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# Emergy-based sustainability evaluation of wind power generation systems

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## HIGHLIGHTS

- Emergy is used to quantify the sustainability level of wind farms.
- A GHG-based indicator is incorporated into emergetic accounting.
- Possible pathways to achieve sustainable wind farm management are analyzed.

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## ABSTRACT

With large-scale commercialization of wind technology, one must investigate economical and sustainable wind resource utilization. In this paper, emergy analysis is used to quantify the environmental pressure, renewability, economic efficiency, and sustainability of a typical wind power system, considering the lifetime stages from extraction and processing of raw materials and resources to the final product (electricity) via material transportation, construction and operation. Possible pathways to achieve sustainable management of wind energy supply chain were also analyzed based on scenario analysis. Results show that wind power is a promising means of substituting traditional fossil fuel-based power generation systems, with the lowest transformity of $4.49 \times 10^4$ sej/J, smaller environmental loading ratio of 5.84, and lower greenhouse gas emission intensity of 0.56 kg/kWh. To shed light on potential pathways to achieve sustainable and low-carbon wind energy supply chain management and make informed choices, a sensitivity analysis was done by establishing scenarios from the perspectives of material recycling and technical development. Results suggest that using new materials of lower energy intensity or recycled materials in upstream wind turbine manufacturing and construction materials are the most effective measures.

## 1. Introduction

Driven by concerns about greenhouse gas (GHG) emissions, rising energy prices, and energy shortages, development of the wind power industry with great GHG emission mitigation potential has been accelerating in recent years, with 51.473 GW of new wind capacity installed globally in 2014 alone [1]. According to the 2013 IEA Technology Roadmap, the share of wind power in electricity supply should continue to increase, from its current 2.6% to 18% by 2050 [2]. Because wind power relies on the wind resource for a portion of its input, it is often presented as a very “clean and sustainable” energy, with little or no consideration of the ecological costs and related environmental impacts. However, wind farms may require higher initial investments in infrastructure than fossil-based power systems [3]. Therefore, one must study the entire supply chain of wind resource utilization to account for its efficiencies, environmental impacts, GHG emissions, and sustainability, thereby facilitating long-term wind resource utilization management and planning.

To determine the environmental impacts caused by wind power penetration, life cycle assessment (LCA), which is advantageous in explicit and rigorous calculation of direct and indirect environmental effects, has been widely used in evaluating the hidden environmental emissions of wind energy technologies [4–14]. However, LCA of wind power systems does not quantify social cost and the

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environment's role in absorbing and processing pollution [15]. Thus, it is not adequate for the evaluation of a technology's net contributions to the economy and sustainability of the energy conversion process.

Emergy ontology, proposed by Odum [16], asserts that "all wealth stems from the environment and its myriad systems and processes, and that the value of services and commodities should be based on the energy and resources required to produce them rather than on what someone is willing to pay for them". Since emergy traces to the beginning and origin of the being (products or services), it is described as "energy memory", which represents a constant presence in a unified way [17]. Emergy analysis considers all systems to be networks of energy flows, and determines the emergy value of the streams and systems involved by multiplying their transformities. The latter are defined as the ratios of emergy required to make products to the energy of those products [18]. Because emergy analysis provides a more feasible approach to assess the status and position of different energy carriers in the universal energy hierarchy, and considers both the natural properties and economic characteristics of a system, it is widely employed to evaluate public policy options and environmental impacts of energy systems. This lends quantitative insight into questions of resource management [19–22].

For emergy analysis of renewable energy systems, there has been widespread research into the sustainability of biofuels and bioenergy, such as wheat plantation/alcohol distillery systems [23], residual material-based bioethanol production [24], corn ethanol production [25], palm-based biofuel refinery systems [26], soybean-based biodiesel production [27], and biogas [28,29]. In terms of renewable power generation systems, since the pioneering work of Brown and Ulgiati [30,31] that evaluated six electricity production systems using energy and emergy accounting techniques to rank their relative thermodynamic and environmental efficiencies, there have been only limited applications. For example, Buonocore et al. [32] performed a LCA and emergy assessment of a 20-MW dry steam geothermal power plant in the Tuscany region (Italy), aiming at understanding the extent to which the power plant was environmentally sound and if there were steps and/or components requiring further attention. Focusing on solar PV power generation systems, Zhang et al. [33] presented an ecological accounting framework based on embodied energy and emergy analyses to examine the performance of the 1.5-MW Dahan solar tower power plant in Beijing. Using a revised operational definition of the emergy yield ratio, Brown et al. [34] investigated performance in two cases, cadmium telluride PV and oil-fired thermal electricity production. Takahashi and Sato [35] proposed two novel indices based on emergy analysis to evaluate public acceptance together with economic and environmental aspects of eight power generation systems. For wind power generation systems, Yang et al. [36] presented a basic emergy diagram and emergy indicators to evaluate the performance of a wind power generation system aggregating various associated renewable/nonrenewable resources and purchased emergy inputs. Iribarren et al. [37] combined emergy analysis with data envelopment analysis for ecocentric benchmarking of wind power generation systems.

All the above studies proved emergy analysis a powerful tool in the assessment of renewable power generation system dynamics. The two existing emergy studies of wind power generation systems provide information on environmental pressure and resource use efficiency. However, environmental emissions (especially GHG), which are undesirable outputs of wind power generation systems, have not yet been incorporated into emergy analysis. Improvements to wind power generation systems using emergy as a benchmark should be further discussed.

In the present work, the renewability, economic efficiency and environmental pressure of wind power generation systems during the whole lifetime stages were evaluated and depicted based on emergy analysis and emergetic ternary diagrams. The indicator $E_m\text{CO}_2$ was proposed as a useful goal function for potential system optimization in the context of low-carbon and sustainable development. Moreover, scenario analysis was conducted to find ways to improve sustainability of wind energy supply chain. The proposed accounting framework may shed light on balancing resource conversion efficiency, environmental pressure, and economic performance of wind power generation, as well as provide managerial implications for the design of sustainable wind power supply chain management strategies.

## 2. Materials and methods

### 2.1. Emergy analysis

With increasing recognition of the importance of environmental integrity, which provides free and necessary inputs (sometimes on a renewable basis) to electric production systems and is a sink for emissions, environmental inputs to energy production processes should be recognized as services performed by the environment [30]. To integrate the environmental loading exerted by wind farm construction and operation into the sustainability accounting framework, emergy analysis, which is a measure of past and present environmental support to a process and explores the interplay of natural ecosystem and human activities, is used in this paper. All resources and energy used to produce electricity are expressed in the form of emergy, with their solar transformities as conversion factors.

The emergy diagram of the studied wind farm is shown in Fig. 1. This diagram reveals the main steps of a wind farm project and all main input flows to each step, along with feedback, degraded resource, and money flows. Thereby, a clear overview of the entire process is obtained for a comprehensive evaluation [23]. In the diagram, only one type of environmental resource is used by the wind farm, namely, the wind resource on the plant site ($R$). This is the direct driving force of electricity production. Nonrenewable environmental resources ($N$) mainly include land losses. Flows of material, equipment, human services from the economy that are used to construct, operate, and maintain the wind farm are categorized as purchased emergy ($F$). The electricity output ($Y$) is the yield of the process, to which the total emergy input is assigned. The coproduct output of pollutants ($C$), i.e., GHG emission, is also shown in the emergy diagram.

Based on a revaluation and subsequent recalculation of energy contributions by Odum [38], the emergy baseline is set as $15.83 \times 10^{24}$ sej/yr.

### 2.2. GHG emission accounting

Two approaches are available in quantifying the GHG emission of wind power generation systems, i.e., the process-based and environmental input–output-based LCA. The conventional process-based accounting is a bottom-up approach, which captures all environmental impacts following the supply chain from cradle to grave. However, there is a cutoff criteria in the process-based method, which neglects parts that are considered unimportant or contribute little to the results. Environmental input–output-based LCA, which is based on the national account, can eliminate the cutoff from process-based accounting. However, accuracy of the results may be reduced because of uncertainty generated by sectoral aggregation [39]. Because process-based LCA is typically used in micro systems [40–42] and environmental input–output-based LCA is more appropriate for national or regional levels [43–50], we choose process-based accounting for