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Study on energy efficiency evaluation index system for fossil-fuel power plant

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Abstract

In this paper, evaluation index system with two levels is established to evaluate energy efficiency of fossil-fuel power plant in a comprehensive and objective way, in order to provide detailed methods for energy-saving and emission reduction. The index system includes five indicators at the first level and two indicators at the second level. Principal component analysis (PCA) model is adopted to comprehensively evaluate energy efficiency of fossil-fuel power units. PCA is a relatively objective evaluation method, which can not only determine weights objectively, but also roundly reflect most information from multiple indicators. The method presented in this paper is implemented on seventeen 1000MW thermal power units. The results obtained agree well with the actual situation and those in the references.

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Keywords: thermal power unit; energy efficiency evaluation; index system; principal component analysis

1. Introduction

In recent decades, energy consumption increases greatly with the rapid development of global economy. Energy becomes a major strategic issue that affects the development of human society and the world political, economical patterns [1]. Fossil-fuel power plant is one of the high energy consumption industries, so increasing its energy efficiency is imperative. Energy efficiency evaluation is an important measurement for improving energy efficiency, in which the index system and evaluation model are the two most important aspects. In this paper, a two-level evaluation index system is established, and principal component analysis (PCA) model is adopted as the final comprehensive evaluation method.

2. The energy efficiency evaluation index system

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Five principles of establishing the energy efficiency evaluation index system are put forward in literature [2]: 1) comprehensiveness; 2) independency; 3) generality; 4) representativeness; 5) procedure. The seven indicators selected in this paper cover all the major energy consuming processes and equipment, thus giving an evaluation result in a comprehensive, scientific, and effective way.

Based on the above principles and data analysis, the two-level evaluation index system is established. The first level indicators are comprehensive ones that reflect the overall level of energy utilization in the factory; second level indicators reflect the level of principal equipment and major working procedures. The first level indicators include standard coal consumption per unit power supplied, standard coal consumption per unit power generated, thermal efficiency, service power rate, and total water consumption per unit power generated. The second level indicators include thermal efficiency of boiler and efficiency of turbine.

3. Brief introduction to PCA

PCA is an acronym of principal component analysis, which is a very useful method in multi-index comprehensive evaluation. This method takes the principal components, as the linear combination of original variables though mathematical manipulation, and then choose several principal components which take larger proportion among the total variation to analyze and evaluate the whole things [3]. This method can not only confirm the objective weight of every indicator, but also comprehensively reflect the energy efficiency level of the power units.PCA algorithm implementation steps are given in appendix A.

4. Energy efficiency evaluation for fossil-fuel power plant using PCA

4.1. Computation procedure

The data used in this paper is from <The contest score statistical table of 500MW~1000MW thermal power units in 2012>, which was published on the China Electricity Council website†. Seventeen 1000MW units are taken as the implement objects of comprehensive energy efficiency evaluation, and the results with comparison to that of literature [4] are shown as follows.

Table 1. The data of 17 1000MW thermal power units

NO.	Standard coal consumption per unit power supplied Z_1 (gce/kW•h)	Standard coal consumption per unit power generated Z_2 (gce/kW•h)	Thermal efficiency Z_3 (%)	Total water consumption per unit power generated Z_4 (m^3/kW•h)	Service power rate Z_5 (%)	Thermal efficiency of boiler Z_6 (%)	Efficiency of turbine Z_7 (%)
A	275.85	265.37	46.35	0.30	3.80	94.30	75.53
B	276.44	265.94	46.25	0.30	3.80	94.30	75.53
C	282.91	274.88	44.75	0.27	2.84	94.06	75.18
D	283.09	275.73	44.61	0.26	2.60	94.06	75.18
E	283.76	272.41	45.15	0.10	4.00	93.72	75.68
F	283.93	272.15	45.20	0.32	4.15	93.72	74.42
G	284.56	273.35	45.00	0.21	3.94	94.00	74.78
H	284.98	271.56	45.29	0.23	4.71	93.86	75.68

† http://kjfw.cec.org.cn/kejifuwu/2013-04-07/99877.html

I	285.08	273.19	45.02	0.28	4.17	93.65	74.42
J	286.60	275.28	44.68	0.16	3.95	93.84	76.40
K	288.77	277.85	44.27	1.65	3.78	93.50	75.45
L	289.51	277.61	44.31	0.40	4.11	93.65	75.68
M	289.61	276.09	44.55	0.19	4.67	93.72	76.57
N	289.72	279.26	44.04	1.87	3.61	93.60	75.75
O	291.87	278.97	44.09	0.39	4.42	93.66	76.03
P	295.69	283.83	43.34	0.19	4.01	93.84	77.75
Q	298.10	284.21	43.28	0.32	4.66	93.20	74.58

Eigenvalue, variance contribution rate and cumulative variance contribution rate are shown in Table 2.

Table 2. Eigenvalue, variance contribution rate and cumulative variance contribution rate

Eigenvalue	3.879	1.237	1.130	0.683	0.071	0.000	2.958E-06
Variance contribution rate(%)	55.415	17.671	16.142	9.757	1.011	0.005	4.226E-05
Cumulative variance contribution rate(%)	55.415	73.086	89.228	98.984	99.995	100.000	100.000

We can find that cumulative variance contribution rate of the first three eigenvalue is 89.228%, more than 85%. Therefore, the first, second and third principal component can be used as the comprehensive indicators, and the reliability of this evaluation is 89.228%.

The first eigenvalue is $\lambda_1 = 3.879$, and the corresponding eigenvector is $L_1 = (0.502, 0.486, -0.487, 0.161, 0.190, -0.439, 0.143)$. Therefore, the first principal component is $F_1 = 0.502 Z_1 + 0.486 Z_2 - 0.487 Z_3 + 0.161 Z_4 + 0.190 Z_5 - 0.439 Z_6 + 0.143 Z_7$.

The second eigenvalue is $\lambda_2 = 1.237$, and the corresponding eigenvector is $L_2 = (0.104, -0.078, 0.083, -0.681, 0.604, 0.075, 0.377)$. The second principal component is $F_2 = 0.104 Z_1 - 0.078 Z_2 + 0.083 Z_3 - 0.681 Z_4 + 0.604 Z_5 + 0.075 Z_6 + 0.377 Z_7$.

The third eigenvalue is $\lambda_3 = 1.130$, and the corresponding eigenvector is $L_3 = (0.017, 0.172, -0.169, -0.013, -0.480, 0.422, 0.730)$. The third principal component is $F_3 = 0.017 Z_1 + 0.172 Z_2 - 0.169 Z_3 - 0.013 Z_4 - 0.480 Z_5 + 0.422 Z_6 + 0.730 Z_7$.

The final evaluation value is $F = 0.55415 \times F_1 + 0.17671 \times F_2 + 0.16142 F_3$.

The final energy efficiency evaluation value and the order are shown in Table 3.

Table 3. The final value of the 17 units

NO.	F	The order obtained by PCA	The order obtained by standard coal consumption per unit power supplied	The order obtained by TOPSIS [4]
A	-1.95468	1	1	1
B	-1.85954	2	2	2
C	-0.72847	3	3	7
F	-0.71544	4	6	13
D	-0.68130	5	4	6
G	-0.64003	6	7	9
I	-0.49134	7	9	11
E	-0.31914	8	5	3

H	-0.27232	9	8	10
J	0.282859	10	10	4
K	0.431363	11	11	5
L	0.589536	12	12	8
N	0.616707	13	14	12
M	0.814762	14	13	16
O	1.036576	15	15	14
Q	1.786908	16	17	17
P	2.103537	17	16	15

4.2. Result analysis

It can be seen from Table 1 and Table 3 that PCA evaluation result is consistent with data-based analysis. However, data–based analysis can only be conducted on typical units with consistent relationship in various indicators. PCA is capable of solving problems on energy efficiency evaluation of units with inconsistency in various indicators.

PCA is a comprehensive evaluation method, which not only considers the influence of standard coal consumption per unit power supplied to the energy efficiency of the unit, but also considers other indicators. It can cover all kinds of energy and every important working procedure, and give a comprehensive and objective result. For example, the unit F in this sample ranking 6^{th} in the order obtained by standard coal consumption per unit power supplied, but ranking 4^{th} in the order obtained by PCA, benefiting mainly from the less standard coal consumption per unit power generated and higher thermal efficiency.

Results obtained by PCA are also in general agreement with that by TOPSIS [4]. However, there are a few different results, like unit C, mainly because of the different weights in the two methods. In the PCA method, indicator of standard coal consumption per unit power supplied is given by a greater weight.

5. Conclusion

Main conclusions are summarized as follows:

1. Compared with traditional methods and methods in literature, it can be seen that the evaluation index system with two levels and PCA method can obtain a comprehensive, objective and reliable result of energy efficiency evaluation for fossil-fuel power units.

2. The evaluation system presented in this paper can cover all kinds of energy and every important working procedure, obtaining objective weight of every indicator, eliminating the mutual interference among different indicators, and giving a comprehensive result.

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Biography

Fan Zhang is a master candidate of Prof. Wenquan Tao in the School of Energy and Power Engineering, Xi'an Jiaotong University, and a researcher in the Key Laboratory of Thermo-fluid Science and Engineering, Ministry of Education. His research mainly focuses on energy efficiency evaluation, and design of heat exchanger.

Appendix A. The algorithm steps of PCA

A.1. Standardization of original variables data

Suppose that there are n samples and p indicators, and then the data matrix is $X=(x_{ij})_{nxp}$, $i=1,2,\cdots,n$, $j=1,2,\cdots,p$, where n represents the number of samples; p represents the number of indicators, and x_{ij} represents the j indicator of the i sample.

Standardize the data by $Z-score$ method:

$$Z_{ij}=(x_{ij}-\overline{x_j})/S_j \tag{1}$$

where $\overline{x_j}=(\sum_{i=1}^{n}x_{ij})/n$, $S_j^2=[\sum_{i=1}^{n}(x_{ij}-\overline{x_j})^2]/(n-1)$, $i=1,2,\cdots,n$, $j=1,2,\cdots,p$.

A.2. Obtain the correlation matrix of indicators

$$R=(r_{jk})_{pxp} \quad j=1,2,\cdots,p,\ k=1,2,\cdots,p \tag{2}$$

where r_{jk} is the correlation coefficient of j and k.

$$r_{jk}=\frac{1}{n-1}\sum_{i=1}^{n}[(x_{ij}-\overline{x_j})^2/S_j][(X_{ik}-\overline{X_k})^2/S_k] \quad i=1,2,\cdots,n,\ j=1,2,\cdots,p,\ k=1,2,\cdots,p \tag{3}$$

Namely, $r_{jk}=\frac{1}{n-1}\sum_{i=1}^{n}Z_{ij}Z_{jk}$, and $r_{ii}=1$, $r_{jk}=r_{kj}$.

A.3. Obtain the eigenvalue and eigenvector of R, confirm the principal components

The eigenvalue λ_g ($g=1,2,\cdots,p$) can be gotten by solving the characteristic equation $|\lambda I-R|=0$. λ_g , arranging in sequence from big to small $\lambda_1\geq\lambda_2\geq\cdots\geq\lambda_p\geq 0$, are the variance of the principal components; meanwhile, they describe influence of the relative principal component to evaluated objects. Every eigenvalue has a corresponding eigenvector L_g ($L_g=l_{g1},l_{g2},\cdots,l_{gp}$), $g=1,2,\cdots,p$.

Transform the indicators, which have been standardized, to principal components:

$$F_g=l_{g1}Z_1+l_{g2}Z_2+\cdots+l_{gp}Z_p \quad g=1,2,\cdots,p \tag{4}$$

where F_1 is called the first principal component, and F_2 is called the second principal component, ⋯, F_p is called the pth principal component.

A.4. Obtain the variance contribution rate, and confirm the number of principal components

Generally, the number of principal components equals to that of the origin indicators, which may cause trouble if there are too many indicators. Principal component analysis is just a comprehensive evaluation method, choosing principal components as few as possible but losing information as little as possible.

$\alpha_g = \lambda_g / \sum_{g=1}^{p} \lambda_g$ is the variance contribution rate, indicating the information that every component reflects. The number of the principal components k is determined by the cumulative variance contribution rate $\sum_{g=1}^{k} \lambda_g / \sum_{g=1}^{p} \lambda_g \geq 85\%$.

A.5. Comprehensive evaluation

Calculate the linear weighted value of every principal component $F_g = l_{g1}Z_1 + l_{g2}Z_2 + \cdots + l_{gp}Z_p$, and then calculate the weighted sum of k principal components, in which the weight is their variance contribution rate, getting the final evaluation value.

The final evaluation value is $F = \sum_{g=1}^{k} (\lambda_g / \sum_{g=1}^{p} \lambda_g) F_g$.