Research on the Development Roadmap of Wind Power Industry Under High Renewable Energy Penetration

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Abstract. Renewable energy with high resource potential and less environmental pollution are receiving more and more attention. Wind power is a relatively mature energy source in renewable energy. As the internal and external uncertainty of the wind power industry chain are various and complex, it is urgent to clarify the uncertainty and relationship. Through big data technique, main uncertainty impacted on the development of the wind power industry chain is identified. And an interpretative structural model is established to analyze the hierarchy structure to the uncertainty. The results can provide valuable reference to identify and solve the key problems in the development roadmap of wind power industry, as well as to make scientific decision.

Keywords: Renewable energy, wind power, interpretative structural model.

1. Introduction
As the consumption of traditional energy sources increases year by year, the ecological environment is deteriorating and the trend of climate warming is obvious. The sustainability of human social development is increasingly threatened. Therefore, renewable energy with high resource potential and less environmental pollution are receiving more and more attention. Renewable energy industries, including wind energy, provide an important guarantee for the sustainable development of society and economy, as in [1]. The wind power industry has developed rapidly in China in recent years. By the end of 2018, the cumulative installed capacity of wind power in China has reached 209.53GW, and the cumulative installed capacity of wind power installed in the grid is 184.26GW, as in [2,3].

As the internal and external influencing factors of each link of the wind power industry chain are various and complex, the interpretative structural model is established to identify and analyze the influencing factors, the degree of influence and the correlation between the factors affecting the development of the wind power industry, and provide a theoretical basis for the healthy development of the wind power industry.

2. The interpretive Structure Model
The Interpretive Structure Model (ISM) is a structured modeling method proposed by Professor J. Warfar in the United States in 1973 for analyzing the structure of complex socio-economic systems. It is a static qualitative model. The basic principle of ISM is that according to the theory of matrix and directed graph, the complex system is decomposed into several subsystems, and then the subsystem is...
subdivided and finally decomposed into a multi-level model with hierarchical structure. The feature of ISM is to transform those ambiguous theories or ideas into intuitive and understandable relationships, thus improving the understanding of the problem. It is applicable to systems with many variables, complex relationships and unclear structure analysis.

The main steps in establishing the ISM are as follows:

- Set key issues and identify the main factors that affect the issues.
- Establish the adjacency matrix based on the correlation between various factors. The adjacency matrix represents the basic binary relationship between elements in the system.
- Establish the reachable matrix. The reachable matrix is a square matrix that represents the binary relationship between features in the system that can be reached by any number of passes.
- Hierarchical division of reachable matrices. The highest-level feature set of a multi-level hierarchical structure (ie, the first-level feature) refers to a set of features that cannot reach other features except those that can reach themselves. After finding the most advanced elements, you can remove the corresponding rows and columns from the reachable matrix, and then continue to find new top-level features (ie, the second-level features) from the remaining reachable matrices. Similarly, the feature set of each level is found out.
- Drawing a multi-level hierarchical directed graph. According to the results of the division between the reachable matrix levels, draw a multi-level hierarchical directed graph of the problem sought.

3. Establishment of ISM for Wind Power Industry Chain Development

3.1. Factors Affecting the Development of Wind Power Industry Chain

The wind power industry chain includes R&D and design, raw material supply and fan parts production, machine manufacturing, wind farm development and construction, wind farm operation and wind power grid access, and is subject to government decision-making, financial loan policies, scientific research institutions and service industries. Influences, as in [4,5]. This paper adopts the expert survey method, selects 60 factors that affect the wind power industry chain, and designs 90 questionnaires for the wind power industry. 12 people come from the wind power industry association, and 35 people come from wind turbine parts and complete machine manufacturing enterprises, and 30 people come from wind power project development operators, and 13 people come from power grid enterprises. Work experience of these people in wind power related fields is more than 5 years. Score the relative importance of each influencing factor, including five levels that are extremely important, important, general, unimportant, and not important. A total of 70 questionnaires were collected, with a recovery rate of 77%, of which 68 were valid questionnaires. The statistical results of the questionnaire are shown in Table I.

A collection of comments that determine the extent of the impact is as follows:

\[ X = \{X_1, X_2, X_3, X_4, X_5\} = \{0.9, 0.7, 0.5, 0.3, 0.1\} \]

The effective questionnaires are summarized, and the number of experts who select relevant comments for each factor is calculated, and the evaluation matrix of the influencing factors of the wind power industry chain is constructed as shown in (1).

\[
R = \begin{bmatrix}
R_1 \\
R_2 \\
R_3 \\
R_4 \\
R_5
\end{bmatrix} = \begin{bmatrix}
\frac{r_{11}}{d_a} & \frac{r_{12}}{d_a} & \frac{r_{13}}{d_a} & \frac{r_{14}}{d_a} & \frac{r_{15}}{d_a} \\
M & M & \frac{r_{2j}}{d_a} & M & M \\
M & M & \frac{r_{3j}}{d_a} & M & M \\
M & M & \frac{r_{4j}}{d_a} & M & M \\
M & M & \frac{r_{5j}}{d_a} & M & M
\end{bmatrix}
\]

(1)

In (1), \( r_{ij} = d_i/d_a \). \( d_i \) is the number of people who selected the j evaluation value for the i factor, and \( d_a \) is the total people.
The evaluation $Y$ is calculated by the following method as shown below in (2).

$$Y = RX^T = (y_1, y_2, M, y_3)^T$$

The evaluation value of each influencing factor $y_i$ can be obtained by calculation (in Table 1). The influencing factors of the evaluation value which are less than 0.70 are screened out, and the remaining 32 factors are relatively important factors affecting the wind power industry chain.

3.2. Establish the Adjacency Matrix

According to the expert's point of view, judging the relationship between the 32 influencing factors, as shown in Table II, the adjacency matrix is obtained according to the following rules:

- $S_i$ has an effect on $S_j$, and is represented by 1;
- $S_i$ has no effect on $S_j$, and is represented by 0.

3.3. Establish the Reachable Matrix

The corresponding $32 \times 32$ order matrix $A$ can be obtained from Table II. The reachable matrix can be obtained through the following calculation process as shown below in (3):

$$A_i = A_i A_i = A_i^2, \quad A_i = A_i^3 \ldots$$

According to the above method, after this calculation, you can get the formula as shown below in (4):

$$A_1 \neq A_2 \neq A_3 \neq \ldots \neq A_{r-1} = A_r = A_{r+1}$$

In (4), $A_r = A_r', r \leq 32 - 1$.

Take the reachable matrix $M = A_r$, obviously $M = A_r = A_{r+1}$.

Finally, the reachable matrix of the influencing factors of the wind power industry chain can be calculated.

3.4. Hierarchical Division of Reachable Matrices

According to the principle of hierarchical division, the system of factors affecting the industrial chain in the model can be divided into seven levels. From the top to the bottom are:

- $L_1 = \{S_{10}, S_{14}, S_{20}, S_{22}, S_{24}, S_{25}, S_{30}, S_{31}\}$;
- $L_2 = \{S_{11}, S_{15}, S_{16}, S_{17}, S_{18}, S_{21}, S_{23}, S_{32}\}$;
- $L_3 = \{S_{6}, S_{19}, S_{26}, S_{29}\}$;
- $L_4 = \{S_{7}, S_{8}, S_{12}, S_{27}, S_{28}\}$;
- $L_5 = \{S_{1}, S_{9}\}$;
- $L_6 = \{S_{2}, S_{3}, S_{4}, S_{5}\}$;
- $L_7 = \{S_{13}\}$.

Then, an explanatory structural model of the influencing factors of the wind power industry chain can be drawn, as shown in Figure 1.
### Table 1. Evaluation form of factors influencing the development of wind power industry chain

| Number | Category                          | Factors affecting the development of wind power industry chain                                                                 | Score (yi) | Main influencing factors |
|--------|-----------------------------------|-----------------------------------------------------------------------------------------------------------------------------|------------|-------------------------|
| 1      | R&D and design                    | establishment of wind power technology standard system                                                                        | 0.76       | S1                      |
| 2      |                                   | national technology innovation encouragement policy                                                                            | 0.72       | S2                      |
| 3      |                                   | international cooperation and joint research and development                                                                   | 0.65       | ——                      |
| 4      |                                   | new technology learning ability                                                                                             | 0.72       | S3                      |
| 5      |                                   | number and quality of design and development personnel                                                                        | 0.77       | S4                      |
| 6      |                                   | patent intellectual property protection policy and implementation                                                              | 0.69       | ——                      |
| 7      |                                   | independent research and development capabilities                                                                               | 0.83       | S5                      |
| 8      | raw material supply and fan parts production | production capacity and quality of special-condition parts (such as anti-dust on land, anti-corrosion at sea, etc.)                     | 0.75       | S6                      |
| 9      |                                   | industry market access conditions                                                                                            | 0.66       | ——                      |
| 10     |                                   | main raw material supply capacity                                                                                            | 0.69       | ——                      |
| 11     |                                   | production and manufacturing personnel quality                                                                                | 0.69       | ——                      |
| 12     |                                   | key component production quality                                                                                             | 0.77       | S7                      |
| 13     |                                   | key component production capacity                                                                                            | 0.73       | S8                      |
| 14     |                                   | raw material quality control                                                                                                  | 0.78       | S9                      |
| 15     |                                   | production balance between parts and machine manufacturing                                                                     | 0.66       | ——                      |
| 16     |                                   | raw material price fluctuations                                                                                            | 0.66       | ——                      |
| 17     |                                   | key component model versatility                                                                                            | 0.66       | ——                      |
| 18     |                                   | imported parts tariff                                                                                                         | 0.58       | ——                      |
| 19     | machine manufacturing             | domestic component supply capacity                                                                                            | 0.71       | S10                     |
| 20     |                                   | strategic cooperation between machine manufacturing and component manufacturers                                               | 0.63       | ——                      |
| 21     |                                   | financing channels and capabilities of wind turbine manufacturers                                                                     | 0.73       | S11                     |
| 22     |                                   | competition level in the whole machine manufacturing market                                                                    | 0.68       | ——                      |
| 23     |                                   | improvement of wind turbine test and certification system                                                                      | 0.71       | S12                     |
| 24     |                                   | number and quality of professional and compound talents                                                                       | 0.75       | S13                     |
| 25     |                                   | balance between wind power equipment capacity and demand                                                                        | 0.71       | S14                     |
| 26     | wind farm development and construction | wind farm site selection                                                                                                          | 0.70       | S15                     |
| 27     |                                   | wind energy resource forecasting and evaluation                                                                                | 0.66       | ——                      |
| 28     |                                   | accessibility of good wind resource sites                                                                                       | 0.70       | S16                     |
| 29     |                                   | renewable energy power generation quota system and sustainability                                                              | 0.68       | ——                      |
|   | wind farm construction quality | 0.73 | S17 |
|---|---|---|---|
| 31 | coordinated planning for wind power project development and power grid construction | 0.72 | S18 |
| 32 | wind energy resource development policy | 0.76 | S19 |
| 33 | wind power project approval system and procedures | 0.67 | —— |
| 34 | wind farm fan layout | 0.66 | —— |
| 35 | wind farm construction loan interest rate | 0.68 | —— |
| 36 | construction land acquisition compensation and coordination | 0.67 | —— |
| 37 | design unit selection | 0.68 | —— |
| 38 | wind power equipment manufacturers' choice | 0.69 | —— |
| 39 | wind farm developers financing capacity and channels | 0.71 | S20 |
| 40 | wind farm construction contractor's choice | 0.67 | —— |
| 41 | wind farm construction investment | 0.67 | —— |
| 42 | local government support | 0.73 | S21 |
| 43 | wind farm construction progress | 0.65 | —— |
| 44 | wind farm environmental restoration and acceptance | 0.63 | —— |
| 45 | limit electricity and wind loss | 0.69 | —— |
| 46 | wind power local consumption capacity | 0.70 | S22 |
| 47 | wind farm installed capacity | 0.63 | —— |
| 48 | wind farm operation and maintenance capability | 0.71 | S23 |
| 49 | wind farm tax and tax reduction policy | 0.70 | S24 |
| 50 | CDM mechanism and continuity | 0.66 | —— |
| 51 | wind farm operation and maintenance costs | 0.69 | —— |
| 52 | long-distance high-voltage transmission capability | 0.71 | S25 |
| 53 | wind power On-grid price | 0.74 | S26 |
| 54 | wind power tariff subsidy policy | 0.74 | S27 |
| 55 | CDM price fluctuations and exchange rate risk | 0.62 | —— |
| 56 | wind power support purchase policy and implementation | 0.70 | S28 |
| 57 | wind power grid-connected technology | 0.77 | S29 |
| 58 | wind energy conversion and energy storage technology | 0.71 | S30 |
| 59 | wind farm annual operating hours | 0.75 | S31 |
| 60 | intermittent and unstable effects of wind power | 0.70 | S32 |
4. Analysis and Suggestions on the Development of Wind Power Industry Chain

From the ISM of the wind power industry chain in Figure 1, it is can be seen that:

1) The development of the wind power industry chain is directly affected by the domestic component supply capacity, the balance between wind power equipment capacity and demand, the wind farm developers financing capacity and channels, the wind farm annual operating hours, the wind farm tax and tax reduction policy, the wind energy conversion and energy storage technology, the wind power local consumption capacity and the long-distance high-voltage transmission capability. The first layer factor is the direct influencing factor of the wind power industry chain development. To improve the efficiency of the industrial chain of the wind power industry, it is necessary not only to increase the country’s economic support policies, but also to focus on improving power conversion and power transmission technology.
2) The wind farm annual operating hours are important factors influencing the profitability of wind farm operators and are subject to the acquisition of excellent wind resources, local government support, construction quality of wind farms, and operation and maintenance capabilities of wind farms. It is important to choose a site with good wind resources, maintain the coordinated development of local wind power project development and power grid construction, and strictly control the construction quality of wind farm project in order to ensure reasonable running time of wind farm.

3) The wind power development policy and the on-grid tariff of the wind farm have a direct impact on the acquisition of excellent wind farms and the location of wind farms. Investors will choose whether to develop wind farms based on the assessment of wind resources and the prediction of profitability. The policy and electricity price policy can ensure the coordinated development of wind power projects and power grid planning.

4) The quantity and quality of professional and compound talents are the most basic layer affecting the development of the entire wind power industry chain, and have the deepest impact on the wind power industry chain. It is necessary to encourage technological innovation at the national level, strengthen and promote cooperation between scientific research institutions, universities and enterprises, and establish an innovation platform based on enterprises and supported by universities to enhance the cultivation of composite wind power professionals. The state should also establish an incentive mechanism to expand and optimize the talent team for wind power professionals.

![Fig.1 Interpretative structural model of factors influencing the development of wind power industry chain](image-url)
5. Conclusion
In this paper, questionnaires and statistical methods are used to identify 32 major factors affecting the development of the wind power industry chain, and an interpretive structure model of these major influencing factors is established. The analysis of the interpretive structure model shows that the number and quality of wind power professionals, independent research and development capabilities and wind power technology standards system are the basic factors affecting the development of wind power industry. Also, coordinated development of wind power project development and power grid construction, wind power technology level, government support, balance of wind power equipment capacity and demand have a direct impact on the development of the wind power industry. The research results can provide a basis and reference for the formulation of wind power industry policies and corporate management decisions.

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