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Multi-Criteria Evaluation of Distributed Energy System Based on Order Relation-Anti-Entropy Weight Method

Wanyu Wang [1], Haochen Li [2], Xueliang Hou [1], Qian Zhang [2],* and Songfeng Tian [2]

[1] Institute of Engineering Management, North China Electric Power University, Beijing 102206, China;
22151126@ncepu.edu.cn (W.W.); 2192214011@ncepu.edu.cn (X.H.)

[2] Department of Power Engineering, North China Electric Power University, Baoding 071003, China;
2192214017@ncepu.edu.cn (H.L.); 2192214079@ncepu.edu.cn (S.T.)

* Correspondence: zhangqian@ncepu.edu.cn; Tel.: +86-312-752-2795

Abstract: Distributed Energy System (DES), a comprehensive energy utilization system distributed on user side, has been recognized as a promising energy utilization method that can improve energy efficiency, reduce greenhouse gas emissions, and achieve sustainable development. However, the DES is usually driven by various energy sources, and it is a complex issue to decide the composition of the system. To improve the incompleteness of a single subjective or objective assessment. So, it is urgent to find a comprehensive and efficient decision-making method for different systems. This paper states a total of 23 indicators in 4 criterion group: technology, economy, environment, and society. Based on the combination of the order relation analysis method (G1) and the anti-entropy weighting method (a-EWM), a comprehensive evaluation model, order relation-anti-entropy weight model (G1-aEWM), of distributed energy is established. This comprehensive evaluation model is used to analyze a hospital in Henan and find the final solution for the distributed energy system of the hospital. The empirical analysis results verify the rationality of the comprehensive evaluation model and provide an evaluation basis for the establishment of distributed energy systems in the future.

Keywords: distributed energy system; index evaluation system; sequential analysis method (G1); anti-entropy weighting method; comprehensive evaluation

1. Introduction

At present, China is the largest energy consumer in the world with its primary energy consumption still dominated by coal and oil, reaching more than 80.8% [1,2]. The extensive use of fossil fuels has brought about a series of problems such as massive carbon dioxide emissions, environmental degradation, melting glaciers, and frequent occurrence of extreme weather events [3–5]. China is in the midst of a quest to replace fossil fuels with clean, sustainable energy sources. However, the efficiency of renewable energy conversion is low and the continuous and stable supply cannot be achieved [6–9]. As a result, the Chinese government has enacted new policies and supports energy system transformations. Distributed energy system, as an important means to improve the utilization rate of renewable energy sources, has become a highlight of the reform [9]. Nowadays, regional energy planning is a fundamental urban construction plan in China [10].

The distributed energy system can be a clean and low-carbon way of energy utilization, which can realize the nearby consumption of renewable energy, guarantee energy supply, and improve the urban living environment [11–13]. With the maturity of technology, policy support, and continuous innovation of business models, China has also witnessed a period of steady growth.

The initial application of distributed energy technologies in China was represented by district heating and cogeneration in the northern part of the country. Nowadays, various renewable energy technologies, waste heat utilization technologies, and distributed triple supply technologies of natural gas are being used in many regions; especially in recent years, there has

been an increasing focus on low-carbon heating methods, including combined heat and power (CHP) technology, heat pumps, solar heating, biomass boilers, and hydrogen boilers. The application of district cooling and heating systems in urban high-density building complexes has also developed rapidly; the projects currently completed or under construction in China include the district cooling project of Nanjing Zhonglou Development Zone, the district cooling system of Xiangtan City Center, the district cooling project of Guangzhou University City, and the water source heat pump cooling and heating system of Dalian Xinghai Bay [14,15]. However, in the practice of some distributed energy systems, the performance is not as good as expected. The evaluation methods of energy system programs are controversial because of the complexity of the evaluation objects themselves and the differences in objectives. Therefore, how to conduct a reasonable and comprehensive evaluation of the system is the focus and difficulty of the current research.

Since the evaluation of the distributed energy system should be comprehensively considered in terms of social, technological, economic, and environmental benefits, the assessment index system is a multi-level index set [16]. In this way, decision makers can take into account the impact of all aspects to make sound decisions based on their priorities. Multi-criteria integrated evaluation approach has been widely used to solve energy-related problems. Chatzimouratidis et al. [17] adopted the analytical hierarchy process (AHP) and evaluated ten types of power plants using renewable energy, nuclear energy, and fossil fuels from three aspects: technology, economy, and sustainability. Jing et al. [18] comprehensively analyzed the feasibility of solid oxide fuel cell based combined cooling heating and power (SOFC-CCHP) applications for public buildings in terms of technology, economy, and environment by combining the grey relational analysis (GRA) method and the information entropy principle. Li et al. [19] evaluated the comprehensive performance of cogeneration systems under different operating conditions using the weighting method and the fuzzy optimum selection method from the perspectives of energy analysis, economic operation, and environmental impact. In order to assess the readiness of a country for sustainable energy transition, Neofytou et al. [20] used the analytic hierarchy process (AHP) and the preference ranking organization method for enrichment of evaluations (PROMETHEE) to conduct an integrated evaluation based on political, economic, technological, and social criteria. Kun et al. [21] constructed a multi-criteria integrated assessment model by combining the optimal weighting method and the grey incidence method, and an optimized CCHP system was evaluated on the basis of this assessment method. The result indicated that the optimized CCHP system was the best solution. The analytic hierarchy process (AHP) included in the above studies determines the weights according to the opinions of experts, and there is a consistency test problem in the determination of subjective weights. The entropy information method is determined based on objective data, but there are problems such as excessive sensitivity of the indicators and fluctuation of the weight values [22–24]. In this paper, some improvements are made to the weighting method.

In this paper, a distributed energy system evaluation model with a total of 23 indicators is constructed based on 4 criteria of technology, economy, environmental, and society protection, and the energy system is evaluated by a combination of the sequential analysis method which is to determine the importance of each criterion through expert stratification to obtain subjective weight and the anti-entropy weighting method that is to calculate the anti-entropy value of each index and obtain the objective weight corresponding to the index according to the anti-entropy value. The sequential analysis method improves the analytic hierarchy process for the selection of subjective weights, which can overcome the shortcomings of AHP that requires complex consistency verification. The anti-entropy weighting method is an objective weighting method that improves the entropy-weighting method, which effectively improves the uncertainty of indicators and reduces the contrast of weights. This comprehensive evaluation method considers both objective and subjective weights, and it not only adopts experts' analysis on the importance of each index, but also makes use of the internal information contained in the objective raw data itself, which can make the evaluation results more rational and accurate. Finally, it is applied in the planning

of a hospital's distributed energy system and select the appropriate option, which can provide a reference for the construction of distributed energy systems in the future.

2. Multiple-Criteria Evaluation Approach based on G1-aEWM

The evaluation of Distributed Energy System (DES) is dominated by diverse criteria, it is of most importance to select criteria. Technology, economy, environment and society are the four criteria, including several sub-criteria, which the studies focus on. The selected sub-criteria are shown in Figure 1. It can be re-selected as the actual conditions considered.
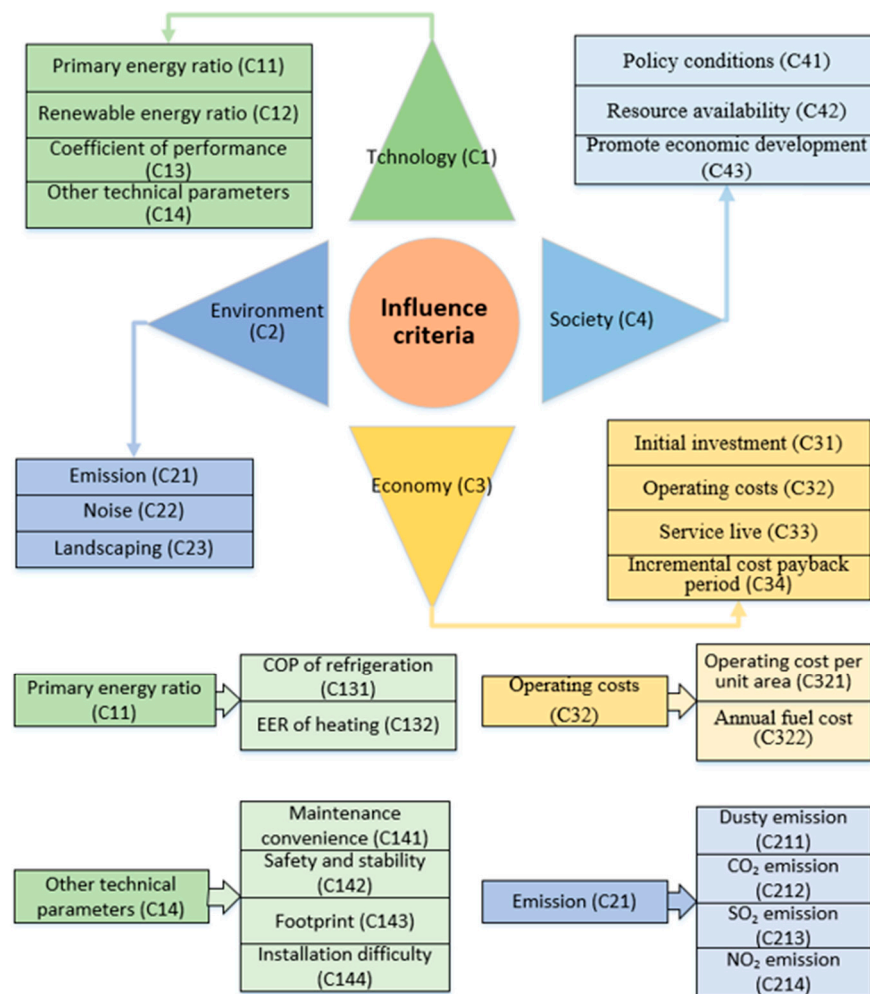

Figure 1. Evaluation criteria of Distributed Energy System (DES).

(1)   Technical criterion (C1)

This criterion is staple for evaluating DES, indicating the utilization, performance coefficient, safety, technical difficulty, etc.

(2)   Economical criterion (C2)

Economic criterion is the pivotal index for the system evaluation. Including various cost, live cycle, incremental cost payback period, etc.

(3)   Environmental criterion (C3)

Generally, it is used to evaluate the environmental pollution level, and it has been increasingly taken seriously, considering the importance of the environmental protection. The index usually involves dusty, CO_2, SO_2, NO_2 emissions, and noise.

(4)   Social criterion (C4)

For this item, it aims to the influences of DES on society. Policy condition, economic development and resource available are primarily considered.

Generally, there is a multiple correlation among the criteria which are divided into three tiers. For example, the advanced technology basically with higher utilization and lower emission, but the investment may increase substantially. It means that there is a positive correlation between C1 and C2, a negative correlation between C1 and C3. The superior maintainability represents better value of maintenance convenience (C14) and service live criterion (C33), however, with worse value of footprint criterion (C143) and emission criterion (C21) and vice versa. Therefore, it is difficult to make the decision without an appropriate method.

3. G1-Anti-Entropy Weight Method Evaluation Model

An effective DES evaluation model can make a comprehensive and reasonable evaluation of DES, helping the decision maker to opt the best proposal by the score of decision function D.

$$D = f(R, W), (R = S \cap E \cap A) \tag{1}$$

where R is information collection consists of S, E and A, S is the options collection, E shows the criteria of options, A contains the information of expert comments. W is the weight collection calculated by G1-AEWM.

Based on the criteria of each option, the criteria matrix is expressed as follows:

$$S = \{s_1, s_2, \ldots, s_m\} \tag{2}$$

$$X = \{x_1, x_2, \ldots, x_n\} \tag{3}$$

$$E = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \tag{4}$$

where m is the number of the options, n is the number of criteria, and a_{ij} represent the j criterion of option s_i.

The evaluation method consists three steps. The framework of this method is shown in Figure 2. Firstly, determine the subjective and objective weights. Secondly, calculate the comprehensive weight. Finally, use the comprehensive evaluation function to obtain the comprehensive evaluation value of each program, and obtain the best option.

In Figure 2, the subjective and objective weight are determined by G1 method and AEWM, respectively.

(1)   Calculate the subjective order relationship

Ranking the criteria in order of the importance lessened by l experts hierarchically, as the most important indicator chose from X is x_1^* and the least important criterion is x_r^*. The order relationship is $x_1^* \succ x_2^* \succ \ldots \succ x_r^*$, and there are tiers of criteria. The order relationship index matrix of tier is constructed as follows:

$$E_j^* = \begin{bmatrix} a_{11}^* & a_{12}^* & \cdots & a_{1r}^* \\ a_{21}^* & a_{22}^* & \cdots & a_{2r}^* \\ \vdots & \vdots & \ddots & \vdots \\ a_{l1}^* & a_{l2}^* & \cdots & a_{lr}^* \end{bmatrix} \tag{5}$$

Setting Ri_{jk} as the relative importance of adjacent index that from evaluation tier j of expert i.

$$Ri_{jk} = \frac{\omega i_{j(k-1)}^s}{\omega i_{jk}^s} (k = r, r-1, \ldots, 2, i = 1, 2, 3, \ldots l) \tag{6}$$

where ωi_{jk}^s and $\omega i_{j(k-1)}^s$ is the subjective criterion weight of xi_{jk}^* and $xi_{j(k-1)}^*$.

The value range of Ri_{jk} is 1.0–1.8, as shown in Table 1, and ωi_{jk}^s takes the value 1.0 when k equals r. For a special case that $\prod\limits_{k=1}^{r} Ri_{jk} > 1.8$, it means that the cumulate importance exceeds the extremely importance situation, to avoid this counterintuitive situation, ensure $\prod\limits_{j=1}^{r} Ri_{kj} \le 1.8$, a ratio factor is proposed, and set the corrected relative importance $Ri_{kj}^{'}$ as follows:

$$ p = \sqrt[r-1]{\frac{1.8}{\prod\limits_{k=1}^{r} Ri_{jk}}}, \tag{7} $$

$$ Ri_{jk}^{'} = Ri_{jk} * p, \tag{8} $$

Table 1. The value range of Ri_{kj}.

Value	Importance of Criteria $\omega_{j(k-1)}^s$ to ω_{jk}^s
A (1.0)	Equally importance
C (1.2)	Slightly importance
E (1.4)	Obviously importance
G (1.6)	Quiet importance
I (1.8)	Extremely importance
B (1.1), D (1.3), F (1.5), H (1.7)	Corresponding to the adjacent situation

The weight is calculated as follows:

$$ \omega i_{jr}^s = \left(1 + \sum_{l=2}^{r} \prod_{k=l}^{r} Ri_{jk}^{'} \right)^{-1} \tag{9} $$

$$ \omega i_{j(k-1)}^s = Ri_{jk}^{'} * \omega i_{jk}^s \quad (k = r, r-1, \ldots, 2) \tag{10} $$

Set ω_t^s as the weighted arithmetic mean of the subjective weight evaluated by experts for each criterium and calculate as follows. So the subjective weight set is $Y = \{\omega_1^s, \omega_2^s, \ldots, \omega_n^s\}$.

$$ \omega i_t^s = \prod_j^z \omega i_{jk}^s \tag{11} $$

$$ \omega_t^s = \frac{1}{l} \sum \omega i_t^s \tag{12} $$

(2)   Evaluation criteria normalization

The criteria are divided into two categories, positive correlated criteria and negative correlated criteria. The positive are the criteria that the larger the value, the better the property, and the negative are the opposite. To avoid the impact of different units and magnitudes, normalize matrix E to $B = \left[b_{ij} \right]_{m \times n}$.

$$ b_{ij} = \begin{cases} \frac{a_{ij} - \min(a_i)}{\max(a_i) - \min(a_i)} & (i) \\ \frac{\max(a_i) - a_{ij}}{\max(a_i) - \min(a_i)} & (ii) \end{cases} \tag{13} $$

where (i) applies to positive correlated criteria, (ii) to the negative correlated criteria.

(3)   Calculate the objective weight

Calculate the entropy and anti-entropy of the criteria by different methods as follows:

$$
\begin{cases}
h_t^1 = -\sum_{i=1}^{m} p_{ij} \ln(1 - p_{ij}) & (1) \\
h_t^2 = -\sum_{i=1}^{m} (1 - p_{ij}) \ln p_{ij} & (2) \\
h_t^3 = -\frac{1}{\ln m} \sum_{i=1}^{m} p_{ij} \ln p_{ij} & (3)
\end{cases}
\tag{14}
$$

where $p_{ij} = \frac{b_{ij}}{\sum_{i=1}^{m} b_{ij}}$, and when $p_{ij} = 0$, set $h_t = 0$.

The objective weight is calculated as follows:

$$
\omega_t^o = \frac{1 - h_t}{n - \sum_{i=1}^{n} h_t}
\tag{15}
$$

(4) Calculate the comprehensive weight

$$
\omega_t = \frac{\omega_t^s * \omega_t^o}{\sum_{t=1}^{n} \omega_t^s * \omega_t^o}
\tag{16}
$$

The comprehensive weight matrix is as $\boldsymbol{D} = [\omega_1 \; \omega_2 \; \ldots \; \omega_n]^T$. Set the normalized comprehensive weight decision matrix $\boldsymbol{Z} = \boldsymbol{B} \cdot \boldsymbol{D} = [b_{ij}]_{m \times n} [\omega_{ij}]_{n \times 1} = [e_1 \; e_2 \; \ldots \; e_m]^T$, the evaluation result of each option is as $D(s_i) = f(S_i, E, A, W) = e_i$, and the best proposal can be obtained at $e_i = e_{\max}$.
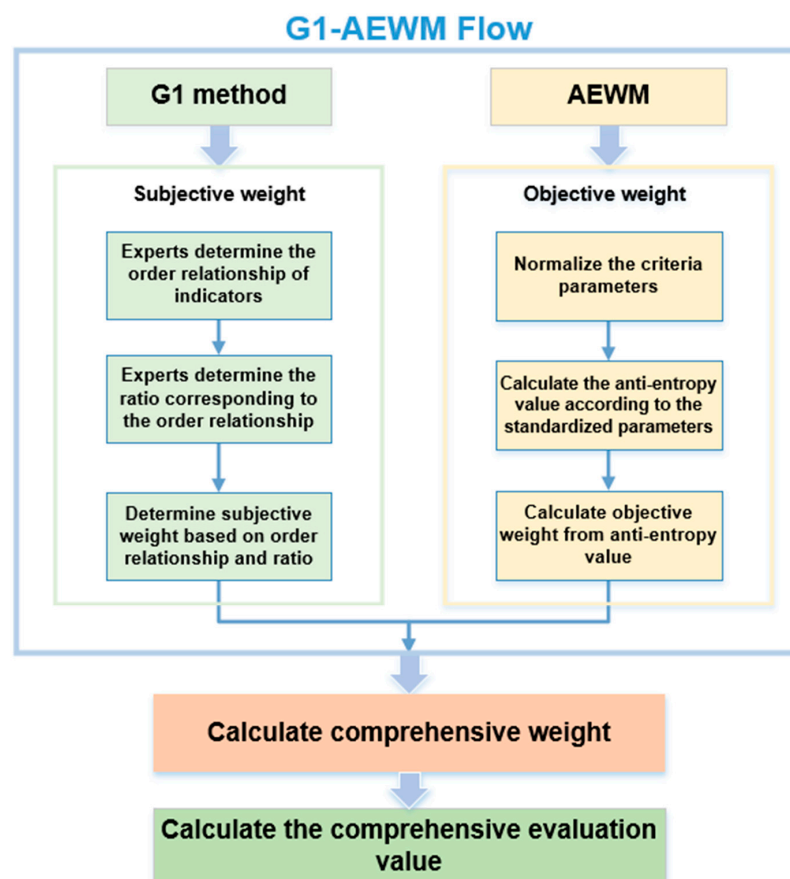

Figure 2. G1-AEWM Flow.

4. Appraisal Analysis of DES

A practical case of a hospital in Xinxiang is evaluated in this section. The energy service area includes three main buildings, with a construction area of 190,000 m^2. The design electric load is 8706.8 kW, there are four months heating demand which designed load is 9235 kW, five months cooling demand with a design load of 12,698 kW. The annual hot water load is 1200 kW.

The five DES schemes, as shown in Table 2, proposed by considering the available energy resource around the hospital in early stage, are evaluated and compared using G1-AEWM.

Table 2. Energy system composition.

Option	System	Component		
S1	Traditional System	Electric Network	Electric Air Conditioner	Gas Boiler
S2	Natural gas combined cooling, heating and power (N-CCHP) system	Gas turbine	Waste heat boiler	Lithium bromide unit
S3	Ground source heat pump (GSHP) system	Electric network	Ground source heat pump unit	Ground source heat pump unit
S4	Solar air source heat pump (S-ASHP) system	Electric network	Air source heat pump unit	Solar thermal device
S5	Multi-energy complementary (MEC)system	N-CCHP unit	Ground source heat pump unit	

In order to compare the practicability of G1-AEWM, the criteria shown in Figure 1 are selected to evaluate the different schemes. For the criterion C322, it is divided into two index as summer (C3221) and winter (C3222), taking into account seasonal difference. For criteria C14, C22, C23, and C4, these indexes are qualitative indexes, valued according to the characteristics of the scheme. The original data of various indicators are given in the Appendix A due to space limitations. The feature of all indexes are shown in Table 3, for convenience, use x1 to x23 to indicate each criteria.

Table 3. The feature of 5 DESs.

Criteria	Symbol	Pertinence	Unit	S1	S2	S3	S4	S5
C11	x1	positive	-	47.8	92.5	76.1	62	81.5
C12	x2	positive	-	18.4	5.4	30.8	25.2	27
C131	x3	positive	-	5.6	1.36	5.4	2.8	3.7
C132	x4	positive	-	0.88	0.93	3.8	2.8	2.6
C141	x5	positive	-	95	85	75	90	80
C142	x6	positive	-	90	75	85	95	80
C143	x7	positive	-	85	80	95	70	90
C144	x8	negative	-	90	85	75	60	95
C211	x9	positive	ton/year	0	11,756	36,313.2	19,491.1	28,946
C212	x10	positive	ton/year	0	743.1	276.2	122.5	416.3
C213	x11	positive	ton/year	0	96.1	115.5	59.7	109.7
C214	x12	positive	ton/year	0	25.4	19.1	9.5	21
C22	x13	negative	-	85	90	60	70	75
C23	x14	positive	-	60	70	90	80	75
C31	x15	negative	million	36.21	62.80	74.41	42.75	51.06
C321	x16	negative	million	77.67	34.94	52.34	58.78	47.12
C3221	x17	negative	RMB/m^2	17.3	39.8	17.9	34.6	24.5
C3222	x18	negative	RMB/m^2	50.2	47.5	20.8	28.2	28.8
C33	x19	positive	year	20	30	30	25	30
C34	x20	negative	year	6.3	9.7	8.4	5.6	9.3
C41	x21	positive	-	50	90	85	80	95
C42	x22	positive	-	90	90	70	75	85
C43	x23	positive	-	70	90	90	85	95

The date in Table 3 are obtained from the date of the hospital above-mentioned in the attachment. The order relations are scored by five experts as shown in Table 4, which using 1 to 4 to represent the criterion of each criteria tier, as for first tier, 1 represents C1, 4 represents C4, and so on. the order of the number in Table 4 represents the order of the importance of the corresponding criteria. According to the order of criteria in Table 4, the ratio of importance between the two criteria is shown in Table 5, as E of p1 in first tier represents the relationship between 3 and 2 in the first tier of p1 in Table 4. In view of the fact that the sub-criteria of C13 and C322 are of same importance respectively, they are not being scored.

Table 4. Order relations scoring of criteria.

Expert	First Tier	C1 Tier	C14 Tier	C2 Tier	C21 Tier	C3 Tier	C32 Tier	C4 Tier
p1	3 > 2 > 1 > 4	1 > 2 > 3 > 4	3 > 1 > 2 > 4	1 > 2 > 3	1 > 2 > 3 > 4	2 > 1 > 3 > 4	1 > 2 > 3	1 > 2 > 3
p2	1 > 3 > 2 > 4	3 > 1 > 2 > 4	1 > 3 > 4 > 2	1 > 3 > 2	2 > 3 > 4 > 1	1 > 2 > 3 > 4	3 > 2 > 1	1 > 3 > 2
p3	3 > 4 > 1 > 2	3 > 2 > 1 > 4	3 > 1 > 4 > 2	1 > 2 > 3	3 > 2 > 1 > 4	1 > 2 > 4 > 3	3 > 2 > 1	1 > 2 > 3
p4	2 > 1 > 3 > 4	4 > 3 > 1 > 2	4 > 3 > 1 > 2	1 > 2 > 3	2 > 4 > 3 > 1	1 > 2 > 3 > 4	3 > 2 > 1	1 > 3 > 2
p5	3 > 1 > 2 > 4	3 > 4 > 1 > 2	3 > 1 > 2 > 4	1 > 3 > 2	3 > 2 > 1 > 4	2 > 1 > 3 > 4	1 > 2 > 3	1 > 2 > 3

Table 5. Relative importance of criteria.

Expert	First Tier	C1 Tier	C14 Tier	C2 Tier	C21 Tier	C3 Tier	C32 Tier	C4 Tier
p1	E-C-D	A-C-E	D-C-B	F-B	B-A-A	B-D-B	D-A	D-A
p2	C-C-B	D-B-D	C-B-A	E-C	A-A-A	B-D-A	A-C	D-B
p3	D-B-C	E-A-C	D-C-B	D-B	C-B-B	C-C-B	A-C	B-B
p4	B-C-D	C-C-B	C-B-B	D-C	B-B-A	C-C-B	A-D	C-B
p5	D-B-C	C-D-B	C-B-A	E-C	B-A-A	C-B-B	B-A	B-A

Firstly, calculating the subjective weight. It is verified that $\prod\limits_{k=1}^{r} R1_{1k} = 2.184 > 1.8$, and for C1 tier $\prod\limits_{k=1}^{r} R2_{2k} = 1.859 > 1.8$, it is necessary to correct the relative importance of these two tiers by Equations (7) and (8). The correct factors are calculated as 0.938 and 0.989. Figure 3 displays the subjective weight ratio. It is obvious that the criteria and x21 should be carefully considered as the ratios are the largest two.

Secondly, calculating the objective weight. In Figure 4. The normalized criteria, calculated by Equation (13), are distributed in concentric circles with a radius coordinates of 0-1, the radius represent the superiority of the index, the father away from the center, the more superior of the index, it means the larger the area enclosed by 23 criteria of a scheme, the better of the scheme in the preselected schemes, and vice versa, and the schemes S3 and S5 correspond to a larger area enclosed by the criteria.

The objective weight is calculated in different methods shown in Equation (14). As shown in Figure 5, there is quite difference between the weight ratios, as the ratio of is quite even, the others are scattered. The difference between the three methods is mainly in the proportions of the four criteria ×4, ×10, ×18 and ×20. This situation is due to the fact that the standardized values of the four indicators have relatively small values during standardization.
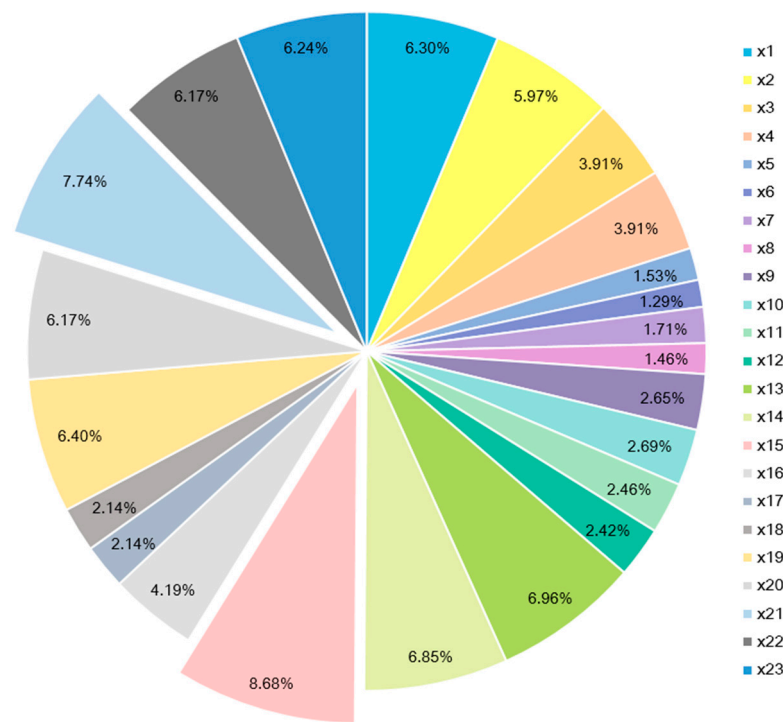
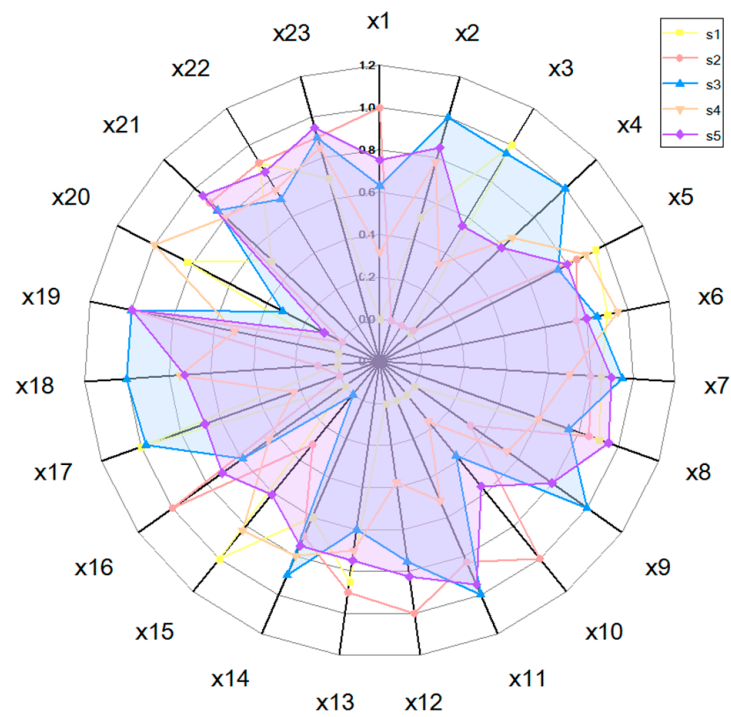**Figure 3.** The subjective weight ratio of the criteria.

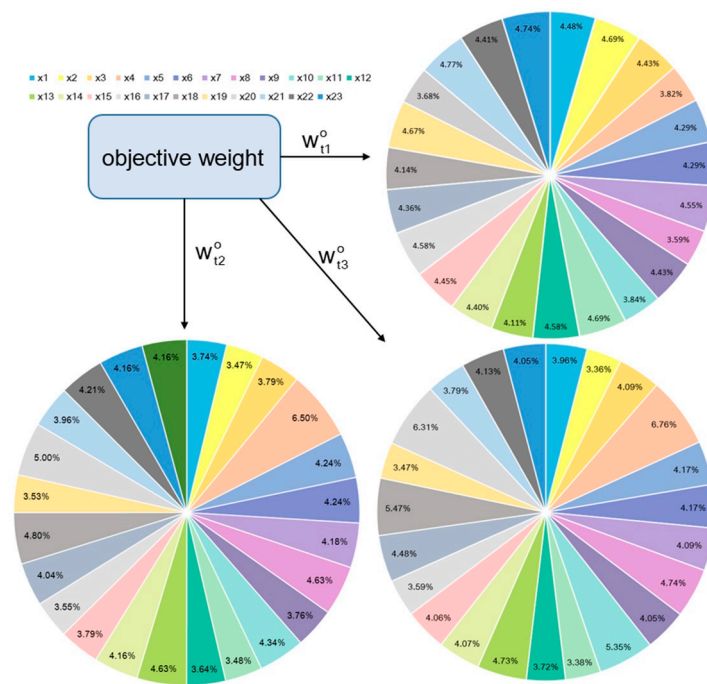**Figure 4.** The normalization value of 5 DESs.

Figure 5. The objective weight ratio of the criteria.

Then the comprehensive weight can be obtained by Equation (16), as shown in Figure 6, the distribution of weight values are roughly the same, but the distribution of w_{t1} is relatively uniform. In addition, the distribution of w_{t3} obtained by the entropy weight method shown as (3) in Equation (14) is scattered, which is caused by its high sensitivity. Although not reflected in this paper, this feature is likely to cause distortion of the result.
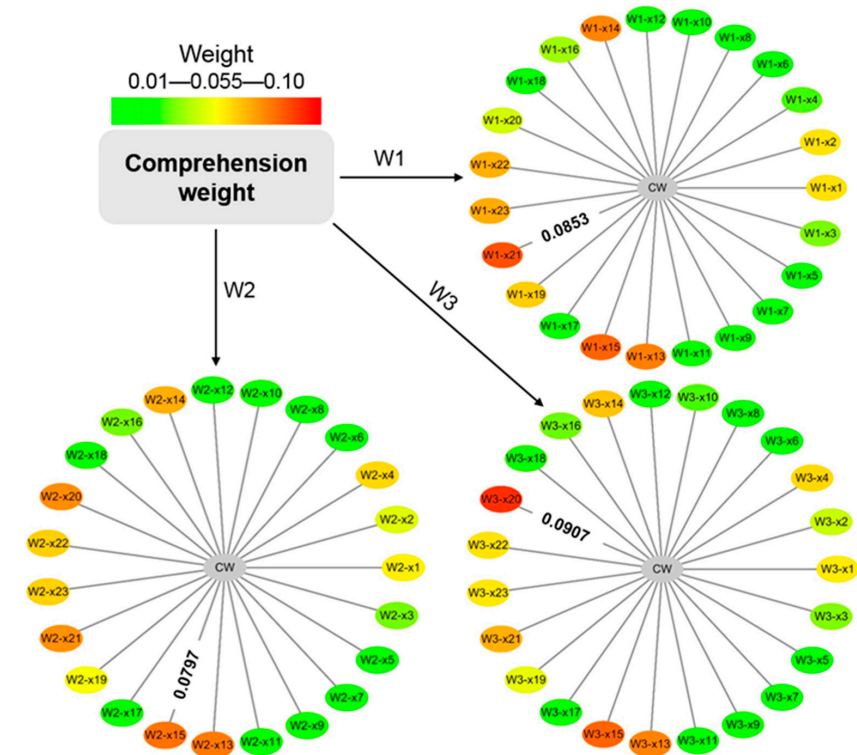

Figure 6. Comprehensive weight value of different methods.

Figure 7 illustrates the evaluative score of each scheme based on different methods, the scoring value is just a comparison value without any actual meaning. From the figures, it is obvious that the evaluation score trends of different schemes, evaluated by various methods, tend to be consistent, as S5 > S3 > S4 > S2 > S1. The index with a relatively high proportion of comprehensive weights in S5 has a higher normalized value. Therefore, the evaluation scores of C1–C4 in the scheme are comparatively high and average, this is consistent with the largest graphic area enclosed by its various indicators after standardization, which also means that after comprehensively considering various factors, S5 is the best one among the five options.
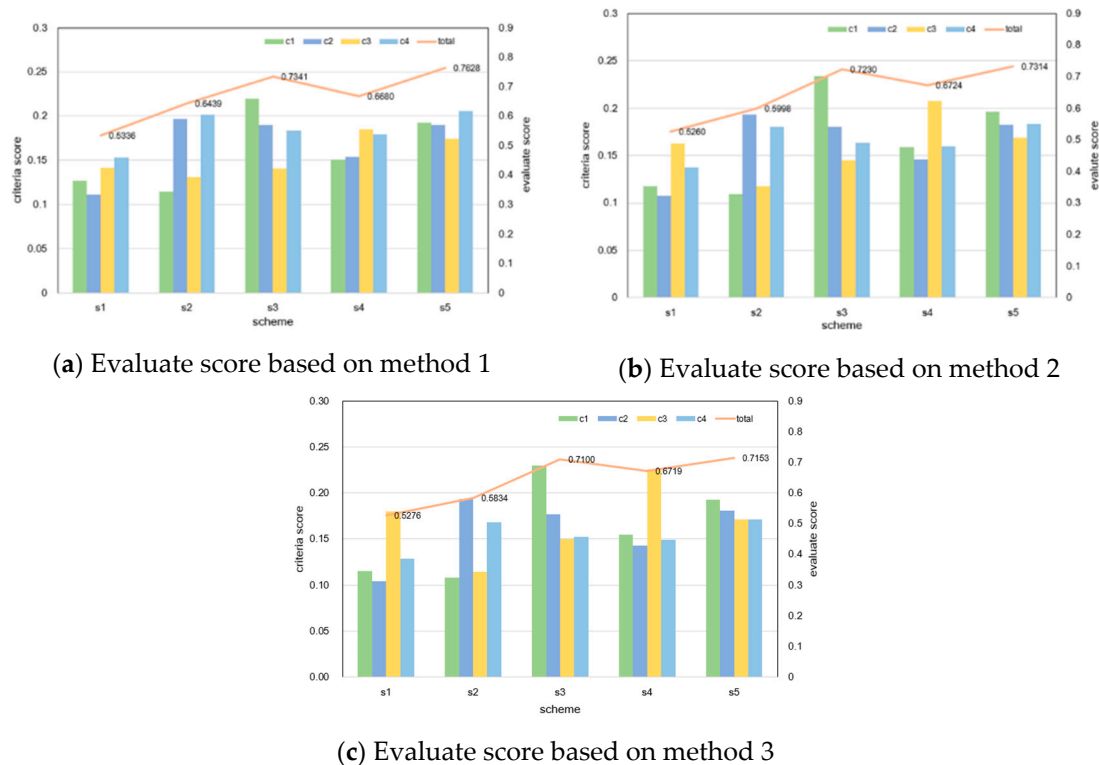

(**a**) Evaluate score based on method 1   (**b**) Evaluate score based on method 2

(**c**) Evaluate score based on method 3

Figure 7. Evaluate scores based on different methods.

From Figure 7 calculated by G1-anti-entropy method and Figure 7c calculated by G1-entropy method, comparing the result value of the same criterion of different schemes and the result value of different criterion of the same scheme, the latter has more fluctuations. This is caused by the sensitivity of the entropy weight method, but there is no distortion in this paper.

For technology priority, the order of scoring value of different methods are the same as S3 > S5 > S4 > S1 > S2. So from technical analysis, S3 is the optimal because of its high renewable energy.

For environmental priority, the scoring values showing stepwise differences are ranked as S3 > S5 > S4 > S2 > S1. For S3, which consumes less electricity to satisfy the community cooling, heating and electric loads, and the pollutant emissions including dusty, SO_2, and NOX are greatly reduced, and the heat exchange device is laid underground to coordinate with the overall environment and of the community for a better landscaping effect, furthermore the noise pollution is also small. So S3 should be preferred from environmental benefits are significant.

For economic priority, there are difference between the orders of various schemes. It was sorted as S4 > S5 > S1 > S3 > S2 for method 1 and method 2, and the order of S1 and S5 are interchanged for method 3. However scheme S4 is still the optimal as the economy considered first, because of the lower initial investment and shorter payback period.

For social priority, the sequence is S5 > S2 > S3 > S4 > S1 according to the evaluation scores. S5 has obvious preponderances over other schemes in terms of government policy support and promote economic development. So it is premier choose S1 when considering social conditions.

Figure 8 shows the results of evaluating different schemes using subjective and objective methods. Compared with Figure 7, when the subjective and objective analysis of the schemes are used separately, the scoring results show that S3 scores the highest, S5 comes in second place, and the ranking of other schemes remains unchanged, but the proportion of each index is quite different.
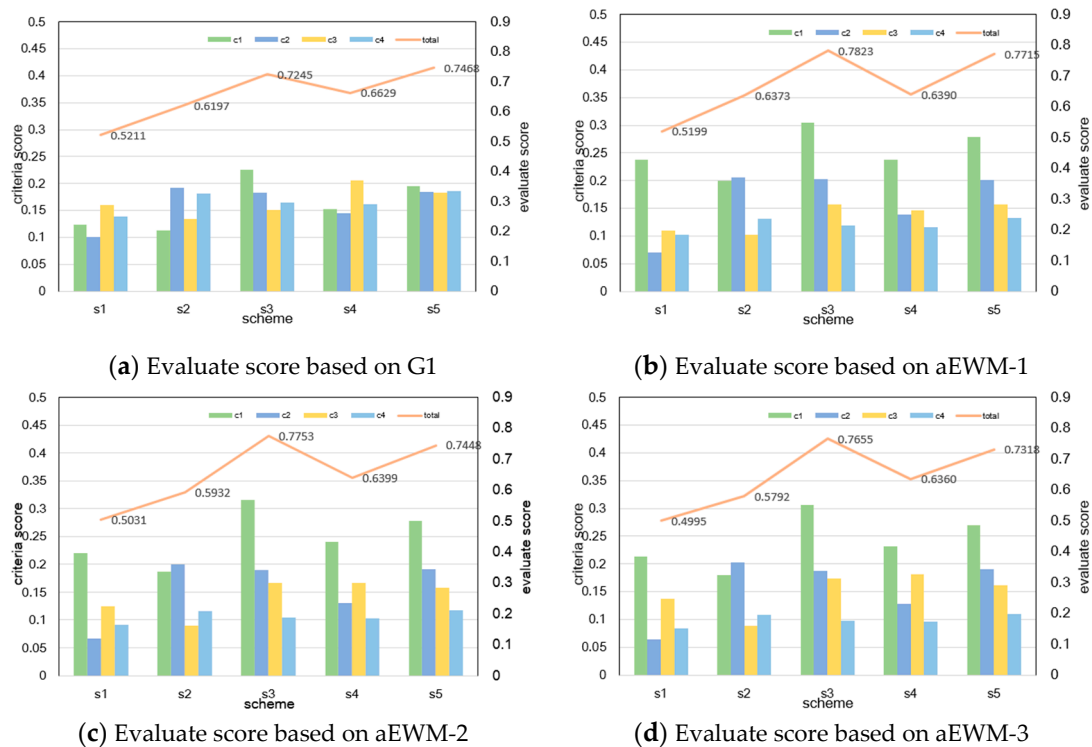

(**a**) Evaluate score based on G1   (**b**) Evaluate score based on aEWM-1

(**c**) Evaluate score based on aEWM-2   (**d**) Evaluate score based on aEWM-3

Figure 8. Evaluation scores based on G1 and aEWM.

Comparing subjective and objective evaluation methods, it can be found that the subjective evaluation method has a relatively higher proportion of economic and environmental criteria than the objective evaluation method, while the technical and environmental criteria are relatively low. This also shows that a single evaluation method has certain limitations. So the G1-Aewn is more comprehensive and explanatory.

5. Conclusions

In this paper, an evaluation system, G1-anti-entropy weight comprehensive evaluation system, based on 23 indicators in 4 criterion levels of technology, environment, economy and society is introduced. Through the example analysis, the following conclusions are drawn:

(a) This method, combined by G1 method and anti-entropy weight method, presents a modified mean for integrated evaluation of DES schemes. It simplifies the AHP calculation process to avoid intricate consistency checks and overcome the defect of entropy weight method that is too sensitive to cause indicator failure. Therefore, it could be helpful to the establishment of energy system evaluation policy.

(b) Multi-criteria evaluation makes it possible for deciders to select the optimal results despite the various criteria are proposed synchronously, which makes it more competitive than other methods.

(c) The comprehensive weight method considers the subjectivity of decision making and the objectivity of system parameters. This can avoid the differences in subjective evaluation from impacting on the evaluation results.

(d) The multi-energy complementary system with N-CCHP unit and GSHP unit is the optimal through the analysis. It is recommended that investment decision makers and related designers choose this scheme first.

Although the G1-anti-weight method has some advantages in the evaluation, there are some limitations which can be optimized, such as the changes in criteria with development. It is convinced that the method is still effective in evaluation as improvement considered.

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Appendix A

Scheme 1: Traditional system.

Table A1. Traditional system main equipment.

Number	Equipment	Parameter		Amount	Remark
1	Electric refrigeration unit	Colling capacity 3863 kW	Cooling power 688 kE	4	
2	Gas vacuum boiler	Heating capacity 5000 kW	Boiler efficiency 88%	2	
3	Domestic hot water boiler	2 t		1	
4	Diesel generators	200 kW		1	spare
5	Other supporting energy equipment	Pump, tower, water treatment and etc.			

Scheme 2: Natural gas combined cooling, heating, and power system.

Table A2. Natural gas combined cooling, heating, and power system main equipment.

Number	Equipment	Parameter		Amount	Remark
1	Gas internal combustion generator set	Rated power generation 2004 kW	Power generation efficiency 44.8%	5	
2	Steam direct combustion unit	Cooling capacity 2908 kW	Heating capacity 2254 kW	5	
3	Other supporting energy equipment	Pump, tower, water treatment and etc.			

Scheme 3: Ground source heat pump system.

Table A3. Ground source heat pump system main equipment.

Number	Equipment	Parameter		Amount	Remark
1	Ground source heat pump unit	Cooling capacity 1396 kW Heating capacity 1089 kW	Cooling power 260 kW Heating power 287.1 kW	10	
2	Diesel generators	200 kW		1	spare
3	Other supporting energy equipment	Pump, tower, water treatment and etc.			

Scheme 4: Solar air source heat pump system.

Table A4. Solar air source heat pump system main equipment.

Number	Equipment	Parameter		Amount	Remark
1	Full heat recovery series air-cooled heat pump unit	Cooling capacity 811 kW Heating capacity 851 kW	Cooling power 285 kW Heating power 297 kW	17	
2	Solar collector	Layout and top of the floor			
3	Diesel generators	200 kW		1	spare
4	Other supporting energy equipment	Pump, tower, water treatment and etc.			

Scheme 5: Multi-energy complementary system main equipment.

Table A5. Multi-energy complementary system main equipment.

Number	Equipment	Parameter		Amount	Remark
1	Gas internal combustion generator unit	Rated power generation 2004 kW	Power generation efficiency 44.8%	2	
2	Gas direct combustion unit	Cooling capacity 2908 kW	Heating capacity 2254 kW	2	
3	Ground source heat pump unit	Cooling capacity 1396 kW Heating capacity 1089 kW	Cooling power 260 kW Heating power 287.1 kW	6	
4	Other supporting energy equipment	Pump, tower, water treatment and etc.			

Table A6. Main equipment price.

Equipment	Price (10 Thousand CNY/Unit)
Electric refrigeration unit	584
Gas vacuum boiler	35
Gas internal combustion generator unit	1720
Steam direct combustion unit	770
Ground source heat pump unit	42.72
Full heat recovery series air-cooled heat pump unit	60
Gas steam boiler	15
Domestic hot water boiler	25
Diesel generators	8

Table A7. Electricity price of Xinxiang City, Henan Province.

Electricity Price (CNY/Kwh)		
Peak	**Flat Section**	**Trough**
8:00–12:00, 18:00–22:00 0.92	00:00–8:00 0.60	12:00–18:00, 22:00–24:00 0.32

Table A8. Gas price of Xinxiang City, Henan Province.

Natural Gas Price (CNY/m^3)	
Non-Heating	**Heating Season**
2.78	3.20

Table A9. Equipment service life.

Equipment	Service Life (Year)
Gas internal combustion generator unit	30
Boiler	15
Electric air conditioner	20
CCHP device	25
Ground source heat pump unit	30
Underground pipe system	50
Air source heat pump unit	25
Solar collector	20
Heat exchanger	30
System pipe network	30

Table A10. Pollutant emission factor.

Pollutants	Unit	Dusty	CO$_2$	SO$_2$	NOx
Coal-fired power generation	g/kWh	0.57	1000	9314	3.32
gas	g/Nm^3	0.62	1940	1.24	4.96

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