovoltaic power generation project, it is evident that such projects contribute significantly to economic, environmental, and social benefits, aligning with China's green and low-carbon development strategies.

To further advance the field, there is a need to reinforce the comprehensive benefit evaluation indicators, methods, and levels within distributed photovoltaic power generation projects. Research efforts should concentrate on identifying challenges in the current promotion process, offering valuable insights, and presenting targeted countermeasures and suggestions for the promotion and development of distributed photovoltaic power generation projects. This approach is crucial for fostering sustainable progress and supporting China's endeavors in implementing green and low-carbon development strategies.

Disclosure statement

The author declares no conflict of interest.

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