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Research on the Evaluation Model of a Smart Grid Development Level Based on Differentiation of Development Demand

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Abstract: In order to eliminate the impact of inter-regional differentiation of development demand on the objective evaluation of the development level of smart grid, this paper establishes the evaluation model of weight modification, transmission mechanism and combination of subjective and objective weights. Firstly, the Analytic Hierarchy Process method is used to calculate the weights of evaluation indices of effect layer and then the indices of development demand are used to modify the weights of them. The association analysis and the correlation coefficient are used to establish the weights conduction coefficient between the effect level and the base level. Then the subjective weights of the indices of the base layer are calculated. The objective weights of the indices of the base layer are obtained by using the entropy method. The subjective weights of the base layer and the objective weights obtained by the entropy method are averagely calculated, and the comprehensive weights of the evaluation indices of the base layer are obtained. Then each index is scored according to the weights and index values. Finally, the model is used to quantitatively inspect the level of development of smart grid in specific regions and make a horizontal comparison, which provides a useful reference for the development of smart grids. The relevant examples verify the correctness and validity of the model.

Keywords: smart grid; differentiation; development demand; comprehensive evaluation

1. Introduction

Based on an integrated and high-speed bi-directional communication network, smart grid is designed to be reliable, safe, economical, efficient, and environment-friendly through advanced sensing and measurement technologies, equipment technologies, control methods, and decision support system technologies. Key features of it include self-healing, motivating and engaging users, defending against attacks, providing power quality that meets 21st century user needs, allowing access to a variety of power generation forms, activating power markets, and optimizing asset applications for efficient operation. As for its application range, it is more and more extensive. For example, in recent years, some areas have combined smart grids with intelligent transportation to build new smart cities [1]. As an important part of the energy internet, it has drawn wide attention from all of the world and has now become a new trend in the development of the world's power grid [2–4].

Investment is the economic foundation for the development of smart grids, but due to the different driving forces of smart grid development in different countries, the focus of investment in the construction of smart grids is also different. In 2010, the top ten countries that the central government invested in the smart grid are shown in the Figure 1. Their total investment has reached \$18.4 billion and will continue to grow in the future. For Europe, its development focus is on the optimal operation of the power grid, the optimization of power grid infrastructure, and the development of communications and information technology. For the United States, its development and construction focus is on low-carbon and energy efficiency. For Japan, its construction focus is on the green economy. In China, its construction focus at present is to improve the resource allocation capability, safety level, and operating efficiency of the power grid. The development of smart grids in China is divided into three stages: pilot stage for planning, stage of comprehensive construction, and stage of guiding and improving. The situation of smart grid investment in each stage is shown in Figure 2 below.

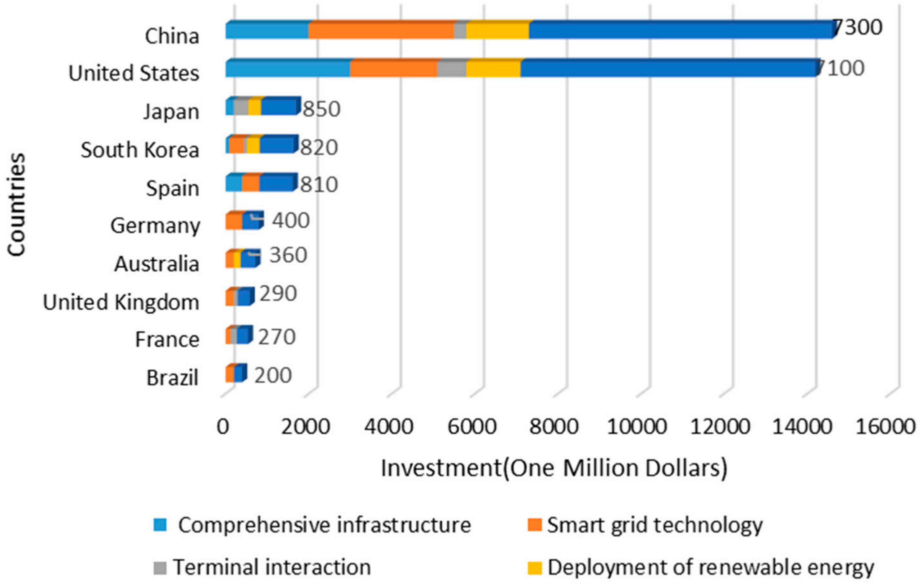

Figure 1. Smart grid investment in top ten countries.

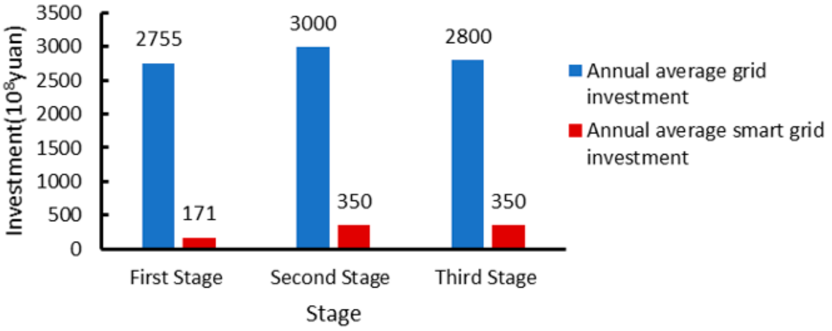

Figure 2. Investment status of China at each stage.

After high-speed construction in recent years, the development of smart grid at abroad has entered a stage of normalization. As developed countries such as Europe and the United States have a high level in the development, construction, and operation management of power grids, a great deal of research work has been carried out on the assessment of smart grids. The experience has been accumulated and relatively rich achievements have been achieved [5–7]. For China, the development of the smart grid has also entered a critical stage. Under the layout of the State Grid Corporation on smart grids, provincial power grid companies have responded to the call to speed up the pace of development and construction. Therefore, it is urgent to establish a sound evaluation system and mechanism to evaluate the level of smart grid development to guide its direction of development. Based on this background, this paper establishes an index system that combines the effect layer and the base layer, evaluates the development level of the smart grid in a specific region, looks for its weak links, and gives corresponding optimization suggestions.

The paper is organized as follows. The second part serves as a literature review. The third part introduces the establishment of the index system. The fourth part and the fifth part respectively introduce the effect layer index system and the base layer index system. In the sixth part, the paper gives the evaluation process of the development level of the smart grid. The seventh part analyzes the examples. Finally, the eighth part offers conclusion.

2. Literature Review

At present, evaluations of smart grids have been conducted by scholars at home and abroad. The specific literatures are shown in the Table 1 below.

Table 1. Research on smart grid evaluation.

Author	Evaluation Content	Indices/Dimensions	Method/Model
Yu et al. (2018) [8]	Power quality (PQ) coupling of smart grid	Pattern construction, pattern representation, and time series pattern matching	Time series pattern
Park et al. (2018) [9]	Intelligent demand management of the micro grid	High-Power LED, System, Demand Resource Management, Micro-Distributed ESS	A micro-distributed ESS-based smart LED streetlight system
Jesus et al. (2018) [10]	Investments of smart grid	Definitions and Assumptions, parameter specification, economics of the smart grid, statement of the optimization problem and solution approach.	Multi-level optimization model
Peng et al. (2018) [11]	Reliability and cascading risk of a smart grid system	Theoretical analysis, Numerical simulations	Model based on complex network theory
Leszczyna (2018) [12]	Cyber security of smart grid	Reviews, Vulnerability identification, Vulnerability analysis	Systematic analysis
Cacciatore et al. (2017) [13]	Cost Analysis of Smart Lighting for Smart Cities	Delay-based (DEL), Encounter-based (ENC), Dimming (DIM)	Heuristics for smart lighting based on the peculiar characteristics of the employed technology
Hashemi-Dezaki et al. (2017) [14]	Reliability of smart grids	The uncertainties of power systems, the stochastic output generation of renewable resources, the behaviors of PHEV owners, availability of physical elements, cyber elements	A new reliability evaluation method simultaneously considering the DCPIs, DGs, and PHEVs
Munshi et al. (2017) [15]	Smart grids	Data acquisition, data storing and processing, data querying, data analytics components	A comprehensive big data framework
Woo et al. (2017) [16]	Cyber Security of smart grid	Information systems, Power Systems	Optimal power flow (OPF), power flow tracing, Analytic hierarchy process
Lloret-Gallego et al. (2017) [17]	Resilience of ICT platforms in Smart distribution grids.	Reliability, Adaptation Capacity, Elasticity, Plasticity, Evolvability	EMPOWER Resilience Evaluation Framework
Vazquez et al. (2017) [18]	Smart Grid Demonstration Project	Mean Absolute Error (MAE), Mean, Absolute Percentage Error, (MAPE)	Adaptive load forecasting methodology
Rossebø et al. (2017) [19]	Risk assessment of Smart	Impact assessment, Threat and vulnerability, Assessment, Risk estimation and prioritization, Risk treatment, Risk acceptance	SEGRID Risk Management Methodology (SRMM)

Table 1. *Cont.*

Author	Evaluation Content	Indices/Dimensions	Method/Model
Coppo et al. (2015) [20]	The Italian smart grid pilot projects	System average interruption frequency index, system average interruption duration index, customer average interruption duration index, customer average interruption frequency index, customers experiencing multiple interruptions	Numerical simulations
Xenias et al. (2015) [21]	UK smart grid	Standards, Technical issues, Data handling, Market structure, Regulation, Co-ordination, Customer engagement, Investment	Policy Delphi
Liu et al. (2015) [22]	Risk of transmission lines in smart grid	Primary Filtering Technique, Secondary Filtering Technique	Bi-level model
Personal et al. (2014) [23]	The degree of goal achievement of Smart Grid	Improve of Energy Efficiency, Increase of Renewable Energy Use, Reduction of Emissions, Secondary Objectives	Hierarchical metric/a set of KPIs
Dong et al. (2014) [24]	Technological Progress of Smart Grid	Investment, labor inputs, technology	Production function theory, DEA, RRA
Hu et al. (2014) [25]	Technology maturity of Smart Grid	Time, production processes and technical features	A model include Time Production Processes, Time Technical Features and Processes Technical Features
Song et al. (2014) [26]	Smart Distribution Grid	Strong degree of the network, facilities intelligence, supply reliability, power quality, operational efficiency, grid interactivity, development coordination	Hierarchical optimization model and DEMATEL-ANP-counter entropy method
Song et al. (2014) [27]	Reliability of Smart Grids	Information subsystem failure, Communication subsystem failure, Intelligent substation failure, Protection subsystem failure, Power supply failure, Failures of other devices depending on the architecture	Layered Fault Tree Model
Bracco et al. (2014) [28]	SG (Smart Grid)/Smart Microgrid	Technical, economic and environmental performance indicators	A mathematical model that the minimize the SPM daily operational costs
Wang et al. (2013) [29]	Operation performance of smart grid	Economic operation, supply quality and services (distribution line length, substation capacity, net assets, loss rate, electricity quantity, supply area).	Optimal fuzzy, algorithm and data envelopment analysis
Niu et al. (2013) [30]	Regional Grid	Safety, Economy, Quality, Efficiency	Hierarchical optimized combination evaluation
Li et al. (2012) [31]	Smart Distribution Grid	The model of two-level index synthesized cloud and remarks cloud	Cloud model
Bilgin et al. (2012) [32]	Performance of ZigBee in smart grid environments	Network throughput, End-to-end delay, Delivery ratio, Energy consumption	Wireless sensor network-based smart grid applications
Xie et al. (2012) [33]	Safety of Smart Grid	Structural safety of transmission network, structural safety of distribution network, high-efficient system and equipment support, operational safety and stability, adequacy and resilience	AHP-Entropy combined, Method
Sun et al. (2011) [34]	Smart grid	IBM smart grid maturity model, The DOE smart grid development evaluation system, the EPRI smart grid construction assessment indicators, The EU smart grid benefits assessment system	Comparative analysis

3. Construction of the Index System

The comprehensive evaluation model of the level of development of the smart grid aims to achieve systematic evaluation of the overall level of the smart grid. Therefore, this paper establishes an index system from the effect layer and the base layer and builds the relationship between the two layers. The effect layer reflects the inherent nature of the development of smart grid and is dedicated to meeting the development needs of smart grid, while the base layer is the focus of smart grid construction. The index system structure of this paper shown in Figure 3.

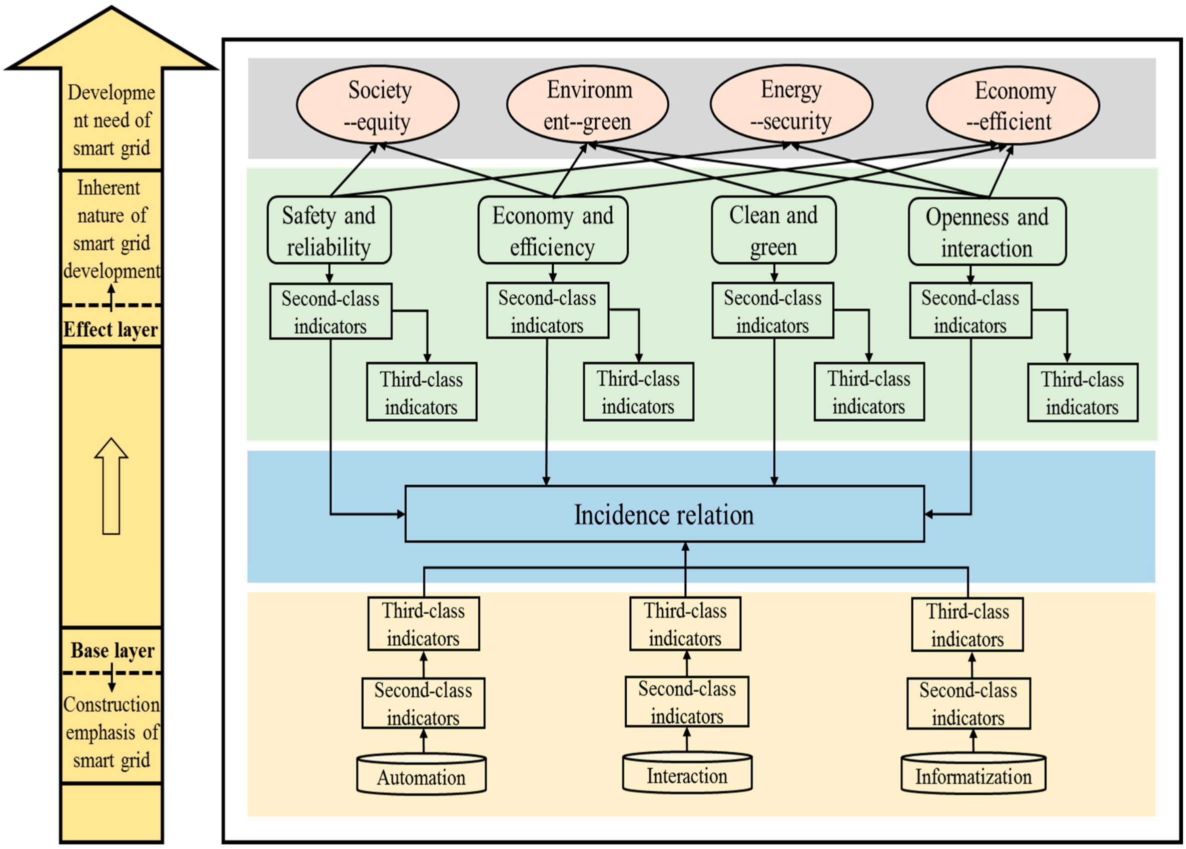

Figure 3. The structure of index system.

4. Index System of Effect Layer

4.1. Safety and Reliability

The safe and reliable operation are the key tasks for the future development of power grid. It involves the power supply security and reliability of power quality [35] and the ability to enhance the safety, stability and accident prevention capability of large power grids. The construction of communication information network is an important part of the intelligent construction of China's power grid, so the safety of communication information is equally worth noting. Therefore, the index system of the safety and reliability of the power grid is mainly established from two aspects: the safety and reliability of power grid and the safety of communication information, as shown in Table 2 [36].

Table 2. Index system of safety and reliability.

Second-Level Indicators	Third-Level Indicators	Code
The safety and reliability of power grid	The number of power transmission accident	E1
	The number of power transformation accident	E2
	The self-healing speed of the distribution network [37]	E3
	The self-healing rate of the distribution network	E4
	The reliability of power supply(urban user) [38]	E5
	The reliability of power supply (rural user)	E6
The safety of communication information	The index of the safe operation of information and communication system	E7
	The number of information events	E8

4.2. Economy and Efficiency

Economy and efficiency is to improve the grid operation and transmission efficiency, reduce operating costs and promote the efficient use of energy resources and power assets, so the index system of economics and efficiency of the power grid is mainly established from three aspects: economic benefits, grid efficiency and staff efficiency, as shown in Table 3.

Table 3. Index system of economics and efficiency.

Second-Level Indicators	Third-Level Indicators	Code
Economic benefits	The revenue of value-added services [39]	E9
	The recovery of electricity	E10
	The fair coefficient of electricity consumption	E11
Grid efficiency [40]	The annual maximum load utilization	E12
	The maximum load rate of power lines	E13
	The annual average equivalent load rate of line operation	E14
	The annual maximum load rate of main transformer	E15
	The annual average equivalent load rate of main transformer operation	E16
Staff efficiency	The efficiency of transmission staff	E17
	The efficiency of transformation staff	E18
	The efficiency of urban distribution network staff	E19
	Overall labor productivity	E20

4.3. Clean and Green

Clean and green means to improve the energy structure, improve the level of electrification, realize the large-scale development of clean energy and optimize the configuration of it in a wide range, replace the fossil energy with clean energy, and make the clean energy gradually become the dominant energy in the future. Therefore, the index system of the clean and green of the power grid is mainly established from three aspects: green power generation, green power grid, and green electricity, as shown in Table 4.

Table 4. Index system of cleanliness and green.

Second-Level Indicators	Third-Level Indicators	Code
Green power generation	The proportion of renewable energy power generation	E21
	The realization ratio of annual utilization hours of renewable energy	E22
	Abandoned wind ratio	E23
	Distributed power energy permeability	E24
Green power grid	The land disturbance area of unit quantity of electricity	E25
	The floor area saved by smart substation	E26
	Comprehensive line loss rate	E27
Green electricity	The electricity saved by demand-side management	E28
	The proportion of electricity in the terminal energy consumption	E29
	Power replacement ratio	E30

4.4. Openness and Interaction

Openness and interaction means that based on the platform of intellectualized service which built by smart grid to adapt to the connection and interaction of various types of power supply and load flexibly to meet the diverse needs of customers. Therefore, the index system of the openness and interaction of the power grids mainly established from four aspects: the transparency of power grid, the openness of power grid, quality service, and interactive effect, as shown in Table 5.

Table 5. Index system of openness and interaction.

Second-Level Indicators	Third-Level Indicators	Code
The transparency of power grid	The depth of information disclosure	E31
	The speed of information update	E32
	The convenience of getting information	E33
The openness of power grid	the growth rate of electric quantity in electric power market transaction	E34
	The investment in the open area of the grid business	E35
	The scale and proportion of the direct power-purchase for the large user	E36
	The completeness that all kinds of users access the standard system	E37
Quality service	The evaluation index of quality service	E38
Interactive effect	The year-on-year growth rate of the grid's annual maximum load utilization	E39
	The proportion of electricity of implementing peak and valley time price [41]	E40
	The power saved by demand-side management	E41
	The capability of load monitoring and control	E42
	The utilization rate of electric vehicles	E43

5. Index System of Base Layer

Based on the basic requirements of the construction of smart grid, this paper divides the basis of intelligent grid construction into three aspects: automation, interaction and information, and takes them as first-level index to establish the evaluation index system of the base layer.

5.1. Automation

Power network automation mainly refers to the automated operation of the power system. By running modern communication technology, network technology and automatic control technology, it reaches the automatic detection and control of grid operation, enhances the ability of online monitoring and self-protection operation, and effectively improves the efficiency of grid operation, to ensure reliable and efficient operation of the power grid. Therefore, the index system of power network automation is mainly established from four aspects: transmission automation, substation automation, distribution automation, and dispatching automation, as shown in Table 6.

Table 6. Index system of automation.

Second-Level Indicators	Third-Level Indicators	Code
Transmission automation	The total capacity of flexible AC transmission device	B1
	The proportion of energy-saving wire	B2
	The application of disaster prevention and reduction technology	B3
	The proportion of the lines applying condition monitoring technology	B4
	The proportion of the lines applying intelligent inspection technology	B5
Substation automation	The proportion of smart substation	B6
	The coverage of the patrol robot of substation	B7
	The coverage of condition monitoring of transformer equipment	B8
Distribution automation	The coverage of distribution automation	B9
	The coverage of feeder automation	B10
	Coverage of the command platform of power distribution repairs in a rush	B11
	Coverage of distribution power automation terminal	B12
Dispatching automation [42]	The coverage of provincial/prefecture (county) level smart grid dispatching control system	B13
	The coverage of provincial/prefecture (county) level standby scheduling	B14
	The coverage of dual access of dispatch data net	B15
	The access rate of station terminal dispatch data network	B16
	the coverage of secondary security system	B17

5.2. Interaction

Interactive technology of the smart grid is a key technology and development direction which can improve the capacity of the grid to carry new energy and ensure the power quality of the grid. It can achieve the multi-directional interaction among the power supply, power grid and users, and allows users to participate more in the process of power balance by changing users' electricity behavior and developing the access of distributed energy. Therefore, the index system of interaction is mainly established from four aspects: interaction of electricity use, electric vehicles, large-scale access to new energy sources, and distributed power supply, as shown in Table 7.

Table 7. Index system of interaction.

Second-Level Indicators	Third-Level Indicators	Code
Interaction of electricity use	The coverage of electricity information collection system	B18
	The coverage of intelligent ammeter	B19
	The coverage of power service management platform	B20
	The method of demand-side response to electricity prices	B21
	The area density of the interactive business hall	B22
Electric vehicles	The area density of city charge (change) power station	B23
	The linear density of highway filling (change) power station	B24
	The matching degree of electric vehicle and charger	B25
Large-scale access to new energy sources	The coverage of new energy power forecasting system	B26
	The completion rate of wind and PV power grid detection	B27
	The proportion of new energy installed capacity	B28
Distributed power supply	The proportion of distributed power installed capacity	B29
	The realization rate of distributed generation forecast	B30

5.3. Informatization

Grid informatization refers to the process of cultivating and developing new productivity represented by intelligent tools such as computers and network communication technologies in the power grid and improving the operation and management of the power grid. It is reflected in the construction of communication network and information construction index system as shown in Table 8.

Table 8. Index system of informatization.

Second-Level Indicators	Third-Level Indicators	Code
Construction of communication network	The optical fiber coverage of substations(35 kV and above)	B31
	The cable coverage of backbone communication network	B32
	The bandwidth capacity of communication transmission network platform	B33
	The fiber coverage of 10 kV communication access network	B34
	The rate of PFTTH	B35
Information construction	The coverage of SG-ERP system	B36
	The automatic monitoring rate of information communication equipment	B37
	The availability rate of information network	B38
	The availability rate of business systems	B39

6. Evaluation Process of Smart Grid Development Level

6.1. Implementation Path of Evaluation Model

The comprehensive evaluation model of the development level of smart grid is based on the theory of system evaluation and can accurately evaluate the overall development level of smart grid. By decomposing and refining the smart grid, it deepens its understanding of the smart grid, enhances the specificity and representativeness of the evaluation index, and improves the accuracy of the evaluation results. Through the research on the coordinative relationship among the indicators, a dynamic weight calculation method is designed to realize the two-way interaction between the effect layer and base layer.

When choosing the evaluation method of smart grid, this paper select the appropriate evaluation method based on the characteristics of each attribute and index, and combine with the application scope of the method, so as to obtain a more accurate and reasonable evaluation result. The evaluation model process of this paper as shown in Figure 4.

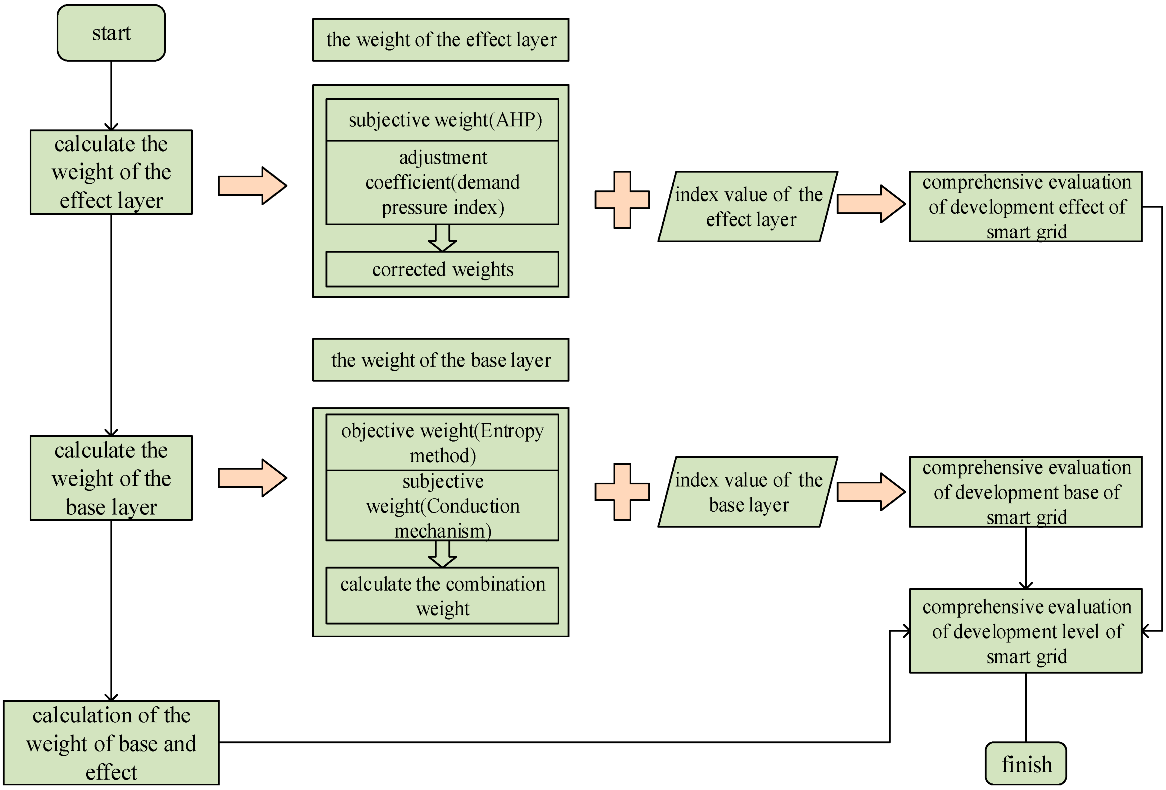

Figure 4. Technical path of comprehensive evaluation model.

6.2. Method of Evaluation Model

6.2.1. Subjective Weights of the Effect Level Indicators by the AHP Method

The Analytic Hierarchy Process (AHP) is a practical multi-objective decision-making method. When AHP is used to analyze the decision-making problem, first of all, we need to rationalize and stratify the issue so as to construct a hierarchical structural model. The basic steps are as follows:

(1) Establish a hierarchical structure.
(2) Construct a judgment matrix.

Hierarchies reflect the relationship between the factors, but the criteria of the criterion layer do not necessarily share the same weight in the target measure. This article uses the numbers 1–9 and their reciprocal as a scale. Table 9 lists the meaning of 1–9 scale:

Table 9. The judgment basis of scale value and related description.

Scale Value	Description
1	Indicates that elements i and j are of equal importance
3	Representing the elements i and j, the former is slightly more important than the latter
5	Representing the elements i and j, the former is significantly more important than the latter
7	Representing the elements i and j, the former is awfully more important than the latter
9	Representing the elements i and j, the former is perfectly more important than the latter
2, 4, 6, 8	The importance is between the above two
Reciprocal	Representing the importance of elements i and j in contrast to the above

(3) Hierarchical single arrangement and consistency checking

Hierarchical single arrangement is based on the judgment matrix, calculating the target element in the previous level, and determining the importance (weight) of level and its associated elements. The method of solving the largest eigenvector of the judgment matrix is used to obtain the weight of single arrangement. The formula is:

$$CW = \lambda_{\max} W \tag{1}$$

where $\lambda_{\max}$ and W denote the maximum eigenvalue of the judgment matrix C and the corresponding eigenvector.

In order to avoid the contradictory judgment result in the process of expert judgment, it is necessary to check consistency of hierarchical single arrangement. Check the consistency of the judgment matrix by calculating the CR value:

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \tag{2}$$

$\mathrm{CI} = (\lambda_{\max} - \mathrm{n})/(\mathrm{n} - 1)$ is the dimension of the judgment matrix, RI is the corresponding random value, as shown in Table 10.

Table 10. RI value that correspond to n.

N	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

If $\mathrm{CR} < 0.1$, then the judgment matrix can be regarded as satisfactory consistency. The judgment matrix can be used as a hierarchical analysis. If $\mathrm{CR} \geq 0.1$, the judgment matrix is not satisfactory, and the judgment matrix needs to be adjusted and corrected.

(4) Hierarchical total ordering and consistency checking

Through the above steps, a set of weight vectors can be obtained. Ultimately, we should obtain the weight of sorting the goals in each element, especially in the lowest level, so as to make a choice of solutions. The total sequencing weight will synthesize the weights of the single criteria from top to bottom.

Suppose that the upper level (level A) contains m factors $A_1, \ldots, A_m$, and the total weight of their levels is $a_1, \ldots, a_m$. The next level (B level) contains n factors $B_1, \ldots, B_n$, whose rank ordering weights for A_j are respectively $b_{1j}, \ldots, b_{nj}$ ($b_{ij} = 0$ when B_i is unassociated with A_j). We now ask for the weight of each factor in the B-layer about the total goal, that is, find the total weight $b_1, \ldots, b_n$ of the hierarchy of each factor in the B-tier. The calculation is performed in the following way:

$$b_i = \sum_{j=1}^{m} b_{ij}a_j, i = 1, \ldots, n \tag{3}$$

The hierarchical total ordering also needs to be checked for consistency. The test is still performed from the high level to the low level layer by layer like the total level of the hierarchy. The pairwise comparison judgment matrix of factors related to A_j in layer B is checked for consistency in a single ranking, and the single-order consistency index is obtained as $CI(j)$, ($j = 1, \ldots$,m), and the corresponding average When the random consistency index is $RI(j)$ ($CI(j)$ and $RI(j)$ have been obtained when the levels are single-ordered), the proportion of random coherence of the total order of the B-level is:

$$CR = \frac{\sum_{j=1}^{m} CI(j)a_j}{\sum_{j=1}^{m} RI(j)a_j} \tag{4}$$

when $CR < 0.10$, it is considered that the hierarchical total ordering results have a satisfactory consistency and accept the analysis result.

6.2.2. Correcting the Weight of the Effect Layer in the Direction of Development Demand

Based on the basic cluster analysis of the development of the provincial power grids in the country, the provincial power grids can be divided into three categories. Provincial power grids A, B, and C are selected from each of them, their development demand index values separately calculated, the development demand index values of the provinces where they are located as the target value averaged, and the demand pressure index calculated separately. The first-level indicators at the effect level are revised to meet the demand-oriented goal. The specific process is as follows in Figure 5.

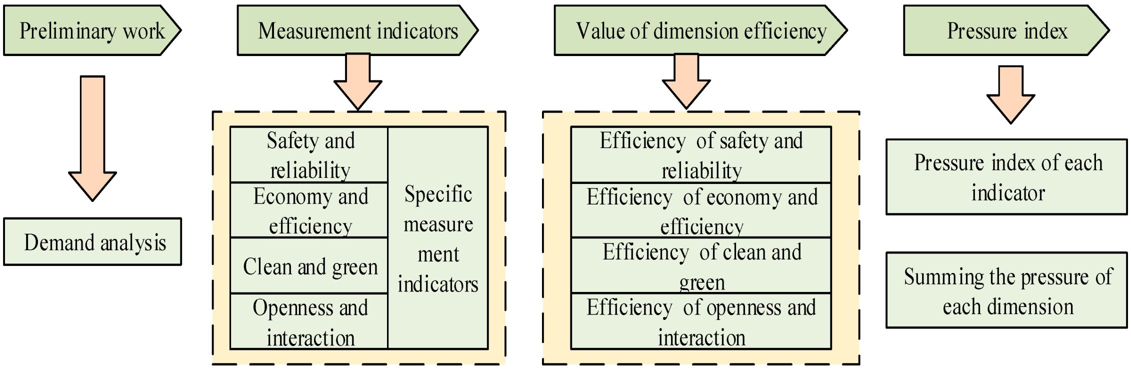

Figure 5. Process of weight modification.

(1) The measurement index of smart grid development demand

Based on the availability of the current indicator data, the measurement indicators of smart grid development demand are shown in Table 11.

Table 11. The measurement indicators of smart grid development demand.

Dimensions of Demand	**Quantitative Measurement Indicators**	**Code of Demand Pressure Indicators**
Safety and reliability (D_1)	The proportion of a type of load	DC_1
	The proportion of secondary industry production GDP	DC_2
	Load density	DC_3
	Capacity-load ratio	DC_4
	Urbanization rate	DC_5
Economy and efficiency (D_2)	Return on assets	DC_6
	Overall labor productivity	DC_7
	Electricity sale of unit assets	DC_8
	Energy intensity	DC_9
	Ratio of power generation and electricity	DC_{10}
Clean and green (D_3)	The proportion of clean energy production	DC_{11}
	Air-quality index	DC_{12}
	Carbon dioxide emissions per unit area	DC_{13}
	Carbon intensity	DC_{14}
	The proportion of electrical energy in terminal energy consumption	DC_{15}
Openness and interaction (D_4)	Reasonable degree of utilization hours of power generation equipment	DC_{16}
	Ratio of urban-rural power supply reliability	DC_{17}
	Quality service evaluation index	DC_{18}
	Per capita electricity consumption	DC_{19}
	The proportion of tertiary industry production GDP	DC_{20}

The demand pressure index formula is shown in Equation (5).

$$demand\ pressure\ index = \frac{Max(actual\ value, target\ value)}{Min(actual\ value, target\ value)} \tag{5}$$

Demand pressure index of safety and reliability (D_1)
$=DC_1 + DC_2 + DC_3 + DC_4 + DC_5$
Demand pressure index of economy and efficiency (D_2)
$=DC_6 + DC_7 + DC_8 + DC_9 + DC_{10}$
Demand pressure index of clean and green (D_3)
$=DC_{11} + DC_{12} + DC_{13} + DC_{14} + DC_{15}$
Demand pressure index of openness and interaction (D_4)
$=DC_{16} + DC_{17} + DC_{18} + DC_{19} + DC_{20}$

(2) After the normalization process as the requirement four-dimensional weight value

The above calculation results and the AHP method are used to correct the weight of the first-level indicators of the effect layer. The two mean values are taken as the final weight of the indicator, and the second-level and third-level indicators' weights of the effect layer are corrected in order.

6.2.3. Determination of Objective Weights of Base Layer Indicators

In this paper, the Entropy Method [43] is used to calculate the objective weights of the base layer indicators. It is a method to determine the weights based on the amount of information provided by the observations of each index. It is an objective method of empowerment that embodies the size of the evaluation of indicators in objective information. The basic implementation steps are as follows:

(1) Evaluation index membership degree matrix standardization

The n object to be evaluated corresponds to the index values of the m evaluation indices and constitutes a membership evaluation standard R.

$$R = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & & & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{pmatrix}$$

In this evaluation index system, there are differences in the dimension, content, merits and demerits of each indicator, etc. Therefore, it is necessary to standardize the value of each indicator. There are two kinds of standardized processing methods: The larger the indicator data is, the better, that is, the positive indicator. The standard formula is:

$$r_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{6}$$

when the indicator data is smaller, the better, that is, the inverse indicator, the standard formula is:

$$r_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{7}$$

(2) Normalize each indicator value and calculate the proportion of the indicator value of the ith evaluation object under the jth indicator:

$$P_{ij} = \frac{r_{ij}}{\sum\limits_{j=1}^{n} r_{ij}} \tag{8}$$

(3) Calculate the entropy of the jth indicator:

$$H_j = -K\sum_{i=1}^{n} P_{ij} \ln P_{ij} (j = 1, 2, \ldots, m) \tag{9}$$

Among them:

$$K = 1/\ln n (K>0, 0 \le P_{ij} \le 1) \tag{10}$$

and assume that:

$$P_{ij} = 0, P_{ij} \ln P_{ij} = 0 \tag{11}$$

(4) Calculate the difference coefficient of the jth indicator:

$$\alpha_j = 1 - H_j \tag{12}$$

(5) Calculate the weight of the jth indicator:

$$w_j = \frac{\alpha_j}{\sum\limits_{j=1}^{m} \alpha_j} \tag{13}$$

6.2.4. Relationship among the Effect Layer and the Base Layer Indicators

Until now, the smart grid construction period is not long, and there are few index data, the correlation analysis based on the index data may have errors. Therefore, this paper first uses the expert scoring method to judge the correlation degree between two-level indicators of effect layer and the key indicators of the basic layer. The specific process is as follows in Figure 6.

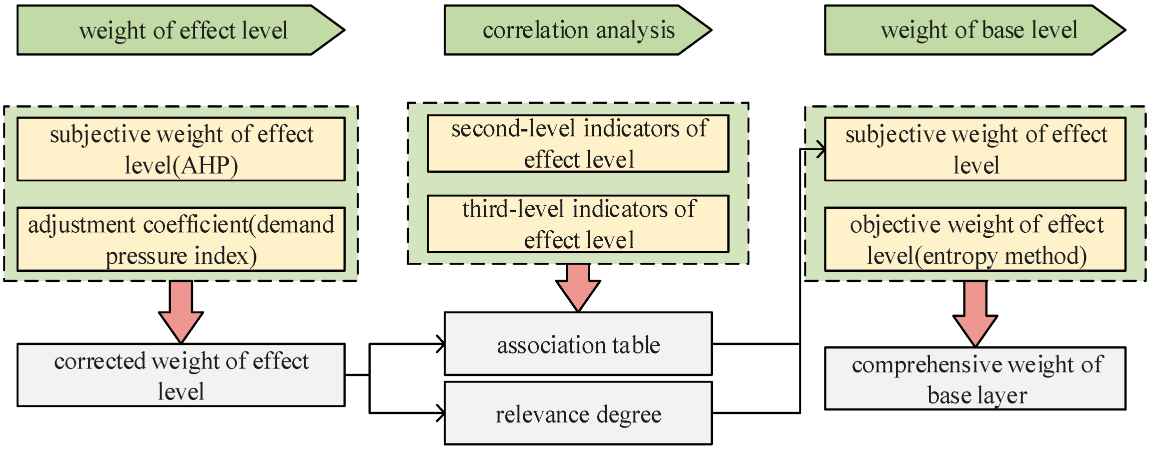

Figure 6. Process of correlation analysis.

The association table between effect layer and base layer indicators is showed in Table 12.

Table 12. Relationship between effect layer and base layer indicators.

Second-Level Indicators of Effect Level	Third-Level Indicators of Base Level Which Associated with It
The safety and reliability of power grid	B1, B3~B14, B26, B27, B30
The safety of communication information	B15~B17, B31~B34, B37~B39
Economic benefits	B18~B21, B23~B25, B35
Grid efficiency	B1, B13, B21
Staff efficiency	B5~B9, B11~B13, B36
Green power generation	B13, B26~B28
Green power grid	B2, B6
Green electricity	B20, B21, B23~B25
Transparent grid	B21, B22
Open grid	B23~B25, B29
Quality service	B11, B20, B22
Interactive effect	B18, B21~B25

There are two factors that affect the subjective weights of the basic layer indicators: one is the weight of the related effect level indicators, and the other is the size of the correlation between them. Therefore, this article uses the multiplication of these two as the subjective weights of the base layer indicators.

The subjective weights and objective weights of the basic layer are arithmetically averaged to obtain the comprehensive weight of the basic layer evaluation indicators.

Through the correlation analysis of qualitative and quantitative analysis between the second-level indicators of the effect layer and the third-level indicators of the base layer, the subjective weights of the effect layer are transmitted to the third-level indicators of the basic level, and the guiding effect of the effect on the foundation is achieved.

7. Case Study

Using the above-mentioned index system and evaluation method, three provincial power grids are selected, and scores are assigned to each aspect of smart grid development in combination with the weights and index values, thereby assessing the development level of smart grids. The results are as follows.

7.1. Province A

The relevant data (for example, the reliability of power supply, overall labor productivity, the proportion of renewable energy power generation, the evaluation index of quality service) that can reflect the first-level indicators of the effect layer in A province is used as a reference. Ten experts are hired to score the importance level of the first-level indicators in the effect layer, and the weights of the first-level indicators are calculated by the judgment matrix given by the experts. Finally, the weight result obtained by the AHP method is the average value of the calculation results of the ten expert judgment matrix, and then the weight is corrected by the indices of development demand to obtain the final weight of the first-level index, and so on, and the weights of the indicators at all levels are calculated.

The weights calculated using the judgment matrix given by one of the experts is showed in Table 13, and has passed the consistency test.

Table 13. The judgment matrix.

	Safety and Reliability	**Economy and Efficiency**	**Clean and Green**	**Openness and Interaction**	**Weight**
Safety and reliability	1	2	3	4	0.4285
Economy and efficiency	1/2	1	5	6	0.3810
Clean and green	1/3	1/5	1	2	0.1170
Openness and interaction	$\frac{1}{4}$	1/6	$\frac{1}{2}$	1	0.0735

Therefore, the average value calculated by the judgment experts is given by the ten experts and then corrected to the final weight of the effect layer index. The weight of the first-level index of the base layer is calculated by the entropy weight method. The final result is shown in Table 14.

Table 14. The weight of the first-level indices.

Index	**Weight**
Safety and reliability	0.3707
Economy and efficiency	0.2444
Clean and green	0.2517
Openness and interaction	0.1332
Automation	0.5039
Interaction	0.2811
Informatization	0.2150

The second-level indicator "Green Power Generation", and its associated indicators, are analyzed and the correlations are shown in Table 15.

Table 15. The relevance of the "green power generation" indicators.

Relevance of the "Green Power Generation" Indicators				
Associated indicators	B13	B26	B27	B28
Degree of association	0.4555	0.1289	0.8795	0.4537

According to the above introduction, the subjective weights of base layer and objective weights of base layer which obtained by using the entropy method are arithmetically averaged to obtain the comprehensive weight of the corresponding base layer evaluation indicators. The results are shown in Table 16.

Table 16. The weight of the corresponding base layer index.

Index of Base Layer	Subjective Weight	Objective Weight	Comprehensive Weight
B13	0.3175	0.0298	0.1737
B26	0.2030	0.0322	0.1176
B27	0.1322	0.0298	0.0810
B28	0.1184	0.0236	0.0710

(1) Evaluation results of effect level

Province A's evaluation results of effect level are showed in Figures 7 and 8.

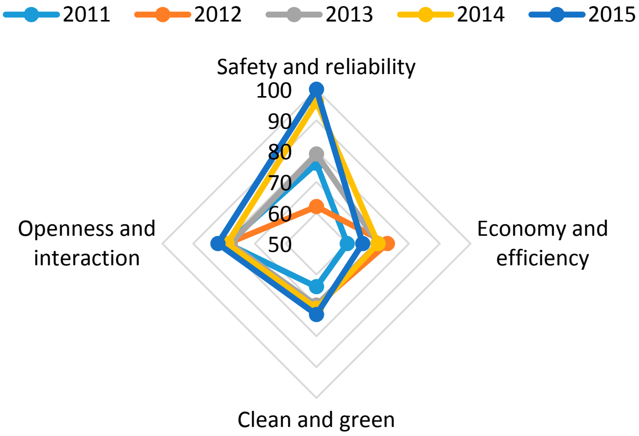

Figure 7. Radar map of construction effect evaluation of Province A.

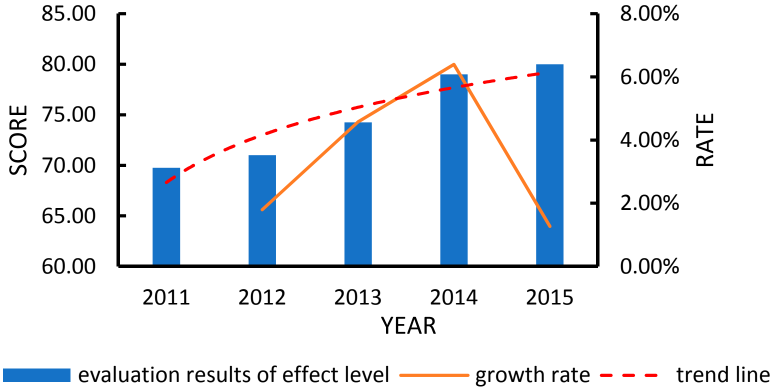

Figure 8. Evaluation results of effect level of Province A.

As can be seen from the above figure, the radar area is increasing year by year, and the score of the effect level development over the years is also gradually increasing, but the growth rate has a certain fluctuation.

In terms of safety and reliability, the power grid company of the province A actively responded to the call and during the "Twelfth Five-year Plan" period [44], it accelerated the construction of a strong smart grid including the ultra-high voltage (UHV), built a comprehensive demonstration project of the eco-city smart grid and promoted its application, ensuring the province's reliable supply of power energy and greatly increasing the safety of the power grid. In terms of clean and green, the province is committed to improving the efficiency of thermal power energy use and promoting energy conservation and emission reduction, therefore, the level of it has been improved to some extent. On the whole, the development level of smart grid effect level of province A should be fully promoted through the two main lines of technological progress and management improvement.

(2) Evaluation results of base level

Province A's evaluation results of base level are showed in Figures 9 and 10.

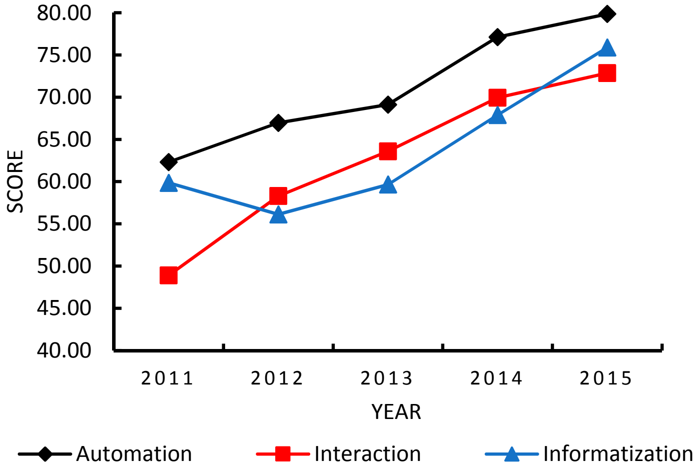

Figure 9. Line chart of construction base evaluation of Province A.

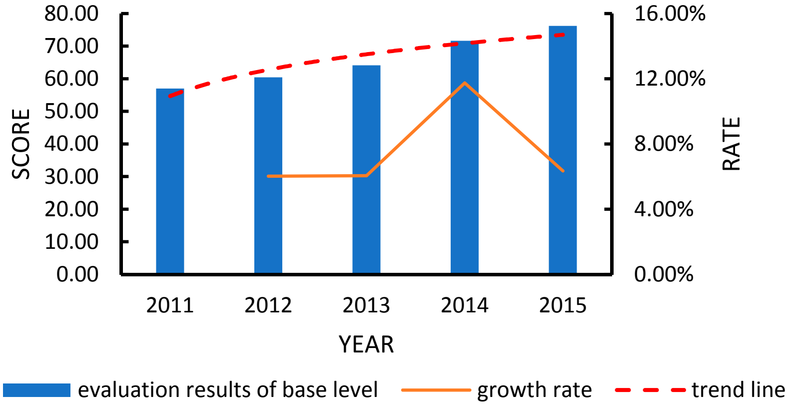

Figure 10. Evaluation results of base level of Province A.

The level of automation, interaction, and informatization of the smart grid in the province has been gradually improved, so the overall level of its base layer is on the rise. The provincial power company's smart grid construction plan was completed in 2010 and entered the full-scale construction phase of the smart grid in 2011. During the "Twelfth Five-Year Plan" period, the provincial electric power company increased its investment in the construction of a smart grid, and extensively adopted modern technology and automation equipment. As a result, the level of the base level of power grid has been comprehensively improved.

7.2. Province B

As mentioned above, the weights of corresponding indicators of province B are showed in Tables 17–19.

Table 17. The weight of the first-level indicators.

Layer	Indicators	Weight
Effect layer	Safety and reliability	0.3961
	Economy and efficiency	0.2352
	Clean and green	0.2367
	Openness and interaction	0.1319
Base layer	Automation	0.5039
	Interaction	0.2811
	Informatization	0.2150

Table 18. The relevance of the "green power generation" indicators.

Relevance of the "Green Power Generation" Indicators				
Associated indicators	B13	B26	B27	B28
Degree of association	0.7212	0.3892	0.4712	0.4807

Table 19. The weight of the corresponding base layer indicators.

Indicators of Base Layer	Subjective Weight	Objective Weight	Comprehensive Weight
B13	0.0464	0.0298	0.0381
B26	0.0179	0.0322	0.0250
B27	0.0107	0.0298	0.0202
B28	0.0135	0.0236	0.0186

7.2.1. Evaluation Results of Effect Level

Province B's evaluation results of effect level are showed in Figures 11 and 12.

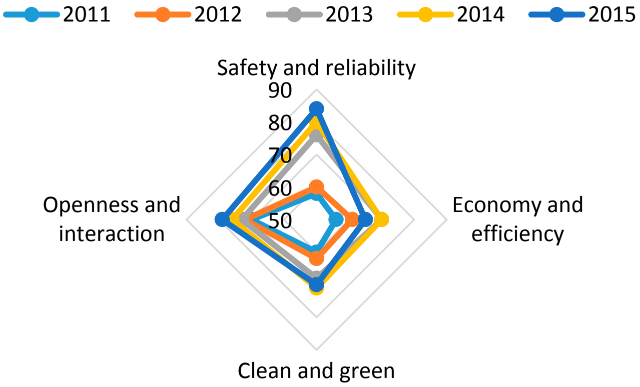

Figure 11. Radar map of construction effect evaluation of Province B.

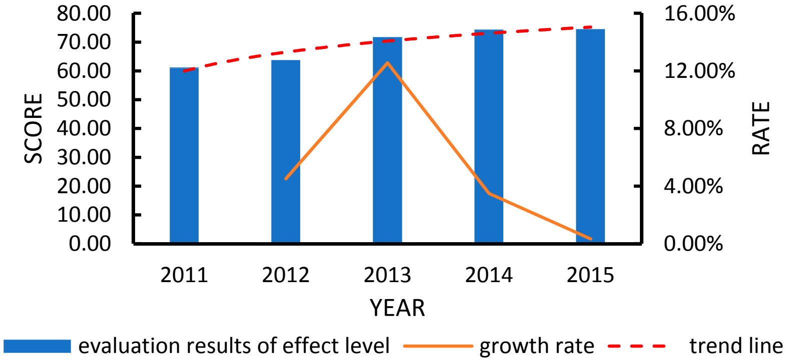

Figure 12. Evaluation results of effect level of Province B.

As can be seen from the radar map, the radar area is increasing year by year, and the improvement of the intelligent effect tends to be flat. Among them, the progress of safety and reliability is relatively fast, indicating that the Province B's smart grid construction has a good effect on the construction of power grids and power supplies. In terms of economy and interaction, it may not perform well because related projects are mostly piloted or promoted. From the above figure, it can also be seen that the level of the power grid effect of the province is slowly growing, and the growth rate is fluctuating.

In the aspect of safety and reliability, it is indicated that the construction of the power grid is under the background of UHV AC and DC landing in the Central Plains, and priority is given to ensuring a wide range of optimal allocation of energy resources. In terms of cleanness and green and openness and interaction, the company is a power grid based on thermal power, and marketing and interactive services are starting. In terms of economic and efficiency, due to the large number of historical problems in the grid, the overall weak distribution network and low operating efficiency have not yet been fundamentally reversed.

7.2.2. Evaluation Results of Base Level

Province B's evaluation results of base level are showed in Figures 13 and 14.

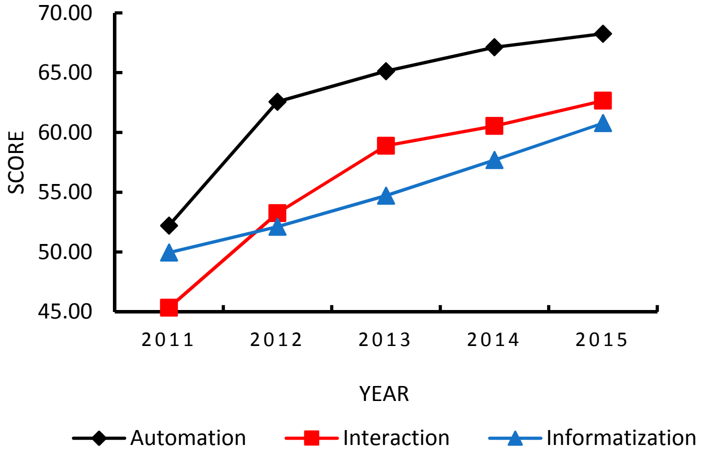

Figure 13. Line chart of construction base evaluation of Province B.

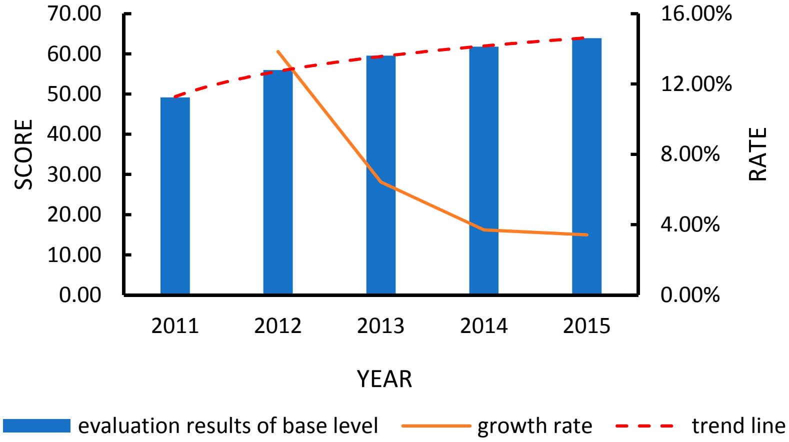

Figure 14. Evaluation results of base level of Province B.

The scores of various indicators have increased year by year, indicating that the basic level of Province B's power grid has become better year by year, among them, the progress of automation and interaction has been greater, indicating that the company's smart grid construction has achieved significant improvement in technology.

In terms of automation, based on the status of the company's balanced power grid, the company's grid security and resource allocation capabilities have been significantly improved through strong cooperation with UHV AC/DC interconnected power grid construction in such areas as power generation, transmission, and dispatch. In terms of informatization and interaction, it can be seen from the above figure that its level is increasing year by year. This is because of the development of related technologies such as measurement, communications, information, and control.

7.3. Province C

As mentioned above, the weights of corresponding indicators of province C are showed in Tables 20–22.

Table 20. The weights of the first-level indicators.

Layer	Indicators	Weight
Effect layer	Safety and reliability	0.2580
	Economy and efficiency	0.2699
	Clean and green	0.2845
	Openness and interaction	0.1876
Base layer	Automation	0.5039
	Interaction	0.2811
	Informatization	0.2150

Table 21. The relevance of the "green power generation" indicators.

Relevance of the "Green Power Generation" Indicators				
Associated indicators	B13	B26	B27	B28
Degree of association	0.3115	0.1919	0.3038	0.5434

Table 22. The weights of the corresponding base layer indicators.

Indicators of Base Layer	Subjective Weight	Objective Weight	Comprehensive Weight
B13	0.0152	0.0298	0.0225
B26	0.0030	0.0322	0.0176
B27	0.0742	0.0298	0.0520
B28	0.0762	0.0236	0.0499

7.3.1. Evaluation Results of Effect Level

Province C's evaluation results of effect level are showed in Figures 15 and 16.

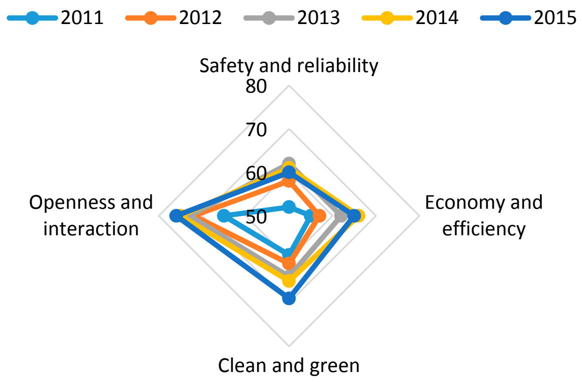

Figure 15. Radar map of construction effect evaluation of Province C.

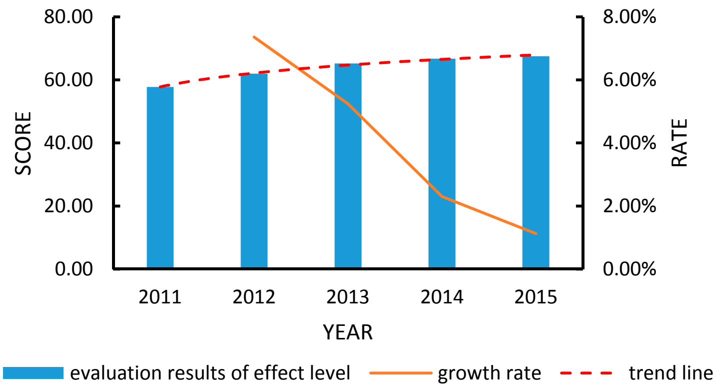

Figure 16. Evaluation results of effect level of Province C.

As can be seen from the above figure, the overall level of the effect layer is increased year by year, but the growth rate fluctuates.

Due to the abundance of wind resources in the province C, ten million kilowatts of wind power bases were built during the period of the Twelfth Five-Year Plan. Some wind power bases are centralized renewable energy generation (CRG) in terms of access methods. After the CRG is connected to the power grid, it has an important and positive effect on energy conservation, emission reduction and energy structure optimization, but it has affected the security and stable operation of the power grid to some extent. At the same time, clean energy alternative projects have been carried out in some areas of the province, which has made great progress in cleaning and environmental protection.

7.3.2. Evaluation Results of Base Level

Province C's evaluation results of base level are showed in Figures 17 and 18.

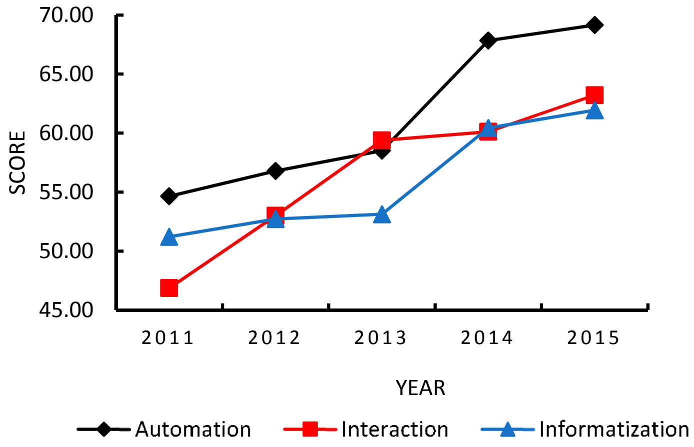

Figure 17. Line chart of construction base evaluation of Province C.

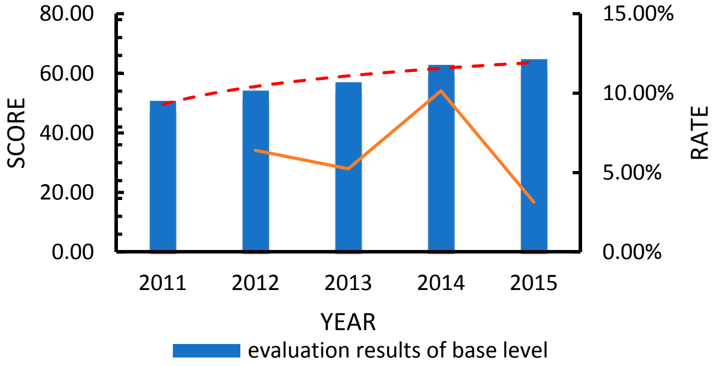

Figure 18. Evaluation results of base level of Province C.

From the above figure, we can see that the level of automation, interaction and informatization of the smart grid in the province has been increasing year by year, but the growth rate is different.

In terms of automation and informatization, the growth rate accelerated in 2013. This is because in 2013, the provincial power grid company carried out all-round power grid geographic information system collection work. As of June 2015, with the province's total 35 kV, 110 The GIS data collection work of the KV transmission line was fully completed. The power company of the province realized visualization, space, and automation management of the power grid through the power grid GIS "big data", thus greatly improving the automation and informatization level of the entire power grid. As for interaction, its growth rate has been relatively stable.

7.4. Comparison

The above method can be used to compare the development level of smart grids in the three provinces. The results are shown in the Figures 19–21.

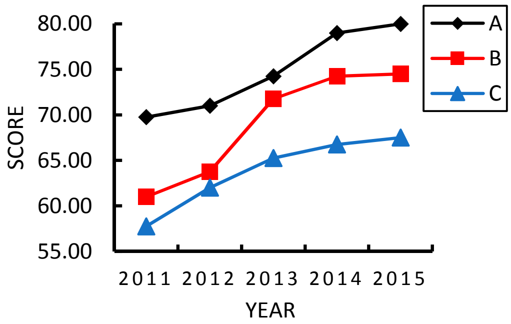

Figure 19. Evaluation results of effect level.

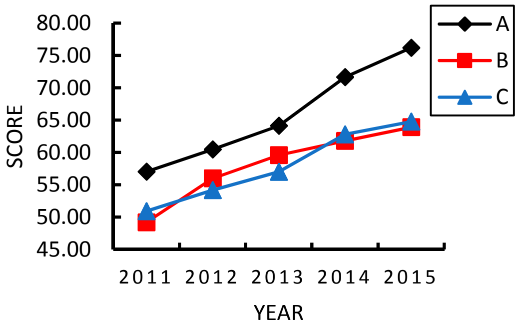

Figure 20. Evaluation results of base level.

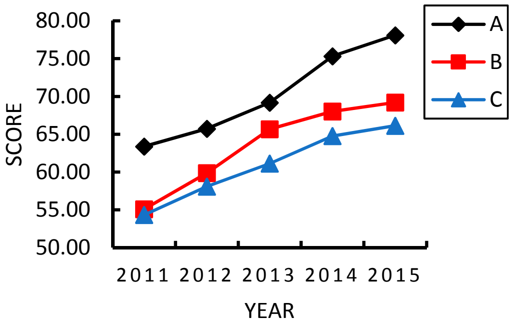

Figure 21. Comprehensive evaluation results.

As can be seen from above figures, in the early stage of smart grid construction in 2011, although the scores of the base layer were low, the construction achievements were remarkable, and the scores in the effect layer were relatively high. With the promotion and construction of the smart grid, although the levels of intelligence of the grid infrastructure keep growing at a certain rate, the speed of the improvement of the effect layer has decreased year by year and tends to be flat; by 2014–2015, although the score of the base layer continues to increase, the score of the effect layer has grown little, which fully reflects the development rule that the smart grid has been in an all-round construction phase.

The final comprehensive evaluation results show that Province A is better than Province B in the overall level of smart grid development, and Province B is better than Province C. Therefore, the power companies in Province B and Province C need to further strengthen the construction and operation management of the smart grid.

8. Conclusions

Based on the difference of demand for the development of smart grid, this paper first establishes its own index system. Subsequently, this paper proposes the implementation path of the evaluation model. Finally, three typical provinces were selected to evaluate and compare the level of smart grid development.

We know that as the smart grid is written into the "Twelfth Five-Year Plan", its status in the country's strategic emerging industries gradually emerged, and the nation's smart grid construction was fully launched. The year 2011 is the first year for the smart grid to enter the comprehensive construction phase. It is also the starting point for the smart grid to achieve leapfrogging from pilot construction to comprehensive construction. By 2015, a strong smart grid operation control and two-way interactive service system has been formed to basically achieve friendly access and coordinated control of renewable energy such as wind power and solar power generation.

Based on this background, this paper proposes to evaluate the development level of smart grid using weight modification, transmission mechanisms, and evaluation methods combining subjective and objective weights, and selects three typical provinces for case demonstration.

For Province A, its development goal in the Twelfth Five-Year Plan is to build a strong, self-reliant, economical, compatible, flexible, and integrated urban power grid that matches the orientation of urban development and is characterized by information, automation, and interaction. Therefore, the government has increased investment, promoted energy-saving construction, and adopted modern technology and automation equipment. As a result, the level of the effect layer and base layer of smart grid is relatively high, and its overall level is also relatively high compared to other provinces. For provinces B and C, due to historical issues and different stages of development, the overall level of smart grid development is relatively low compared to province A.

Through the analysis of relevant examples, it can be proved that the evaluation model can make an association analysis between the construction foundation and the construction effect, and make a comprehensive and deep evaluation of the development level of the smart grid in our country, which is of guiding significance to the future intelligent construction of the power grid.

When using this evaluation method to calculate the weight, the general indicators such as the number of transmission and transformation accidents, overall labor productivity, the proportion of renewable energy power generation, the rate of electricity market transaction power growth, the ratio of intelligent substation, the coverage of smart electric meter, and so on, can be directly applied to different regions and countries, but it should be noted that because different metrics are used around the world, such as assessing the reliability of power systems, there are different indicators, such as SAIDI/SAIFI, and the indicators proposed in this paper are not all versatile, therefore, when applying this method, some substitutions can be made appropriately without affecting the content embodied in the indicator.

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