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Evaluation of the Maturity of Urban Energy Internet Development Based on AHP-Entropy Weight Method and Improved TOPSIS

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Abstract: With the rapid development of communication technology and information processing technology, the construction of the Urban Energy Internet (UEI) has become one of the important construction elements of the new power system, and it is necessary to assess and analyse its development status and potential. However, the results of the current assessment of the maturity of UEI development are relatively rare, and the transformation path of urban smart energy construction needs to be studied in depth. On this basis, this study aims to propose an improved and comprehensive evaluation model for the maturity of UEI development. This study first considers the dynamic development process of the UEI and proposes an evaluation index system for the maturity of UEI development that includes three dimensions of development status, development benefits and development prospects. Secondly, a comprehensive evaluation model based on GRA-KL-TOPSIS is constructed by using the AHP-entropy weighting method to calculate the combined weights of indicators and considering the Kulla back-Leibler distance to replace the Euclidean distance in the traditional evaluation method. Finally, the maturity of Energy Internet development is calculated for five typical first-tier cities in China (Beijing, Shanghai, Guangzhou, Tianjin and Shenyang), and the final ranking of the five cities is Shanghai > Beijing > Guangzhou > Tianjin > Shenyang. The results of the study prove the scientific validity of the model. Compared to the unimproved Topsis method, the evaluation results calculated based on the improved Topsis evaluation model are more objective and realistic in reflecting the score and rating of the cities. The analysis of the empirical results shows that cities at different stages of development should make up for their shortcomings and increase their investment in infrastructure development, technological innovation and the introduction of talents in order to accelerate the digital and intelligent development of energy.

Keywords: Energy Internet; GRA-KL-TOPSIS; evaluation indicators

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1. Introduction

The core point of smart cities is to develop smart energy [1,2]. Smart energy refers to the application of the Internet, the Internet of Things and other new generation information technologies to monitor and analyse the production, storage, transmission and use of energy in real time and to carry out real-time detection, reporting and optimisation processing on the basis of big data and cloud computing in order to form an integrated management system that is optimal, open, transparent and decentralised with broad voluntary participation and to use this integrated management system to obtain a new form of energy production and utilisation [3–5].

The Energy Internet (EI) is the organisational approach and form that enables smart energy. The concept of EI was first proposed in 2011 by American scholar Rifkin. He saw the Energy Internet as a distributed, open and shared network based on renewable energy, characterised by a deep integration of new energy technologies and information

technology. The EI concept has formed a broad consensus in the energy industry and has become an important factor in promoting the energy revolution and ensuring sustainable energy supply [6–8]. The development and construction of Urban Energy Internet (UEI) is an important means for cities to achieve green, low-carbon, safe and efficient energy development. Building the UEI will solve the bottleneck of local balance of urban energy and electricity, promote the conversion of various types of energy and electrical energy, increase the proportion of clean energy in the supply side and the use of electrical energy in the consumption side, optimise the urban energy structure, improve the efficiency of energy use, promote the development and use of clean energy and ultimately achieve the basic carbon-free urban energy consumption [9]. With the accelerated industrialisation of China's cities, the problem of energy mismatch has become increasingly prominent, the situation of sustainable urban energy development has become more serious, urban areas have gradually become energy consumption centres and the construction of urban regional EI has become one of the most important construction elements of the new generation power system [10]. It is therefore imperative that efforts are made to improve the carrying capacity and operational quality of energy facilities in cities and to accelerate the reform of urban energy supply methods, the replacement of clean resources and the optimal distribution of energy, and the establishment of the modern UEI. In order to better guide the planning and development of the UEI industry, it is important to make a scientific and reasonable evaluation of its development.

The analysis of the theoretical framework shows that most of the studies related to indicators for the evaluation of EI development are stuck on multi-stakeholders and the distribution of benefits, lacking consideration of its global dynamic evolutionary process [3,11–13]. Research on the construction of UEI has mainly focused on the key technical systems for the construction of EI, with fewer research results on the development status and potential of UEI [4,5,9,14]. In addition, the existing comprehensive evaluation methods do not adequately address the problems of ambiguity and randomness that exist in some of the indicators. The traditional TOPSIS method usually requires a large amount of systematic data and meets statistical requirements and also suffers from the problem that the closer the evaluation objective is to the positive ideal solution, the closer it may also be to the negative ideal [15]. In this context, the study aims to establish a model for evaluating the maturity of the UEI development based on the GRA-KL-TOPSIS method, which uses the AHP-entropy weighting method to calculate the combined weights of indicators and uses the Kulla back-Leibler distance instead of the Euclidean distance in the traditional TOPSIS model, which can solve the problems of ambiguity and randomness in the evaluation indicators, so as to obtain accurate and reliable results for evaluating the maturity of the UEI development. The improved evaluation model is verified to be reasonable and scientific through examples, and the findings of the study can provide theoretical guidance and recommendations for the construction of smart cities.

2. Literature Review

In terms of maturity research and evaluation, a prior study [16] defines maturity as the degree of matching between the research object and its optimal state. Current research areas on maturity evaluation mainly focus on management systems, engineering projects, technology applications and other aspects. Wang et al. [17] add new evaluation factors for the degree of industrial security and controllability, including autonomous controllability and industry dominant capability, to construct a new evaluation model for the maturity of the industrial system. Wang et al. [18] define maturity as the relative value of the current state of the research object and its perfect state, apply the portrait technology to classify, filter and compare the electricity consumption characteristics of regional electricity users, and finally build a regional electricity user portrait based on user maturity. Xiao et al. [19] use the project organisational structure maturity evaluation index model to define the project organisational structure operation level rating situation. Xiang et al. [20] introduce maturity evaluation into enterprise management, combine it with the current situation

and business characteristics of power grid enterprise performance management, improve enterprise management evaluation criteria and promote management-level improvement. Jiang et al. [21] apply maturity evaluation to the field of power grid construction projects and construct a set of maturity evaluation models for power grid construction projects. Considering the abovementioned results, the first hypothesis of this study is formulated as follows:

Hypothesis 1. *Maturity can be applied in management evaluation to scientifically assess the current state of development and prospects of a field.*

In terms of EI development evaluation, Lin et al. [22] construct a development potential evaluation system from three perspectives of EI development potential in terms of support, guarantee, production and consumption capacity. Taking rural areas as the entry point, Tan et al. [23] study the development status of rural EI and construct a multi-dimensional index system for the maturity of EI construction based on the characteristics of resources, energy consumption, energy development trends and future development goals in rural areas. Zhang et al. [24,25] construct an evaluation system for EI development from three aspects: engineering projects, low carbon and high efficiency and value-added services, as well as from economic, energy, environmental, social and engineering dimensions, respectively. Liu et al. [26] construct a comprehensive benefit evaluation system for county EI covering multiple dimensions of reliability, economy, ecology, resilience and sociality. Jiang et al. [27] establish an indicator system from five perspectives: economic, energy, environmental, social and engineering, to evaluate the EI development in a smart grid innovation demonstration zone. Jiang et al. [28] construct a comprehensive benefit evaluation model of EI based on system dynamics theory including four aspects of economy, society, resources and environment. Yan et al. [29] establish an evaluation index system for the applicability of the EI business model in five dimensions: the level of economic benefits, the quality of energy services, the capacity for sustainable operation, the effect of energy conservation and emission reduction and the ability to drive social development. Wen et al. [30] combine the characteristics of the evaluation of integrated energy systems under the EI, establish the corresponding evaluation index system from the three dimensions of energy production, transmission and distribution and consumption, and form an evaluation method of the operation level of integrated energy systems based on game and evidence theory. Considering the abovementioned results, the second hypothesis of this study is formulated as follows:

Hypothesis 2. *Most of the evaluation indicators of UEI development are targeted at economic, social and environmental benefits and do not take into account the dynamic urban development process.*

In terms of indicator assignment and comprehensive evaluation methods, Xie et al. [31] select the hierarchical analysis method and entropy method for combined assignment and apply the TOPSIS method to empirically analyse the business environment of many coastal provinces. Nie et al. [32] introduce grey correlation analysis based on the cosine similarity method to improve the TOPSIS method. Peng et al. [33] modify the G1 assignment method based on generalised entropy value, reducing the subjective arbitrariness of indicator assignment and taking into account the importance of indicator experience. Meng et al. [34] use a combined assignment method based on AHP and CRITIC to construct an urban resilience assessment model using the Approximated Ideal Solution Ranking (TOPSIS) method. Jiang et al. [35] introduce theoretical analysis and frequency analysis into the process of fuzzy comprehensive evaluation. Shen et al. [36] use a fuzzy integrated evaluation method to assess the multidimensional aspects of the integrated regional energy system at the campus level. Zeng et al. [37] assign weights to indicators through ordered weighted averaging and improve hierarchical analysis and then evaluate the operational risk of virtual power plants based on a cloud model evaluation method with Bayesian feedback correction. Zu et al. [38] construct a multidimensional evaluation system for CNC

machine tools from multiple dimensions and propose a comprehensive evaluation method for RAMS of CNC machine tools considering various methods such as the total time to failure method and the Weibull proportional failure rate model. Hao et al. [39] use the AHP-Delphi assignment method for source-net-load-storage coordination level evaluation. Based on non-linear mapping and principal component analysis, Xiong et al. [40] conduct a comprehensive evaluation of regional distribution networks. Considering the abovementioned results, the third hypothesis of this study is formulated as follows:

Hypothesis 3. *The current comprehensive evaluation method does not adequately address the problem of interactions between indicators, and the introduction of KL distance into the TOPSIS method can make up for the shortcomings of the traditional TOPSIS method.*

In summary, current research on the assessment of the maturity of UEI development is relatively rare. In addition, the selection of indicators does not fully take into account the dynamic development process of the EI, the existing comprehensive evaluation methods do not adequately address the ambiguity and randomness of some indicators and the evaluation results still need to be improved in terms of accuracy. Therefore, this paper calculates the index weights based on the subjective-objective AHP-entropy weighting method and constructs an evaluation model for the maturity of UEI development based on the GRA-KL-TOPSIS method. Finally, five typical first-tier cities are selected as examples to verify the rationality of the proposed method and reveal the development status and future development trend of different cities' EI.

3. Materials and Methods

3.1. Indicator System Construction

The EI is essentially an open and complex giant system, and the complexity of its many components and their interactions makes it more difficult to construct and evaluate indicator systems [24]. Based on the development and construction requirements of UEI, the multiple subjects and objectives involved in UEI are fully considered, instead of only starting from a single economic dimension, the development status, development benefits and development prospects are selected as the first-level indicators [41] and the subdivided indicators are optimised by using the explanatory structure model [42]. The steps to construct an explanatory structural model of the factors influencing the maturity of EI development are as follows [43,44]:

Step 1: Set the problem and identify the set of influencing factors. Based on the literature research and practical experience involved in the UEI, the set of influencing factors for the first level indicators is analysed and the set of influencing factors: development status, development benefits and development prospects, is clarified.

Step 2: Construct a linkage matrix. After specifying the set of influencing factors, determine whether there is a relationship between the influencing factors and represent it in the form of a linkage matrix named $A = (a_{ij})_{m\times n}$. Set $i \neq j$, $a_{ij} = 1$ when there is a linkage between the influences and $a_{ij} = 0$ when there is no linkage between the influences.

Step 3: Construct the reachable matrix. Calculate the reachable matrix M from Equations (1) and (2). when $k < n - 1$, if $(A + I) \neq (A + I)^2 \neq \cdots \neq (A + I)^K = (A + I)^{K+1} = L$, then there are:

$$M = (A + I)^{K+1} \tag{1}$$

where the unit matrix is denoted by I.

Step 4: Construct a hierarchy of influencing factors. Based on the reachable matrix M, the impact factors are stratified:

$$\begin{cases} P(e_i) = \{e_j | m_{ij} = 1\} \\ Q(e_i) = \{e_j | m_{ji} = 1\} \end{cases} \tag{2}$$

The reachable set is a factor that can directly correlate with e_i, denoted as $P(e_i)$; The antecedent set is the factor that affects e_i, denoted as $Q(e_i)$. Based on Equation (3), the set L_1 of influencing factors is obtained.

$$L_1 = \{e_i | P(e_i) \cap Q(e_i) = P(e_i)\} \quad (3)$$

L_1 is the set of factors in layer 1, in which the factors have the following characteristics: Other influencing factors can be associated with this factor, but this factor cannot be associated with other factors; then, find the factors in each layer in turn, as shown in Table 1 where L_1–L_4 are four layers, S_1 is the maturity of EI development, S_2 is the current state of EI development, S_3 is the benefits of EI development, S_4 is the EI development prospects, S_5 is the state of urban infrastructure security, S_6 is the state of EI application technology, S_7 is the economic benefits of EI development, S_8 is the social benefits of EI development, S_9 is the environmental benefits of EI development, S_{10} is the security benefits of EI development, S_{11} is the EI market space, S_{12} is the digital prospects of EI, and S_{13}–S_{15} are the factors affecting S_5–S_{12}.

Table 1. The level of influencing factors of the maturity of UEI.

Levels	Key Elements
L_1	S_1
L_2	S_2, S_3, S_4
L_3	S_5, S_6, S_7, S_8, S_9, S_{10}, S_{11}, S_{12}
L_4	S_{13}, . . . , S_{35}

Step 5: Constructing the hierarchy diagram. Based on the reachable matrix M, a multi-level recursive model of the relationship between the influencing factors is constructed as shown in Figure 1.

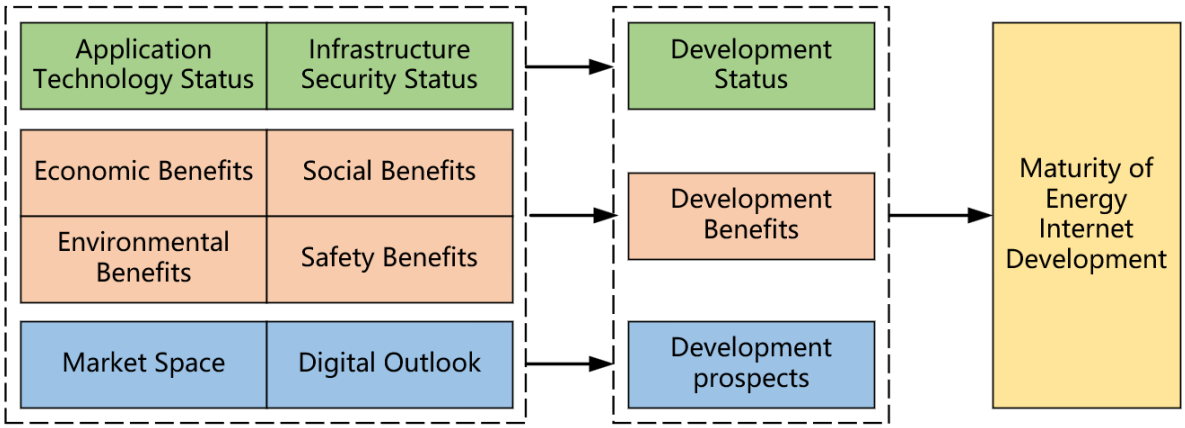


Figure 1. A hierarchical structural relationship model of the influencing factors of the development maturity of UEI.

Based on the constructed structural model for explaining the maturity of EI development, infrastructure security, core technology, economic benefits, social benefits, environmental benefits, security benefits, market space and digitalisation prospects were identified as secondary indicators, and then an indicator system was constructed, as shown in Table 2.

Table 2. UEI development maturity evaluation index system.

	Tier 1 Indicators	Secondary Indicators	Tertiary Indicators	Description
EI Development Evaluation Indicator System	Development status A1	Infrastructural security B1	Smart Grid Investment Scale C1	Amount of investment in regional smart grids
			Smart meter penetration rate C2	Regional smart meter adoption share
			Share of installed renewable energy C3	Total installed renewable energy as a share of total regional installed capacity
			Share of renewable energy generation C4	Renewable energy generation as a share of total regional electricity generation
		Core technologies B2	New technology adoption rate C5	Share of new technologies applied
			Domestic replacement rate C6	Proportion of self-developed equipment
	Development benefits A2	Economic benefits B3	Operating income C7	Annual profit amount
			Subsidy benefits C8	Government subsidies for the year
			Energy cost reduction rate C9	Level of energy cost reduction from project construction
			Operating cost reduction rate C10	Level of operating cost reduction due to project construction
		Social benefits B4	User satisfaction C11	Customer satisfaction with the provision of integrated energy services
			Employment-led capacity C12	Employment generated during the construction and application of the project
		Environmental benefits B5	Rate of change of pollutant emissions C13	The effect of the project on the reduction of pollutant emissions after operation
			Energy consumption reduction rate C14	Level of energy reduction after project operation
			Energy efficiency improvement rate C15	Level of energy efficiency improvements after project operation
		Safety benefits B6	Reliability of energy supply C16	Uptime for users
			Grid Line Loss Ratio C17	Average line loss ratio of the transmission network
			Peak-to-valley differential rate C18	Ratio of peak-to-valley difference to maximum load
	Development prospects A3	Market space B7	Promoted adoption rate C19	Integrated energy demonstration projects as a share of the market
			Industry chain driven level C20	The pulling effect of the project on the upstream and downstream of the industry chain
			User growth rate C21	Level of growth in customers being provided with integrated energy services
		Digital prospects B8	Level of energy information integration C22	Extent of integration with Internet IT applications
			Project interconnectedness and shareability C23	The extent to which distributed generation systems within the project share a wide area interconnection with all types of loads

Indicators in the category of development status, including two secondary indicators of infrastructure security and core technologies, reflect the development status of the UEI in terms of infrastructure and technology applications. The Development Benefits category includes four secondary indicators: economic benefits, social benefits, environmental benefits and safety benefits, reflecting the comprehensive benefits of the UEI in terms of improving energy efficiency, increasing safety and reliability, reducing energy costs and reducing carbon emissions and other pollutant emissions through the construction of a modern energy system. The Development Prospects category includes two secondary indicators, namely Market Space and Digital Prospects, which reflect the development prospects of the UEI in terms of prosperity and digital empowerment.

3.2. Combined Weight Calculation

Once an evaluation indicator system has been established, the selected indicators need to be used to evaluate the maturity of UEI development. In order to arrive at an overall final evaluation value based on the existing multi-indicator system, it is firstly necessary to determine the weights of the indicators and secondly to select a suitable comprehensive evaluation method [45]. In general, the weights of multiple indicators need to be assessed with reference to expert experience and therefore the AHP subjective allocation method is often used. However, the weighting results following the use of subjective assignment methods may be influenced by the preferences of expert supervisors. The objective assignment method can make the weighting of indicators more reasonable, but the single entropy method ignores the relevant experience of professionals, and the use of only a single method can make the evaluation results relatively one-sided [46–48]. Therefore, this paper uses AHP to obtain subjective weights and the entropy weighting method to obtain objective weights, ultimately forming a composite weight with a fusion of subjectivity and objectivity [49,50].

Hierarchical analysis modelling is implemented in the following steps [51,52]:

Step 1: Construct the recursive hierarchy model and judgement matrix. The model includes a target layer, a quasi-lateral layer and a programme layer, and a judgement matrix is built using the Saaty 1–9 scaling method.

Step 2: Hierarchical single ranking and consistency tests were performed. The importance ranking of same-level factors to hierarchical factors is determined by determining the eigenvector w corresponding to the largest eigenvalue λ_{max} of the judgment matrix $A = (a_{ij})_{n\times n}$. The judgement matrix $A = (a_{ij})_{n\times n}$ is normalised to determine the matrix $\overline{A} = (\bar{a}_{ij})_{n\times n}$, i.e.,

$$\bar{a}_{ij} = \frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}}, \ (i, j = 1, 2, \cdots, n) \tag{4}$$

Calculate the average of the sum of the elements of the rows of the matrix $\overline{A}$, i.e.,

$$w_i = \frac{1}{n}\sum_{j=1}^{n} \bar{a}_{ij} \tag{5}$$

where $w = [w_1, w_2, \cdots, w_n]^T$ is the requested eigenvector, while its maximum eigenroot λ_{max} is calculated.

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} \frac{(A\omega)_i}{\omega_i} \tag{6}$$

Calculate the consistency index CI of the judgment matrix.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{7}$$

The stochastic consistency ratio is set to CR, i.e., $CR = \frac{CI}{RI}$, where RI is the average stochastic consistency index of the judgment matrix. A smaller CR indicates a better consistency of the matrix.

Step 3: Perform a hierarchical total ranking and consistency test. Calculate ranking weights and perform consistency tests.

The specific steps of the entropy method are as follows [53–55]:

Step 1: Data standardisation. The evaluation matrix $Y = \left(y_{ij}\right)_{n\times m}, i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$ was constructed, setting n and m as evaluation indicators and evaluation objects respectively, and standardised as follows:

$$E_{ij} = \frac{y_{ij}}{\sum_{j=1}^{m} y_{ij}} \tag{8}$$

Step 2: Solving for information entropy. The entropy value of the indicator i is

$$H(i) = -\frac{1}{\ln m}\sum_{j=1}^{m} E_{ij} \ln E_{ij} \tag{9}$$

Step 3: Calculate the entropy weight of each indicator. The entropy weight of the indicator i can be expressed as

$$w_i'' = \frac{1 - H(i)}{\sum_{i=1}^{n} (1 - H(i))} \tag{10}$$

The final vector of indicator weights W'' based on the entropy weighting method is obtained:

$$W'' = (w_1'', w_2'', \ldots, w_n'') \tag{11}$$

The combined AHP-entropy weight method can calculate the combined weights of the evaluation indicators, combining subjective and objective, and the formula for calculating the combined weights is as follows:

$$W_j = \frac{\sqrt{\alpha_j \beta_j}}{\sum_{j=1}^{n} \sqrt{\alpha_j \beta_j}} \tag{12}$$

where α_j and β_j are the subjective and objective weights, respectively, and W_j is the combination weighting factor.

3.3. Evaluation Model Construction

The fuzzy comprehensive evaluation method is based on the concept of fuzzy mathematics, uses the principle of fuzzy relationship synthesis to quantify some factors that cannot be quantified and has become one of the most widely used comprehensive evaluation methods at present. Due to the large number of comprehensive evaluation indicators for the maturity of EI development, the intersection of quantitative and qualitative indicators and the complexity of content, this paper chooses the fuzzy comprehensive evaluation method to carry out the evaluation work [56,57]. Approximating ideal solution ranking (TOPSIS) is a comprehensive evaluation method using distance as a criterion. The traditional TOPSIS method generally requires an adequate amount of underlying data, and the closer the objective of the evaluation is to the positive ideal solution, the closer it is likely to be to the negative ideal solution [58]. Based on this, this paper uses the grey correlation method (GRA) to integrate the basic data of UEI development, based on the Kulla back-Leibler distance instead of the traditional Euclidean distance, in order to solve

the distance calculation problem [59], and the steps of the improved TOPSIS algorithm are as follows.

Step 1: Construct a weighted normalised evaluation matrix. The evaluation matrix under the original data is set as $R = \left(r_{ij}\right)_{m^*n}$, then standardise it.

$$\begin{aligned} y_{ij} &= \frac{r_{ij} - \min\limits_{j} r_{ij}}{\max\limits_{j} r_{ij} - \min\limits_{j} r_{ij}} (j \in J^+) \\ y_{ij} &= \frac{\max\limits_{j} r_{ij} - r_{ij}}{\max\limits_{j} r_{ij} - \min\limits_{j} r_{ij}} (j \in J^-) \end{aligned} \tag{13}$$

where m and n represent the number of evaluation objects and evaluation indicators, respectively, and the positive and negative indicators are represented by J^+ and J^-, respectively, to establish a standardised evaluation matrix at $Y = \left(y_{ij}\right) m * n$ and calculate the weighted standardised evaluation matrix Z:

$$Z = Y_{(m^*n)} W_{j(n^*n)} = \left(z_{ij}\right)_{m^*n} \tag{14}$$

Step 2: Calculate the positive ideal solution at Z^+ and the negative ideal solution at Z^-.

$$\begin{aligned} Z^+ &= \left\{ \max z_{ij} \mid i = 1, 2, \ldots, n \right\} = \left\{ z_1^+, z_2^+, \ldots, z_n^+ \right\} \\ Z^- &= \left\{ \min z_{ij} \mid i = 1, 2, \ldots, n \right\} = \left\{ z_1^-, z_2^-, \ldots, z_n^- \right\} \end{aligned} \tag{15}$$

Step 3: Determine the grey correlation matrix $F = \left(f_{ij}\right)_{m^*n}$ between the values of the indicators of the evaluation object and the positive ideal solution.

$$f_{ij} = \frac{\rho \max\limits_{i} \max\limits_{j} \left| z_j^+ - z_{ij} \right| + \min\limits_{i} \min\limits_{j} \left| z_j^+ - z_{ij} \right|}{\rho \max\limits_{i} \max\limits_{j} \left| z_j^+ - z_{ij} \right| + \left| z_j^+ - z_{ij} \right|} \tag{16}$$

where the grey correlation resolution is set to ρ with a value range of (0, 1], and $\rho = 0.5$ is set.

Step 4: Determine the positive and negative ideal solutions of the grey correlation coefficient matrix F.

$$\begin{aligned} F^+ &= \left\{ \max f_{ij} \mid i = 1, \quad 2, \ldots, \quad n \right\} = \left\{ f_1^+, f_2^+, \ldots, f_n^+ \right\} \\ F^- &= \left\{ \min f_{ij} \mid i = 1, \quad 2, \ldots, \quad n \right\} = \left\{ f_1^-, f_2^-, \ldots, f_n^- \right\} \end{aligned} \tag{17}$$

Step 5: Calculate the KL distances d_i^+ and $d_{\bar{i}}$ from the indicator values of the evaluation object to the positive and negative ideal solutions of the matrix F.

$$\begin{aligned} d_i^+ &= \sum_{j=1}^{n} \left[f_j^+ \lg \frac{f_j^+}{f_{ij}} + \left(1 - f_j^+\right) \lg \frac{1 - f_j^+}{1 - f_{ij}} \right] \\ d_i{}^- &= \sum_{j=1}^{n} \left\{ f_j^- \lg \frac{f_j^-}{f_{ij}} + \left(1 - f_j^-\right) \lg \frac{1 - f_j^-}{1 - f_{ij}} \right\} \end{aligned} \tag{18}$$

Step 6: Determine the comprehensive closeness of the evaluation target Cr_i.

$$Cr_i = \frac{d_i^+}{d_i^+ + d_i^-} \tag{19}$$

This paper uses the closeness to express each city's EI development maturity. The city EI maturity index takes values in the range [0, 1], with the highest maturity when $Cr_i = 1$ and the lowest maturity when $Cr_i = 0$.

The overall evaluation process based on the improved TOPSIS model is shown in Figure 2.

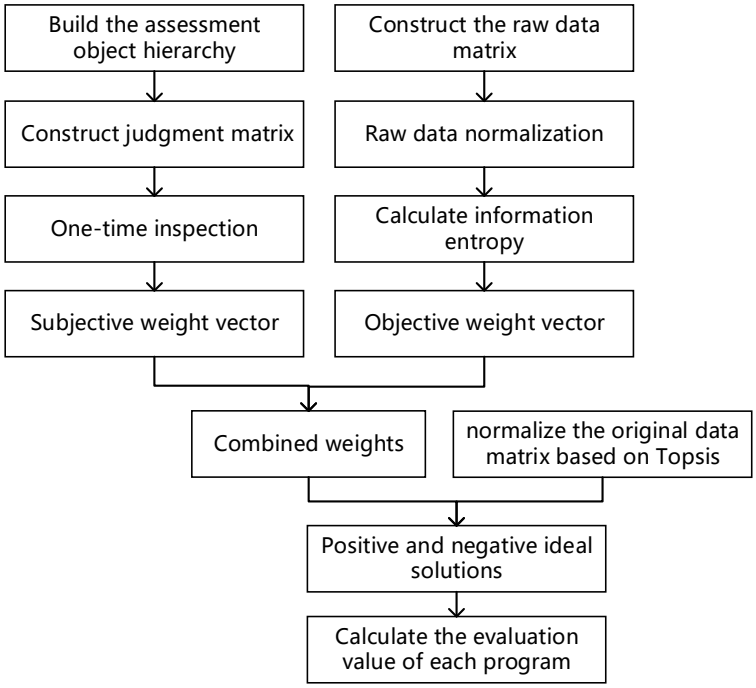


Figure 2. AHP-Entropy Weight-TOPSIS Method Operation Steps.

4. Results

4.1. Index Weight Calculation

Based on the above-mentioned methods and indicators, data on the relevant indicators of each city are collected to evaluate the maturity of EI development in typical cities. At present, the level of EI development varies greatly among cities in China, the first-tier cities are in a leading position compared to other cities and the data are more easily accessible. Moreover, the evaluation of the maturity of EI development in first-tier cities is more representative and forward-looking and can provide a reference basis for the development of EI in other cities. This study takes into account the comprehensive development level, city rank and scale of each city, selects five first-tier pilot cities, including Beijing, Shanghai, Guangzhou, Tianjin and Shenyang, for EI construction and collects relevant data for 2021, with the raw data mainly coming from the National Bureau of Statistics, the National Energy Administration and provincial and municipal power grid companies, while using MATLAB (2021a) to calculate the comprehensive weights of the index system and the scores of each index of the evaluation objects.

According to the weighting method proposed in this study for the combination of subject and objective, the comprehensive weight of each tier of indicators in the city was calculated. From the measured results, among the tier 1 indicators, development effectiveness has the greatest impact on the maturity of the city's EI, with a combined weight of 0.4251, which is 5.16% and 22.37% higher than the development status and development potential decibels. The UEI is built to support the sustainable development of the city from economic, social and environmental aspects in order to bring comprehensive development benefits, while the evaluation of the maturity of EI development mainly examines the benefits generated in the process of its development, so the results of the weight calculation are consistent with its maturity positioning. Among the secondary indicators, core technology has the greatest impact, with a combined weight of 0.2211, because core technology is necessary for the development of the EI and is related to its sustainability, reliability and various performance advantages and disadvantages, and

improving core technology is one of the main objectives of UEI development. The impact weight distribution of other indicators is shown in Table 3 and Figure 3.

Table 3. The weight of indicators at each level of the EI construction level index system.

	Tier 1 Indicators	Weighting	Secondary Indicators	Weighting	Tertiary Indicators	Weighting	Ranking
EI Development Maturity Evaluation Index System	Development status A1	0.3735	Infrastructural security B1	0.1524	Smart Grid Investment Scale C1	0.0337	12
					Smart meter penetration rate C2	0.0232	20
					Share of installed renewable energy C3	0.0436	9
					Share of renewable energy generation C4	0.0518	6
			Core technologies B2	0.2211	New technology adoption rate C5	0.1039	2
					Domestic replacement rate C6	0.1172	1
	Development benefits A2	0.4251	Economic benefits B3	0.0987	Operating income C7	0.0327	14
					Subsidy benefits C8	0.0066	23
					Energy cost reduction rate C9	0.0392	11
					Operating cost reduction rate C10	0.0202	22
			Social benefits B4	0.0523	User satisfaction C11	0.0293	17
					Employment-led capacity C12	0.0230	21
			Environmental benefits B5	0.1321	Pollutant emission reduction rate C13	0.0495	7
					Carbon emission reduction rate C14	0.0586	5
					Energy efficiency improvement rate C15	0.0240	19
			Safety benefits B6	0.1420	Reliability of energy supply C16	0.0695	4
					Grid Line Loss Ratio C17	0.0331	13
					Peak-to-valley differential rate C18	0.0394	10
	Development prospects A3	0.2014	Market space B7	0.0874	Promoted adoption rate C19	0.0308	15
					Industry chain driven level C20	0.0298	16
					User growth rate C21	0.0268	18
			Digital prospects B8	0.1140	Level of energy information integration C22	0.0698	3
					Project interconnectedness and shareability C23	0.0442	8

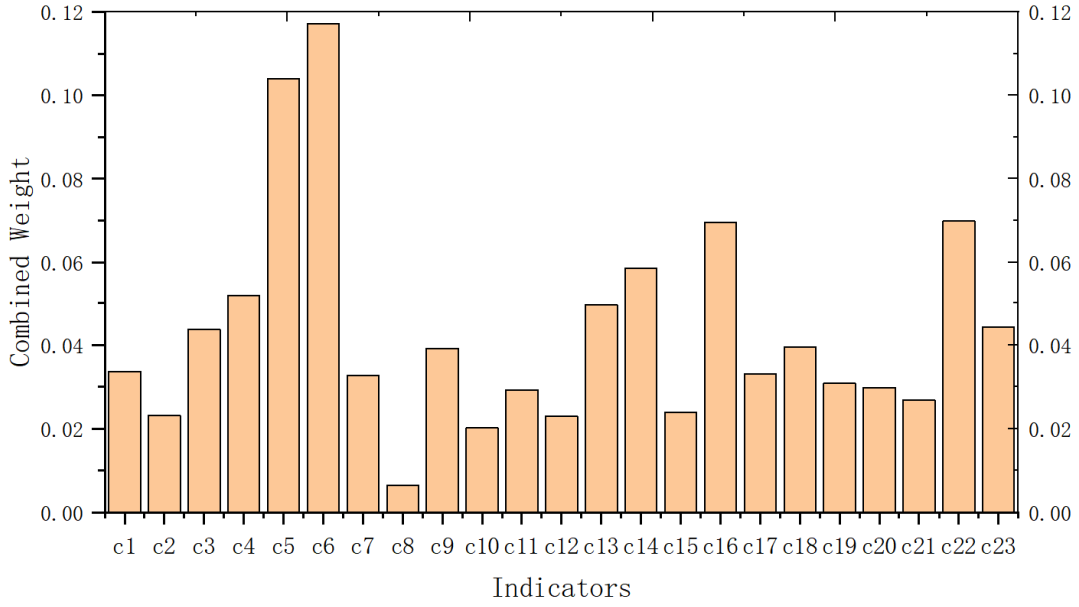


Figure 3. Comprehensive weighting of three-level indicators.

4.2. Evaluation Results of the Maturity of Energy Internet Development

Based on the above evaluation model, the closeness of the indicators of each layer of the evaluation object is determined to reflect the advantages and disadvantages of the development process of EI in five first-tier cities, and finally, the distribution of the closeness of the development status, development benefits and development prospects is obtained, as shown in Figure 4.

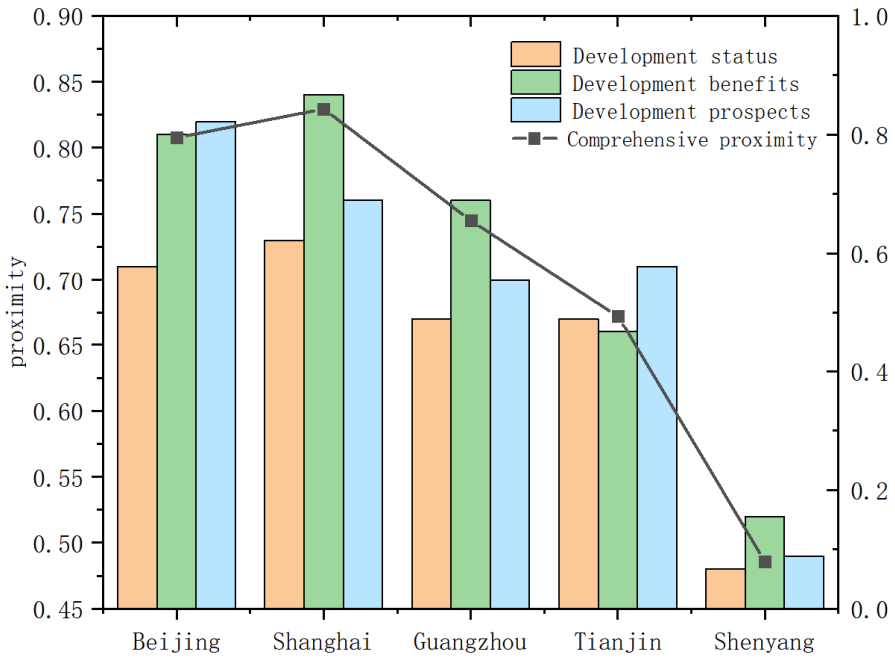


Figure 4. The combined closeness of the development status, development benefits and development prospects of the energy Internet in each city.

Overall, Shanghai has the highest maturity level of EI development, with a 2.44% and 2.94% higher closeness to the current development status and development benefits respectively compared to the second-ranked Beijing but a 5.93% lower closeness to the development prospects than Beijing. In terms of current development status, the closeness

of Beijing and Shanghai is 0.8076 and 0.8294, respectively, with Shanghai having a slight advantage over Beijing, followed by Guangzhou and Tianjin and Shenyang having the lowest closeness. In terms of development benefits, Shanghai ranks first in terms of closeness, being 2.94%, 8.03%, 22.35% and 32.28% higher than Beijing, Guangzhou, Tianjin and Shenyang, respectively, with Beijing, Guangzhou, Tianjin and Shenyang in decreasing order of closeness. In terms of development prospects, Beijing ranks first in terms of closeness, being 5.93%, 5.54%, 16.88% and 26.99% higher than Shanghai, Tianjin, Guangzhou and Shenyang, respectively.

Based on the above results the maturity of UEI development is divided into several echelons [60], with Shanghai, Beijing and Guangzhou belonging to the first echelon with more mature UEI development. These cities are in the advanced camp of smart cities as they excel in the current state of development, development benefits and development prospects of the UEI. Shanghai is more mature in the development of the EI. The city's size, economic strength and technological level are at the forefront of the country, and it has accumulated rich experience in technology research and development, application innovation and business model innovation and therefore has the highest level of development benefits and approximation. Beijing, on the other hand, benefits from a large number of users and a stronger level of information and other indicators and performs well in terms of the development prospects of the EI. As an important economic centre city in the south, Guangzhou has the advantage of extensive regional cooperation and city cluster building and has achieved some results in innovation and application of smart energy, with good customer satisfaction and pollutant emission rates contributing positively to its development maturity rating.

Tianjin's current development status, development benefits and development prospects have a low level of closeness, and it is in the second tier of the medium level of UEI development. As one of the core cities of the Beijing-Tianjin-Hebei Synergistic Development, Tianjin has the advantages of developing a global energy logistics centre and building a green, low-carbon city, and its complete industry chain level enhances the closeness of its development prospects.

Shenyang has the lowest closeness in terms of development status, development benefits and development prospects and belongs to the third tier. This means that there is still much room for improvement in Shenyang's EI development. As a key industrial city in the northeast, it has a good geographical location and transportation conditions, a strong location advantage and industrial base and good potential for development.

4.3. Comparison of Methods

In order to compare the improvement effect, this paper uses the traditional TOPSIS method to calculate the maturity of EI development for the same group of research subjects, and the results of the combined closeness calculations for the two algorithms are shown in Table 4 and Figure 5.

Table 4. Comparison of the closeness of the TOPSIS method and the GRA-KL-TOPSIS method.

City	GRA-KL-TOPSIS Posting Progress	TOPSIS Posting Progress
Beijing	0.7796	0.8215
Shanghai	0.7892	0.8452
Guangzhou	0.7338	0.6939
Tianjin	0.6204	0.6415
Shenyang	0.5193	0.4809

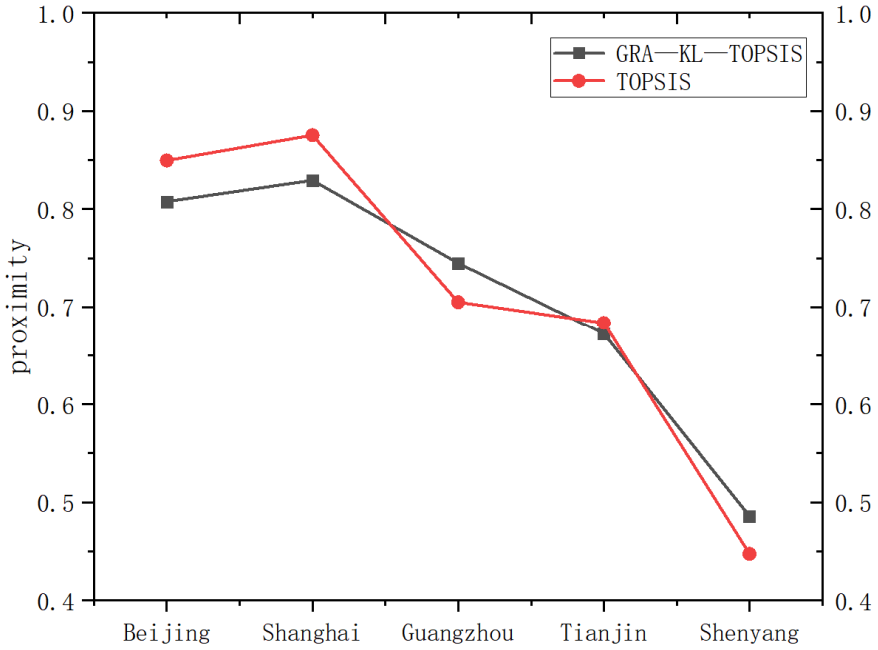


Figure 5. Comparison of the combined closeness of the TOPSIS method and the GRA-KL-TOPSIS method.

According to the ranking of the integrated maturity, the top five first-tier cities are ranked as follows: Shenyang < Tianjin < Guangzhou < Beijing < Shanghai. Although the final ranking of the EI development maturity of the five cities is the same under both algorithms, the results of the calculation of the integrated closeness are different. The combined closeness of Guangzhou and Tianjin calculated based on the improved TOPSIS method is 0.7338 and 0.6204, with Guangzhou being 11.34% higher than Tianjin. The combined closeness of Guangzhou and Tianjin based on the traditional TOPSIS method is 0.6939 and 0.6415, with Guangzhou being 5.24% higher than Tianjin, indicating that although the maturity of Guangzhou's EI development is better than that of Tianjin, the difference between the two is not too great. In the field research, there is still a gap between Guangzhou and Tianjin in terms of the level of EI development, and Guangzhou has far more EI pilot projects than Tianjin. Therefore, the comprehensive closeness calculated based on the improved TOPSIS method is more in line with the actual situation, can objectively and scientifically reflect the ranking and score of city development and is more suitable for the study of the maturity of EI development that includes more cities.

5. Discussion and Conclusions

Some current scholars rank the degree of UEI development [22–30,41]. For example, [23] constructed a multi-dimensional index system for the maturity of EI construction in rural areas based on the characteristics of resources, energy use, energy development trends and future development goals in rural areas. Refs. [24,25] construct an evaluation system for EI development from three aspects: engineering projects, low carbon and high efficiency and value-added services, as well as from economic, energy, environmental, social and engineering dimensions, respectively. Ref. [26] constructs a comprehensive benefit evaluation system for county EI covering multiple dimensions of reliability, economy, ecology, resilience and sociality. Ref. [28] constructs an evaluation model for the comprehensive benefits of the EI based on the system dynamics theory, including four aspects of economy, society, resources and environment. Ref. [29] establishes an evaluation index system for the applicability of the EI business model in five dimensions: the level of economic benefits, the quality of energy services, the ability of sustainable operation, the effect of energy saving and emission reduction and the ability to drive social development. Ref. [30] establishes an evaluation index system for the operation level of integrated energy

systems in three dimensions: production, transmission and distribution and consumption of energy. Most of these studies focus on the evaluation of the comprehensive benefits and key technologies of the EI, with less evaluation of the maturity of its development, and the evaluation indicators do not adequately take into account the various stages of UEI development. In addition, the traditional TOPSIS method cannot distinguish between the strengths and weaknesses of points on the vertical line between positive and negative ideal points [61], but the KL-TOPSIS model used in this study can solve this problem.

Based on existing research, this study considers the dynamic evolution process of cities, constructs an index system for evaluating the maturity of UEI development based on an explanatory structure model, calculates index weights using a subject-objective combination assignment method based on the AHP-entropy method, considers KL distance instead of Euclidean distance and constructs a comprehensive evaluation model of UEI maturity based on GRA-KL-TOPSIS. After the empirical analysis, the improved TOPSIS model can better overcome the influence between the factors of each indicator and improve the reasonableness of the evaluation results of the maturity of UEI development. The evaluation results are also used to analyse the development of the city's EI and to make corresponding recommendations for urban transformation. For cities with high rankings in the maturity of EI development, they should give full play to the head effect and make up for the shortage in resource supply in terms of technology, capital and talents and drive the development of EI in the surrounding areas and even the whole country. For cities ranked in the middle echelon of EI development maturity, they should increase the level of investment in new industries in the future, promote independent research and development and innovation iteration of relevant technologies, prioritise the benefits of EI development and narrow the development gap with the first-tier cities. For cities with a low ranking in the maturity of EI development, priority should be given to improving relevant infrastructure construction, creating a good environment for the development of new industries, renovating and upgrading facilities according to their own location characteristics, integrating the original industrial base with digital technology and enhancing the competitiveness of the city.

The current study also has some limitations. The next step should be to build a more complete UEI maturity evaluation index system by adding indicators, such as the number of customer links, business online rate and data response speed based on the characteristics of different types of cities and their different stages of development, and being oriented towards the development requirements of UEI such as multi-energy synergy, green and low-carbon, security and efficiency. At the same time, based on big data-driven, artificial intelligence and other technologies, the impact of subjective factors and external random factors on the evaluation results can be fundamentally resolved, and the objectivity and scientificity of the comprehensive evaluation of UEI maturity can be improved.

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