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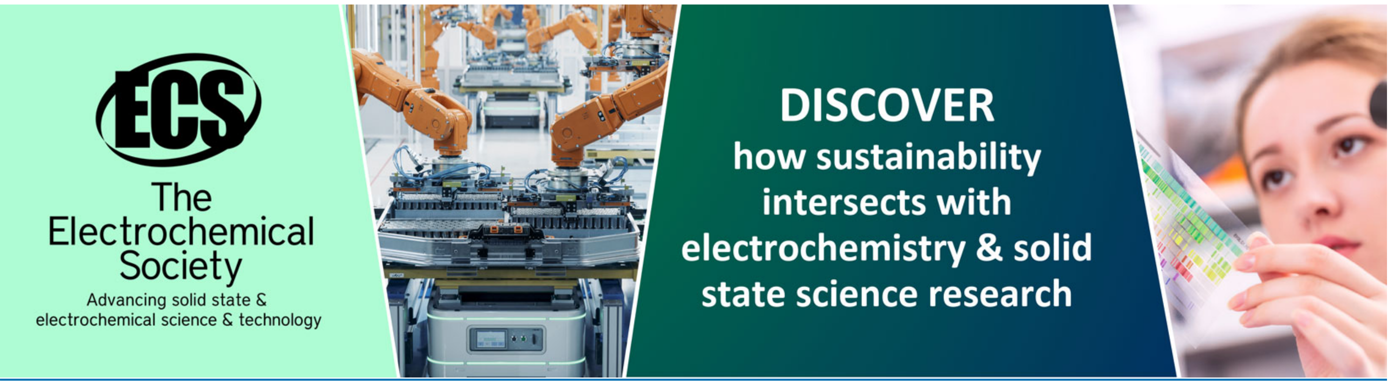

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A Practical Classification Evaluation Approach for Comprehensive Competitiveness of Distributed Energy Supply Systems

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Abstract. The distributed energy supply system(DESS) is widely used in power grids. This paper proposes a practical classification evaluation approach (PCEA) based on analytic hierarchy process-entropy weight method (AHP-EWM), with the goal of the quantitative evaluation values of DESS. Firstly, a practical evaluation index system (PEIS) considering soft competitiveness and hard competitiveness is constructed and scenes of DESS are classified into types under the consideration of developmental characteristics. Then, to break the hierarchies between intertypes and improve the fairness of evaluation results, an index-contributing coefficient (ICC) based on EWM is introduced to estimate the influence degree of different indexes on classification evaluation between different types of scenes. Next, with the input valuables of practical evaluation indexes from the PEIS, the classification evaluation results of DESSs are obtained by PCEA. Finally, the DESSs in southern part of China are taken for an example for analysis and further results verify the adaptability of PCEA.

1. Introduction

DESSs can achieve energy cascade utilization by adopting combined supply mode [1-2]. Due to the characteristics of small scale, small capacity and advantages of high energy efficiency and environmental protection, DESSs are widely implemented in hospitals, hotels, supermarkets and etc.

Currently, remarkable works providing evaluation models of DESSs are available and reviewed [3-5]. Paper [5] puts forward to optimize the operation based on primary energy consumption and carbon dioxide emissions for different conditions. It is apparent that each evaluation work mentioned above has certain features. Although contents of them are different, the basic idea is roughly consistent. Improvement of this idea as well as innovation of PCEA can be summed up as follows.

Existing evaluation indexes lack adequate attention of the holistic system. Most works tend to focus only on one or several aspects, such as energy cost [6], environmental protection [7-8] and other operating characteristics [9]. Practical indexes closely correspond to different aspects of comprehensive competitiveness and are chosen on the principle of higher contribution rate, easier accessibility and quantifiable characteristic.

As characteristics of different scenes vary with types of the application field[10], in this paper, DESSs are mainly classified into three types: building sites, regional sites and island sites.

Analytic hierarchy process (AHP) is an assignment method to apportion weight of indexes by combining qualitative method with quantitative method[11]. However, some indexes of one type of DESSs have larger (or smaller) values comparing with that of other types. This will cause the problem that evaluation results by AHP are excessively concentrated by the type. The PCEA is designed in this paper to deal with the problem by introducing ICC, which is solved out by EWM. As ICC can be used to estimate the influence degree on different types of DESSs by the same index, this method can break the hierarches between them.

Purpose of existing evaluations for DESS can be summarized as follows: to compare different configuration schemes or operating strategies in order to make valuable and optimal decision-making[7], to conduct assessment of various benefits and improve the renewable energy system based on lower cost or less emission[8]. However, evaluations of comprehensive competitiveness from a macro perspective to provide reference for investment and construction planning are non-existent at present. Therefore, PCEA is proposed to deal with this issue. With regard to the soft competitiveness, analysis of operational status and weak links are given to provide experience for operation and maintenance management of similar scenes. As to the hard one, conditions for development of DESSs are gathered to analyze economic, environmental benefits.

This paper is organized as follows. In Section II, practical evaluation index system is established. Section III describes the classification framework. The procedures of PCEA are elaborated in Section IV. Section V presents case studies. Finally, this paper concludes in Section VI.

2. Practical Evaluation Index System

2.1. Influencing Factors of Classification Evaluation

Comprehensive competitiveness of DESSs contains two aspects: soft and hard competitiveness. Its specific components are shown in Fig.1.

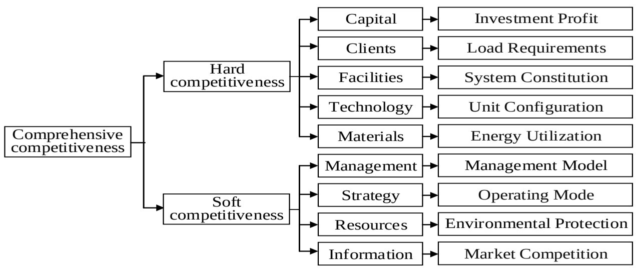

Figure 1. Specific components of comprehensive competitiveness.

According to the theoretical analysis, factors affecting the evaluation of comprehensive competitiveness of DESSs are refined into five aspects, which are described below:

(1) Economic Benefit

As reflected in capital, management and information, economic benefit plays a significant role in popularizing prospect of DESSs. Economic benefit is the primary influencing factor.

(2) Characteristic of Combined Supply

In different sites, there are mainly four kinds of supply requirements: power, cooling-power, heating-power and cooling-heating-power. Characteristic of combined supply, which reflected specifically in clients and technology, is used to measure the hard competitiveness of DESSs.

(3) Energy Utilization

Energy utilization mainly focuses on the energy reserves. It evaluates the abilities to effective mining local diverse energy sources and realizing the cascade utilization of DESSs.

(4) Operating Mode

The main research contents of operating mode are aspects related to operation performance when DESSs are connected to the power grid.

(5) Environmental Benefit

Environmental benefit is to reflect the energy-saving and emission-reduction benefit provided by DESSs. While renewable energy and fuel cell replace the traditional fossil fuel power, pollution emissions will be significantly reduced.

2.2. Practical Evaluation Index System
According to the principle of higher contribution rate, easier accessibility and quantifiable characteristic, a practical evaluation index system is established, which contains nine practical indexes.

(1) Investment Per kW: x_1(yuan/kW)

This index reflects the investment feasibility of DESSs from side and directly measures the raw material cost, moving cost, etc.

(2) Profit Rate of Investment: x_2 (%)

If the profit rate of investment is not less than the standard investment profit rate, the project is considered to be acceptable, otherwise unfeasible.

(3) Payback Period of Investment: x_3 (year)

Payback period of investment represents the duration lasting from the date when the DESS project starts working to the day on which the original investment is totally paid off by using the net income of this project.

(4) Capacity of Power Supply: x_4 (MW/hour)

This index gives a direct reflection of load capacity and scale of the system. It can be utilized to provide valuable experience for operation and maintenance management of DESSs.

(5) Energy Utilization Ratio: x_5 (%)

Energy utilization ratio means the rate of consumption amount of the energy accounting for the total supplied to the system. The utilization efficiency and degree of energy of DESS is better reflected by this index.

(6) Power Generation Ratio of New Energy: x_6 (%)

Power generation ratio of new energy equals to the proportion that new energy power generation accounts for the total power supply per year. The technology level of new energy development can be revealed by this index.

(7) Annual Utilization Hours of Power: x_7 (hour)

Annual utilization hours of power are counted by hours and means annual operational time of DESSs. Ability of power supply is well reflected by this index.

(8) Total Emission Reduction: x_8 (thousand tons)

When comparing with the traditional centralized fossil fuel power under circumstance of providing the same load supply, total emission reduction refers to the total -emission reduction of DESSs.

(9) Total Emission Reduction Rate: x_9 (%)

Total emission reduction rate means the ratio that amount of total emission reduction by DESSs accounts for that by traditional fossil fuel power per year while providing the same load supply. This index is more obvious to reflect the environmental value of DESSs.

3. Classification Framework
In the classification framework, DESSs are mainly divided into three types based on the scale and application field. These three types are defined as building sites, regional sites and island sites.

3.1. Building Sites
Building sites consist of hotels, hospitals, commercial centers, public buildings, etc. Their economic relationships are simple, which can result in flexible application. In addition to small scale, less varieties of terminal loads and lower energy efficiency, building sites have the characteristic of long-time operation per year as well. Hence, they will be competitive only under certain conditions. Meanwhile, load requirements in this type can roughly coincide with the supply ratio of cooling and power or heating and power of gas engine. Besides, grid-connected operation as well as maximum energy cascade utilization is achievable for building sites [10].

3.2. Regional Sites
Regional sites are mainly composed of industrial parks, university towns, shopping malls, integrated parks, large residential parks, etc. Such large-scale type of sites has various terminal loads, such as

production areas, tourist centralized service areas, large commercial facilities and so on. Load types may be summed up as follows: civil heat load, industrial heat load, etc. Annual operating time of regional sites can be flexibly adjusted according to actual needs. They are highly competitive on the economic front which can be proved by the significantly lower investment Per kW and high profit rate. While meeting the power supply, these sites can realize complementary operation with large power grid by means of peak load shifting. DESS of Guangzhou University Town is currently the largest distributed energy projects in China, which is a regional site.

3.3. Island Sites
The island type of scenes, whose main developing form is smart micro-grid, generally refers to the independent island with high permeability of distributed generations. The entire system of this type is "single-unit and single-grid" with fluctuating loads and isolated operation. To satisfy the internal rate of return, power price of island end-users will reduce and economic efficiency of power will increase. Areas around the island are rich in renewable energy. Effective development of island energy can greatly ease the power shortage. In the planning of island sites, it is necessary to forecast the output of distributed energy, optimize the energy storage and build a comprehensive energy network.

4. Practical Classification Evaluation Approach

4.1. Designing Idea of PCEA
In the longitudinal dimension, considering five influencing factors: economic benefit, characteristic of combined supply, energy utilization, operating mode and environmental benefit, the practical evaluation index system is constructed. Meanwhile, in the horizontal dimension, DESSs are divided into three types based on the scale and application field.

4.2. The Overall Procedure of AHP-EWM
The AHP-EWM mainly focuses on solving two basic issues. The first issue is how to make full use of such many evaluation indexes to evaluate DESSs. Under the consideration of expert opinion, AHP can be utilized to deal with the first issue. The other one is the problem that evaluation results are excessively concentrated by the type. Based on the information theory, the information entropy presented by the same index of different types of DESSs is different. Given to this point, ICC based on EWM is introduced to break the hierarchies between the evaluation results of different types of DESSs.

Procedures of the approach are listed as follows.

(1)Data pre-processing:

The number of evaluated DESSs is defined as: $m=m_L+m_Q+m_H$, where m_L、m_Q、m_H represents the number of building sites, regional sites and island sites. The number of practical evaluation indexes is defined as n. Hence, raw $m\times n$ matrix is written as follows:

$$X_{m\times n}=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

Z-score standardized transformation is used to improve the representation of sample data considering the universality of the normal distribution. The standardized equation is written as follows:

$$x_{ij}^{'}=\frac{x_{ij}-x_{jmean}}{x_{jstd}} \tag{2}$$

Where $i \in \{1,2,...,m\}$, $j \in \{1,2,...,n\}$. x_{jmean} and x_{jstd} are respectively the mean value and standard deviation value of the column data of the raw matrix. Then the $x'_{m\times n}$ is solved out by Z-score standardized transformation.

Numerical deviations of different indexes are very large. Indexes with larger values play a strengthen role in comprehensive analysis while indexes with smaller values play the opposite role. To deal with this problem, 0-1 standardized transformation is adopted to eliminate the influence.

$$r_{ij} = \frac{x'_{ij} - x'_{ij\min}}{x'_{ij\max} - x'_{ij\min}} \tag{3}$$

Where x'_{ijmax} and $x'_{ijmin}$are the minimum value and maximum value of the matrix$x'_{m\times n}$. Through the two-step transformation, the raw evaluation matrix is transformed into the standardized matrix$R_{m\times n}$.

(2)Calculation of index-contributing coefficient (ICC):

Evaluation values of a certain type of DESSs will be collectively too large (or too small), which results from that some indexes of this type have larger (or smaller) values comparing with these indexes of other types. This causes the problem that evaluation results are excessively concentrated by the type. Hence, EWM based ICC is introduced to measure the influencing degree of the same index from different types of DESSs.

Detailed steps are listed as follows:

Firstly, information entropy of a index from different DESSs can be solved by the following equation:

$$E_{\alpha j} = -\ln(m)^{-1} \sum_{i=1}^{m_\alpha} p_{ij} \ln p_{ij} \tag{4}$$

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m_\alpha} r_{ij}}, \ (p_{ij} \neq 0) \tag{5}$$

$$\lim_{p_{ij}\to 0} p_{ij} \ln p_{ij} = 0, \ (p_{ij}=0) \tag{6}$$

Then the ICC of a practical evaluation index from different types of DESSs is defined as $C_{\alpha j}$ and can be solved by the following equation:

$$c_{\alpha j} = \frac{1 - E_{\alpha j}}{n - \sum_{j=1}^{n} E_{\alpha j}} \tag{7}$$

ICC matrix: $C_{3\times n}=[C_L \ C_Q \ C_H]^T$ is composed of ICC from all types of DESSs. Influences made by practical evaluation indexes on each type are different.

(3)Evaluation results:

AHP is adopted to calculate weights of practical evaluation indexes for DESSs. This method avoids the limitations as a result of simply relying on the data.

Firstly, according to the importance between each pair of indexes combined by the accuracy requirements of evaluation results, the judgment matrix $D_{n\times n}$ is obtained.

Secondly, to calculate the maximum eigenvalue λ_{max} and the corresponding eigenvector $W_{AHP}=\{W_{1(AHP)}, \ W_{2(AHP)}, \ \cdots, \ W_{n(AHP)}\}$of the judgment matrix $D_{n\times n}$.

Finally, due to the estimation error, which will destroy consistency of the judgment matrix $D_{n\times n}$, the consistency checking is indispensable. If the inconsistency caused by deviation is acceptable, the normalized eigenvector W_{AHP} will be the weight vector, otherwise the judgment matrix should be re-constructed. Procedures of the consistency checking are presented as the reference [11].

Equation for evaluation results of the comprehensive competitiveness without ICC is written as follows:

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$$M_i=\sum_{j=1}^{n} r_{ij}\omega_{j(AHP)}=\left[r_{11}\ r_{12}\ \dots\ r_{1n}\right]\begin{bmatrix}\omega_{1(AHP)}\\ \omega_{2(AHP)}\\ \dots\\ \omega_{n(AHP)}\end{bmatrix} \tag{8}$$

Where M_i is the evaluation result of DESS i. $w_{j(AHP)}$ represents the weight of index j.
Equation for evaluation results of the comprehensive competitiveness with ICC is written as follows:

$$W_{\alpha j}=\frac{c_{\alpha j}\omega_{j(AHP)}}{\sum_{j=1}^{n} c_{\alpha j}\omega_{j(AHP)}} \tag{9}$$

$$M_{m_\alpha}=\left[M_{\alpha 1}\ M_{\alpha 2}\ \dots\ M_{\alpha m_\alpha}\right] \tag{10}$$

$$M_{\alpha i}=\sum_{j=1}^{n}\left(r_{ij}W_{\alpha j}\right) \tag{11}$$

Where $W_{\alpha j}$ refers to the weight of index j for some type of DESSs based on ICC. M_{m_α} is made up of evaluation results of all evaluation objects.$M_{\alpha i}$ represents evaluation result of DESS i.
Through the practical evaluation index system and weights of indexes based on AHP combined with ICC, PCEA transforms the comprehensive competitiveness into quantitative evaluation results. By comparison of evaluation results of comprehensive competitiveness, competitive level of DESSs can be obtained. If evaluation result is larger, the DESS will be more competitive in accomplishing high effective utilization of local diversified energy, giving full play to potential economic value and providing valuable reference.

5. Case Studies

Statistical data of practical evaluation indexes from 21 DESSs in southern part of China were collected for case studies. In order to facilitate the comparison of evaluation results, numbers of three sites are 7. The raw statistical data are shown in Tab.1, in which X1~X9 represent practical evaluation indexes, L1~L7 represent building sites, Q1~Q7 represent regional sites, H1~H7 represent island sites.

Table 1. Raw Statistical Data

No.	X1	X2	X3	X4	X5	X6	X7	X8	X9
L1	1.140	7.720	11.000	28.014	72.300	0.243	3.378	0.500	8760
L2	1.345	6.099	14.520	40.060	61.455	0.287	2.669	0.660	8760
L3	1.630	7.257	9.350	33.056	95.436	0.348	3.175	0.425	8000
L4	1.345	6.099	14.520	40.060	61.455	0.287	2.669	0.660	8000
L5	1.630	7.257	9.350	33.056	95.436	0.348	3.175	0.425	8760
L6	1.345	6.099	14.520	40.060	61.455	0.287	2.669	0.660	8760
L7	1.630	7.257	9.350	33.056	95.436	0.348	3.175	0.425	8500
Aver.	1.438	6.827	11.801	35.337	77.568	0.307	2.987	0.536	8506
No.	X1	X2	X3	X4	X5	X6	X7	X8	X9
Q1	0.533	7.880	12.210	108.207	73.630	0.468	7.030	0.700	8000
Q2	0.608	6.068	16.606	160.147	38.288	0.533	5.413	0.952	8400
Q3	0.789	7.013	6.349	123.356	100.137	0.692	6.256	0.364	7980
Q4	0.608	6.068	16.606	160.147	38.288	0.533	5.413	0.952	7000
Q1	0.789	7.013	6.349	123.356	100.137	0.692	6.256	0.364	7900
Q2	0.608	6.068	16.606	160.147	38.288	0.533	5.413	0.952	6500
Q3	0.789	7.013	6.349	123.356	100.137	0.692	6.256	0.364	8000
Aver.	0.675	6.732	11.582	136.959	69.843	0.592	6.005	0.664	7683
No.	X1	X2	X3	X4	X5	X6	X7	X8	X9
H1	1.141	16.550	19.240	26.360	81.000	0.488	1.041	0.650	2500
H2	1.403	13.075	21.741	37.695	68.850	0.600	0.822	0.735	2600

H3	1.631	15.392	16.354	32.423	91.530	0.698	0.968	0.553	2000
H4	1.403	13.075	21.741	37.695	68.850	0.600	0.822	0.735	3000
H5	1.631	15.392	16.354	32.423	91.530	0.698	0.968	0.553	4000
H6	1.403	13.075	21.741	37.695	68.850	0.600	0.822	0.735	4000
H7	1.631	15.392	16.354	32.423	91.530	0.698	0.968	0.553	4500
Aver.	1.463	14.564	19.075	33.816	80.306	0.626	0.916	0.644	3229

At first, raw statistical data of practical evaluation indexes from case DESSs were normalized by the data pre-processing according to equations (2)~(3).
Secondly, according to the AHP method, the measurements of importance degree between each pair of indexes were set as: 1, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, where 1 represents the same importance degree between two indexes, 2.6 represents the largest disparity between two indexes. The disparity of importance degree varies from small to large corresponding with figures from small to large. Weights of practical indexes by using AHP are shown in Tab.2.
Thirdly, index-contributing coefficient matrix $C_{3\times n}$ for practical evaluation indexes was carried out by equations (4)~(7). Results are shown in Tab.3.
Finally, according to equation (10), evaluation results and corresponding radar chart of comprehensive competitiveness without ICC are shown in Tab.4 and Fig. 2(a). And, evaluation results by equations (9)~(11) are shown in Tab.5 and Fig.2(b).
Comparing Tab.1 and Tab.2, on the one hand, the practical evaluation index X2 has the largest weight of 0.18. Values of index X2 from island sites are far bigger than that from building sites and regional sites. Moreover, weights of indexes X5 and X8 are relatively higher. They are 0.16 and 0.14 respectively. Average values of X5 and X8 from island sites are respectively not less than or only slightly smaller than that from the other two types of DESSs. On the other hand, in terms of the building sites and the regional sites, average value of X4 with a relatively higher weight from regional sites is even up to more than four times of that from building sites.
As shown in Tab.4 and Fig.2(a), evaluation results of island sites are always larger than that of regional sites, which are always greater than that of building sites. This may lead impractical results that DESS with lower comprehensive competitiveness from island sites may have larger evaluation result than that of the DESS with higher comprehensive competitiveness from other types.
To avoid the above problems and improve the evaluation rationality of comprehensive competitiveness from each type of DESSs, EWM was used to introduce the ICC. Results of ICC are shown in Tab.3. Through the horizontal comparison of ICC of each index, X1 and X4 have higher contribution degree to comprehensive competitiveness. Furthermore, objective contribution coefficient of index X2 and index X5 are smaller than that of index X1 and index X4. This helps solve the problem that evaluation results from island sites are always higher than that from the other two types. Thus, objective ICC based on the EWM reduces the impact of pure subjective weights calculated by AHP. Evaluation results of comprehensive competitiveness are restrained and corrected by objective ICC, which improves the objective rationality of evaluation results.

Table 2. Weights of Indexes Based on AHP

No.	X1	X2	X3	X4	X5	X6	X7	X8	X9
Weight	0.0905	0.1899	0.0787	0.1044	0.1684	0.1203	0.0688	0.1484	0.0607

Table 3. The index-contributing coefficient(ICC)

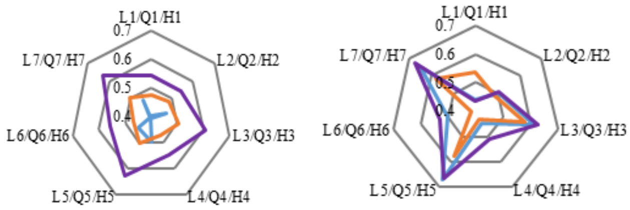
No.	X1	X2	X3	X4	X5	X6	X7	X8	X9
L	0.1233	0.1040	0.0969	0.1233	0.0969	0.1233	0.1040	0.0969	0.1316
Q	0.1063	0.1018	0.1081	0.1063	0.1081	0.1063	0.1018	0.1081	0.1532
H	0.1356	0.0993	0.0987	0.1356	0.0987	0.1356	0.0993	0.0987	0.0985

Table 4. The Evaluation Results of Comprehensive Competitiveness without ICC

No.	1	2	3	4	5	6	7
L	0.3116	0.3417	0.3997	0.3349	0.4066	0.3417	0.4042
Q	0.4766	0.4864	0.5042	0.4739	0.5034	0.4694	0.5043
H	0.5442	0.5448	0.6090	0.5484	0.6270	0.5574	0.6315

Table 5. The Evaluation Results of Comprehensive Competitiveness with ICC

No.	1	2	3	4	5	6	7
L	0.4414	0.5029	0.6131	0.4476	0.6684	0.5029	0.6495
Q	0.5367	0.4852	0.5786	0.4331	0.5756	0.4144	0.5794
H	0.4365	0.5054	0.6267	0.5127	0.6634	0.5311	0.6726



(a)without ICC (b) with ICC

Figure 2. Radar chart of evaluation results.

Eventually, as in Tab.5 and Fig.2(b), brief summaries are listed as follows:

(1) From the microscopic classification perspective:

1). Evaluation results of comprehensive competitiveness from building sites {L5，L7}, regional sites {Q3，Q5，Q7} and island sites {H5，H7} are larger in their respective types. These DESSs have higher reference values for operation and maintenance management of respective type of DESSs.

2). Evaluation results of comprehensive competitiveness from building sites {L1, L4}, regional sites {Q4, Q6} and island sites {H1} are smaller in their respective types. Appropriate measures should be taken to rectify the management of operation and maintenance to improve the competitiveness in time.

(2) From the macroscopic overall perspective:

Introduction of the ICC solves the problem that evaluation results are excessively concentrated by the type. Taking the Q1 and H1 as an example, before introducing the ICC, evaluation results are $M_{H1} > M_{Q1}$; but after introducing the ICC, evaluation results are just the opposite $M_{H1} < M_{Q1}$.

6. Conclusion

The PCEA is intended to address the quantification problem in investment and construction planning of DESSs. Innovation points and main research contents can be concluded as follows:

Practical evaluation index system closely corresponds to different aspects of comprehensive competitiveness. Classification framework is established under the consideration of developing features. Indexes and classification results can be applied to classification evaluation of DESSs AHP efficiently applies evaluation indexes to comprehensive evaluation of DESSs. By introducing ICC based on EWM, the issue that evaluation results are excessively concentrated by the type can be solved. Hence, approach proposed in this paper will provide valuable evaluation results of DESSs.

In summary, on the one hand, PCEA takes full consideration of differences among different types of DESSs, on the other hand, evaluation results can not only provide competitive DESS model for planning, but also discover low competitive DESSs timely. Rationality and potential promotional value of PCEA are verified by case results of DESSs in southern part of China.

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