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Comprehensive evaluation method for energy efficiency of virtual power plants

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Abstract. The virtual power plant integrates multiple supply entities through the information system to achieve the goal of efficient use of power consumption, and provides multi-directional support for demand response and auxiliary services for power grid operation. This paper is oriented to the virtual power plant infrastructure, considering the impact of virtual power plants on the electric power system, and constructing a comprehensive evaluation index system for energy efficiency of virtual power plant projects through three dimensions of safety, economy and environmental protection. This integral comprehensive evaluation system is a combination of AHP and TOPSIS. Finally, the typical virtual power plant design scheme is selected for comprehensive evaluation.

1. Introduction

In order to alleviate the negative effects and give full play to the positive effects of new energy resources, virtual power plants (VPP) have attracted widespread attention. The owner or operational manager of the virtual power plant can optimize and control the distributed energy resources within its jurisdiction through information technology to achieve technical, economic and environmental benefits. In the current research, the financing problem of virtual power plant energy efficiency resource development project is the main content of scholars' research, but there is no relevant literature reference in performance evaluation. At present, there is a lack of systematic research on performance evaluation, so it is necessary to conduct in-depth exploration in this field. In this paper, the principal components analysis method is used to refine the generated indicators to eliminate the correlation between the indicators. At the same time, the TOPSIS is used to sort, compare and analyze the indicators, so that the whole analysis process is more accurate and reasonable. Through the evaluation of the performance of energy efficiency resource development projects, it is hoped that the actual energy efficiency resource management work will be carried out, a feasible long-term mechanism will be established, and demand side management will be improved.

2. The impact of virtual power plants on power systems.

The cost of virtual power plants is relatively low. There is no need to requisition large amounts of land like public power plants. According to the test, the cost per kilowatt of virtual power plant implemented



in Jiangsu Province is about 0.12 yuan. Similar to public power plants, virtual power plants have a power consumption increasing curve with cost and output. Its fixed cost is mainly the equipment investment in the previous period. The variable cost mainly refers to the compensation cost to the user.

Virtual power plants do not have any impact on the environment. Public power plants, whether hydropower, thermal power, nuclear power or new energy power generation, always have more or less environmental pollution or environmental impact. For example, coal-fired or gas-fired power plants generate large amounts of CO₂, SO₂ and NO during production, resulting in environmental pollution; hydropower plants do not form CO, SO and NO in the production process. However, the construction of hydropower stations will inevitably stop the flow, raise the water level, block the migration of fish, destroy the living environment of specific animals and plants, and thus affect the ecological balance; nuclear power is faced with the disposal of nuclear waste. The virtual power plant really achieved zero emissions. No matter how much electricity is produced, there is no pollution at all.

Virtual power plants can also participate in the spare capacity market and ancillary services market. At present, the spare capacity for power generation is provided by the power plant, and the power grid gives certain compensation. Although spare capacity is necessary to ensure the stability of the power grid, it also causes waste of power resources. If the virtual power plant involves in the spare capacity market and auxiliary service market, it can reduce the waste of power resources ^[1-2].

3. Virtual power plant energy efficiency evaluation index system

3.1 Energy efficiency assessment indicators

The comprehensive evaluation of energy efficiency of virtual power plants should be measured from economic value, social value and national policy implementation. It refers to the achievements of the project in terms of investment intensity, energy consumption, comprehensive utilization of resources, and energy-saving technology. In the construction of the indicator system, based on the concept of energy conservation and emission reduction, follow the principles of rationality, hierarchy, and combine qualitative and quantitative analysis to comprehensively select assessment indicators ^[3-5]. The final performance indicator system is composed of three indicators: target layer, criterion layer and indicator layer. Table 1 shows the three-level indicator system constructed.

Tab.1 Performance evaluation index system.

Target layer	Criteria layer	Indicator layer
Energy efficiency resource development performance level A	Energy saving investment intensity A1	Energy saving capital investment A11, Investment ratio A12
	Policy implementation A2	Implement energy conservation regulations A21, Execution energy quota A22, Energy-saving policy formulation A23, Energy-saving policy promotion A24
	Energy efficiency A3	Annual electricity savings A31/CWh*a-1, Cut peak load A32/MW*a-1
	Technology management level A4	New technology research and development capabilities A41, Energy metering tool A42, Energy saving training A43 Project tracking monitoring A44
	Economic benefit A5	Average cost of electricity A51/yuan*KW*h-1 Cumulative net benefit A52

Among the 14 three-level indicators, there are 6 quantitative indicators and 8 qualitative indicators. For the evaluation value of the qualitative indicator, the evaluation is performed by the expert scoring method. Take the energy measurement tool equipped with A42 as an example. If the energy metering tool is fully equipped, the item will be awarded 100 points; with the most basic measurement tool, it will be awarded 50 points; if it is not equipped with measurement tools, it will be awarded points. The evaluation value of the quantitative indicator is obtained from the actual measured data.

3.2 Pretreatment of indicators

Samples with multiple indicators provide a wealth of information, but also increase the complexity of

the analysis to a certain extent; at the same time, each indicator reflects some information of performance to varying degrees, there will be overlap between the indicators. Therefore, Principal Component Analysis (PCA) is used to preprocess the data. The basic idea is to recombine a large number of variables with certain correlations to form a new minority of several independent variables to replace the original variables, so that the data is simplified and the dimensions are reduced.

The model idea of principal component analysis is to assume that there are n samples, p indicators, and construct a sample matrix: $X = (x_{ij})_{n \times p} = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{np} \end{pmatrix}$ $X_{i1}, X_{i2}, \dots, X_{ip}$ are the original variable indicators. The purpose of principal component analysis is to construct a few new variables using p 's original variables $X_{i1}, X_{i2}, \dots, X_{ip}$ ($i = 1, 2, \dots, n$), so that the new variable is a linear combination of the original variables. The new variables are irrelevant and contain most of the information about the original variables.

Since there are large differences in the magnitude and dimension of qualitative data and quantitative data, the original indicators are first dimensionlessly processed so that qualitative and quantitative indicators can be compared. After standardization, a standardized matrix is obtained:

$$Z = (z_{ij})_{n \times p} = \begin{pmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{np} \end{pmatrix}$$

The eigenvalues, eigenvectors, and variance contribution rates of

the matrix Z are calculated by SPSS software. According to the principle that the cumulative variance contribution rate is not less than 85%, a new comprehensive variable index is extracted, and each new comprehensive variable index is a linear combination of the original variable index p and is irrelevant. The formula for calculating the weight of the indicator is $W_i = P_i / (1)$ where P_i is the contribution rate of the i -th common factor of each indicator.

4. Comprehensive evaluation method for energy efficiency of virtual power plants

The TOPSIS method is an evaluation method that sorts the evaluation objects by means of the ideal solution and the negative ideal solution of various index attributes, and weighs the comprehensive benefits of the evaluation object according to the relative proximity size.

The principal component analysis method is used to obtain a simplified one-dimensional comprehensive variable index. The number of new indicators is described as m , and then we multiply the new comprehensive variable indicator by the corresponding weight to construct a weighted normalization matrix, which can be described as V . Constructing the ideal matrix V_+ and the negative ideal matrices V_- for V , respectively $V_+ = (V_{1+}, V_{2+}, \dots, V_{M+})$, $V_- = (V_{1-}, V_{2-}, \dots, V_{M-})$, where $V_{j+} = \max\{V_{ij} \mid i = 1, 2, \dots, m\}$, $V_{j-} = \min\{V_{ij} \mid i = 1, 2, \dots, m\}$

Calculate the sample point to the most advantageous distance D_i^+ and D_i^- and calculate the relative proximity C_i . The relevant formula is as follows:

$$D_i^+ = \left(\sum_{j=1}^M V_j^+ \right)^{1/2} \quad (1) \quad D_i^- = \left(\sum_{j=1}^M V_j^- \right)^{1/2} \quad (2)$$

$$C_i = D_i^- / (D_i^+ + D_i^-) \quad (3) \quad i=1, 2, \dots, m \quad (4)$$

5. Case analysis

Taking the energy efficiency resource development project carried out in Jiangsu Province, one of the pilot cities of virtual power plants, as an example, the data of the three energy-efficient power plant projects of the province's lighting renovation^[6], industrial motor dragging scheme and household appliances were carried out in 2009. After standardization and quantitative indicators are standardized, the data is first preprocessed according to principal component analysis. Factor analysis by SPSS software, the main components of energy efficiency power plant indicators are Z_1 , Z_2 , and the corresponding eigenvalues and contribution rates are shown in Table 2:

Tab.2 Total Variance Explained

Main ingredient	Initial eigenvalue		
	Variance	Contribution rate/%	Cumulative contribution rate/%
Z1	10.181	72.723	72.723
Z2	3.819	27.277	100.000

After determining the principal components, calculate the factor load matrix, as shown in Table 3:

Tab.3 Component matrix

Factor	Main ingredient	
	Z1	Z2
X ₁	0.862	-0.507
X ₂	0.724	-0.690
X ₃	0.998	-0.590
X ₄	0.985	0.173
X ₅	0.955	-0.297
X ₆	0.638	0.770
X ₇	0.384	-0.923
X ₈	0.979	0.206
X ₉	0.995	-0.100
X ₁₀	0.955	-0.297
X ₁₁	0.944	0.331
X ₁₂	0.994	0.107
X ₁₃	0.273	0.962
X ₁₄	0.817	0.577

According to the feature value table and the factor load matrix, call the Compute Variable command to obtain the eigenvector matrix and the expression of the principal component:

$$Y_1 = 0.27X_1 + 0.23X_2 + 0.31X_3 + 0.31X_4 + 0.3X_5 + 0.2X_6 + 0.12X_7 + 0.31X_8 + 0.31X_9 + 0.3X_{10} + 0.3X_{11} + 0.31X_{12} + 0.09X_{13} + 0.26X_{14}$$

$$Y_2 = -0.26X_1 - 0.35X_2 - 0.3X_3 + 0.09X_4 - 0.15X_5 + 0.39X_6 - 0.47X_7 + 0.11X_8 - 0.05X_9 - 0.15X_{10} + 0.17X_{11} + 0.05X_{12} + 0.49X_{13} + 1.95X_{14}$$

After normalizing the indicators X₁ to X₁₄ in the principal component expression, the standardized variables with the variable names ZX₁ to ZX₁₄ are obtained. Call the Compute Variable command to calculate the principal component, as shown in Table 4:

Tab.4 Principal component

Project	y ₁	y ₂
Lighting renovation	2.72	3.21
Industrial motor driving system	0.81	-0.301
Household appliances	-3.53	-0.20

Compared with the original data, the matrix has changed from 3×14 to 3×2, and the amount of data is 6/7 less. Next, the evaluation steps of the TOPSIS method are used for evaluation. Calculate the weight of each new principal component according to formula (1), multiply the data of the new principal component by the corresponding weight, and obtain the weighted normalization matrix V: $V =$

$\begin{bmatrix} 1.9856 & 0.8667 \\ 0.5913 & -0.8127 \\ -2.5769 & -0.054 \end{bmatrix}$ The ideal solution V⁺ is the maximum value of the corresponding column, and the negative ideal solution V⁻ is the minimum value of the corresponding column. The results are shown

in Table 5:

Tab.5 The Ideal Solution and Negative Ideal Solution Value

V^+	1.9856	0.8667
V^-	-2.5769	-0.8127

Calculate the distance from the sample point to the most advantageous and the relative proximity according to formulas (2), (3), and (4). The calculation results are shown in Table 6:

Tab.6 Distance from Sample to Ideal Solution and Relative Proximity

C_1	0.8129	C_2	0.5921	C_3	0.1402
D_1^+	1.1189	D_2^+	2.1828	D_3^+	4.6545
D_1^-	4.8618	D_2^-	3.1682	D_3^-	0.7587

From the calculation results, it can be seen that the lighting renovation project has the best performance and the greatest strength. The government has strongly supported the lighting renovation project and actively promoted urban green lighting. In 2010, the urban lighting energy-saving appliances penetration rate reached more than 85%. According to statistics, in the project of energy efficiency power plant of Jiangsu Dangong Industrial Co., Ltd., it invested 190,200 yuan to replace 3,000 sets of energy-saving lamps, saving up to 1030.755kW·h, annual electricity saving of 567,000 yuan, the average energy saving rate of the green lighting energy efficiency power plant project is as high as 66.59%, and the energy saving effect, economic benefit and social benefit have been successful. Lighting is one of the biggest energy-saving opportunities. Compared with other energy-saving retrofits in energy-efficient resource development projects, the implementation of lighting renovation is more intense, and the attention given by all parties is higher.

6. Conclusion

This paper mainly expounds the methods and steps of comprehensive evaluation of energy efficiency of virtual power plants. The evaluation provides a theoretical reference, which projects are not sufficiently innovated, and which projects have the greatest transformation. The comprehensive evaluation of energy efficiency can be seen at a glance, so that the participants can better understand the focus of the next transformation plan. In addition, scientifically evaluating the performance of virtual power plant energy efficiency resource development projects can, to a certain extent, motivate more energy-using units to implement virtual power plants and have a positive role in further energy-saving retrofit projects.

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