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Short Communication

Sustainable development of the wind power industry in a complex environment: a flexibility study

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HIGHLIGHTS

- Wind power industry shall improve flexibility to deal with complex environment.
- Critical components of flexibility of wind power industry chain were identified.
- An operating mechanism model for flexibility of wind power industry is proposed.
- Fuzzy cognitive mapping method is employed to model the dynamics of flexibility.
- Policies play a pivotal role in fostering an industry environment toward flexibility.

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ABSTRACT

As a new and developing green energy business in emerging economies such as China, the wind power industry chain faces some complex issues that are further compounded by turbulent internal and external environments. To deal with the complex environment, the wind power industry needs to improve its level of flexibility so that it can become more adaptable to the changing environment. Hence it is important to explore the dynamics of the wind power industry chain flexibility with respect to the ever changing environment. This study uses questionnaire surveys and expert interviews to identify the influential flexibility components of the wind power industry chain. Subsequently a fuzzy cognitive mapping (FCM) methodology was used to establish a flexibility operating mechanism model. The research found that special attention should be paid to competition flexibility, technology flexibility, and intellectual property and talent flexibility. Policies play a pivotal role in regulating the driving effects of these components of flexibility with the aim being long term sustainability of a healthy level of overall flexibility of the wind power industry chain. This should in turn facilitate the sustainable development of the industry.

1. Introduction

The wind power industry is influenced by a number of factors including policy, technology, market, finance, tariff and on-grid mechanism (Zhao et al., 2013; Joanna and Ryan, 2007). It also faces numerous challenges such as the complex and constant industry changes, the high level of uncertainty associated with both internal and external environments (Zhao et al., 2012). The environmental dynamics have significant impacts on the sustainable development of the wind power industry. As a result, it is imperative to improve the flexibility of the wind power industry chain to be more resilient to the turbulent environment. The issue of flexibility first appeared in the manufacturing industry. Environmental changes (Mourtzis et al., 2012) were widely accepted as a common attribute of flexibility while the focus was turned to the supply or industrial chain level (Candace et al., 2011). Therefore, flexibility is defined as "*a comprehensive capacity of the industry chain to identify and respond to the dynamics of internal and external environment*". This capacity helps to adapt the overall operation of the industry chain to the changing environment. Both internal environment (e.g. development strategy, technological innovation, production and operation) and external environment (e.g. laws and policies, supply and demand, cooperation between related sectors) affect the health and sustainability of the wind power industry. A flexible industry chain helps the wind power industry and related sectors to improve their capacity of dealing with environmental dynamics.

Previous studies recognized the critical role of flexibility in achieving competitiveness in the modern business environment

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accordingly mechanisms should be in place to deal with the associated environmental dynamics (e.g. Child, 1972; Henk, 1998; Zhao et al., 2014). Other theories include contingent theory (Fan, 2010), structural equation modelling (Wang et al., 2010), fuzzy set theory (Zhang et al., 2011), genetic algorithm (Zhao, 2013), complementary and integration theory (Claire et al., 2014). However, little empirical research has occurred in investigating the dynamic relationship between factors affecting the flexibility of the wind power industry chain. It is imperative to identify those factors that influence the flexibility and to explore the associated driving mechanism. These identified factors and mechanisms provide useful inputs for the continuous improvement of policies for enhancing the overall flexibility level. This study uses a questionnaire survey and fuzzy cognitive map (FCM) method to investigate the flexibility of the wind power industry chain in China. This study will provide novel theoretical and practical support for the sustainable development of the wind power industry.

2. Methods

2.1. Fuzzy cognitive map (FCM)

A FCM is a signed fuzzy graph within which the relationships between the elements (e.g. concepts, events, characteristics, and influencing factors) of a mental landscape used to compute the strength of impact of those elements (Bart, 1986; Kosko, 1997). The FCM approach has been widely employed in modeling the uncertainty and complexity of processes and systems. The FCM method in this study is used to model the causation amongst factors that are influential to the flexibility of the wind power industry chain.

A FCM network consists of nodes and directed arrows as shown in Fig. 1. Each node represents a key factor in the system that summarizes its basic properties, while the arrows show the causations between nodes. The weight W_{ij} indicates the strength of relationship between C_i and C_j. When $W_{ij} > 0$, it indicates that node C_i has a positive effect on the node C_j. In contrast, when $W_{ij} < 0$, node C_i has a negative effect on the node C_j. There is no causation between node C_i and C_j when $W_{ij} = 0$.

The mathematical description of the FCM model is shown from Eqs. (1) to (4) as follows,

$$C = [C_1, C_2 \ldots C_n] \quad (1)$$

Where **C** represents a collection of nodes;

The state value of node C_i at time t can be calculated by Eq. (2),

$$A_i(t) \in [-1, 1]; i = 1, 2, \ldots, n \quad (2)$$

The causation matrix **W** can be used to describe the relationship between each node (the weight w_{ij}) according to the Eq. (3),

$$W = \begin{bmatrix} w_{11} & w_{12} & \ldots & w_{1n} \\ w_{21} & w_{22} & \ldots & w_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ w_{n1} & w_{n2} & \ldots & w_{nn} \end{bmatrix} \quad (3)$$

The state value of node C_i at time $t+1$ can be calculated by Eq. (4),

$$A_j(t+1) = f\left(\sum_{i=1}^{n} A_i(t) \times Wij\right) \quad (4)$$

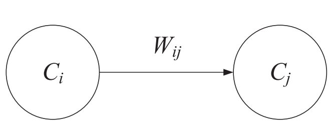

Fig. 1. An example of FCM.

Where A_i and A_j are the state values of node C_i and C_j respectively; $f(x)$ is the threshold function of C_j. The causations between the nodes are transformed into the relationship fuzzy-matrix by the method of FCM. After the iterative calculation of the matrix, the change of the state value of the system can be described.

2.2. Questionnaire survey

A questionnaire is used to explore the most influential factors for a flexible wind power industry chain. The instrument was designed according to a critical review of the literature related to industry chain flexibility. A total of 28 factors (Table 1) were identified that were related to industry technology (Zhao et al., 2014; Ru et al., 2012; Fredrik and Patrik, 2009), industry market (Zhao et al., 2013; Wang et al., 2012), industry competition (Zhao et al., 2012; Zhao et al., 2013), and industry policy (Zhao et al., 2011; Zhao et al., 2012; Kang et al., 2012).

This is followed by a series of interviews with experts to confirm the rationality of these factors in the Chinese context. A total of 11 interviews were undertaken between September and December in 2013. All the interviewees held senior positions (e.g. general managers, chief engineers, and department directors) in the Chinese wind power industry. Their expertise in the wind power industry well qualifies them to participate into this study. With consistent positive feedback from a diverse group of interviewees, the questionnaire is expected to cover the various aspects of flexibility issues associated with the wind power industry chain in China. Interviewees did make some recommendations. For instance, factor 6 was originally labelled as “Adequate training for employees”. Many interviewees regarded this factor to be too general and suggested that it be more specific. Consequently, this factor was reworded as “Enterprise often trains the technological personnel to upgrade technologies”.

The respondents were asked to express the level of agreement of each factor as related to the flexibility of the wind power industry against a 5 point Likert scale from“1” for “extremely disagree” to “5” for “extremely agree”.

The questionnaire was distributed through the professional network of the wind power industry in China. A total of 290 questionnaires were distributed and 214 were returned with a response rate of 74% (Fig. 2).

As shown in Table 1, “wind power enterprises pay more attention to services than their competitors do” is perceived by respondents as the most influential factor for the wind power industry chain flexibility. The average score of all 28 statements is 4.14, which indicates that the factors covered in the questionnaire relate well to the flexibility of the wind power industry chain.

3. Results

3.1. PCA of wind power industry chain flexibility

Principal components analysis was employed to determine the major forces driving the flexibility of the wind power industry chain. The loading matrix of the principal components is shown in Table 2. Variables x_1 to x_{28} are set as descriptions of 28 factors shown in Table 1. As a result, 9 components were drawn with Eigen value > 1.0.

3.2. Operating mechanism model of flexibility based on FCM

3.2.1. Nodes definition

Modelling the dynamics of wind power industry chain flexibility is a complex process. The most critical step is defining nodes. In this study, nodes are defined according to the results of