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

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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 basis of solar emjoules (abbreviated seJ), the major inputs from the human economy and the contribution of ecosystem can be integrated to analyze the environmental performances and to support policy recommendations. Emergy inflows driving a system are categorized by different characteristics, i.e. renewable and nonrenewable resources, locally available versus purchased inputs from outside. A set of emergy indices can be used to evaluate the sustainability and thermodynamic efficiency of the whole system, as well as its interactions with external environment. The general concepts, principles and methodologies of emergy analysis, as well as the emergy-based indices, have been extensively developed and intensively illustrated (e.g.,Odum [42], and developed by Brown and Ulgiati [43], JØrgensen [44], Bakshi [45], and Chen [46]).

Recently, emergy method has been widely used to evaluate ecological economic systems, with extensive literatures appeared on assessing various sectors including industry(e.g., [47–51]), construction (e.g., [52–59]), agricultural systems(e.g., [38,39,60–77]), and hybrid systems (e.g., [29,30,78,79]) with different scales such as regional scales (e.g.[47,77,80–87]), national scales (e.g., [62,88–91]) and global scales (e.g.[42,92,93]). As for emergy analysis of renewable energy technologies, most studies focused on evaluating the biomass-derived fuels [38,39,67,75,95–98], while few studies on other renewable power generation. Zhang et al. [99] evaluated the performance of a concentrating solar power (CSP) system by embodied energy and emergy analyses. Paoli et al. [100] performed emergy analysis to compare the sustainability and efficiency of two solar technologies. The results showed that solar thermal plant was more sustainable than the photovoltaic (PV) one, due to the high dependency of PV on external and imported resources. More recently, Brown et al. [101] discussed a common framework consistent with both LCA and emergy synthesis to calculate performance indicators. Two case studies, namely CdTe PV system and oil-fired power plant, were investigated by a revised operational definition of the emergy yield ratio (EYR). Nevertheless, studies addressed to the evaluation of modern wind farms based on emergy are still lacking in open literature.

This paper aims to fill the gap by using emergy analysis to assess the performance and environmental sustainability of a typical wind farm in Guangxi Province, China. And the emergy-based indices including transformity, percent renewable, emergy yield ratio, environmental loading ratio, and emergy sustainability index were compared with other energy production systems to shed insight into the outstanding environmental sustainability of wind power technology. The results of emergy analysis can serve as ecological indicators for the environmental performance of wind farms and lead to policy recommendations for further wind power development in China.

2. Materials and methods

2.1. Emergy analysis

Emergy analysis is a method of environmental accounting to illustrate the relative position of different energy carriers in the thermodynamic hierarchy of the biosphere. This top-down eco-centric approach measures all the inputs required to sustain a process on a common basis as solar emergy. In this way, different kinds of commodities, services and environmental work can be quantified by means of a transformation ratio called transformity to represent the conversion efficiency of a system in the global energy hierarchy [102]. It is defined as “the emergy of one type required to make a unit of energy of another type” [42] with the unit of solar emjoules per joule (abbreviated seJ/J). Thus, the total emergy of any product or service can be calculated by multiplying its raw amount by its transformity.

Solar transformities for a wide variety of goods and services can be obtained from previous studies to facilitate the emergy analysis. However, transformity of a given object of the same category may have different values due to the specific geographic location and production process. In this paper, transformities of materials and resources associated with the investigated wind farm are mainly adopted from Zhou [103], as the first effort in embodied ecological elements accounting of Chinese national economy by combining the input–output analysis with ecological thermodynamics. This database can effectively avoid choosing dispersed and inappropriate transformities, and thus guarantee the accuracy of emergy analysis in this study.

2.2. Emergy evaluation procedure

The emergy evaluation procedure of wind farm consists of the following steps. Firstly, evaluation starts with overview diagraming to identify sources and pathways in the interactive networks of a system. Diagrams are constructed of special emergy language symbols invented by Odum [34]. An emergy systems diagram of wind power plant is shown in Fig. 1. Since a wind farm system contains both natural ecosystem and artificial engineering works associated with renewable and nonrenewable energy and resource inputs,

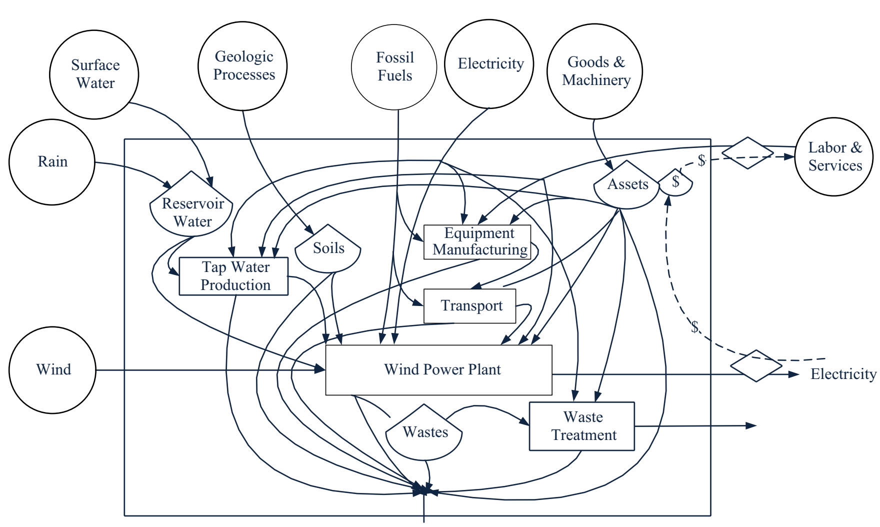

Fig. 1. Emergy systems diagram of wind power plant.

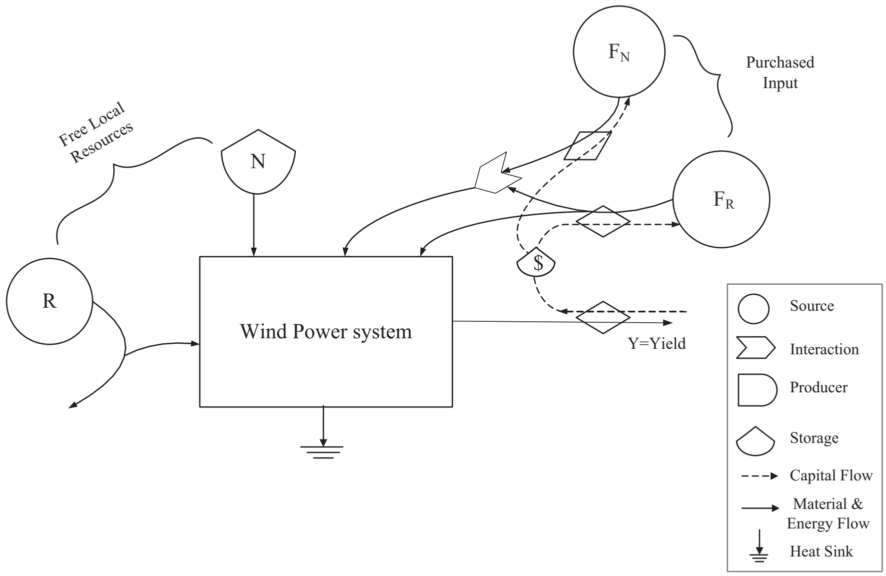

Fig. 2. Aggregated emergy flow diagram of wind power system.

Table 1
Main characteristics of the wind power plant.

Turbine type	SEC-1250 kW
Turbine number	24
Blade diameter	64 m
Hub height	68 m
Mean wind speed (at hub height)	7.22 m/s
Average wind power density	248.73 W/m²
Working wind speed	3.0 m/s–20 m/s
Time of working wind speed	8269 h/yr
Total land area	8.0 km²
Permanent personnel	18
Operating lifetime	20 years
Annual electricity output	6.54E+07 kW h
Capacity factor	24.90%
Project developer	China Huadian Corporation
Greenhouse gas emissions	0.002 t $CO_{2\text{-eq}}$/GW h[11]
Employment	0.6/MW

all these energy and material can be classified and aggregated, as shown in Fig. 2. The second step is to establish an emergy evaluation table listing all the items and data to be considered in the system. The items include not only initial material and capital investment for plant construction and the continuous inputs for operation and maintenance, but also nonresource factors such as human labor and services. Different units of actual flows in the table are multiplied by the corresponding transformities to convert them into solar emergy. The final step is to calculate emergy indices based on the evaluation table. These indices have been shown to be particularly useful to promote a sustainable pattern for human-dominated systems, where many influencing factors are adjustable and choices have to be made cautiously [104].

2.3. Emergy-based indices

All the system inputs are generally categorized into three types: local renewable resources (R), such as sunlight, wind and rain; local nonrenewable resources (N) refers to those available in limited amount within system boundary, such as soil erosion and groundwater, etc.; purchased input (F) includes those bought in from the economy, such as electricity, machinery and human labor, etc. As is shown in Fig. 2, the F group is sometimes further divided into purchased renewable input (F_R) and purchased nonrenewable input (F_N). The total emergy use (U) is equal to the sum of emergy inflows (N+R+F), which determines the total emergy cost driving the system. Based on the above characteristics of emergy flows, several emergy-based indices were proposed to investigate the efficiency and sustainability of various systems [104,105].

(1) Percent renewable (PR)$=R/U$ is the percentage of emergy inputs provided by renewable resources. A system using higher fraction of renewable resources is considered more sustainable in the long run.
(2) Emergy yield ratio (EYR)$=U/F$ measures the efficiency of a process using purchased inputs to exploit local resources. The higher the EYR , the larger the contribution to the economy per unit of emergy invested.
(3) Environmental loading ratio (ELR)$=(N+F)/R$, it is the ratio of purchased and local nonrenewable resources to renewable emergy inputs. It indicates the potential environmental impact and ecosystem stress due to the transformation process.
(4) Emergy investment ratio (EIR)$=F/(R+N)$ is the ratio of investment from outside the system to local resources. EIR evaluates whether the system is an economical user of emergy compared to other alternatives. The system with a lower ratio is more likely to prosper in the market.
(5) Emergy sustainability index (ESI)=EYR/ELR measures the potential contribution of a process per unit of environmental loading. This index reflects the overall sustainability of a production process, accounting for both economical and ecological compatibility.

2.4. The case wind farm description

The wind farm is located in the Darong Mountain Resort (110°11′26″E–110°15′23″E, 22°51′36″N–22°52′49″N) in Yulin City, Guangxi Zhuang Nationality Autonomous Region, China. Main characteristics of the wind farm are presented in Table 1. It is comprised of 24 wind turbines each with a generating capacity of 1.25 MW, a hub height of 68 m and a blade diameter of 64 m (total height 100 m). The whole turbine, weighing approximately 156.8 t, is made up of three components: rotors, nacelle, and tower. The nacelle sits atop the tower and houses the generator, gearbox, main shaft, and yaw system, etc. The rotor is bolted to the nacelle and is comprised of three blades, the hub and the nose cone. Each blade is 31 m long, weighs 3.6 t and is made of fiber glass and resin material. The tower is assumed to be 100%

Table 2
Emergy analysis of the Yulin wind farm during 20 years' lifetime[a].

Note	Classification	Item	Materials	Raw amount	Unit	Solar transformity (seJ/unit)	Ref. of transf.	Solar emergy (seJ)
Local resources								
1	100%R	Wind (kinetic energy)		6.67E+14	J	2.45E+03	[42]	1.63E+18
2	100%N	Land loss[b]		3.69E+03	m²/Year	8.00E+10	[42]	5.90E+15
Wind turbines								
3	$100\%F_N$	Rotor	Resin and fiber glass	2.64E+02	T	8.07E+15	[103]	2.13E+18
			Cast iron	1.90E+02	T	3.23E+15	[103]	6.12E+17
4	$100\%F_N$	Nacelle	Iron	4.82E+02	T	3.23E+15	[103]	1.56E+18
			Steel	5.64E+02	T	3.23E+15	[103]	1.82E+18
			Silica	9.60E+00	T	5.05E+15	[103]	4.85E+16
			Copper	9.12E+01	T	1.01E+16	[103]	9.21E+17
			Resin and fiber glass	5.28E+01	T	8.07E+15	[103]	4.26E+17
5	$100\%F_N$	Tower	Steel	2.11E+03	T	3.23E+15	[103]	6.81E+18
Substation								
6	$100\%F_N$	Transformer	Silica	6.00E−01	t	5.05E+15	[103]	3.03E+15
			Steel	1.08E+01	t	3.23E+15	[103]	3.49E+16
			Copper	4.80E+00	t	1.01E+16	[103]	4.85E+16
7	$100\%F_N$	Control system	Computer	5.00E+00		5.77E+14	[103]	2.89E+15
Transportation							[103]	
8	$100\%F_N$	Transport fuel[c]	Diesel	1.58E+02	t	1.41E+15	[103]	2.23E+17
Building works[d]								
9	$100\%F_N$	Tower foundation	Concrete	8.33E+03	m³	3.03E+14	[103]	2.53E+18
			Steel bar	9.92E+02	t	4.82E+15	[103]	4.78E+18
10	$100\%F_N$	Substation	Concrete	1.64E+02	m³	3.03E+14	[103]	4.97E+16
			Steel bar	7.90E+00	t	4.82E+15	[103]	3.81E+16
11	$100\%F_N$	Cable	Copper and plastic	9.37E+01	t	8.11E+15	[103]	7.60E+17
12	$20\%F_R,80\%F_N$	Power supply	Electricity	6.48E+11	J	3.14E+05	[103]	2.03E+17
13	$100\%F_R$	Water supply	Reservoir water	2.70E+04	t	9.75E+09	[42]	2.63E+14
Operation and maintenance								
14	$100\%F_N$	Machine oil	Lubricant	2.95E+01	t	1.55E+15	[103]	4.57E+16
15	$100\%F_R$	Water supply	Tap water	2.55E+04	t	4.65E+11	[103]	1.19E+16
16	$100\%F_N$	Blade substitution	Resin and fiber glass	8.64E+01	t	8.07E+15	[103]	6.97E+17
17	$100\%F_N$	Generator substitution[e]	Silicon	7.20E-01	t	5.05E+15	[103]	3.64E+15
			Copper	7.92E+00	t	1.01E+16	[103]	8.00E+16
			Steel	1.66E+01	t	3.23E+15	[103]	5.35E+16
Labor and services[f]								
18	$26\%S_R,74\%S_N$	Labor for operation and maintenance		3.29E+06	$	5.87E+12	[107]	1.93E+19
19	$26\%S_R,74\%S_N$	Construction manpower		5.05E+06	$	5.87E+12	[107]	2.96E+19
20	$26\%S_R,74\%S_N$	Cost of land occupation		1.29E+06	$	5.87E+12	[107]	7.57E+18
Electricity production								
21		Lifetime yield	Electricity	4.71E+15	J			
Total emergy use					seJ			8.21E+19
Transformity of wind electricity				1.74E+04	seJ/J		This study	

[a] Data for the wind farm was provided by the developer [106]. All transformity values used in this study are relative to the most recent emergy baseline (total emergy driving the biosphere: 15.83×10^{24} seJ/year. Calculation formulas are presented in details in Appendix A.
[b] Only a small area of turbine foundations is considered lost and taken out of production. Land loss is incorporated to take into account opportunity costs associated with lost production. Vegetation nearby is assumed not affected.
[c] Major components were firstly transported from the manufacturer to Yulin City on the highway by diesel vehicles, and then from Yulin City to Darong Mountain, a distance of 40 km. Transport activities related with regular maintenance of wind turbines were ignored due to the unavailable data.
[d] Building works mainly include the construction of tower foundations and substation. Tower foundations are made on site.
[e] During the average useful life of a wind turbine, it is supposed to substitute one blade and 15% of generator's component [19].
[f] Labor includes only those directly associated with plant construction, operation and maintenance.

steel. Each wind turbine tower is connected to a 35 kW box-type transformer. The tower is installed on flat lay-bay and anchored with a foundation, which consists of filling up a 3.3 m deep hole with some concrete reinforced by steel. All the detailed data and specifications of this wind farm are provided by the developer, China Huadian Corporation [106].

Wind resource in this farm was assessed using WAsP software, developed by Risø National Laboratory, Denmark. The results showed that annual mean wind speed is 7.26 m/s and the average wind power density is 248.73 W/m² at hub height in Darong Mountain. Working wind speed (3.0 m/s–20 m/s) was estimated to be 8269 h per year. Based on the characteristic power curve and hourly wind data of the location, the annual gross energy production of the wind farm is calculated to be 6.54E+07 kW h [106]. Thus the annual grid-connected electricity for each turbine will be 2.73E+06 kW h with an availability of 2179.5 h/year on average.

3. Results

3.1. Emergy of wind power plant

An emergy diagram referring to the wind power plant is shown in Fig. 1. Dashed lines show the inflow of money from electricity sale and the outflow of money for the purchase of goods and

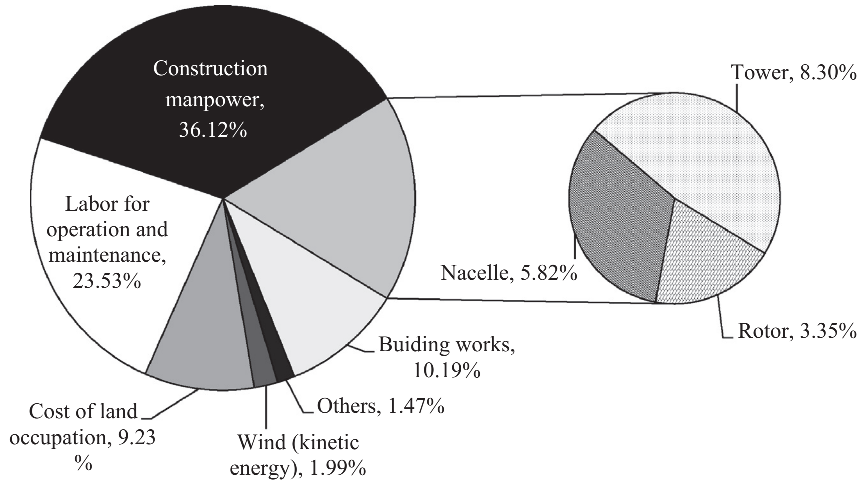

Fig. 3. Fractions of emergy inputs for a Chinese wind farm.

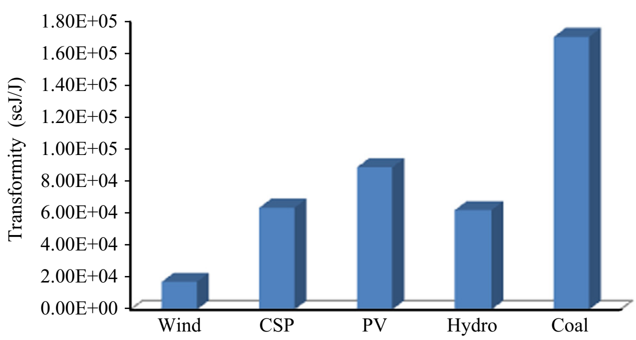

Fig. 4. Comparison of transformities of electricity from wind farm with other electricity production systems.

services. Based on the diagram, detailed emergy flows driving the entire system are presented in Table 2. The evaluation table incorporates different categories of resources, human labor, and economic investment supplied for the concerned wind farm. The solar emergy of each item is obtained by multiplying the raw amount by its transformity.

The total emergy use (U) of the wind farm during 20 years' lifetime is summed up to be 8.21E+19 seJ. As described in Section 2.4, gross electricity output of the wind farm is calculated to be 4.71E+15 J. Therefore, transformity of electricity produced by the wind farm equals to 1.74E+04 seJ/J, indicating that wind power requires 1.74E+04 seJ of solar emergy to generate 1 J of electricity. The major emergy inputs can be ascribed to labor and services, with labor for operation and maintenance, construction manpower and the cost of land occupation, taking up nearly 70% of total emergy input (see Fig. 3). Total purchased input (F) amounts to 6.57E+19 seJ. As for materials to install and maintain the wind power plant, wind turbines (17.47%) and building works (10.19%) are the two largest contributors to emergy inputs. The inventory of purchased resources showed that steel plays a significant role in determining the emergy cost of wind farm, accounting for 13.90% of total emergy use. Renewable emergy input (R+F_R+S_R) reaches a total of 1.64E+19 seJ. As the only local nonrenewable resource (N), land loss taken by turbine foundations is a negligible amount of 5.90E+15 seJ.

3.2. Plant emergy indices

Emergy indices of the wind power plant are listed in Table 3. Those indices show a relatively good sustainability performance for wind power, which will be discussed later in Section 4. The percentage renewable (PR) is 0.20 for wind power. The emergy input from wind's kinetic energy for electricity generation amounts to 1.63E+18 seJ during 20 years' lifespan (refer to Table 2). Additional renewable fraction comprises natural water and a substantial portion from outside the system, mainly in the form of labor and services. Water from a nearby reservoir was used for building works in a three months' construction period and tap water production for plant operation and maintenance. As a common practice in emergy analysis, labor and services are divided into renewable (S_R) and nonrenewable (S_N) fractions. In China, labor and services are considered 26% renewable, according to the percentage of renewables (including traditional biomass energy) driving Chinese economic system [38].

4. Discussion

4.1. Transformity comparison between various electricity production systems

Transformity is a very important parameter, which can be used to measure the overall efficiency of production systems from the viewpoint of the biosphere. Those with greater transformities demand more emergy to generate the same amount of product. Transformity of electricity from modern wind farm is much lower than other typical electricity production systems (see Fig. 4). It is revealed that wind power transformity has a value much lower than that from a CSP plant (6.39E+04 seJ/J) in China [99]. It can be explained by the big difference of output capacity between a 30 MW wind farm and a 1.5 MW CSP plant, while both are efficient renewable technologies and have great potential to replace fossil fuels in the future. According to Paoli et al. [100], the transformity of PV electricity (8.92E+04 seJ/J) is approximately five times higher than that of wind-generated electricity. This indicates that wind power is much more efficient and requires less emergy input from environment and society than photovoltaic. A large transformity for PV can be attributed to the complexity and high energy consumption of crystalline silicon wafer production, as well as its higher costs of plant design and maintenance. In comparison, coal-fired power plant has the largest transformity (1.71E+05 seJ/J) and hydroelectricity has a similar transformity with CSP, as studied by Brown and Ulgiati [35]. In fact, the transformity of electricity from wind power has also been reported as 6.21E+04 seJ/J in their study on five 500 kW Italian wind turbines constructed in 1996. The current value of wind power transformity (1.74E+04 seJ/J) demonstrates the remarkable technological progress and sustainable performance of modern large-scale wind farm during the last decade.

4.2. Comparison of emergy indices for renewable energy systems

In order to assess the relative performance and sustainability of wind power, the resulting indices are compared with solar thermal and photovoltaic plants [100] and various nonelectric energy carriers from biomass [36,38,40,95,99,100,108,111,112]. Those studies have adopted the similar assumptions and standard methods for conducting emergy analysis. So the comparison of emergy ratios and indices can effectively provide insight into their individual sustainability.

The emergy-based indices for those renewable energy systems are listed in Table 4. Wind power has a higher PR (0.20) than solar thermal (0.15) and photovoltaic (0.02), indicating a better level of renewability. PRs of biomass energy production are even higher in average due to their less dependency on nonrenewable emergy support from human society. The emergy yield ratio (EYR) of wind power is 1.25, in the medium level of those of traditional electricity production systems (1.06–1.51) [113], which proves that wind farm is relatively efficient at harnessing local resources to provide net benefit to society. The environmental loading ratio (ELR) measures the potential environmental impact of a system, thus assisting EYR to give a comprehensive evaluation. ELR of photovoltaic plant (48.93) is much higher than that of wind power (4.00), solar thermal plant (5.54) and biofuel production systems (0.52–7.84). It can be inferred that wind power, compared with PV, has less environmental stress to generate the same amount of electricity. The sustainable performance of wind farm is further verified by possessing a higher ESI (0.31), which is an aggregated measure by EYR and ELR to account for both economical and ecological compatibility. It is also the key advantage of wind power over solar technologies to have a large emergy yield per unit of environmental loading. As seen from the emergy indices in Table 4, biomass-derived fuels, especially biogas by anaerobic digestion, show a better ecological performance and environmental sustainability than wind and solar technologies.

It can be noted that emergy investment ratio (EIR) has approximately the same value with ELR for wind, solar and biodiesel production systems. The reason is that those systems have a negligible utilization of local nonrenewable resources (N), which can be derived from the respective calculation formulas in Table 3.

When comparing different categories of systems by the emergy-based indices, there are certain limitations in illustrating the numerical variation. In fact, the variation is inherently rooted in their characteristic fractions of emergy input and different consideration by each system. This highlights the need for a broader perspective to assess the relative sustainability of different production systems. However, for the same kind of production system, discrepancy of emergy indices can also be found in the literature. For example, emergy indices for bioethanol and biodiesel production, as listed in Table 4, show some variation. This is mainly attributed to the differences in feedstock, production efficiency and the respective technological process considered in emergy analysis. Meanwhile, the renewable fraction of labor and services (S_R) changes with the share of the renewables driving the economic system in different location and time period, which directly affects the emergy indices of the investigated system. In order to arrive at a comparable result, consistency must be strictly guaranteed during the implementation of emergy analysis.

4.3. Human labor and services

Although usually neglected in traditional energy analysis, labor and services are important system inflows in emergy-based method. As shown in Fig. 3, human labor for plant construction, operation and maintenance represents a large fraction of total emergy use (59.65%). Therefore, wind power highly relies on emergy input of human services, reflecting the need to simplify and optimize the process to make it more cost-effective. On the other hand, wind industry offers considerable employment opportunities during the different phases of wind farm development, such as turbine manufacture, plant construction, operation and maintenance, as well as indirect employment. According to the Global Wind Energy Council, annual market for wind energy will create 13 jobs for every megawatt of new capacity in that year, employing 524,000 people in the wind energy sector by 2020 [110]. As wind power continues to expand in China, it has great potential to stimulate economic growth and employ surplus labor, especially in the rural areas.

Wind power demands a relatively large footprint on the land to get large-scale, with the cost of land occupation taking up a big

Table 3
Emergy-based indices for the investigated wind farm.

Index	Calculation	Wind power
Percent renewable (PR)	$(R+F_R+S_R)/U$	0.20
Emergy yield ratio (EYR)	$U/(F_N+S_N)$	1.25
Environmental loading ratio (ELR)	$(N+F_N+S_N)/(R+F_R+S_R)$	4.00
Emergy investment ratio (EIR)	$(F_N+S_N)/(R+F_R+S_R+N)$	4.00
Emergy sustainability index (ESI)	EYR/ELR	0.31

Table 4
Comparison of emergy indices for renewable energy systems.

Item		Reference	Published year	PR	EYR	ELR	EIR	ESI
Wind		In this study		0.20	1.25	4.00	4.00	0.31
Solar thermal		[99]	2011	0.15	1.19	5.54	5.54	0.21[a]
Photovoltaic		[100]	2008	0.02	1.03	48.93	37.27	0.02[a]
Biofuel refinery		[95]	2010	0.25[a]	1.05	3.02	0.95	0.35
Bioethanol	Wheat	[38]	2008	0.20	1.24	4.05	2.38[a]	0.31
	Corn	[38]	2008	0.11	1.14	7.84	5.36[a]	0.15
	Sugarcane	[108]	2010	0.31	1.57	2.23	1.44[a]	0.71
	Cassava	[40]	2011	0.28	1.07	2.55	2.47[a]	0.42
Biodiesel	Vegetable oil	[112]	2007	0.06	3.68	3.55	3.57	1.04
	Soybean	[111]	2010	0.31	1.62	2.26	2.26[a]	0.72
Biogas		[36]	2011	0.66	2.93	0.52	0.52[a]	5.67

[a] Not considered in the literature. We recalculated the values to supplement the comparison.

portion of capital investment (9.23% of total emergy use). Land must be expropriated from local government for infrastructure installation, temporary land use during construction and access roads. But wind turbines are usually spaced 5–9 rotor diameters apart to maximize performance. In order to save emergy cost and increase the whole sustainability degree of regional land use, space between the towers should be fully utilized for other compatible purposes, such as food production and ecological vegetation.

4.4. Waste treatment

A lot of wind farm facilities are made up of recyclable materials. Waste treatment is an efficient method to reduce the harmful environmental impacts after the plant's disassembly and disposal. Detailed data regarding the Yulin wind farm is currently unavailable. The recycling of plant wastes is estimated based on a scenario depicted in a previous work [11].The potentially recyclable emergy of a Chinese wind farm is calculated to be 6.69E+18 seJ, accounting for 28% of total purchased materials. An integrated waste management strategy for the wind farm should be implemented to reduce the emergy consumption and optimize the resource efficiency by more recycling. It should be pointed out that other resources are consumed during the process of waste treatment. Therefore, the role of waste treatment in improving the comprehensive emergy performance of wind farm still needs further consideration.

5. Concluding remarks

This paper focused on the emergy analysis of a modern wind farm in China. Compared with embodied energy metrics, emergy analysis proves to be a valid approach to evaluate the environmental sustainability of human-dominated production systems. Emergy seems to provide a more adequate coverage of the dimensions of sustainability by considering different forms of materials, environmental support, human labor and economic services on a common basis. The outstanding performance and sustainability degree of wind power technology was confirmed by the calculated emergy ratios and indices. The transformity of electricity from the wind farm is the lowest among various electricity generation processes, indicating that it has a higher thermodynamic efficiency from the viewpoint of the biosphere. In order to assess the relative performance and sustainability of the investigated system, different kinds of renewable energy systems were compared by several emergy-based indices, including emergy yield ratio, environmental loading ratio, emergy sustainability index, etc. The result shows that wind power, in comparison with solar technologies, has a better level of renewability and is a more efficient and productive user of emergy investment with a lower environmental impact. When measured by emergy-based indices, the sustainability performance of those renewable energy systems, from an ecological point of view, is ranked as follows: biomass-derived fuels > wind power > solar thermal and photovoltaic plant. As two important contributors to the total emergy use, human labor and cost of land occupation deserve special attention in future wind farm projects. Moreover, emergy saving from waste treatment has also been estimated and need further consideration.

The present study of emergy analysis of modern wind farm, with broader spatial and time frames, can assist in comprehensive environmental planning and policy-making. Given the rapid expansion of wind market in China, it is recommended that great importance should be attached to future wind power development to enhance sustainability.

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Appendix

1. **Wind (kinetic energy)**
   Area swept by the rotor: $3.14\times(32\ \text{m})^2\times 24$ turbines $=7.72\text{E}+04\ \text{m}^2$.
   Average wind speed: 7.22 m/s.
   Annual working time: 8269 h = 2.98E+06 s.
   Air density: 1.3 kg/m^3.
   Maximum wind turbine efficiency: 0.593 (Betz limit).
   Energy input $=0.5\times 1.3\ \text{kg/m}^3\times 7.72\text{E}+04\ \text{m}^2\times(7.22\ \text{m/s})^3\times 0.593\times 2.98\text{E}+06\ \text{s/year}\times 20\ \text{years}=6.67\text{E}+14$ J.
2. **Land loss**
   Area of tower foundation: $3.14\times(7\ \text{m})^2\times 24$ turbines $=3.69\text{E}+03\ \text{m}^2$.
   Land class: pasture and livestock.
   Transformity of pastureland with livestock: 8.00E+10 seJ/m^2/year.
   Total land loss $=8.00\text{E}+10\ \text{seJ/m}^2\text{/year}\times 3.69\text{E}+03\ \text{m}^2\times 20$ years $=5.90\text{E}+15$ seJ.
3. **Rotor**
   Three blades and nose cone: 6.6 t Resin+4.4 t fiber glass.
   Total mass of resin and fiber glass = $(6.6\ \text{t}+4.4\ \text{t})\times 24$ turbines = 26.4 t.
   Blade hub: 7.9 t cast iron.
   Total mass of cast iron = $7.9\ \text{t}\times 24$ turbines = 189.6 t.
4. **Nacelle**
   Bed frame: 11.4 t iron.
   Main shaft: 6.6 t steel.
   Transformer: 0.2 t silica+3.6 t steel+1.6 t copper.
   Generator: 0.2 t silica+2.2 t copper+4.6 t steel.
   Gearbox: 8.7 t iron+8.7 t steel.
   Nacelle cover: 1.3 t resin+0.9 t fiber glass.
   Total mass of iron = $(11.4\ \text{t}++8.7\ \text{t})\times 24$ turbines = 482.4 t.
   Total mass of steel = $(6.6\ \text{t}+3.6\ \text{t}+4.6\ \text{t}+8.7\ \text{t})\times 24$ turbines = 564 t.
   Total mass of silica = $(0.2\ \text{t}+0.2\ \text{t})\times 24$ turbines = 9.6 t.
   Total mass of copper = $(1.6\ \text{t}+2.2\ \text{t})\times 24$ turbines = 91.2 t.
   Total mass of resin and fiber glass = $(1.3\ \text{t}+0.9\ \text{t})\times 24$ turbines = 52.8 t.
5. **Tower**
   Total mass of steel = $87.9\ \text{t}\times 24$ turbines = 2109.6 t.
6. **Transformer**
   Transformer: 0.6 t silica +10.8 t steel +4.8 t copper.
7. **Control system**
   Control system: 5 computers.
8. **Transport fuel**
   Rotor and nacelle (produced in Shanghai): $68.9\ \text{t}\times 24$ turbines $\times(2185\ \text{km}+40\ \text{km})=3.68\text{E}+06$ t km.
   Transformer (fabricated in Nanjing): $16.2\ \text{t}\times(2103\ \text{km}+40\ \text{km})=3.47\text{E}+04$ t km.
   Steel bar for tower (purchased in Yulin City): $87.9\ \text{t}\times 24$ turbines $\times 40\ \text{km}=8.44\text{E}+04$ t km.
   Diesel intensity: 0.05 L/(t km).
   Diesel density: 0.83 kg/L.
   Total diesel consumption $=(3.68\text{E}+06\ \text{t km}+8.44\text{E}+04\ \text{t km}+3.47\text{E}+04\ \text{t km})\times 0.05\ \text{L/(t km)}\times 0.83\ \text{kg/L}=1.58\text{E}+02$ t.

9. **Tower foundation**
   Total volume of concrete: 347.23 m^3/tower × 24 turbines =8333.6 m^{-3}.
   Total mass of steel bar: 41.33 t/tower × 24 turbines =992.0 t.
10. **Substation**
   Substation: 163.8 m^3 concrete+7.9 t steel bar.
11. **Cable**
   Grounding cable from wind farm to booster station: 18 km × 5076 kg/km.
   Overhead line from wind farm to substation: 23 km × 103 kg/km.
   Total mass of cable: 18 × 5076 kg+23 × 103 kg=93.74 t.
12. **Power supply**
   Electricity consumption: 2000.0 kW h/day.
   Construction period: three months (90 days).
   Total consumption of electricity=2000.0 kW h/day × 90 days=6.48E+11 J.
13. **Water supply**
   Water consumption: 300.0 t/day.
   Construction period: three months (90 days).
   Total consumption of water=300.0 t/day × 90 days=2.70E +04 t.
14. **Machine oil**
   Lubricant for tower: 37.9 kg/year/turbine × 20 years × 24 turbines=18.19 t.
   Lubricant for nacelle: 11.4 kg/year/turbine × 20 years × 24 turbines=5.45 t.
   Lubricant for transformer: 12.2 kg/year/turbine × 20 years × 24 turbines=5.87 t.
   Total mass of lubricant=18.19 t+5.45 t+5.87 t=29.51 t.
15. **Water supply**
   Water for operation and maintenance: 3.5 t/day.
   Total consumption of water=3.5 t/day × 365 days × 20 years=25.55 t.
16. **Blade substitution**
   Mass of resin and fiber glass=3.6 t/blade × 24 turbines =86.4 t.
17. **Generator substitution**
   Substitution ratio: 0.15.
   Mass of silica=0.2 t/generator × 24 turbines × 0.15=0.72 t.
   Mass of copper=2.2 t/generator × 24 turbines × 0.15 =7.92 t.
   Mass of steel=0.2 t/generator × 24 turbines × 0.15= 16.56 t.
18. **Labor for operation and maintenance**
   Permanent staff: 18 person.
   Annual salary: 6.35E+04 RMB/person (9.14E+03 $/person).
   (Yearly average exchange rates in 2008: 1 $=6.95 RMB).
   Total cost of permanent personnel=9.14E+03 $/person × 18 person × 20 years=3.29E+06 $.
19. **Construction manpower**
   Reconnaissance and design of wind farm: 5.10E+06 RMB (7.34E+05 $).
   Plant construction (Wind turbine and the affiliated equipments installation): 3.00E+07 RMB (4.32E+06 $).
   Total cost of construction manpower=7.34E+05 $+4.32E +06 $=5.05 E+06 $.
20. **Cost of land occupation**
   Permanent land use: 180 RMB/m^2 × 16865 m^2 (5400 m^2 wind generator set+9360 m^2 substation+others)=3.04E +06 RMB.
   Access road for plant maintenance: 72 RMB/m^2 × 69300 m^2=5.00E+06 RMB.
   Temporary land use for construction: 30 RMB/ m^2 × 30200 m^2=9.06E+05 RMB.
   Total cost of land occupation=3.04E+06 RMB+5.00E+06 RMB+9.06E+05 RMB=8.94E+06 RMB=1.29E+06 $.
21. **Lifetime yield**
   Annual electricity generation of wind farm: 6.54E+07 kW h (2.35E+14 J).
   Lifetime yield=2.35E+14 J/year × 20 years=4.71E+15 J.

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