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Environmental sustainability of wind power: An emergy analysis of a Chinese wind farm

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ABSTRACT

After a decade of astonishing growth of wind power capacity worldwide, sustainable utilization of wind energy resources has become an issue of utmost importance. For a comprehensive assessment of the environmental sustainability of a wind power, basic emergy flow diagram and emergy indices are presented in this paper to aggregate various renewable/nonrenewable local resources and purchased economic inputs associated with a wind power system, with concrete illustration by a case study of a modern wind farm in Guangxi, China. It is revealed that the solar transformity of wind electricity is the lowest among typical electricity generation technologies. Emergy-based indices are then calculated to provide integrated information of the investigated wind farm from an ecological point of view. Comparison between the results with existing data for other renewable energy systems reflects the substantial advantages of wind power technology over solar thermal power and photovoltaic technologies in terms of sustainability and ecological cost. Nevertheless, biomass-derived fuels, especially biogas by anaerobic digestion, show a better ecological performance and environmental sustainability than wind and solar technologies. In addition, potential for improvements of Chinese wind farm are identified by optimization effort in human labor, land use and waste treatment.

Contents

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1. Introduction

Due to the increasing concerns over surging energy demand and climate change, the world is paying much more attention on sustainable energy future. Renewable energy can serve as feasible and environmentally responsible alternatives to reduce dependence on fossil fuels, enhance flexibility of local power supply, and provide tremendous potential for mitigating climate change [1].The transition for renewable energy substituting fossil fuel in the global energy mix is happening unprecedentedly fast. According to the International Energy Agency [2], the use of renewable energy will triple between 2008 and 2035 with a share in electricity supply rising from 19% to 32%. Compared with other renewable resources, wind power has achieved maturity of commercially integrating into the energy market. Annual growth rate of cumulative wind power capacity averaged 30% in the last decade, bringing global installed capacity to 197 GW by the end of 2010 [3]. In 2011, worldwide wind capacity sets a new record by adding another 42 GW, the largest among all renewable technologies [3].

China, on its way of industrialization and urbanization, surpassed US to be the world's largest energy consumer [4] mainly dependant on coal, which is a key contributor to escalating environmental deterioration, such as greenhouse effect, acid rain, air pollution, etc. To address challenges both from environment and energy supply, China pledged to cultivate a greener economy by emphasizing on the energy efficiency and diversifying energy supply structure by renewable energies. In its 12th Five-Year-Plan, the Chinese government has vowed to increase the proportion of non-fossil fuels to 15% of primary energy consumption and reduce carbon dioxide emissions per unit of GDP by 40–45% from the 2005 level to 2020 [5]. In this context, wind power proves to be one of the most attractive solutions to meet China's goal of sustainable development. The total exploitable capacity of inland and offshore wind power in China is about 700–1200 GW (at a height of 10 m), according to China Meteorological Administration [6]. During the 11th Five-Year-Plan (FYP), the Chinese government has issued a series of polices to promote the development of wind power industry, including supporting localization of wind power equipment, establishing mandatory institution of wind power accessed to the grid, formulating mandatory targets of wind power quotas, and providing subsidy and tax support [7,8]. Recently, China became the world's biggest wind power market, reaching a total of 42.3 GW in 2010, with its installed capacity doubling every year between 2006 and 2009. However, wind power in a time of rapid growth has also exposed many problems in the economics, technologies and policies. In order to guarantee a sustainable future, it is very important to conduct a comprehensive systems accounting on wind power, especially while wind power in China is not cost competitive to coal-based thermal power for the time being.

Extensive studies on the evaluation of various renewable energy sources and industrial systems in China have been carried out [8–14]. Previous studies focused on the net energy consumption and associated greenhouse gas emissions of wind power system using life cycle assessment (LCA) [15–23]. LCA is a technique to evaluate the environmental impacts throughout the whole life-cycle of a product or system. But the above studies, indicating a considerably favorable energy return and GHG mitigation, have certain limitations in assessing the overall environmental performance of wind turbines. None of these studies took account of the resource use due to human labor and environmental work. Particularly, the potential environmental, social and economic impacts of wind power, although currently remain controversial and under debate, should not be ignored [24]. Developing environmental conscious wind power system requires a more integrated analysis, since its potential negative impacts will be amplified rapidly as wind power continues the seemingly unhampered expansion and turbine sizes get larger in the near future. It is imperative to analyze the sustainability of wind turbines comprehensively.

"Sustainability" is derived from the Latin "sustinere", for which dictionary provided more than ten meanings, with the main ones being to "maintain", "support" or "endure" [25]. As a result, "sustainability" is explained as "the capacity to endure" in one dictionary [26]. The definition of sustainability is widely quoted as a part of the concept "sustainable development", which was defined by Brundtland Commission of the United Nations in 1987 as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [27]. However, the reality of this definition of sustainable development in the total biosphere as a compromise of different political wills is critically examined by Svirezhev and Svirejeva-Hopkins [28]. In assessment of the sustainability of a system,there are at least three aspects to be taken into account [29,30]: economic cost that determines the investment, operation and maintenance of the system, input/output efficiency that is essential for scarce resource allocation, and the "ecological cost" (firstly defined as "the total consumption of the exergy of natural resources in all the relative processes that lead to the certain product" by Szargut [31]) of restoration that is important to assess the interaction between biosphere and human society. There is no generally accepted evaluation method to assess sustainability. Nevertheless, these methods mentioned above have their own advantages that provided us with an integrated picture of the sustainability of a system from different perspectives.

In this context, thermodynamic concepts and models in ecological economics can identify the relevant constraints and scarcities of the ultimate driving forces [32] and make bridges between energy, economic and environment hence, can be regarded as appropriate tools to describe the sustainability of a complicated production system [33]. As one of the most promising methods in ecological economics, emergy analysis first introduced by Howard Odum in systems ecology [34], can be used to evaluate integrated relationship between the economy system and its environment.

For this purpose, emergy analysis can serve as a valid and complementary approach to determine the environmental sustainability of renewable technologies [30,35–41]. Emergy is defined as the sum of available energy consumed in transformations directly and indirectly to make a product or service [42]. Solar energy is regarded as the primary energy source that drives earth's various ecological and economical systems. By converting all forms of energy, resources and human services into a common