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A cross-country study on the relationship between diffusion of wind and photovoltaic solar technology

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ABSTRACT

In this paper, we employed a revised Lotka–Volterra model to study the evolution of wind and photovoltaic solar technologies, as well as the relationship between these two innovations in leading countries around the globe. Further, we analysed the possible reasons for the coming results in terms of the different policies implemented in each country. By comparing the estimated parameters and simulation results, some new findings were revealed: First, the scale-dependent effect is prevalent in all the targeted countries for the wind market. Second, countries such as the US, Japan, the UK and Italy, whose PV industries are characterised by distributed rooftop systems and off-grid applications, may not be influenced by the scale-dependent effect. This implies that the use of distributed energy systems might be an effective way of coping with scale-dependence. Third, relationship between PV solar and wind technology is dominated by mutualism, while the predator–prey relationship is found only in a small number of countries, such as Italy, the United Kingdom (UK) and France. Finally, except for Germany, France and Spain, the other countries are facing an uncertain future in terms of the development of wind power and PV solar technology; factors contributing to this uncertainty include the lack of long-term and uniform programmes and targets, as well as a stable policy environment.

1. Introduction

Global energy consumption has skyrocketed with the rapid development of the world economy over the last several decades. The International Energy Agency (IEA) has forecasted that global energy demand will surge from 12 billion tonnes of oil equivalent in 2010 to 17.7 billion tonnes in 2030, with an average growth rate of 2.4% per year for the next 20 years. Under the increasing pressure of an energy shortage and the threat of climate change, the search for low-carbon alternatives is a common goal among countries worldwide, which will undoubtedly provide a wonderful opportunity for the development of new technologies.

Nuclear power was once considered one of the most promising and effective options to replace fossil energy and cope with climate change issues. However, the situation changed after Japan's Fukushima nuclear accident in March 2011; following this disaster, almost all of the nuclear countries took a cautious position against the development of nuclear power, particularly Germany, Sweden and Italy, who all announced the gradual abandonment of their future nuclear power plants. To some extent, this shift away from nuclear power can be viewed as another incentive for the development of renewable technologies.

Wind power and solar power, the dominant alternatives to fossil fuels, are plentiful, renewable and widely distributed, and their unit cost has largely decreased with their cumulative installed capacity growing to a substantial level. In fact, the unit cost of wind power is quite similar to that of new coal and natural gas installations, making it the most reasonable option for coping with the rapidly growing energy demand and increasingly stringent climate change situation. The total installed capacity of wind energy has expanded substantially, from 17.4 GW in 2000 to 238.4 GW in 2011, growing at more than 26.9% per annum, and it will continue to grow in the next

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decades [1]. According to predictions by the Global Wind Energy Council (GWEC), in the reference scenario, the cumulative installed capacity of wind power will reach 415 GW in 2020; this figure further expands to 830 GW in the moderate scenario [1]. Another significant and sustainable renewable energy option has been the deployment and development of photovoltaic (PV) solar energy, which has greatly accelerated due to its strong adaptability, simplified installation and lower operation and maintenance (O&M) costs. The cumulative capacity of global PV solar installations surged from 678 MW in 2000 to 42.6 GW in 2011, and the annual growth rate reached 46.4% over the last decade [2]. Under the incentive of more positive policies, the installation scale of PV solar technology must attain a higher level in the future.

As we know, policy incentives play a significant role in expanding the niche markets of renewable energy technologies, especially in their early stages. The support mechanisms that are prevalent among countries to promote the growth of wind and solar energy mainly include renewable energy schemes, tradable green certificates, feed-in tariffs, consumer tax deductions, direct subsidies and income tax credits. Owing to different economic developmental stages and energy demand status quos, as well as divergent renewable resource endowments, different countries take distinct measures to foster their internal markets. For example, the income tax credit scheme is one of the main ways of developing PV solar technology in Germany, and investment tax credit deductions and property tax relief are supported by the Ministry of Economy, Trade and Industry (METI) of Japan, while performance-based incentives and renewable portfolio standards are popular in the United States (US). Moreover, feed-in tariffs are the most common incentives for the majority of countries to expand their renewable energy markets, including the US, Japan, Germany, Spain, the United Kingdom (UK) and China.

Our first intention in this paper is to describe the competitive dynamics in a niche market dominated by two competitors and to explore the potential relationship between wind and PV solar technologies. As outstanding examples of carbon-free technology, wind and PV solar may be in strong competition throughout the world. Just as the battle for food and space never ends for different biological species sharing the same ecosystem, the "crowd out" effect also exists for wind and PV solar technologies regarding the allocation of funds, land utilisation, etc. Since the end product of both wind and solar technology is electricity, product homogeneity may be another issue that creates competition between these two technologies in the niche market. Predator–prey, mutualism, and competition are three of the most common relationships between biological species; it will be interesting to explore whether these types of relationship can also be explored in the renewable energy market. Our second task is to determine the impact of different energy technology development modes on the diffusion of renewable technologies. Centralised mode and distributed mode are the most popular ways of developing wind and solar energy. In fact, wind is widely used in a centralised way, such as large-scale wind power plants, while PV solar may be mainly exploited in distributed mode, especially in remote areas. Hence, we seek to explore how the different development patterns may affect the penetration of wind and PV solar technologies. Determining the existence of equilibrium states of the wind and PV solar technology markets in different countries is also a focus of this paper, and, based on our findings, we will share some short-term forecasts for the future diffusion of wind and PV solar technologies.

By closely following these issues, we propose a technology diffusion framework by using a revised Lotka–Volterra model and performing a country-level study. We also attempt to explain the outcome of the results in terms of the different policies that have been implemented in the targeted countries. In fact, incentive policies are indispensable for the development of wind and PV solar technologies, especially in their early stages, when the costs for use are still significantly higher than conventional fossil fuels [3,4].[1] We believe that our work will illustrate the historical growth patterns of wind and PV solar energy, provide useful insights for the future evolution of both technologies, and contribute to the creation of strategic development plans related to the diffusion of wind and PV solar technologies throughout the world.

The remainder of this paper proceeds as follows. In the next section, we review the relevant literature, with a focus on diffusion models and their applications. In Section 3, we describe the model details and show the data. Section 4 provides the estimated parameters and simulation results; the equilibrium calculation and policy analysis for the results are also included in this section. Then, we will present the short-term forecasts of wind and solar technology for the equilibrium-stable countries. Uncertainty analysis is introduced in Section 6 to test the reliability of our model results. In Section 7, we conclude and provide relevant policy recommendations.

2. Literature review

The theory of innovation diffusion models mathematically stems from the contagion models in epidemiology [5], and early diffusion models were developed to cope with the timing of the initial purchase of new consumer products, with innovative and imitative behaviour serving as the core behavioural rationale. Examples of these works include Bass [6], the follow-up studies related to Bass and the revised Bass model [7–10]. Jager [11] argues that PV energy technology possesses the five properties of innovations mentioned in Rogers [12], bridging the diffusion of new product innovation and energy technologies. Since then, the new product diffusion models have been used to investigate the diffusion of energy technology. SÖderholm and Klaassen [4] investigated wind technology diffusion based on the rational option model, and they demonstrated that investment cost is another significant factor influencing the penetration rate of wind technology, along with feed-in tariffs. According to Davies and Diaz-Rainey [13], wind energy in 25 OECD countries will have conventional logistic diffusion with similar speeds of diffusion in the absence of effective and strong policy interventions, and policy plays an important role in the patterns of innovation diffusion. Guidolin and Mortarino [14] employed a generalised Bass model (GBM)

[1] At present, the costs of power generation from the most advanced wind energy and PV solar technology are higher than conventional thermal power, especially for PV, whose generation cost is around 200 USD/MW, which may be fourfold than that of thermal power (BNEF). The high cost of power generation and delayed returns make emerging technology investments very risky, which implies that policy incentives are essential if they are to be developed successfully.

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