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Application of a fuzzy cognitive map based on a structural equation model for the identification of limitations to the development of wind power

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HIGHLIGHTS

- Apply SEM to explain interrelationships between the obstacles of wind power.
- Adopt '*what if*' simulation analysis to explore the optimal management strategies.
- Intermediary variables were existed in the potential paths.
- The results prove that correlations do exist between the obstacles.
- The "policy aspect" is the main obstacle faced by wind power.

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ABSTRACT

Despite numerous researchers having investigating the development of wind power, the correlation between the elements influencing wind power development has often been ignored. Hence, this research hopes to incorporate both structural equation model (SEM) and fuzzy cognitive map (FCM) to identify a mutual relationship between the various elements, so as to provide feasible recommendations for management strategies. Initially, SEM is used for identification of correlation between the elements and indicating their direction and strength. A standardized causal coefficient from SEM was then used to create an FCM illustrating the effect of the status of one component on the status of another component. The research results pointed out that "policy" would be the major challenge faced by wind power development, as well as the main cause for other obstructions. Therefore, under the objective of maximizing economic benefits, short-term strategies can adopt suitable measures for the two dimensions of "technology" and "environment"; and while mid-term strategies must consider the indirect influences from "social" dimension, long-term strategies must work on "policy".

1. Introduction

Energy is a necessity of modernized societies (Al-Badi et al., 2011; Mirza et al., 2007). Sustainable development perspectives are promoted to achieve a balanced development for the three dimensions of economic growth, environmental protection and social justice. Hence, development and the utilization of renewable energy (RE) is seen as an effective method to achieve these objectives (Chien and Hu, 2008; Dehghan, 2011; Kumar et al., 2010; Praene et al., 2012; Surendra et al., 2011). Amongst numerous forms of RE, wind power not only produces zero pollution and is indefinitely sustainable (Chiu and Chang, 2009; Han et al., 2009; Luickx et al., 2010; Tuğrul Oğulata, 2003; Wang and Chen, 2010), but its features also include high technical feasibility and cost-effectiveness (del Río, 2011; International Energy Agency (IEA), 2008; McLaren Loring, 2007; Morthorst and Chandler, 2004; Nalan et al., 2009; Nguyen, 2007; Sovacool, 2009a; Xu et al., 2010).

The literature on wind power for the past five years has mainly focused discussions on a specific set of topics, with the majority of research focused on describing current statuses of wind power development in certain countries, and possible opportunities and challenges that may be encountered in the future (Mondal et al., 2010; Al-Badi et al., 2011, 2009; Dehghan, 2011; Ghobadian et al., 2009; Han et al., 2009; Kelly, 2011; Kumar et al., 2010; Liao et al., 2011, 2010; Mirza et al., 2009, 2007; Nalan et al., 2009; Praene et al., 2012; Sahir and Qureshi, 2008; Surendra et al., 2011; Wang and Chen, 2010; Xu et al., 2010; Zhang and Qi, 2011). Sample research topics include the utilization of current statuses and

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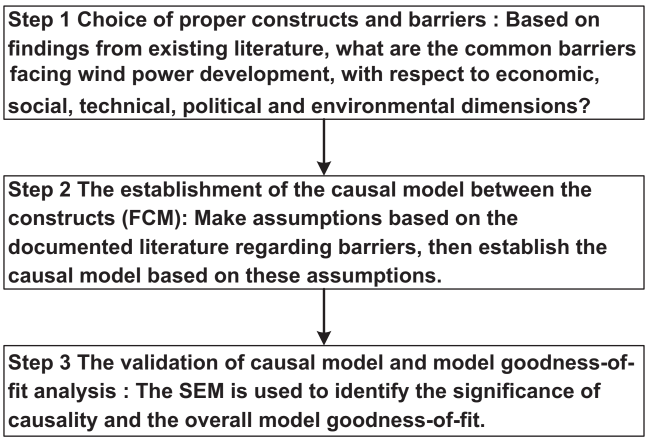

Fig. 1. Research design flow chart.

policy effectiveness indices to investigate RE development in the EU (Klessmann et al., 2011), application of quantitative energy-economy models to investigate development, and obstructions faced by RE technology. Other types of research involve investigations into the feasibility and equipment system choices for large scale integration of wind power into the power grid (Li et al., 2012), applied simulation models to investigate optimized policies to support RE (Liu et al., 2011) as well as investigating the four factors for success on wind power development, including the degree of public participation, network stability, public acceptance and project planning (McLaren Loring, 2007). Some studies focus on the application of GIS-based analytical methods to investigate financially feasible RE development models and promotion of market penetration strategies (Nguyen, 2007; Oikonomou et al., 2009), or applying innovation diffusion theory and logistic regression to investigate how diffusion measures would influence sustainable energy standards or green energy policy implementation (Chandler, 2009; Vachon and Menz, 2006). Finally, some researches apply the structural equation model (SEM) to investigate how RE might influence GDP (Chien and Hu, 2008) while others conduct interviews and literature reviews to investigate the issue of RE intermittence (Sovacool, 2009a). Despite this substantial amount of research approaches, very few researches have investigated the possible correlation between the elements influencing wind power development. This is an interesting issue, and one that deserves to be explored. An investigation of the correlation between these elements, particularly in developing countries, would be the most effective way to assist energy and cultural reform (del Río, 2011; Valentine, 2010).

In order to begin investigation into this question, this study first primarily focused on existing literature regarding wind power related issues in order to reveal the obstructions to wind power development that were presently functioning in the economic, social, technical, policy and environmental areas; and secondly, to establish a causal model of constructs (fuzzy cognitive map, FCM), which would be based on assumptions made from conclusions drawn regarding the relationships between the barriers that are documented in the literature. The causal model is used to represent the interaction between the constructs. The purpose of this study was to gain an in-depth understanding of the different constructs and how they influence each other, and then to validate alleged correlations between them through data collection and structural equation model (SEM). With an understanding of the correlation between the constructs, we expect to be able to clarify the cause of the barriers and provide suggestions for possible short, medium and long-term management strategies.

2. Methodology

The limitations placed on the development of wind power can be identified by literature reviews, but in most situations, it can be difficult to determine the precise correlation between the limitations by direct observation, because they may be intertwined among various different sectors. In other words, complex causalities often exist, stemming from multiple areas. However, in this situation, a cognitive map (CM) is quite useful in modeling such complex systems that involve many factors (Kang et al., 2004; Lee et al., 2004).

A CM is composed of nodes that represent the factors most relevant to the decision environment and arrows indicating different causalities between the factors (Lee et al., 1992). A fuzzy cognitive map (FCM) is a CM that takes advantage of fuzzy set theory (i.e., the calculation of the fuzzifying edge values or causality values) extending upon the application of CM to address the uncertainty in relationships. An FCM can be seen as a 'fuzzy' structure used to illustrate the uncertainty causality. In addition, by considering various decision environments, FCM can be used to analyze the effect of the status of one component on the status of another component, and a corresponding result list is obtainable through a matrix calculation (i.e., the inference procedure of the adjacency matrix). This process is referred to as a 'what-if' simulation analysis (Kang et al., 2004; Lee and Ahn, 2009; Lee and Han, 2000; Lee et al., 2004), and will be our inference mechanism for FCM. It is worth noting that the choice of factors, the hypotheses of the relationship between the factors and the validation of model are the most important steps for the establishment of FCM. The aims of this study were accomplished by following three major steps (see Fig. 1): (1) the appropriate choice of constructs and barriers, (2) the establishment of the causal model between the constructs (FCM), and (3) the validation of a causal model and model goodness-of-fit analysis. Detailed descriptions of these steps are given in Fig. 1.

2.1. Choice of proper constructs and barriers in previous research

Wind power development among different countries faces a range of challenges. Thus, the choice of appropriate constructs and barriers is a vital step prior to the establishment of the causal model. In previous studies, Klessmann et al. (2011) and Valentine (2010) showed that wind power development was limited not only by economic factors, but also non-economic causes, arising from the political, technical, social and environmental arenas. Therefore, when discussing barriers to the development of wind power, it is necessary to include the possible impacts that come from all these sectors. This point of view is also confirmed by the researches of Krupa (2012), Praene et al. (2012), and Richards et al. (2012), which pointed out that development of any form of energy must consider the influences stemming from economic, technological, social and other dimensions. Second, in regards to choice of barriers, a complex model might not necessarily contribute to the development of wind power; on the contrary, a well-defined, simple result of the analysis can provide clearer insights. Therefore, this study is based on the existing literature of wind power development-related issues (Mondal et al., 2010; Al-Badi et al., 2011, 2009; Beise and Rennings, 2005; Buen, 2006; Butler and Neuhoff, 2008; Chandler, 2009; Dalton and Ó Gallachóir, 2010; del Río, 2011; Edquist and Hommen, 1999; Faulin et al., 2006; Ghobadian et al., 2009; Han et al., 2009; Kelly, 2011; Klessmann et al., 2011; Krupa, 2012; Lauber, 2004; Liao et al., 2010, 2011; Luickx et al., 2010; Malik and Al-Zubeidi, 2006; Menanteau et al., 2003; Menegaki, 2008; Menz and Vachon, 2006; Meyer and Koefoed, 2003; Meyer, 2003; Mirza et al., 2009, 2007; Mitchell et al., 2006; Morthorst, 2000; Nalan et al., 2009; Nguyen, 2007;