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Energy Efficiency Evaluation and Optimization of Industrial Park Customers Based on PSR Model and Improved Grey-TOPSIS Method

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ABSTRACT Energy efficiency evaluation of industrial park customers is carried out to help customers develop optimization strategies and improve the energy efficiency level. The evaluation indexes are proposed based on pressure-state-response (PSR) model and the redundant indexes are selected by combining principal component analysis (PCA) and correlation analysis. Thus the dynamic energy efficiency index system is constructed. The weight of indexes is calculated by the entropy weight method (EWM). An energy efficiency evaluation model based on improved Grey-technique for order preference by similarity to ideal solution (TOPSIS) is proposed, which replaces the Euclidean distance by weighted grey correlation degree and can accurately evaluate customers' energy efficiency level. An energy efficiency optimization model is proposed, which can maximize optimization benefits while improving energy efficiency. The validity of the evaluation and optimization models is verified by the case study of an industrial park.

INDEX TERMS Energy efficiency evaluation, industrial park customers, pressure-state-response model, Grey-technique for order preference by similarity to ideal solution, energy efficiency optimization.

I. INTRODUCTION

Energy is vital to the existence and development of modern society. In the last few decades, energy and environmental issues have become increasingly prominent in global economic growth [1]. The improvement of energy utilization efficiency is an important way to reduce energy consumption intensity and to release the contradiction of energy supply-demand structure [2], [3]. Statistical data show that the industry currently consumes approximately 37% of the total energy used in the world each year, which is more than any other sector [4]. With the characteristics of high energy density, high reliability of power supply and strong uncertainty of energy demand, the industrial park is facing an urgent contradiction between economic development and energy conservation. Industrial customers have a lot of energy consumption equipment and complex energy consumption situation, so they have certain energy efficiency improvement potential [5], [6].

Before optimizing the energy efficiency of customers in the industrial park, it is necessary to carry out effective energy efficiency evaluation to provide a reference for improving energy efficiency. Many studies have exploited methods of energy efficiency evaluation. With the help of the data envelopment analysis (DEA) method, the industrial energy efficiency of 28 administrative regions in China was measured in [7]. A comprehensive evaluation model provided for the industrial energy management system (EMS) to fully evaluate the operational level of energy-intensive equipment was proposed based on the analytic hierarchy process (AHP) and fuzzy comprehensive evaluation method in [8]. A novel DEA model based on the affinity propagation (AP) clustering algorithm (AP-DEA) was proposed. Through the AP clustering algorithm, high influence input data of the energy efficiency can be obtained. The merits and demerits can be identified with a high degree of discrimination to obtain better efficiency groups [9]. For high energy consumption users, the TOPSIS method was used to evaluate economic benefits of efficiency power plant projects to provide guidance for users in [10]. A multi-index and multi-working condition energy efficiency evaluation solution for the ethylene-cracking furnace was proposed based on technique for order preference by similarity to ideal solution (TOPSIS)-DEA model in [11]. A municipal power grid comprehensive energy efficiency evaluation system based on TOPSIS method was established and AHP-entropy weight method (EWM) was adopted to

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determine the comprehensive weight of indexes in [12]. Although existing research focuses on the selection of energy efficiency evaluation index system and evaluation methods, indexes proposed in previous papers do not apply to energy efficiency evaluation of industrial parks, the dynamic logical relationship between indexes is ignored, and the evaluation method needs improving. There is a lack of a comprehensive energy efficiency evaluation model for industrial park customers.

Power efficiency optimization is based on results of energy efficiency evaluation, taking effective measures to improve the energy efficiency of users and reduce the energy cost. Power efficiency optimization measures include load management techniques, economic means, technical methods. Load management improves power efficiency through load control and load dispatch [8], [13], [14]. The economic mean is to apply dynamic pricing schemes such as Real-Time Pricing (RTP) and Time-of-Use (TOU) to adjust the power consumption time of users [15]–[17]. The technical method is to use harmonic suppression, reactive power compensation and other optimization technologies to improve energy efficiency [18]–[20]. But there are some problems when optimization technologies are taken to improve users' power efficiency. On the one hand, advanced technology and equipment are blindly used in the optimization process and the investment cost is ignored, which leads to the inconspicuous benefit of power-saving. On the other hand, the impact between objectives is ignored, only considering the optimization of the single index. Thus, a comprehensive power efficiency optimization model considering both energy conservation and investment cost should be established.

This paper proposes a comprehensive energy efficiency evaluation method for industrial park customers based on Grey-TOPSIS model and establishes an energy efficiency optimization model. Firstly, a multi-dimensional energy efficiency index system based on pressure-state-response (PSR) model is established, which selects indexes from different dimensions and considers the dynamic relationship between energy efficiency indexes. With the combination of principal component analysis (PCA) and correlation analysis, redundant energy efficiency indexes are removed to determine the final evaluation index system. Then, the energy efficiency evaluation model of park customers is constructed base on Grey-TOPSIS and the index weight is calculated by EWM. The TOPSIS evaluation method is improved by combining the grey correlation degree analysis, and the grey-weighted correlation degree is used as the new distance measure to make up for the defects of the Euclidean distance. In addition, considering the economic and technological factors, an energy efficiency optimization model is established to maximize the energy efficiency optimization benefits of customers. Finally, the proposed models are used to evaluate and optimize the energy efficiency of industrial park customers, and the validity of the models is verified.

The paper is organized as follows. Section II analyzes the process of energy efficiency evaluation and relevant methods. Section III establishes an improved Grey-TOPSIS energy efficiency evaluation model. Section IV establishes an energy efficiency optimization model for the industrial park customer. Section V demonstrates the effectiveness of the proposed models through a case study of industrial park customers. Section VI briefly describes the conclusions of this paper.

II. ENERGY EFFICIENCY EVALUATION

The energy efficiency evaluation process of the industrial park is illustrated in Fig. 1, which is divided into three parts. These parts are data preprocessing, index screening and evaluation analysis.

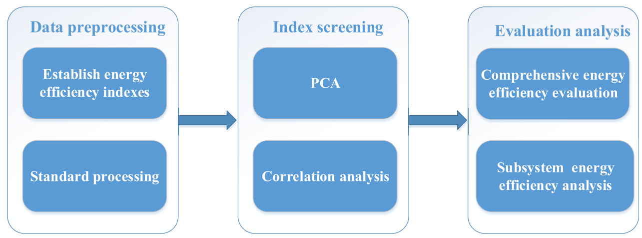


FIGURE 1. Energy efficiency evaluation process of industrial park customers.

A. INDEX SYSTEM BASED ON PSR MODEL

''Pressure–State–Response'' (PSR) framework is used to evaluate the impact of human activities on the ecological environment. At present, the evaluation based on PSR framework has been widely used in ecological security, economy and other fields [21], [22]. PSR framework model can represent the interaction and sustainable development process between a system and external influencing factors. Based on the grid background, this study analyzes the composition of the index system from the perspectives of pressure, state, and response. The dynamic energy efficiency index system can reveal the internal and external factors that lead to the change of energy consumption, reflect the quality of customers' energy consumption, and avoid the limitation of index selection. The relationship between subsystems and indexes in the PSR model is shown in Fig. 2.

1) PRESSURE INDEX

The pressure index indicates pressure factors that lead to the change of energy efficiency of users. In this article, the annual power consumption is defined as the pressure index.

2) STATE INDEX

The state index indicates the actual energy consumption of customers under the effect of pressure factors, which can effectively reflect the impact of power quality on customer energy efficiency level.

3) RESPONSE INDEX

The response index reflects the different degrees of response results that customers change their original habits and

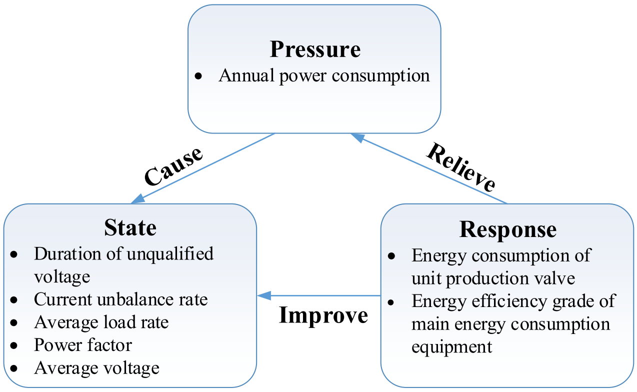


FIGURE 2. Pressure–state–response framework.

promote the healthy development of energy consumption behavior.

B. CONSTRUCT A STANDARDIZED EVALUATION MATRIX

Before the energy efficiency evaluation, it is necessary to carry out data preprocessing to unify data types and conduct dimensionless processing. Original index data is collected to construct an evaluation matrix $Z^{(1)}$:

$$Z^{(1)} = \begin{bmatrix} z_{11}^{(1)} & z_{12}^{(1)} & \cdots & z_{1n}^{(1)} \\ z_{21}^{(1)} & z_{22}^{(1)} & \cdots & z_{2n}^{(1)} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ z_{m1}^{(1)} & z_{m2}^{(1)} & \cdots & z_{mn}^{(1)} \end{bmatrix} \quad (1)$$

where $Z_{ij}^{(1)}$ is the j-th index value of the i-th customer.

The energy efficiency indexes are divided into benefit type, cost type and interval type. Benefit type indicates that the larger the index value is, the higher the energy efficiency level of customers is. Cost type indicates that the smaller the index value is, the higher the energy efficiency level of customers is. Interval type indicates that when the value is in a certain range, the energy efficiency level of users is higher. To facilitate the data processing, the other two types of indexes are converted into benefit indexes and the matrix Z^* is constructed.

(1) Benefit index:

$$z_{ij}^* = z_{ij}^{(1)} \quad (2)$$

(2) Cost index:

$$z_{ij}^* = \max z_j - z_{ij}^{(1)} \quad (3)$$

(3) Interval index: The best interval of the index is [a, b].

$$z_{ij}^* = \begin{cases} 1 - \dfrac{a - z_{ij}^{(1)}}{M}, & z_{ij}^{(1)} < a \\ 1, & a \le z_{ij}^{(1)} \le b \\ 1 - \dfrac{z_{ij}^{(1)} - b}{M}, & z_{ij}^{(1)} > b \end{cases}$$

$$M = \max\{a - \min\{z_j^{(1)}\}, \max\{z_j^{(1)}\} - b\} \quad (4)$$

where $z_{ij}^{(1)}$ represents the original index value; z_{ij}^* represents the value after positive management.

To avoid the negative influence of different dimensions on the results, dimensionless processing of $Z*$ is carried out according to equation (10).

$$z_{ij}^{(2)} = z_{ij}^* / \sqrt{\sum_{i=1}^{m} z_{ij}{}^{*2}} \quad (5)$$

After data preprocessing, the standardized energy efficiency evaluation matrix $Z^{(2)}$ is established.

$$Z^{(2)} = \begin{bmatrix} z_{11}^{(2)} & z_{12}^{(2)} & \cdots & z_{1n}^{(2)} \\ z_{21}^{(2)} & z_{22}^{(2)} & \cdots & z_{2n}^{(2)} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ z_{m1}^{(2)} & z_{m2}^{(2)} & \cdots & z_{mn}^{(2)} \end{bmatrix} \quad (6)$$

where $Z_{ij}^{(2)}$ is the standardized value of the j-th index.

C. ENERGY EFFICIENCY INDEX SCREENING

To ensure the representativeness of energy efficiency evaluation indexes, the PSR energy efficiency index system is screened by combining PCA and correlation analysis.

1) PCA

PCA is a mathematical transformation approach that converts a given set of related variables into another set of unrelated variables by the orthogonal transformation [23]. The main role of PCA is to reduce noise and redundant data (i.e., dimensionality reduction) while preserving all critical information in the original dataset as much as possible. In this article, PCA is utilized to screen redundant indexes in the dynamic energy efficiency index system.

The correlation coefficient matrix of the standardized matrix $Z^{(2)}$ is calculated.

$$\begin{aligned} R &= [r_{ij}]_{m\times m} \\ r_{ij} &= \mathrm{cov}(Z^{(2)}(:;i), \quad Z^{(2)}(:;j)) \end{aligned} \quad (7)$$

where r_{ij} is the covariance between the data of i-th and j-th indexes. $z^{(2)}(:,i)$ and $z^{(2)}(:,j)$ represent i-th and j-th columns of the matrix $z^{(2)}$.

Solving the characteristic equation $|R - \lambda E_m| = 0$, m characteristic roots are obtained and ranked from largest to smallest, representing the first to the m-th principal component. Generally, the first n ($n < m$) principal components can reflect most of the information, so we only need to analyze the n principal components and remove the index with smaller principal component coefficients.

The unit eigenvector $B_j = [B_{1j}, \ldots, B_{Mj}]^T$ OF λ_j ($j = 1, 2, \ldots, n$) is calculated, then the principal component analysis matrix B is constructed according to the unit eigenvector.

$$B = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ b_{m1} & b_{m2} & \dots & b_{mn} \end{bmatrix} \tag{8}$$

If the absolute value of b_{ij} $(j = 1, 2, \ldots, n)$ is much smaller than that of other elements in the same column, it indicates that the i-th index has little influence on the whole index system and can be removed.

2) INDEX SCREENING METHOD

PCA forms several comprehensive variables by recombining the original variables so that each principal component can reflect most of the information of the original variable without repeating the information. The first and second principal components extracted by PCA can contain most of the information, so the composition coefficients of the first and second principal components are calculated in this article. The indexes with larger coefficients are reserved and the secondary indexes are deleted.

Correlation analysis is based on the correlation coefficient between variables to determine whether there are linear correlation redundant indexes. If the correlation coefficient of the two indexes is larger, it means that the correlation of information contained in them is higher, so redundant indexes should be deleted to avoid information repetition.

When the results of correlation analysis are contrary to those of PCA, PCA results should be the main results. If an index is linearly related to multiple indexes, it should be retained when it accounts for a large proportion in the composition of principal components.

D. CALCULATE INDEX WEIGHT WITH EWM

The objective difference between index data should be considered when determining the index weight, to avoid the influence of subjective preference on the results. EWM is used to calculate the index weight and objectively quantify the importance of the index, which introduces entropy in information theory to evaluate the relative intensity of the index in the sense of competition [24], [25]. When the index values of evaluation objects differ greatly, the entropy value is small, and the information provided by the index is large, so the weight of the index is also large.

(1) Calculate the entropy of the j-th evaluation index.

$$H_{ij}^{*} = -k \sum_{i=1}^{m} f_{ij} \ln f_{ij}, \quad 1, 2 \ldots, q \tag{9}$$

where $f_{ij} = z_{ij} / \sum_{i=1}^{m} z_{ij}$, $k = 1/\ln m$. If $f_{ij} = 0, f_{ij} \ln f_{ij} = 0$.

(2) Calculate the entropy weight of the j-th index.

$$w_j = \frac{1 - H}{q - \sum_{j=1}^{q} H_j} \tag{10}$$

where $0 \leq w_j \leq 1$, $\sum_{j=1}^{q} w_j = 1$. $W = [w_1, w_2, \ldots, w_q]$ is the index weight vector.

E. IMPROVED TOPSIS METHOD

The TOPSIS method is developed for solving multicriteria decision making problems on the basis that the best alternative is the one with the shortest distance from the positive ideal solution and the farthest from the negative ideal solution [26]–[28]. However, the traditional TOPSIS method has the following disadvantages:

(1) The traditional TOPSIS method uses Euclidean distance to calculate the distance between the evaluation object and the positive and negative ideal solution. If the linear relationship between the evaluation indexes cannot be considered, the Euclidean distance will be invalid and the accuracy of the evaluation result may be affected.

(2) Because of the defect of Euclidean distance, the TOPSIS method can not accurately reflect the position of each scheme. There may be evaluation schemes close to the positive and negative ideal solutions, so it can not fully reflect the advantages and disadvantages of each evaluation scheme.

In order to solve the above problems, this paper improves the traditional TOPSIS method combined with grey correlation degree to evaluate energy efficiency. The grey correlation analysis provides a quantitative measure for the change of a system, which is suitable for dynamic process analysis [29]. The new model uses the weighted grey correlation degree as the distance measure to replace the original Euclidean distance.

III. IMPROVED GREY-TOPSIS ENERGY EFFICIENCY EVALUATION MODEL

The energy efficiency evaluation model is established to analyze the energy efficiency of customers in the industrial park. The steps of energy efficiency evaluation based on improved Grey-TOPSIS are as follows:

(1) According to equation (2)-(5) and the screening process, the final energy efficiency evaluation matrix $Z = (z_{ij})_{m \times q}$ is constructed. q $(q < n)$ is the number of energy efficiency indexes after the index screening and m is the number of evaluated industrial park customers.

(2) Calculate the positive-ideal alternative Z^+ and negative-ideal alternative Z^-.

$$Z^+ = \left\{ \max_j z_{ij} \right\} = \left\{ z_1^+, z_2^+, \ldots, z_q^+ \right\}$$

$$Z^- = \left\{ \min_j z_{ij} \right\} = \left\{ z_1^-, z_2^-, \ldots, z_q^- \right\} \tag{11}$$

where $z_1^+, z_2^+, \ldots, z_q^+$ represent the index value of positive-ideal alternative; $z_1^-, z_2^-, \ldots, z_q^-$ represent the index value of negative-ideal alternative.

(3) Calculate the grey correlation coefficient γ^+ and γ^-.

$$\gamma_{ij}^{+} = \frac{\min_i \min_j \left| z_{ij} - z_j^+ \right| + \rho \max_i \max_j \left| z_{ij} - z_j^+ \right|}{\left| z_{ij} - z_j^+ \right| + \rho \max_i \max_j \left| z_{ij} - z_j^+ \right|}$$
$$\gamma_{ij}^{-} = \frac{\min_i \min_j \left| z_{ij} - z_j^- \right| + \rho \max_i \max_j \left| z_{ij} - z_j^- \right|}{\left| z_{ij} - z_j^- \right| + \rho \max_i \max_j \left| z_{ij} - z_j^- \right|} \tag{12}$$

where $\rho \in [0, 1]$; we usually define $\rho = 0.5$.

(4) Calculate the distance measure S_i^+ and S_i^- of the Grey-TOPSIS method. The weighted grey correlation degree calculated by weighted sum of the grey correlation coefficient is used as the distance measure.

$$S_i^+ = \sum_{j=1}^{q} w_j \gamma_{ij}^+$$
$$S_i^- = \sum_{j=1}^{q} w_j \gamma_{ij}^- \tag{13}$$

where, S_i^+ is the distance from i-th alternative to positive-ideal alternative, and S_i^- is the distance from i-th alternative to the negative-ideal alternative. The index weight is calculated by EWM.

(5) Measure comprehensive evaluation index D_i of alternative S_i

$$D_i = \frac{S^+}{S^- + S^+} \tag{14}$$

where, the larger the value of D_i, the closer the scheme is to the positive-ideal alternative.

The energy efficiency evaluation results of customers in the industrial park are sorted and compared based on D_i. According to the weighted grey correlation degree of energy efficiency index of each subsystem, the relative closeness degree of PSR subsystem is calculated, which is used to analyze the dimensional performance of the customer.

IV. ENERGY EFFICIENCY OPTIMIZATION

Generally, the more advanced optimization technologies are used to optimize the key power efficiency factors, the better the energy-saving effect will be. However, the implementation of energy efficiency optimization brings an increase in investment cost, the economic return will gradually approach the limit value and the economic benefit will be worse. Thus, customers should consider the investment cost in energy efficiency improvement and choose the most economical combination of optimization measures, so as to obtain the maximum benefits of energy efficiency optimization.

A. ENERGY EFFICIENCY OPTIMIZATION COST FUNCTION

When selecting energy efficiency optimization technology, factors such as economy and technology should be considered and not all technologies are suitable for specific optimization objects. Therefore, the best technology combination should be determined. Without considering the interaction and compatibility of optimization technologies, energy efficiency optimization cost for i-th index is defined as

$$C_i = \sum_{j=1}^{m} \alpha C_i^j \tag{15}$$

where α represents the applicability of the technology; when its value of is 1, the technology applies to the index. when its value is 0, the technology does not apply to the index; C_i^j represents the cost of optimizing i-th index with j-th technology; m is the number of optimization technologies.

B. ENERGY EFFICIENCY OPTIMIZATION REWARD FUNCTION

The weight coefficient of each optimization index should be considered when calculating the energy-saving of the total objective. The total energy saving reward of a customer can be defined as

$$E = \sum_{i=1}^{n} \sum_{j=1}^{m} E(C_i^j) = \sum_{i=1}^{n} \sum_{j=1}^{m} \alpha w_i p d_i^j \tag{16}$$

where d_i^j is energy-saving of i-th index optimized by j-th optimization technology; p is the electricity price; w_i is the weight of index i; $E(C_i^j)$ is the energy-saving reward of i-th index optimized by j-th technology; n is the number of energy efficiency optimization indexes.

C. ENERGY EFFICIENCY OPTIMIZATION BENEFIT FUNCTION

The benefit of energy efficiency optimization is defined as the difference between the energy-saving reward and the investment cost.

$$X = \sum_{i=1}^{n} \sum_{j=1}^{m} X(C_i^j) = \sum_{i=1}^{n} \sum_{j=1}^{m} \alpha w_i p d_i^j - \alpha C_i^j \tag{17}$$

where, $X(C_i^j)$ is the energy efficiency benefit of i-th index optimized by j-th technology; X is the total optimization benefit of the customer.

D. ENERGY EFFICIENCY OPTIMIZATION MODEL

The purpose of energy efficiency optimization is to maximize the customer's benefit while saving energy and reducing consumption.

1) OPTIMIZATION OBJECTIVE OF THE MODEL

The objective of. energy efficiency optimization model is to pursue the benefit maximization.

$$\max X = \max \left[\sum_{i=1}^{n} \sum_{j=1}^{m} \alpha w_i p d_i^j - \alpha C_i^j \right] \tag{18}$$

2) MODEL CONSTRAINTS

The related constraints of the optimization model include the index weight, the cost and the power-saving. The index weight value should be between 0 and 1 and the sum of index weights of each subsystem is 1.

$$S.T. = \begin{cases} 0 \leq w_i \leq 1 \\ \sum_{i=1}^{n} w_i = 1 \\ C_i^j \geq 0 \\ d_i^j \geq 0 \end{cases} \tag{19}$$

V. CASE STUDY

Energy efficiency evaluation is carried out to analyze typical customers in an industrial park in Hebei Province and the energy using condition of the industrial customers is different. Then the energy efficiency optimization analysis is carried out for the low energy efficiency user based on the energy efficiency evaluation results.

A. ENERGY EFFICIENCY EVALUATION

According to the data of 10kV users in an industrial park, the energy efficiency of 10 customers is evaluated and analyzed based on the proposed evaluation model.

1) CONSTRUCT ENERGY EFFICIENCY INDEX SYSTEM BASED ON PSR MODEL

The initial PSR energy efficiency index system of park customers is shown in Table 1. According to China energy efficiency label, the energy efficiency of energy consumption equipment (R2) is divided into five grades, 1 represents the best energy efficiency, and 5 represents the worst energy efficiency.

TABLE 1. Initial PSR energy efficiency index system.

Subsystem	Label	Index	Type
pressure	P1	Annual power consumption (kWh)	cost
state	S1	Duration of unqualified voltage (h)	cost
	S2	Current unbalance rate	cost
	S3	Average load rate	benefit
	S4	Power factor	benefit
	S5	Average voltage	interval
response	R1	Energy consumption of unit production valve (kWh/ ￥10,000)	cost
	R2	Energy efficiency grade of main energy consumption equipment	cost

The standardized energy efficiency index data is obtained by positive and standardized processing, as shown in Table 2.

2) SCREEN INDEXES

The energy efficiency indexes are screened based on the data in Table 2. The first and the second principal components are calculated for index screening with PCA, as shown in Table 3. The correlation coefficient between indexes is shown in Figure 3.

TABLE 2. Standardized energy efficiency index data.

user	Pressure	State					Response	
	P1	S1	S2	S3	S4	S5	R1	R2
1	0.211	0.354	0.238	0.456	0.330	0.046	0.395	0.149
2	0.357	0.373	0.408	0.224	0.323	0.491	0.384	0.447
3	0.372	0.136	0.299	0.244	0.327	0.000	0.143	0.149
4	0.000	0.362	0.328	0.158	0.313	0.092	0.398	0.298
5	0.346	0.281	0.257	0.141	0.320	0.108	0.000	0.298
6	0.377	0.366	0.439	0.574	0.317	0.287	0.243	0.447
7	0.366	0.372	0.000	0.135	0.263	0.450	0.161	0.447
8	0.296	0.365	0.216	0.160	0.327	0.491	0.458	0.298
9	0.379	0.000	0.125	0.249	0.313	0.087	0.289	0.000
10	0.249	0.320	0.509	0.449	0.323	0.450	0.374	0.298

TABLE 3. Principal component coefficient.

Index	First	Second
P1	-0.013	-0.236
S1	0.384	0.028
S2	0.228	0.570
S3	0.103	0.631
S4	-0.009	0.066
S5	0.711	-0.293
R1	0.237	0.324
R2	0.478	-0.161

The first and the second principal component coefficients of power factor (S4) are small (−0.009 and 0.066), so the redundant index should be eliminated. There is a significant correlation between S1 and R2, with a correlation coefficient of 0.810 (>0.75). However, the two indexes should be retained according to the principle of index selection, because

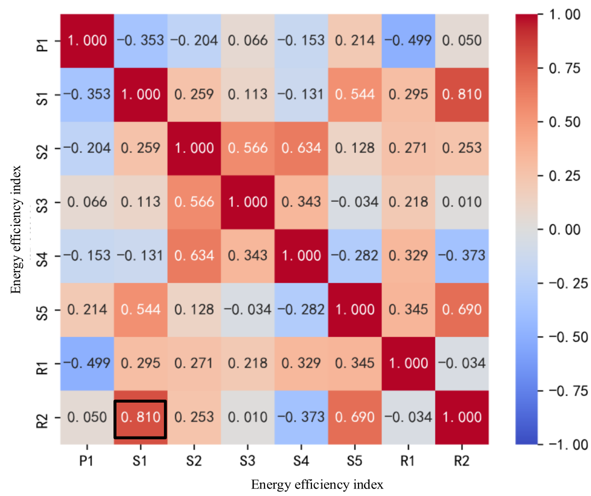


FIGURE 3. Correlation analysis results.

of their large principal component coefficients in PCA. After the index screening, the final PSR energy efficiency index system is constructed, which contains 7 energy efficiency indexes.

3) CALCULATE INDEX WEIGHTS

The final energy efficiency evaluation matrix Z is established after screening indexes. The weights of energy efficiency indexes are calculated with EWM, as shown in the vector W.

$$W = [0.073, 0.081, 0.104, 0.328, 0.211, 0.100, 0.102]$$

The weights of the average load rate (S3) is the largest, while the weight of annual power consumption (P1) is the smallest.

4) ENERGY EFFICIENCY EVALUATION AND ANALYSIS

Energy efficiency evaluation results of park customers are calculated based on the improved Grey-TOPSIS evaluation model, as shown in Table 4. The customer's comprehensive energy efficiency level is evaluated by relative closeness (D_i).

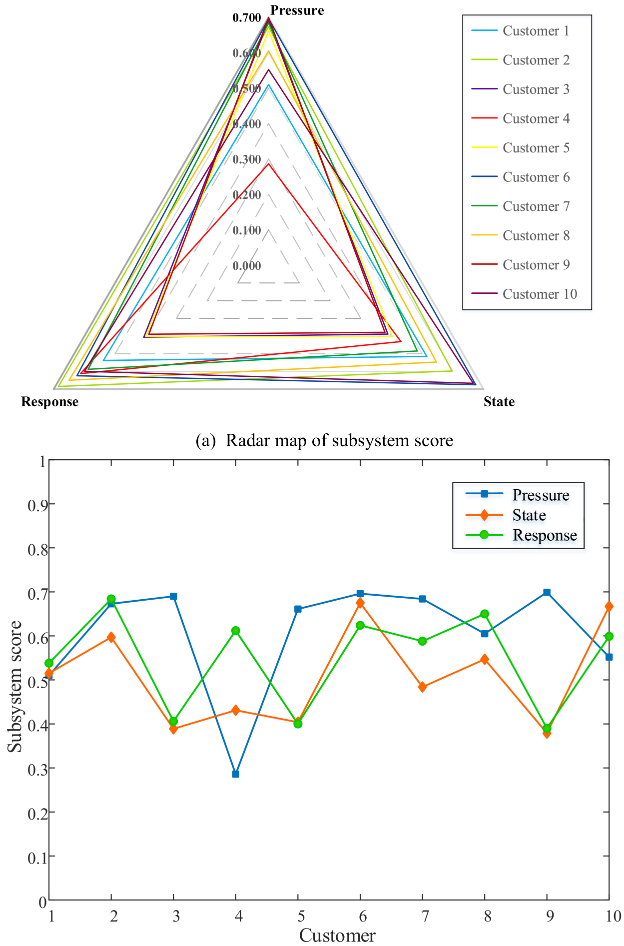
TABLE 4. Grey-TOPSIS evaluation results.

Customer	S_i^+	S_i^-	D_i	Rank
1	0.599	0.553	0.520	6
2	0.752	0.456	0.623	3
3	0.477	0.660	0.420	9
4	0.520	0.621	0.456	7
5	0.483	0.653	0.425	8
6	0.835	0.418	0.666	1
7	0.636	0.581	0.523	5
8	0.683	0.509	0.573	4
9	0.471	0.675	0.411	10
10	0.761	0.419	0.645	2

Customer 6 has the highest energy efficiency level (0.666), and customer 6 has the lowest energy efficiency level (0.411). The customer's comprehensive energy efficiency ranking is 6>10>2>8>7>1>4>5>3>9.

The energy efficiency performance of industrial park customers in the pressure, state and response subsystem is analyzed. The evaluation scores and the dynamic performance of customers in different subsystem dimensions are illustrated in Fig. 4.

Customer 6 achieves the best performance in the state and response subsystems of all customers, so the comprehensive energy efficiency level of customer 6 is better than the other park customers. Further energy-saving measures can be taken to optimize the response index and improve its energy efficiency, because response indexes can generate feedback on pressure and state subsystems. Customer 9 has low evaluation scores in all three subsystems, and the state system score is the lowest among 10 customers. There is still room for improvement in the state and response subsystem of customer 9. The state score of customer 2 is slightly low, which leads to a lower comprehensive energy efficiency level compared with customer 6. The response system performance of customer 2 is good, which improves its comprehensive energy efficiency level, and finally gets a higher ranking.



(a) Radar map of subsystem score

(b) Subsystem evaluation result

FIGURE 4. Performance in subsystem dimensions.

Besides, there are differences in the performance of users in PSR subsystems, resulting in their different comprehensive energy efficiency evaluation results. The customers with better response performance obtain higher comprehensive energy efficiency evaluation results, which shows that optimizing the response dimension index is the most effective measure to improve energy efficiency level. Therefore, customers should pay attention to the performance of the response subsystem.

The above analysis verifies that the energy efficiency index system based on the PSR model is scientific and feasible. Based on the improved Grey-TOPSIS energy efficiency evaluation model, the comprehensive energy efficiency level of customers in the industrial park can be effectively evaluated, which can provide a reference for energy efficiency optimization. Moreover, the performance of PSR subsystems can be analyzed to find the factors influencing the energy efficiency level.

5) ENERGY EFFICIENCY EVALUATION ADAPTABILITY ANALYSIS OF EVALUATION MODEL

Different evaluation methods are used to evaluate the energy efficiency of industrial customers. The evaluation ranking of

TABLE 5. Results of different evaluation methods.

Method	Customer 1	2	3	4	5	6	7	8	9	10
	Ranking									
AHP	6	3	9	7	8	1	5	4	10	2
Fuzzy	6	3	9	7	8	1	5	4	10	2
TOPSIS	6	3	9	7	8	1	4	5	10	2
The proprosed model	6	3	9	7	8	1	5	4	10	2

the proposed model is compared with the other three methods, as shown in Table 5.

The evaluation results of different evaluation models are basically consistent, which verifies the effectiveness of the new evaluation model proposed in this paper.

Compared with the TOPSIS method, customers 7 and 8 have different energy efficiency ranking. Because Euclidean distance in TOPSIS can not accurately reflect the location of each scheme, the weighted grey correlation degree measurement distance in the improved model can accurately reflect the distance measurement relationship between each scheme and the optimal scheme. Therefore, the evaluation results of the new model are more reasonable.

In the fuzzy evaluation method, the evaluation is more dependent on subjective experience and lacks a detailed analysis of indexes. The proposed model makes full use of the data of PSR dynamic energy efficiency index, combines objective data with subjective information, and can sense the dynamic changes of customers in pressure, state and response dimensions.

B. ENERGY EFFICIENCY OPTIMIZATION AND ANALYSIS

According to the result of the evaluation and investigation, customer 10 with improvement space is chosen for energy efficiency optimization. The annual electricity consumption of customer 10 is 9.55 million kWh, and the electricity price is 0.7¥/kWh.

1) ENERGY EFFICIENCY OPTIMIZATION INDEXES

According to the preliminary research, there are 10 energy efficiency optimization indexes in terms of power information and power quality. The optimization indexes and weights are shown in Table 6. The information about energy efficiency optimization technology is illustrated in Table 7.

2) ENERGY EFFICIENCY OPTIMIZATION TECHNOLOGY

Different energy efficiency optimization technologies are selected to optimize these indicators. According to the energy-saving technology and equipment price, the cost of energy efficiency optimization is determined. The power-saving rate of optimization technology is the middle value of the energy-saving experience in Table 7. The energy-saving rate, energy-saving value and investment cost of relative technologies are shown in Table 8. The applicability of optimization indexes and technologies is shown in Table 9.

TABLE 6. Energy EFFICIENCY Optimization index.

Type	Symbol	Index	Weight
Power Information	A_{11}	Voltage	0.3078
	A_{12}	Current	0.1128
	A_{13}	Power factor	0.2402
	A_{14}	Active power	0.1508
	A_{15}	Three-phase voltage phase difference	0.1884
Power quality	A_{21}	Voltage unbalance factor	0.2882
	A_{22}	Total time of unqualified voltage	0.2569
	A_{23}	Total time of overload	0.1849
	A_{24}	Voltage deviation	0.0910
	A_{25}	Harmonic distortion	0.1690

TABLE 7. Energy EFFICIENCY Optimization technology.

Symbol	Technology	Energy-saving experience
S_1	Reactive power compensation	10%-20%
S_2	Variable frequency	20%-50%
S_3	Electromagnetic balance	20%-30%
S_4	Harmonic suppression	5%-20%
S_5	Phase Control Voltage	20%-30%
S_6	Energy storage	10-30%

TABLE 8. Energy-saving rate, energy saving amount and cost of optimization technology.

Technology	Energy saving rate（%）	Energy saving （10,000 kWh）	Cost （￥10,000）
S_1	15	143.25	18
S_2	35	334.25	30
S_3	25	238.75	30
S_4	12.5	119.375	20
S_5	25	238.75	15
S_6	20	191	25

3) SINGLE-INDEX OPTIMIZATION

The cost, reward and benefit of each technology for optimizing the single index are calculated to support customers to select the best combination of energy efficiency optimization schemes. The optimization results of the single index are shown in Fig.5. The ranking of single-index optimization benefits is shown in Table 10.

As shown in Fig. 5, when the customer uses different technologies to optimize the single index, the energy efficiency optimization benefits obtained are different, with positive or negative values. Thus, customers can gain benefits or may lose money when the single energy efficiency index is optimized.

When the single index is optimized, the benefits of 18 schemes are greater than 0, which indicates that customers can obtain benefits when they adopt these optimization

TABLE 9. Applicability of optimization indexes and technologies.

Optimization index	Optimization technology					
	S_1	S_2	S_3	S_4	S_5	S_6
A_{11}	1	0	1	0	0	1
A_{12}	0	0	1	0	1	0
A_{13}	1	1	0	0	1	1
A_{14}	1	1	1	1	0	1
A_{15}	1	0	1	0	1	0
A_{21}	0	0	1	0	0	0
A_{22}	1	0	1	0	0	0
A_{23}	1	1	1	0	0	1
A_{24}	1	0	0	0	0	0
A_{25}	0	0	1	1	0	0

TABLE 10. Ranking of single-index benefit.

Benefit	Ranking of benefit
$X(C_i^j) > 0$	$X(C_{13}^2)>X(C_{13}^5)>X(C_{11}^3)>X(C_{21}^3)>X(C_{15}^5)>X(C_{11}^6)$ $>X(C_{23}^2)>X(C_{22}^3)>X(C_{11}^1)>X(C_{22}^1)>X(C_{13}^6)>X(C_{13}^1)$ $>X(C_{14}^2)>X(C_{12}^5)>X(C_{15}^3)>X(C_{23}^3)>X(C_{15}^1)>X(C_{23}^1)$
$X(C_i^j) < 0$	$X(C_{23}^6)>X(C_{25}^3)>X(C_{14}^1)>X(C_{14}^3)>X(C_{14}^6)$ $>X(C_{25}^4)>X(C_{14}^4)>X(C_{24}^1)>X(C_{12}^3)$

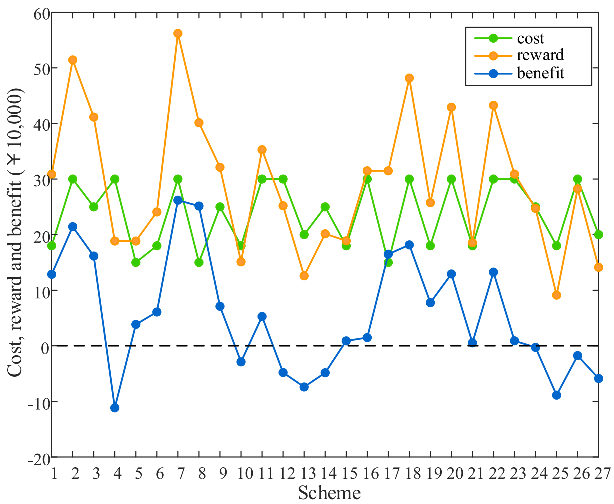


FIGURE 5. Cost, reward and benefit of optimizing single index.

technologies. $X(C_{13}^2)$ is the largest in Table 10, which indicates that the customer can obtain the maximum single-index benefit when using optimization technology 2 to optimize indicator A_{13}. Therefore, the variable frequency technology (S_2) should be used priorly to optimize the power factor index (A_{13}) and then the phase-control voltage technology (S_5) is adopted to optimize the index.

4) COMPREHENSIVE OPTIMIZATION

According to the ranking of single-index optimization benefit, the schemes are combined to optimize energy efficiency. According to equation (16)-(18) in the energy efficiency optimazition model, the cost-reward and cost-benefit changes of multi-index optimization are shown in Fig. 6.

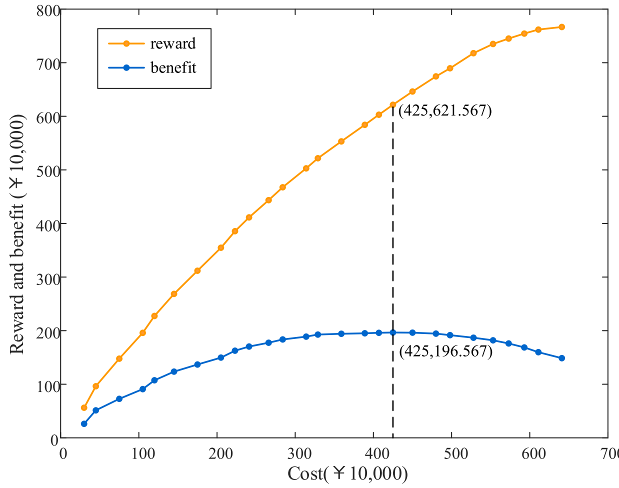


FIGURE 6. Results of comprehensive optimization.

With the increase of customers' investment cost in energy efficiency optimization, the energy-saving reward also increases and tends to the extreme value gradually, which indicates that when the energy-saving reaches the extreme value, the customer's power-saving will not increase even if more advanced optimization technology is adopted.

With the increase of investment cost, the benefit gradually increases, reaches the maximum value and then decreases, which shows that the economy of energy efficiency optimization gradually becomes bad. According to equation (18), the optimization result can be obtained. The highest point of the cost-benefit curve is (425, 196.567), which indicates that when the investment cost is 4.25 million yuan, the customer 10 can get the maximum benefit (1.96567 million yuan) of energy efficiency optimization.

The results of the case study verify the correctness and effectiveness of the proposed optimization model. The case analysis shows that the reasonable and economic combination of energy efficiency optimization technologies can improve energy efficiency and bring economic benefits to customers. Thus, the competitiveness of industrial park customers is improved by maximizing the benefit of energy efficiency optimization.

VI. CONCLUSION

This paper proposed the energy efficiency evaluation model based on improved Grey-TOPSIS and the optimization model for industrial park customers. Firstly, the dynamic energy efficiency evaluation index system was established based on PSR model and the indexes were screened with the combination of PCA and correlation analysis, which made the evaluation index system more scientific. The Grey-TOPSIS evaluation model was proposed to evaluate the energy efficiency level of industrial park customers. The improved model can more accurately reflect the internal changes of each evaluation scheme and make up for the deficiency of European distance in the traditional TOPSIS. Then, the energy efficiency optimization model was proposed to pursue the maximization of customer benefits while improving energy efficiency. Finally, the comprehensive energy efficiency level of industrial park customers and their performance in PSR subsystem dimension were evaluated, and the energy efficiency optimization of customer 10 with improvement space was analyzed. The case study verified the effectiveness of the proposed models.

Future work needs to consider the mutual influence and compatibility of different energy efficiency optimization technologies and improve the model of energy efficiency optimization.

REFERENCES

[1] D. Borozan and L. Borozan, "Examining the industrial energy consumption determinants: A panel Bayesian model averaging approach," *Energies*, vol. 13, no. 1, pp. 1–17, Dec. 2019.

[2] N. G. Paterakis, O. Erdinç, and J. P. S. Catalão, "An overview of demand response: Key-elements and international experience," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 871–891, Mar. 2017.

[3] Y. Chen, Y. Han, and Q. Zhu, "Energy and environmental efficiency evaluation based on a novel data envelopment analysis: An application in petrochemical industries," *Appl. Thermal Eng.*, vol. 119, pp. 156–164, Jun. 2017.

[4] *International Energy Outlook 2013*, Int. Energy Agency, Paris, France, 2013.

[5] Z. Wen, Y. Wang, H. Li, Y. Tao, and D. De Clercq, "Quantitative analysis of the precise energy conservation and emission reduction path in China's iron and steel industry," *J. Environ. Manage.*, vol. 246, pp. 717–729, Sep. 2019.

[6] Z. Chen, Y. Sun, A. Xin, S. Majeed Malik, and L. Yang, "Integrated demand response characteristics of industrial park: A review," *J. Modern Power Syst. Clean Energy*, vol. 8, no. 1, pp. 15–26, 2020.

[7] G.-M. Shi, J. Bi, and J.-N. Wang, "Chinese regional industrial energy efficiency evaluation based on a DEA model of fixing non-energy inputs," *Energy Policy*, vol. 38, no. 10, pp. 6172–6179, Oct. 2010.

[8] Y. Li, Z. Sun, L. Han, and N. Mei, "Fuzzy comprehensive evaluation method for energy management systems based on an Internet of Things," *IEEE Access*, vol. 5, pp. 21312–21322, 2017.

[9] Z. Geng, R. Zeng, Y. Han, Y. Zhong, and H. Fu, "Energy efficiency evaluation and energy saving based on DEA integrated affinity propagation clustering: Case study of complex petrochemical industries," *Energy*, vol. 179, pp. 863–875, Jul. 2019.

[10] W. Kuihua, Z. Zhijie, L. Hao, L. Bo, L. Zhao, L. Kai, Z. Wen, and L. Shuli, "Study on economic benefit evaluation model of energy-efficient power plant projects with high energy consumption users," in *Proc. 5th Asia Conf. Power Electr. Eng. (ACPEE)*, Jun. 2020, pp. 923–927.

[11] D. Meng, C. Shao, and L. Zhu, "A new energy efficiency evaluation solution for ethylene cracking furnace based on integrated TOPSIS-DEA model," *Int. J. Energy Res.*, vol. 44, no. 2, pp. 732–755, Dec. 2019.

[12] J. Du, C. Cai, Z. Xie, and M. Geng, "Comprehensive energy efficiency evaluation of municipal power grid based on TOPSIS method," in *Proc. 5th Asia Conf. Power Electr. Eng. (ACPEE)*, Jun. 2020, pp. 829–833.

[13] A. Safdarian, M. Fotuhi-Firuzabad, and M. Lehtonen, "Optimal residential load management in smart grids: A decentralized framework," *IEEE Trans. Smart Grid*, vol. 7, no. 4, pp. 1836–1845, Jul. 2016.

[14] Q. Lu, Z. Zhang, and S. Lü, "Home energy management in smart households: Optimal appliance scheduling model with photovoltaic energy storage system," *Energy Rep.*, vol. 6, pp. 2450–2462, Nov. 2020.

[15] E. Sarker, M. Seyedmahmoudian, E. Jamei, B. Horan, and A. Stojcevski, "Optimal management of home loads with renewable energy integration and demand response strategy," *Energy*, vol. 210, pp. 118602–118614, 2020.

[16] M. S. Javadi, M. Gough, M. Lotfi, A. Esmaeel Nezhad, S. F. Santos, and J. P. S. Catalão, "Optimal self-scheduling of home energy management system in the presence of photovoltaic power generation and batteries," *Energy*, vol. 210, pp. 118568–118580, 2020.

[17] H. Zhu, Y. Gao, Y. Hou, Z. Wang, and X. Feng, "Real-time pricing considering different type of smart home appliances based on Markov decision process," *Int. J. Electr. Power Energy Syst.*, vol. 107, pp. 486–495, May 2019.

[18] M. Roesch, D. Bauer, L. Haupt, R. Keller, T. Bauernhansl, G. Fridgen, G. Reinhart, and A. Sauer, "Harnessing the full potential of industrial demand-side flexibility: An end-to-end approach connecting machines with markets through service-oriented IT platforms," *Appl. Sci.*, vol. 9, no. 18, p. 3796, Sep. 2019.

[19] M. Arens and E. Worrell, "Diffusion of energy efficient technologies in the German steel industry and their impact on energy consumption," *Energy*, vol. 73, pp. 968–977, Aug. 2014.

[20] N. Mohamed, J. Al-Jaroodi, and S. Lazarova-Molnar, "Leveraging the capabilities of industry 4.0 for improving energy efficiency in smart factories," *IEEE Access*, vol. 7, pp. 18008–18020, 2019.

[21] D. Zhang, J. Shen, P. Liu, and F. Sun, "Allocation of flood drainage rights based on the PSR model and pythagoras fuzzy TOPSIS method," *Int. J. Environ. Res. Public Health*, vol. 17, no. 16, pp. 1–19, 2020.

[22] D. Zhou, Z. Lin, L. Liu, and D. Zimmermann, "Assessing secondary soil salinization risk based on the PSR sustainability framework," *J. Environ. Manage.*, vol. 128, pp. 642–654, Oct. 2013.

[23] C. Skittides and W.-G. Früh, "Wind forecasting using principal component analysis," *Renew. Energy*, vol. 69, pp. 365–374, Sep. 2014.

[24] Z. Huang, W. Zhao, Z. Shao, Y. Gao, Y. Zhang, Z. Li, J. Li, and Q. Xixi, "Entropy weight-logarithmic fuzzy multiobjective programming method for evaluating emergency evacuation in crowded places: A case study of a university teaching building," *IEEE Access*, vol. 8, pp. 122997–123012, 2020.

[25] K. Zhang, W. Kong, P. Liu, J. Shi, Y. Lei, and J. Zou, "Assessment and sequencing of air target threat based on intuitionistic fuzzy entropy and dynamic VIKOR," *J. Syst. Eng. Electron.*, vol. 29, no. 2, pp. 305–310, Apr. 2018.

[26] C. Yan, Y. Chen, F. Wang, Y. Wen, S. Fu, and W. Huang, "A multi-objective video crowdsourcing method in mobile environment," *IEEE Access*, vol. 7, pp. 133787–133798, 2019.

[27] M. A. Zytoon, "A decision support model for prioritization of regulated safety inspections using integrated delphi, AHP and double-hierarchical TOPSIS approach," *IEEE Access*, vol. 8, pp. 83444–83464, 2020.

[28] L. Wang, Y. Ali, S. Nazir, and M. Niazi, "ISA evaluation framework for security of Internet of health things system using AHP-TOPSIS methods," *IEEE Access*, vol. 8, pp. 152316–152332, 2020.

[29] Z. Zhang, H. Li, L. Yue, and Y. Du, "End of life vehicle disassembly plant layout evaluation integrating gray correlation and decision making trial and evaluation laboratory," *IEEE Access*, vol. 8, pp. 141446–141455, 2020.

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