Evaluation of Smart Grid Construction Development Impact Based on Analytic Hierarchy Process

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Abstract. The smart grid become a consensus for the development of power industry in the world, which can bring out the economic development of the world. Evaluation of the smart grid’s development scientifically, systematically and objectively will beneficial to get better further development of smart grid construction. This paper creates an evaluation index system of smart grid construction development impact from four aspects, including technology influence, energy influence, environment influence and social influence and the four aspects contains 20 indicators. The indicator’s weights are determined by AHP, then an empirically analysis is given by the grid development evaluation of China, America and European Union. The results show the relevant differences of the three countries, and some suggestions of China’s smart grid construction in the future are also given.

1. Introduction
Environmental pollution pays much attention to all of the world, and the demands for establishing a sustainable development system and developing harmonious green economy have been increasingly prominent. The social demands for energy conservation and emission reduction are increasing continuously, the clean electricity energy’s requirements are also increasing. Nowadays, there has been a broad consensus for domestic and foreign experts on building safe, reliable, clean and high quality electric power delivery systems to optimize the low carbon energy. In order to meet the demand for consumers’ independent choice of energy and develop economy cleaner, the concept of smart grid has been put forward by the United States and the European Union as the representative. Depending on its technical advantage, smart grid has been named as the power grid 2.0 era. Most of the developed countries are building smart grid with the highly integrated communication network, advanced sensing, control and measurement scheme, scientific planning, decision-making and smart management functions. Smart grid has become the future work direction of the development of power industry. The smart grid will provide more convenient and economical electric energy with high security, stability, efficiency, self-healing power and friendliness.

As the smart grid becomes one of the current research hotspot, some researches about the evaluation system of smart grid, which guide and promote the healthy development of smart grid are present. IBM presents a mature degree model to evaluate the development level of smart grid from four aspects, including the reliability, high effectiveness, new energy acceptance degree and interactive competence. According to the understanding of smart grid construction by IBM, the model divides the level into 5 stages, 8 aspects and 200 indicators in total for countries finding the differences and determining the development direction of the smart grid[3-4]. U.S. Department of Energy evaluates smart grid from six aspects, including user participation, introduction of new product,
operation efficiency of power network, service quality of electric energy, energy storage device and grid’s capacity of the calamity reduction, while U.S. Electric Power Research Institute makes some extension and thinning that it builds evaluation index system for specific single grid construction project [5]. In Europe, the evaluation system is created around the purpose of smart grid construction, which is to achieve low carbon economy by increasing the grid-connected proportion of renewable energy such as wind power and improving the technologies like distributed generation and demand side management. These above-mentioned research can provide some guidance and references to the development of smart grid in developed countries.

The construction and development of smart grid will bring some huge impacts not only in electric source planning, power generation, transmission, transformation and supply of electric power industries, but also in society, economy and energy. So the evaluation of smart grid construction influence should be a comprehensive system. This paper builds a development impact evaluation index system of smart grid, and uses AHP to evaluate and analyze, and finally a case is employed in order to provide some related decision reference.

2. Fundamental theories and Evaluation Index System

2.1. Analytic hierarchy process method

Analytic hierarchy process (AHP), presented by professor T.L. Saaty, put forward a kind of effectively dealing with the complicated and ambiguous relationship between how to translate into quantitative analysis method, it is according to the laws of the people's thinking, in the face of complex selection problem, people will tend to be breaking them down into the component factors, and according to these factors will govern formation are grouped class structure, through comparing the pairwise matrix to determine the relative importance of various factors in the hierarchy, and then decision makers determine the relative importance of the overall decision sorting. Using the AHP method of level analysis method to determine the index weight steps are as follows:

(1) Construct comparative judgment matrix

First of all, the discriminant compared matrix should be built, in the matrix, $U_{ij}$ is the importance of the relative to the proportion of the scale, whose values are shown in table 1.

| Proportion criteria | Meanings                                      |
|---------------------|-----------------------------------------------|
| 1                   | The importance is equal between these two elements |
| 3                   | One of the two elements is slightly more important than the other |
| 5                   | One is more important than the other           |
| 7                   | One is much more important than the other      |
| 9                   | One is extremely more important than the other |

Then, calculate the weight of each index. The steps are as follows:

1) Calculate the product of the judgment matrix each line factors

$$M_i = \prod_{j=1}^{n} x_{ij} , i = 1, 2, \ldots, n$$  \hspace{1cm} (1)

2) Calculation of the root

$$W_i = \sqrt[n]{M_i}$$  \hspace{1cm} (2)

3) Normalization

$$W = [W_1, W_2, \ldots, W_n]^T$$  \hspace{1cm} (3)

Then, the vector W changes to be the weights. However, it is impossible to ensure the absolute consistency when the elements are comparing with each other. Thus, to keep the reliability of Analytic Hierarchy Process, the consistency of the judgments must be checked after normalizing. And the checking steps are as follows:
4) Calculate random consistency index $CR$

$$CI = \frac{\lambda_{\text{max}} - n}{n - 1}$$  \hspace{1cm} (4)

In the formulas, $n$ is the judgment matrix order, while $\lambda_{\text{max}}$ is the largest eigenvalue of the judgment matrix.

5) Calculate consistency ratio

$$CR = \frac{CI}{RI}$$  \hspace{1cm} (5)

In the formulas, $RI$ is an average random consistency index, which can be queried in the RI index table. The consistency of the judgment matrix can be accepted when $CR < 0.1$. If not, the appropriate modification of the judgment matrix is needed until the consistency can be accepted.

6) Finally, define a candidate set $X = \{x_1, x_2, \ldots, x_n\}$, and give an evaluation score matrix $R$ by experts. Combined with the weights calculated in the above step, the final comprehensive evaluation result can be gotten.

2.2. The Index Evaluation System

The construction of smart grid will have a direct impact on the related technologies of power grid, and with the power network as a carrier converted from primary energy, electricity power will have some certain impacts on energy consumption structure. In addition, the smart grid construction will have a profound impact on electric power industry, which is closely connected with the economy development. In conclusion, this paper builds a development impact evaluation index system of smart grid construction with three-layer index structure from the four aspects: the technology influence, energy structure influence, environmental influence and influence on national economy. The detail influence of these four aspects is as follows:

(1) Technology influence analysis of smart grid

The target of smart grid construction in China is to develop the intelligent power transmission and distribution system with information, interaction and automation, achieve intelligent scheduling by handling data stream to promote further coordinated development of power generation, transmission, distribution and supply, it is rely on the advanced sense and measurement electronic components, decision simulation control technology and related power distribution monitoring technology. In addition, smart grid has a bilateral interaction response ability. One of the representative units is the use of smart meters. With the help of smart meters and a series of sensing processing of intelligent electronic components, the intelligent meticulous demand response can be achieved, and then the use of intelligent electrical apparatus. Beyond this, in order to help the transformation of energy, smart grids should have strong and flexible grid-connected technology, which can achieve the flexible grid-connection of intermittent and large-scale renewable energy generation with power transmission.

(2) The energy influence analysis of smart grid

The construction of smart grids will increase the proportion of clean renewable energy conversion, the same to the proportion of electric energy in energy consumption terminal. Because of the enhancement of user side demand response and intelligent power distribution capability, which are based on the information and intelligence of smart grids, the grids will improve utilization efficiency of electric energy, with the performance indicators: controlled peak shifting and valley filling load, load peak-clipping rate, TOU power price response load ratio and line loss rate. Moreover, energy storage technology, distributed power grid and micro grid technology, accompanied by the use of smart grids, are also aspects of the reasonable use of energy.

(3) The environmental influence analysis of smart grid

The construction of smart grid will improve the effective use of renewable energy and reduce the harmful gas emissions brought by fossil fuels burning. With the reasonable use of renewable energy resources, the pollution caused by energy transportation will also be reduced. Thus, annual reduction of CO2 emission per unit electric energy, annual reduction of other waste gas emission per unit electric energy, trans-provincial connection capacity and renewable energy power generation grid-connected ratio can be used to measure the environmental influence of smart grid.

(4) The social influence analysis of smart grid
As a complex long-term and huge investment project, smart grid construction needs the participation of all social parts and then better serves the society and electricity customers. Therefore, the social influence of smart grid can be evaluated from two aspects: investment pulling or economic transition ability of all social parts and improving the social electricity transition degree. The smart grid construction can pull the development of electric power equipment industry, which can be measured by the grid fixed-asset investment acceleration. And the construction will have a direct social impact on labour market. Moreover, the smart grids will improve the development of smart cities, which can be evaluated by the use degree of intelligent electrical apparatus and electric vehicles. The influence on national economy can be measured by traditional assessment indexes such as electricity supply-requirement ratio and electricity elasticity coefficient.

In a word, the development impact evaluation index system of smart grid construction can be established as follow:

| Table 2. The development impact evaluation index system of smart grid construction |
|-----------------------------|-----------------------------------------------------------------------------|
| criterion level            | indicators level                                                             |
| Technology influence (B1)  | Sensing and measurement technology (C11)                                    |
|                            | Decision simulation control technology (C12)                                 |
|                            | Power distribution monitoring technology (C13)                               |
|                            | The grid-connected ability of renewable energy generation (C14)             |
|                            | Installation proportion of smart meters (C15)                               |
|                            | The proportion of electric energy in energy consumption terminal (C21)      |
| Energy influence (B2)      | Controlled peak shifting and valley filling load (C22)                     |
|                            | Load peak-clipping rate (C23)                                               |
|                            | Demand response load ratio (C24)                                            |
|                            | Line loss rate (C25)                                                        |
| Environmental influence (B3)| Annual reduction of CO₂ emission per unit electric energy (C31)            |
|                            | Annual reduction of other waste gas emission per unit electric energy (C32)  |
|                            | Trans-provincial connection capacity (C33)                                  |
|                            | Renewable energy power generation grid-connected ratio (C34)                |
|                            | Grid fixed-asset investment acceleration (C41)                              |
|                            | Employment of grid enterprises (C42)                                        |
| Social influence (B4)      | The production growth of intelligent electrical apparatus (C43)             |
|                            | The ownership growth of electric vehicles (C44)                             |
|                            | Electricity elasticity coefficient (C45)                                     |
|                            | Electricity supply-requirement ratio (C46)                                  |

3. Empirical analysis

According to the above evaluation method, we can evaluate the development impact of smart grid construction with the actual situation. And the calculation process and result are as follows:

| Table 3. The pairwise comparisons matrix and weights of rule hierarchy |
|-----------------------------------------------------------------------|
| Technology influence | Energy influence | Environmental influence | Social influence | Weight |
| Technology influence | 1                | 1/3                      | 1/3              | 1/3    | 0.0982 |
| Energy influence     | 3                | 1                        | 1                | 1      | 0.2946 |
| Environmental influence | 3                | 1                        | 1                | 1/2    | 0.2508 |
| Social influence     | 3                | 1                        | 2                | 1      | 0.3564 |

CI is 0.0202, CR=0.023<0.1, pass the consistency test

According to the above index calculation result of rule hierarchy, the weights of these four aspects
are slightly different with each other. The smallest one is the weight of technology influence, and the weight of social influence is greatest, with the weights of energy influence and environmental influence respectively taking the second and third places. And the weights of the third grade indexes under the rule hierarchy can be seen from Table 4 to Table 7.

Table 4. The pairwise comparisons matrix and weights of technology influence

|   | C11 | C12 | C13 | C14 | C15 | Weight |
|---|-----|-----|-----|-----|-----|--------|
| C11 | 1   | 1/3 | 1/3 | 1   | 3   | 0.1370 |
| C12 | 3   | 1   | 1   | 3   | 3   | 0.3262 |
| C13 | 3   | 1   | 1   | 3   | 3   | 0.3262 |
| C14 | 1   | 1/3 | 1/3 | 1   | 3   | 0.1370 |
| C15 | 1/3 | 1/3 | 1/3 | 1/3 | 1   | 0.0736 |

CI is 0.05, CR=0<0.044, pass the consistency test

Table 5. The pairwise comparisons matrix and weights of energy influence

|   | C21 | C22 | C23 | C24 | C25 | Weight |
|---|-----|-----|-----|-----|-----|--------|
| C21 | 1   | 1/3 | 1/3 | 1/3 | 1/5 | 0.0674 |
| C22 | 3   | 1   | 1   | 1   | 3   | 0.2646 |
| C23 | 3   | 1   | 1   | 1   | 3   | 0.2646 |
| C24 | 3   | 1   | 1   | 1   | 3   | 0.2646 |
| C25 | 5   | 1/3 | 1/3 | 1/3 | 1   | 0.1387 |

CI is 0.084, CR=0<0.075, pass the consistency test

Table 6. The pairwise comparisons matrix and weights of environmental influence

|   | C31 | C32 | C33 | C34 | Weight |
|---|-----|-----|-----|-----|--------|
| C31 | 1   | 1/2 | 3   | 3   | 0.2839 |
| C32 | 2   | 1   | 5   | 5   | 0.5183 |
| C33 | 1/3 | 1/5 | 1   | 1   | 0.0989 |
| C34 | 1/3 | 1/5 | 1   | 1   | 0.0989 |

CI is 0.0014, CR=0.002<0.1, pass the consistency test

Table 7. The pairwise comparisons matrix and weights of social influence

|   | C41 | C42 | C43 | C44 | C45 | C46 | Weight |
|---|-----|-----|-----|-----|-----|-----|--------|
| C41 | 1   | 3   | 1/3 | 1/2 | 1/3 | 1/5 | 0.0718 |
| C42 | 1/3 | 1   | 1/5 | 1/3 | 1/5 | 1/7 | 0.0372 |
| C43 | 3   | 5   | 1   | 2   | 1/2 | 1/3 | 0.1630 |
| C44 | 2   | 3   | 1/2 | 1   | 1/3 | 1/5 | 0.0956 |
| C45 | 3   | 5   | 2   | 3   | 1   | 1/2 | 0.2347 |
| C46 | 5   | 7   | 3   | 5   | 2   | 1   | 0.3977 |

CI is 0.033, CR=0.027<0.1, pass the consistency test

Add it all up, the final weights can be listed in Table 8. Combined with the final weights and index system, smart grids construction development impacts of China, America and European Union can be compared and evaluated. And each of the final scores is the average of the scores marked by experts in questionnaires, with a score range [0,100]. The calculation results are as shown in Table 8.
Table 8. The evaluation results of smart grids construction development of China, U.S and European

| Index                                                                 | w     | China | U.S. | EU  |
|----------------------------------------------------------------------|-------|-------|------|-----|
| Sensing and measurement technology (C11)                            | 0.013 | 68    | 90   | 85  |
| Decision simulation control technology (C12)                        | 0.032 | 75    | 92   | 90  |
| Power distribution monitoring technology (C13)                       | 0.032 | 82    | 85   | 85  |
| The grid-connected ability of renewable energy generation (C14)      | 0.013 | 95.7  | 63.5 | 47.2|
| Installation proportion of smart meters (C15)                        | 0.007 | 60    | 90   | 86  |
| The proportion of electric energy in energy consumption terminal (C21)| 0.020 | 90    | 86   | 85  |
| Controlled peak valley filling load (C22)                           | 0.078 | 76    | 84   | 81  |
| Load peak-clipping rate (C23)                                       | 0.078 | 72    | 80   | 85  |
| Demand response load ratio (C24)                                    | 0.078 | 46    | 72   | 76  |
| Line loss rate (C25)                                                | 0.041 | 93.3  | 93.4 | 95.6|
| Annual reduction of CO\textsubscript{2} emission per unit electric energy (C31)| 0.071 | 91    | 81   | 79  |
| Annual reduction of other waste gas emission per unit electric energy (C32)| 0.130 | 93    | 82   | 85  |
| Trans-provincial connection capacity (C33)                           | 0.025 | 75    | 81   | 79  |
| Renewable energy power generation grid-connected ratio (C34)         | 0.025 | 84    | 86   | 82  |
| Grid fixed-asset investment acceleration (C41)                       | 0.026 | 90    | 75   | 72  |
| Employment of grid enterprises (C42)                                | 0.013 | 82    | 75   | 78  |
| The production growth of intelligent electrical apparatus (C43)      | 0.058 | 75    | 82   | 86  |
| The ownership growth of electric vehicles (C44)                      | 0.034 | 80    | 81   | 86  |
| Electricity elasticity coefficient (C45)                             | 0.084 | 72    | 89   | 84  |
| Electricity supply-requirement ratio (C46)                           | 0.142 | 81    | 86   | 84  |
| Total                                                               | 1     | 78.88 | 82.96| 82.88|

According to the result of the calculation, the development impacts of smart grid construction in China is slightly lower than the U.S. and European Union. And as the scores, the intelligence of smart grid in China is low, and the same to the scores of intelligent electronic components, smart meters and intelligent electrical apparatuses. Thus, if China want to improve the impacts of smart grid, the use of electronic components should be spread. However, because of the construction of smart grid, comprehensive line loss rate, the use of clean energy resources and energy-saving and emission-reduction in China provide significant contribution, and power structure optimization and adjustment have been improved, which provides a solid foundation for the multi driving wheels electric power production and supply system and the coordinated development of all kinds of electricity, including hydropower, renewable energy, nuclear power, coal power and gas-electricity. And it has a great impact on China’s future energy structure adjustment.

4. Conclusion
This paper has studied the development impact evaluation of smart grids in China, and establish the evaluation index system based on the four aspects: technology influence, energy influence, environment impact and social influence, which contains 20 indexes in total. And the weights of these indexes with AHP are calculated, and empirically analyze the evaluation of grid development in China, America and European Union with the expert investigation method. The analysis results lead to the difference and suggestions of strengthening intelligence influence of China’s smart grids in the future.

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