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Wind energy generation technological paradigm diffusion

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This paper investigates the role of the technological paradigm for the development of wind energy technology, and aims to contribute towards recommendations on technology policy and management. The paradigmatic research was conducted using a novel data analysis system (DAS) and a wind energy generation technological diffusion mathematical model. The wind energy generation technological paradigm (WEGTP) composed of paradigm competition, diffusion and shift was established to explain the technological changes in the use of wind energy. Simulation results show that the development of installed capacity for wind energy generation has a strong inertia force along with the S-curve. Global annual installed wind capacity reached a peak in 2012 and is estimated to be saturated by 2030. Hybrid wind and solar energy generation technology appeared to be more promising than wind energy technologies that rely only on onshore or offshore winds. To further accelerate wind energy development, specific subsidies and incentives need to be provided in areas such as capital costs and technological support.

Contents

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1. Introduction

In the New Policies Scenario, global energy demand is expected to increase by one-third from 2011 to 2035, and electricity demand is expected to grow by more than any other final energy form [1]. Energy generation related CO_2 emissions play a significant role in environmental degradation. The application of renewable energy technologies has been selected as useful technical and policy-based choices that ensure a certain extent of environmental sustainability. Compared with fossil energies, renewable energy sources, such as wind, solar, and biomass, have abundant long run raw materials. As the global economy continues to grow through the twenty-first century, it is well known that there is enough power in the earth's winds for wind to be the primary source of near-zero-emissions electric power.

Wind energy has seen an impressive development over the last two decades, from only 3.5 GW in 1994 to around 320 GW of cumulative global capacity at the end of 2013. In the New Policies Scenario, electricity generation from wind (onshore and offshore) is projected to increase at an annual average rate of 6% between 2011 and 2035, and governments could act to significantly reduce the cost of wind power and increase its energy contribution share of global power supply from its current 2.6% to 18% by 2050 according to the International Energy Agency (IEA) Roadmap [1]. China, the European Union and the United States expect to see the largest increases in wind electricity and it is expected that by 2035 around 70% of the world's wind power generation capacity will be in these three regions. Wind energy now accounts for one-third of total investment in renewable capacity, followed by hydropower (27%) and solar PV (23%) [2]. According to one study, the production cost of wind turbines, and consequently the power production costs, can decline by as much as 15% when cumulative volumes double [3]. Another statistical analysis has claimed that the cost of producing one kilowatt hour (kWh) of electricity has decreased to 20% of the initial cost [4].

Many studies have examined wind energy generation. The use of wind energy goes back nearly 3000 years, and was originally used to propel ships, drive windmills to grind grain and to pump water. After the two oil crises in 1973 and 1979, wind power's traditional uses were expanded to encompass electricity production. An overview of the wind energy technological development path indicated that wind turbine technology has now reached a reliable and sophisticated level [5,6], with offshore wind farm technologies having been developed [7,8] and studied in China [9], Europe and North America [10]. As wind is seen to be somewhat unreliable, offshore wind energy generation technology needed development breakthroughs, so hybrid renewable energy system (HRES) methodologies and models were investigated and described in [11–13]. Many scholars have expressed concern regarding the wind energy generation technological diffusion problem. Given the potential of renewable energy technologies for sustainable development, different diffusion theory based models and their applicability to renewable energy technologies diffusion analysis have been proposed [14,15], such as the diffusion of wind energy in Japan using an interaction between the technology and the markets [16]. Further, a focused study concluded that clear and focused energy policies can assist in increasing wind energy technological diffusion [17,18].

There has been thousands of research papers focused on wind energy generation. However, due to the lack of a systematic analytical framework, much of this research has little integrity or universality. When seeking to describe technological change and innovative research, the technological paradigm provides a sound method for the investigation of past trends as well as being able to predict future possibilities. This article adopts a technological paradigm to determine a wind energy technologies road map which could pave the way to the expansion of supply and an increase in efficiency.

The term paradigm first appeared as part of Kuhn's theoretical contemplation on the historical development of science [19]. Dosi applied the paradigm to technological innovation and proposed the technological paradigm concept, which still has substantial underexploited analytical potential [20–23]. The technological paradigm is mainly applied to analyze technological change and innovation in engineering fields [24]. By combining the technological paradigm concept with the wind energy generation technological diffusion process, in this paper, a wind energy generation technological paradigm (WEGTP) is proposed which aims to contribute recommendations for technology policies and the consequent management. The WEGTP was established using two procedures. The first, which was used to determine the keyword trends from a qualitative perspective, was a data analysis system (DAS) made up of the Web of Science database (WoS), NoteExpress and NodeXL. The WoS was chosen as the primary database to search for relevant wind energy utilization literature, NoteExpress was applied to review the general characteristics by reading the papers' titles, abstracts and keywords, and NodeXL was used to analyze the selected articles' bibliographies. Therefore, the DAS, as a comprehensive integrated approach, was able to guide our research in the potential WEGTP development direction. Compared with more simplistic statistical tools, this method was able to elaborate the mutual relationships between the keywords and time. The second method was a mathematical model based on physics field theory, which was used to simulate and forecast the installed wind energy generation capacity from a quantitative perspective. The WEGTP illustrates wind energy's technological utilization evolution from a qualitative and quantitative perspective, which, to the best of our knowledge, is a new research area.

The rest of this article is organized as follows. Section 2 discusses the Data Analysis System (DAS), which identified and summarized the main technological trajectories and uncovered wind energy field development trends. The wind energy technological diffusion mathematical model and three stages of WEGTP are presented in Section 3. Section 4 puts forward the wind energy generation evaluation and some constructive suggestions about how to promote wind energy technological diffusion. Conclusions and recommendations for future research are provided in Section 5.

2. Literature mining

Wind energy has an extensive and wide ranging history. However, the quantity of research in this field makes it difficult to determine the knowledge gaps or to explore future research possibilities. Literature mining is a powerful method for elucidating major trends across time in published scientific literature and allows for topic maps to be built [25]. Garfield believed that the citation indexing of academic literature was crucial for researching similar research topics [26]. A citation index is a synthesized result based on journal articles, keywords, publication dates and abstracts and is able to demonstrate the influences in a specific field. Moreover, research which has the greatest impact in a specific field can be easily identified using a citation index. In this way, current developments, technologies, trends and potential fields of research emerge. In this section, the development of the DAS and the research process are described and the visualization results presented.

2.1. The data analysis system

Literature review metrics have been used in supply chain analyses to increase performance and overcome the barriers to