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A Decision-making Framework for the Site Selection of PV Deployment along High-speed Railway

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ABSTRACT

The development of photovoltaic industry can effectively alleviate the energy crisis and environmental pollution. The deployment of photovoltaic power stations along the high-speed railway is a new mode combining photovoltaic new energy with infrastructure. This paper constructs a comprehensive decision-making framework for the site selection of PV power station along high-speed railway combining the subjective method and the objective method. A scientific and reasonable evaluation index system comprehensively considering multiple factors is constructed in this framework. Analytic hierarchy process and Entropy weight method are combined to determine the weight of every index, which combines the expert knowledge and data information effectively, relatively reducing systematic error and random error. Grey relational analysis is used to choose scheme among several alternatives, which greatly deal with the strong grey correlations among indexes. The framework established in this paper is used to select PV power stations along the Beijing-Shanghai high-speed railway, which also verifies the effectiveness of the framework.

Keywords: Decision-making framework, site selection, PV integration, High-speed railway.

1. INTRODUCTION

To facilitate the realization of climate targets and reach a CO_2 emissions peak before 2030,energy transition is vitally needed. Solar energy, as one of the most potential form of renewable energy, plays a key role on the transition process of energy system[1], making the photovoltaic deployment an important path to achieve this transition.

There is one integration named distributed photovoltaic focuses on self-supply units like individual buildings. Researches shows a promising approach that integrating PV system and infrastructure facilities PV development and further a sustainable transition of traditional industry through clean energy generation[2]. Transportation facilities are important infrastructures since the global transportation industry has vigorously developed over the few decades[3; 4], not only China’s aviation industry experienced rapid development and has increasing prosperous[5], the integration of PV system and high-speed railway also has a promising future and worth being studied. Currently, most of the research on the integration of PV and HSR base on the roofs of the trains or stations and ignore system economics[6;7], which limits the power generation potential due to the highly vulnerability of PV panels on train roofs when the train speed increases.

For the purpose of fully usage of the potential of PV integration effect of HSR systems and inspired by previous experience， we proposed a PV+HSR mode, focusing on the open areas along rail lines donated as the railway PV system. By doing this, it can achieve self-sufficiency and even supply surplus power to surrounding areas ideally. Therefore,reasonable site selection will become extremely important.

In order to solve this question, we construct a effective decision-making framework.The process of modeling includes constructing a scientific and reasonable evaluation index system, finding a comprehensive method to determine weight of each index and collecting index data of all alternatives to choose the better schemes.After that,Beijing-shanghai High-speed Railway (BS-HSR) is selected to apply the decision-making framework constructed by this paper.

2. EVALUATION INDEX SYSTEM

The site selection of PV deployment is a complex process, and there are many factors that affect it. Therefore, constructing a scientific and reasonable evaluation index system is a key point for the site selection of PV deployment along high-speed railway. By studying the situation along the high-speed railway with GIS technology, consulting relevant documents and reports, and analyzing various factors, this paper determines the final evaluation index system as shown in Table 1. It includes three levels.These evaluation indexes are all quantitative indexes whose specific data can be obtained.

Table 1. Evaluation index system

	The first indicators(B)	The second indicators(C)
Site selection of PV power station along high-speed railway(A)	Construction conditions(B_1)	Slope(C_1)
		Land use coefficient(C_2)
	Technical performance(B_2)	Hours of sunshine(C_3)
		PV capabilities(C_4)
	Economic performance(B_3)	Employee wages(C_5)
		Land lease costs(C_6)
		Electricity price(C_7)
		Policy subsidies(C_8)
	Social benefits(B_4)	Impact on the local economy(C_9)
		Job creation(C_{10})

2.1 Construction conditions(B_1)

In the process of PV deployment site selection, construction conditions first determine whether the project can be carried out. Slope(C_1) affects the site utilization rate. The smaller the slope, the higher the site utilization rate. If the slope is greater than a certain limit, the construction difficulty and project cost will be significantly increased. Land use coefficient(C_2) depends on land type. The land along the high-speed railway can be divided into five types, including forest, grassland or shrub, cultivated land, urban area, wasteland, etc. Each type of land has corresponding land use coefficient[8].

2.2 Technical performance*(B_2)*

Hours of sunshine(C_3) is a necessary parameter to measure solar energy resources, which will directly affect the power generation efficiency of photovoltaic power plants. The data can be obtained by geographic information technology. In addition, the PV deployment occupies a large area, so it is necessary to ensure that the site can accommodate a certain amount of PV capabilities(C_4) in the process of site selection to meet the power generation demand.

2.3 Economic performance*(B_3)*

Economic performance is the key factor affecting investment. Employee wages(C_5) and Land lease costs(C_6) are the two basic expenditures in the construction and use of PV deployment, and the data vary greatly in different regions. Because of their regional heterogeneity, employees' wages and land lease costs should be regarded as important indexes of economic sustainability. PV power plants use solar energy resources to generate electricity and sell it to gain revenue, for this reason electricity price(C_7) affects the revenue level of PV projects. The PV project needs to invest a large amount of capital in the early stage and has a long payback period, so it needs Policy subsidies(C_8) to provide financial support. Different provinces have different photovoltaic subsidy policies, which should be regarded as one of the indicators of economic sustainability.

2.4 Social benefits(B_4)

The construction of PV power station will create employment opportunities for local residents, and the income from the operation of photovoltaic power station will be included in the scope of local economic assessment. Impact on the local economy(C_9) measures the contribution of PV power generation revenue to local GDP. For the Job creation(C_{10}) factor, construction and installation jobs, operation and maintenance jobs and decommission jobs created by PV projects are considered.[9]

3. DETERMINATION OF THE INDEX WEIGHT

In this paper,subjective weight method and objective weight method are combined to determine the final weight of indexes. This can well integrate the advantages of the two methods. Analytic hierarchy process(AHP) is chosen to determine the subjective weights, and Entropy weight method is chosen to determine the objective weights.

3.1 Use AHP to determine the subjective weights

AHP decomposes the problem into different components, and combines them according to the correlation between the factors and the subordinate relationship, forming a multi-level analytical structure model. The steps are as follows:

(1) Construct the evaluation hierarchical framework model.

(2) Construct the pairwise judgment matrix.

(3) Nine scale method is universally used to get it by scoring 1-9 points based on the experts opinions.

(4) Use the normalization method to calculate the index weights of every judgment matrix

Normalize column vectors and sum up row elements through Eq.(1) and Eq.(2), and then obtain the weights through Eq.(3).

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad ,(i = 1,2,3\ldots n; j = 1,2,3\ldots m) \tag{1}$$

$$W_i = \sum_{j=1}^{m} a'_{ij} \tag{2}$$

$$W'_i = \frac{W_i}{\sum_{i=1}^{n} W_i} \tag{3}$$

Where j represents the number of indexes, i represents the number of values based on experts for every index; a_{ij} represents the element of the judgment matrix; $\mathrm{a}'_{\mathrm{ij}}$ represents the element of the judgment matrix after normalizing; W'_i represents the weight of index.

(5) Check the consistency

Only when the consistency test is carried out and passed, can the model be verified to be correct. It includes calculating the maximum eigenvalue λ_{max} of the judgment matrix and the consistency index CI and consistency ratio. If CR<=0.1, the consistency is acceptable. In the contrary, if CR>0.1,then a reexamination of the pairwise judgments is recommended until CR<=0.1.

$$\mathrm{CI} = \frac{\lambda_{max} - n}{\mathrm{n}-1} \tag{4}$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{5}$$

(6) Assign index weights

According the the evaluation hierarchical framework model,if W_x and W_y represent the weight of the first-level indicators and the second-level indicators respectively through the above calculation process,Eq.(6) is used to calculate of the final comprehensive weight of each index belonging to the second level.

$$W_{xy} = W_x * W_y \tag{6}$$

3.2 Use Entropy weight method to determine the objective weights

The basic idea of entropy weight method is to determine the objective weight according to the variability of index, which avoids the influence of subjective factors.The steps are as follows:

(1) Establish the original matrix R

$$\mathrm{R} = (\mathrm{r_{ij}})_{\mathrm{m*n}} = \begin{bmatrix} \mathrm{r_{11}} & \cdots & \mathrm{r_{1n}} \\ \vdots & \ddots & \vdots \\ \mathrm{r_{m1}} & \cdots & \mathrm{r_{mn}} \end{bmatrix} \tag{7}$$

(2) Normalize index

The indexes are divided into cost-based indexes and benefit-based indexes. Different types of indexes have different normalization methods.

For cost-based indexes:

$$r'_{ij} = \frac{r_j^{max} - r_{ij}}{r_j^{max} - r_j^{min}} \tag{8}$$

For benefit-based indexes:

$$r'_{ij} = \frac{r_{ij} - r_j^{min}}{r_j^{max} - r_j^{min}} \tag{9}$$

Where, r_j^{max} represents the maximum value of index j ; r_j^{min} represents the minimum value of index j .

(3) Calculate the ratio of each index in each scheme.

$$e_j = -\frac{1}{ln\ m} \sum_{i=1}^{m} r'_{ij} * ln\ r'_{ij} \tag{10}$$

(4) Calculate the entropy value of each index.

$$W_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)} \tag{11}$$

3.3 Combination weighting

Suppose $\mathrm{W_{aj}}$ represents the subjective weight , $\mathrm{W_{ej}}$ represents the objective weight and $\mathrm{W_j}$ represents the combination weight , their relation is as follows:

$$W_j = \alpha \mathrm{W_{aj}} + \mu \mathrm{W_{ej}} \tag{12}$$

Where α and μ are two parameters, $\alpha+\mu=1$.In this paper, $\alpha = \mu=0.5$.

4. CHOOSE THE BSET SCHEME AMONG SEVERAL ALTERNATIVES

Grey relational analysis refers to the method of quantitative description and comparison of the development and change of a system. It can be applied to deal with the grey correlations among index for the site selection of PV deployment along high-speed railway and determine optimal scheme. The steps of using grey relational analysis (GRA) to choose scheme are as follows:

(1) Construct the analysis matrix $R=(r_{ij})_{m*n}$.

(2) Normalize index through Eq.(8) and Eq.(9).

(3) Determine the reference series $G=\{1,1,1...1\}$.

(4) Calculate grey correlation coefficient.

$$\beta_{ij}=\frac{\Delta_{min}+\alpha\Delta_{max}}{\Delta_{ij}+\alpha\Delta_{max}} \quad (13)$$

Where Δ_{ij} is equal to $|x_j - r'_{ij}|$; x_j is the corresponding value of each index in the reference series G, x_j is equal to 1 in this paper; Δ_{max} is the maximum value of Δ_{ij}; Δ_{min} is the minimum value of Δ_{ij}.

(5) Sort according to the grey correlation degree.

According to the results of weight in part 4, the grey correlation degree is computed by Eq.(14).

$$D_j=\sum_{j=1}^{m}\beta_{ij}*W_j \quad (14)$$

(6) Calculate grey correlation degree.

5. CASE STUDY

Beijing-shanghai High-speed Railway (BS-HSR) is selected to apply the decision-making framework constructed by this paper. BS-HSR connect Beijing and Shanghai, which was officially opened to traffic on June 30th, 2011. It has 24 stations, passing through North China and East China. It is one of the largest investment projects since the founding of New China, and also a passenger dedicated line with busy passenger and freight transportation.

5.1 Acquire data of each index

The area along the BS-HSR is divided into 5236 cells through the use of geographic information technology. Except for places that are not suitable for PV deployment, there are still 4,676 cells left. Based on remote sensing data, the Slope(C_1) , land type and the amount of available area of each cell is evaluated by the ArcGIS software. According to the land type, the corresponding Land use coefficient(C_2) can be allocated. Hours of sunshine(C_3) can be acquired by using the global radiation data provided by the global solar atlas. Considering the size of photovoltaic module and the performance of photovoltaic power generation system, the PV capabilities(C_4) can be calculated by the following formula:

$$\text{PV capacity}=\frac{\text{area}_{\text{available}}}{\text{area}_{\text{PV}}}*P_{max}*\varphi \quad (15)$$

Where $\text{area}_{\text{available}}$ is the amount of available area of each cell, $\text{area}_{\text{available}}$ is the size of photovoltaic module, P_{max} is the maximum capacity of each solar panel, and φ is the overall performance coefficient of photovoltaic power generation system, which is usually between 0.75 and 0.85. This paper uses 0.78 for calculation.

Employee wages(C_5) of each cell can be found in the China Statistical Yearbook. The data of Electricity price(C_7) and Policy subsidies(C_8) is obtained from provincial policy documents.

5.2 Weight determination

Firstly, seven experts from universities participated in the index weight scoring of AHP and constructed a judgment matrix. Through calculating each judgment matrix and carrying out the consistency test, the specific subjective weight of each index is obtained and shown in table 2.

Table 2. The weight of each index obtained by AHP

The first indicators(B)	The weight	The second indicators(C)	The weight	The comprehensive weight
B_1	0.161	C_1	0.167	0.027
		C_2	0.833	0.134
B_2	0.261	C_3	0.167	0.044
		C_4	0.833	0.217
B_3	0.509	C_5	0.075	0.038
		C_6	0.319	0.162
		C_7	0.453	0.231
		C_8	0.153	0.078
B_4	0.069	C_9	0.800	0.055
		C_{10}	0.200	0.014

Secondly, use the entropy weight method to calculate the objective weight of each index. After the operation of each step, the results are obtained and shown in table 3.

Finally, use Eq.(12) to combine the subjective weight results and the objective weight results. The combination weights are shown in table 4.

Table 3. The weight of each index obtained by the entropy weight method

Index	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
Weight	0.007	0.322	0.048	0.238	0.028	0.006	0.026	0.078	0.139	0.109

Table 4. Combination weights of each index

Index	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
Weight	0.017	0.228	0.046	0.227	0.033	0.084	0.128	0.078	0.097	0.062

5.3 Select the best scheme

The 4676 cells mentioned in Section 5.1 will be used as alternatives in this case study. Use grey relational analysis(GRA) to choose the best scheme among these alternatives. The grey correlation degree of every alternative is computed and shown in figure 1.

Under the decision-making framework designed in this paper, the scores calculated by GRA among these alternatives along the BS-HSR are displayed, and the results are closely related to factors such as the slope, sunshine hours, PV capacity, employees' wages and social benefits of each cell.

Through the contrast of colors, we can clearly find a more suitable area for PV deployment. The green areas in the figure are distributed in some areas in the south of Jiangsu Province, which shows that some outlets in this area are the best scheme for the site selection of PV deployment; The red areas are distributed in Beijing, Tianjin, Hebei, Anhui and other areas where the BS-HSR passes.The calculation results show that these areas are not suitable for PV deployment.

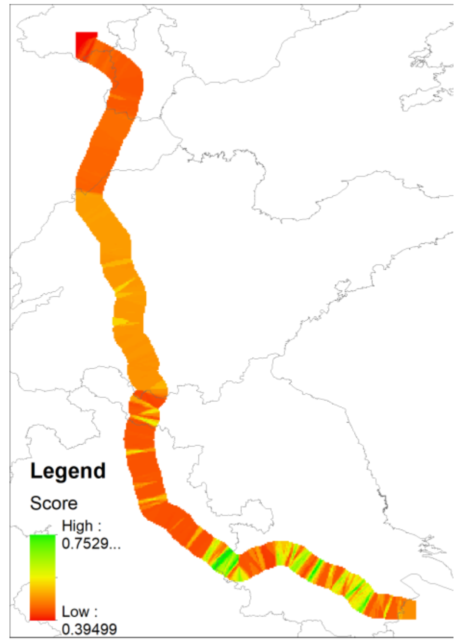
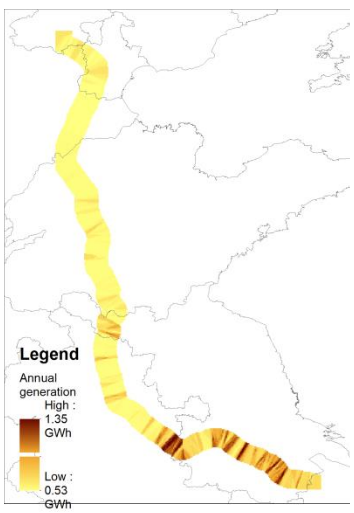
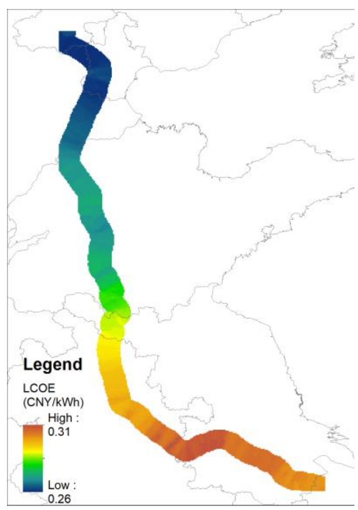


Figure 1. GPA scoring results of every alternative





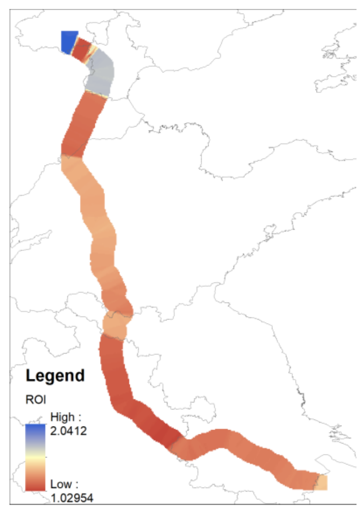


Figure 2. annual power generation results **Figure 3.** LCOE results **Figure 4.** ROI results

In order to make a more accurate analysis of the results, this paper calculates the technical and economic indicators of each alternative scheme, such as annual power generation, levelized cost of energy (LCOE) and return on investment (ROI), and compares the score results with their technical and economic performance.

Firstly, we compare the score results with the annual power generation results. It can be seen from Figure 2 that the best schemes with high annual power generation potential are distributed in the south of Jiangsu Province, that is, the downstream stage of BS-HSR, which is similar to the results in Figure 1. In Figure 2, the scoring results of alternatives based on annual power generation from Beijing to Anhui is generally low, which is different from the results in Figure 1. This is because the power generation index is related to PV capacity and sunshine hours, but has nothing to do with cost. However, the scores calculated under the decision-making framework in this paper are related to power generation, cost, subsidies, social benefits and other factors.

Secondly, comparing the score results with the LCOE results, it can be seen from Figure 3 that from Beijing to

Jiangsu, the LCOE of each cell along the BS-HSR gradually decreases, which is closely related to the local land rent and employee wages. However, because cost is only one of the factors considered in the decision-making framework of this paper, the results of the two figures are quite different.

Thirdly, comparing the score results with ROI results, it can be found that the ROI results are more similar to the scoring results compared with the annual power generation results and LCOE results. This is because many aspects such as power generation, cost and benefit are considered in the calculation of ROI, and these factors are covered in the evaluation index system according to part 3 in this paper. The difference between the two is that the decision-making model considers social benefits such as impact on local economy and job creation and their weights accounts for 0.069, which are not included in ROI results.

6. DISCUSSION AND CONCLUSION

In summary,the main purpose of this paper is to construct a decision making framework as an effective tool for site selection of PV deployment along high-speed railway. On this basis,a scientific and reasonable evaluation index system considering construction conditions, technical performance, economic performance and social benefit is established. The supplement of social benefit can be regarded as a innovation in our modeling process. Then subjective weight method and objective weight method are combined to determine the final weight of indexes which can well integrate the advantages of the two methods. For the reason to synthesizes the interrelationship between the ideal optimal scheme, grey relational analysis is used,which comprehensively and accurately reflects the differences among all alternatives.

To sum up, it can be seen that the decision-making framework of this paper is complicated,taking many factors into account , which is more comprehensive than simply considering the power generation, LCOE and ROI. The case study of BS-HSR also fully proves the robustness and effectiveness of the decision-making framework established in this paper.

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