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Emergy-based ecological footprint analysis of a wind farm in China

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ABSTRACT

Wind power generation has always been considered as clean energy, according with national ecological civilization construction and responding to climate change. However, from the perspective of resource conservation, wind farms directly or indirectly occupy a large amount of land resources along the entire life cycle. Based on the emergy analysis, this paper estimates the ecological footprint of a wind farm in Dalian, evaluates its sustainability, and analyzes the ecological footprint of the four phases which include wind turbines production and transportation, construction, operation and maintenance, and demolition during the life cycle of the wind farm. It was concluded that the emergy carrying capacity of the wind farm was 3879.57 hm^2/a, and the emergy ecological footprint was 5117.59 hm^2/a. The wind farm was in an ecological deficit. Among the four phases, the ecological footprint of construction was the largest (60.93%), wind turbines production and transportation phase (33.77%) took the second, followed by operation and maintenance (4.59%) and demolition (0.71%). The main contribution of the materials was steel, followed by concrete, ecological protection investment, fiber glass, land occupation and epoxy resin. Finally, in order to illustrate the way to achieve sustainable development of the wind farm, uncertainty analysis and scenario analysis were carried out. It was found that when 62% of the recycled materials were used for wind turbines production, the wind farm realized ecological balance. Reducing the solar transformity (UEV) of steel and concrete can also decrease the ecological footprint of the wind farm.

1. Introduction

In recent years, due to the shortage of fossil energy, the aggravation of global climate change and the serious environmental pollution problems, the demand for renewable energy has increased (Bangga et al., 2018). The share of renewable energy in primary energy will increase from less than one-sixth to two-thirds, 86% of which will be used for power generation (Agency, 2019) by 2050. The world's wind market installed 51.3 GW in 2018, and it is predicted to be more than 300 GW of new installations in the next five years. China became the first country in the world with a total installed capacity of more than 200 GW in 2018 (Council, 2018). Developing wind power vigorously will be an important way to achieve energy transformation, cope with climate change and achieve environmental protection.

Wind is known as clean energy. Wind farms use wind as the main energy to generate electricity and do not emit pollutants directly, but their ecological costs and environmental effects are rarely considered (Yang and Chen, 2016). However, from the perspective of the resource conservation, the whole life cycle of a wind farm, which includes production and transportation of wind turbines, construction, operation and maintenance, and final demolition and landfill will occupy large amounts of land resources directly or indirectly. For example, the construction of wind farms needs to occupy the land, most of which belong to cultivated land and forest land. Although there is no direct use of land, wind farms often require more materials than fossil fuel power plants (Singh et al., 2011; Arvesen and Hertwich, 2012; Hertwich et al., 2015), such as the mining and synthesis of various materials, the consumption of gasoline and diesel, the land required for landfill. At present, Chinese land resources are in short, so it is particularly significant to use land effectively, save land resources and avoid land waste. For the current situation of wind power, the objective of this paper is to demonstrate the ecological footprint of the entire life cycle of the wind farm, summarize the area needed to sustain the wind farm, judge whether it is sustainable and help policy-makers promote the positive interaction between industrial development and ecological protection to advance cleaner power transformation moving forward in China.

In previous studies, most literatures have used carbon emission as the environmental indicator (Yang et al., 2011; Ji and Chen, 2016; Kadiyala et al., 2017; Kelly et al., 2019) to assess GHG emissions and carbon footprint accounting of wind power systems to determine the environmental impact and renewability of wind power in China.

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However, environmental issues aren't just climate change. Some industrial activities with similar carbon footprints may differ by several orders of magnitude in other environmental impacts, so policy-makers that rely solely on information provided by carbon footprints to make decisions may ignore other environmental impacts (Laurent et al., 2012). A more systematic and comprehensive approach is used to assess environmental sustainability, such as life cycle assessment methods (Siddiqui and Dincer, 2017; Schreiber et al., 2019) assessing the environmental impact of wind power throughout its whole life cycle and determining which phase is the greatest contributor, life cycle sustainability evaluation (Atilgan and Azapagic, 2016; Akber et al., 2017; Kabayo et al., 2019), emergy analysis methods (Yang et al., 2013; Yang and Chen, 2016), etc. Yang et al. (2018) quantified the environmental pressure, renewability, economic efficiency, and sustainability of a typical wind power system based emergy analysis and illustrated that wind power is a promising tool of substituting fossil fuel-based power generation systems. The ecological footprint can better assess the relationship between ecological carrying capacity and ecological stress (Yang et al., 2018). But the traditional ecological footprint has some defects in the application (Peng et al., 2018), it is mainly reflected in the following six aspects: (1) The parameters ignore the differences in ecological advantages of various regions and the impact of social economy on biological productivity; (2) The ecological function of different lands is not accurately calculated; (3) The absorption of greenhouse gases is not considered adequately, only the forest area is considered; (4) The ecological function of the non-productive land is ignored; (5) The impact of the non-materials is not considered; (6) It ignores the openness and fluidity brought by material circulation, energy conversion and information transmission in ecosystems. In order to solve these problems, Zhao et al. (2005) proposed an improved method based on emergy analysis and ecological footprint.

Pan et al. (2019) established an ecological footprint framework based on emergy analysis to study the dynamic changes of sustainable development from 2007 to 2016 in Shanghai and analyzed the interaction of its economy and ecosystem. Li et al. (2019) analyzed and evaluated the ecological safety of Central Asia from 1992 to 2014 based on the emergy ecological footprint (EEF) model. Liu et al. (2017) used EEF to compare the sustainability of straw utilization cycle models. Wu et al. (2015) used EEF model to evaluate comprehensively the sustainability of household biogas utilization system, the "pig-biogas-fish" system, which has instructive meaning for promoting the integrated biogas utilization model in rural areas. Cano Londoño et al. (2019) combined emergy and Life Cycle Assessment to evaluate the sustainability of an open-pit gold mine and an alluvial gold mine in Colombia, and performed sensitivity analysis to determine the potential significance of uncertainty in the input data.

This research uses emergy ecological footprint method to calculate the sustainability of a wind farm in Dalian during its life cycle, and calculates the bio-productive land area that the wind farm needs to occupy. We evaluates the sustainability of the wind power plant from its direct or indirect use of land in all-life cycle, and describes uncertainty in solar transformity (UEV) to increase transparency in emergy ecological footprint calculations. Firstly, the case study will be described together with the modified emergy ecological footprint method and sustainability indices. Results will be presented and discussed with regard to the factors and phases that have a greater impact on the ecological footprint, thus to provide guiding for the planning, construction, operation management, final maintenance and disposal of the wind farm.

2. Methods and data

2.1. An overview of the study area

The present study was carried out in a wind farm located in Dalian, China, which has a total land area of about 145.5 km^2. In fact, the permanent land occupation area is 1.881 km^2. The wind farm has a total installed capacity of 330 MW, including 219 wind turbines with a unit capacity of 1.5 MW, a hub height of 70 m and a hub diameter of 77.4 m. The total weight of the wind turbine is about 188 t, which consists of three parts: the nacelle, the tower and the impeller. It's estimated that the annual effective power generation hours is 2321.18 h, the annual on-grid electricity is 10.35E+08 kW, and the designed running time is 20 a. The basic parameters of the wind farm are shown in Table 1.

Table 1
The basic parameters of the wind farm.

Turbine type	SL1500/77
Rated power	1500 kW
Hub diameter	77.4 m
Hub height	70 m
Rated wind speed	11 m/s
Cut-in wind speed	3 m/s
Cut-out wind speed	20 m/s
Turbine number	219
Turbine availability	≥95%
Operating lifetime	20 a
Annual electricity output	10.35E+08 kW
Total land area	145.5 km^2
Permanent land area	1.881 km^2

2.2. Method

2.2.1. Ecological footprint

The ecological footprint was first proposed and developed by Wackernagel and Rees (Inch, 1995). It refers to the area of biological productivity that sustains the survival of a person, region, or country, or can accommodate waste discharged by humans. It provides a methodological guide for measuring and comparing the gap between the natural ecosystem service needed by the human economic system and the carrying capacity of natural ecosystems (Zhongmin et al., 1999). It's considered to be an important indicator to characterize environmental degradation and sustainable development (Ulucak and Lin, 2017; Ulucak and Apergis, 2018). The calculation of ecological footprint mainly includes the calculation of ecological footprint and ecological carrying capacity. In the traditional ecological footprint model, the world's average productivity is used to convert the materials and energy consumed and the waste generated by humans into the biological productive area. Due to the different productivity of different land use types, equilibrium factor is introduced, resulting in a relatively uniform ecological footprint. In calculating the ecological carrying capacity, the carrying capacity represented by six types of land use such as cultivated land, forest land, grassland, water area, fossil energy land, and construction land is considered. The production factor is imported, which makes the same land use type in different regions be added (Wackernagel et al., 1999).

2.2.2. Emergy analysis

The emergy analysis was first proposed and developed by Odum (1988), which is defined as the amount of energy contained in another class of energy flowing or stored. Odum further explained that the amount of effective energy directly or indirectly applied to the product or service formation process is the emergy it possesses (Odum, 1996). Based on the emergy, different types of non-comparable energy can be converted into the same standard that can be compared. UEV refers to the solar emergy required to form 1 J product or service. UEV of a product is equal to its emergy divided by its energy, and the unit is sej/J. If the transformity of an item is known, then the total emergy of the item can be expressed as (Eq. (1)):

$$\text{Emergy} = \text{available energy or mass of item} \times \text{transformity} \tag{1}$$

2.2.3. Modified emergy ecological footprint

The emergy analysis method and the ecological footprint method are combined, because both methods solve the same problem by accounting for resources and production. Ecological footprint and emergy analysis are complementary, and their combination has become one of the most typical methods for assessing sustainability. This theoretical model is mainly applied to countries, regions, cities, enterprises, schools, industries, and etc (Venetoulis, 2001; Zheng et al., 2011; Liu et al., 2017; Yang et al., 2018; Chen et al., 2019). The ecological carrying capacity can be measured by the consumption of renewable resources, and the output data can be converted into the energy flow (Pereira and Ortega, 2012). The principal differences between the modified method and the traditional ecological footprint are as follows: the modified method starts from the energy flows of a system, while the traditional one starts from the mater flows or value flows. The major advantage of emergy analysis is that its common unit allows all resources to be compared on a fair basis (Zhao et al., 2005). The advantage of emergy ecological footprint model is that it can better reflect the regional ecological security reality by emergy accounting, offsetting any incomplete evaluations in the traditional ecological footprint model (Li et al., 2019).

(1) Emergy carrying capacity (ECC)

The emergy ecological carrying capacity refers to the equivalent of the global average carrying capacity of renewable resources (Zhao et al., 2013), reflecting the ability of ecosystems which can provide space and resources for human survival. The ECC formula is as follows (Eq. (2)):

$$ECC = (1 - 12\%) \times R/P_1 \tag{2}$$

where: ECC is the emergy carrying capacity of the system (m^2/a); R is the total emergy of the system's natural renewable energy (sej); p_1 is the annual global emergy density (sej/m^2·a), which is the ratio of emergy amount of the earth to the global surface area. The formula is as follows (Eq. (3)):

$$p_1 = \frac{total\ emergy\ of\ the\ earth}{area\ of\ the\ earth} = \frac{15.83 \times 10^{24}}{5.1 \times 10^{14}} = 3.1 \times 10^{10}\ \text{sej/m}^2\bullet\text{a} \tag{3}$$

The total emergy of the earth in one year refers to the new emergy baseline proposed by Odum, which includes solar energy, deep geothermal energy and tidal energy. The global surface area is 5.1E+14 m^2. 12% refers to that in order to protect biodiversity, the emergy ecological carrying capacity can be reduced by 12% (World Commission On Environment and Development, 1987; Wackernagel et al., 1999). Renewable resources include solar energy, wind energy, chemical energy in the rain, potential energy in the rain, and global cycle energy. In order to avoid double counting, the renewable resource with the highest emergy is regarded as the total renewable energy, so the wind energy of the wind farm is the total renewable energy in this paper.

(2) EEF

The emergy ecological footprint reflects the regional ecological economic and represents the human load intensity. Wind farm emergy ecological footprint calculation process is as follows. Firstly, count the main materials and energy consumption of the wind turbines production and transportation, construction, operation and maintenance, and disassembly and recycling of the wind farm (Q_i). The unit of materials and energy input in each phase is inconsistent, so the UEV is introduced. The materials and energy consumption of each phase of the wind farm are multiplied by the respective UEV (ST_i), that is, the emergy of each corresponding material and energy is obtained (E_i). The formula is expressed as follows (Eq. (4)):

$$E_i = Q_i \times ST_i \tag{4}$$

Secondly, calculate the summary of each phase of material and energy consumption (E_w).

$$E_w = \sum E_i \tag{5}$$

Finally, the total solar emergy is converted into EEF.

$$EEF = E_W/p_2 \tag{6}$$

where: p_2 is the regional emergy density (sej/m^2·a), which includes five kinds of renewable resources such as solar, wind, chemical energy in the rain, potential energy in the rain and the earth's cycle energy in the calculation. In order to avoid duplication calculation, the maximum emergy term is took as the total emergy of the region.

$$p_2 = total\ emergy\ of\ the\ region/area\ of\ the\ region \tag{7}$$

(3) Sustainability

To measure the sustainability of wind farms, the following two indicators are used:

① Flux

$$Flux = ECC - EEF \tag{8}$$

This indicator characterizes the ecological deficit/surplus and reflects the absolute value of changes in ecological flux. If Flux > 0, it indicates that the system is in an ecological surplus, showing that the ecosystem capacity of the system is sufficient to support its load. The income of natural capital in the region is larger than the demand flow of consumption, and the consumption pattern is relatively sustainable. If Flux < 0, it means the system is in an ecological deficit, indicating that the system's load exceeds its ecological capacity, and the development model is relatively unsustainable. If Flux = 0, it represents a balance between human consumption and ecological capacity.

② Ecological footprint intensity (EFI)

$$EFI = EEF/ECC \tag{9}$$

The ecological footprint intensity evaluates the ecological security. When EFI > 1, It indicates that the area cannot achieve ecological safety. When 0 < EFI < 1, it indicates the area is in an ecological security. When EFI = 1, it reflects an ecological balance. At the same time, the larger EFI is, the worse the sustainability and the ecological security become.

Fig. 1 is the emergy diagram that defines the boundary framework for a life cycle system of the wind farm, and overviews the four phases of the wind farm that includes wind turbines production and transportation, construction, operation and maintenance, and disassembly and disposal. The materials and energy consumption of each phase from the input and output streams are determined by the framework. The

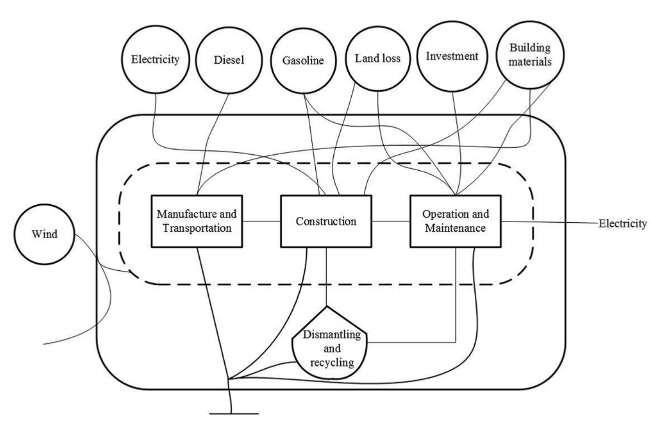

Fig. 1. Emergy diagram of the wind farm.

wind power input is mainly wind energy which belongs to clean energy. The pollutant discharge is very small, so the direct environmental pollutant emissions aren't included in the accounting process of this study.

2.3. Data sources

The data in this study is mainly from the planning and environmental assessment report and feasibility study report of the wind farm. The inventory data of the wind farm comes from the developer, and some unattainable data is calculated by analogy with similar wind farms. The imported resources include steel, cast iron, aluminum, epoxy resin, copper, fiber glass, carbon fiber, silicon, plastic, lubricant, PVC, coating, gasoline, diesel, concrete, steel bars, land occupation, electricity consumption, materials for replacement of fan parts, direct investment for ecological protection, and landfill emergy consumption. In the calculation, considering the energy and materials loss in the production process, and due to the difficulty of getting data (Raadal et al., 2014), some calculations are still not included. The UEV of each material and energy source is derived from relevant references.

Table 3
The value of ECC and EEF for the wind farm.

	ECC (hm^2/a)	EEF (hm^2/a)	Flux (hm^2/a)	EFI
value	3879.57	5117.59	−1238.02	1.32

3. Results and discussion

3.1. Emergy ecological footprint and emergy carrying capacity of the wind farm

The emergy flow of the wind farm is shown in Table 2. Table 2 calculated the materials and energy consumption of the four phases of the wind farm based on the emergy system diagram of Fig. 1. The total emergy of the wind farm was 7.81E+20 sej. The transformity of the wind farm was found to be 9.98E+03 sej/J. Since the operating time of the wind farm is 20 years, there is no relevant examples of applying the materials recycled to the production of wind turbines after disassembly. The emergy saved by the materials recovered during the disassembly phase is not included in the calculation of the total emergy of the wind farm.

Table 2
Emergy analysis of the wind farm during 20 years' lifetime.

Phase	Materials	Quantity	Units	Solar transformity (sej/suit)	Ref.	Emergy (sej)
Manufacture and transportation	Steel	3.09E+10	g	7.80E+09	(Brown and Ulgiati 2004)	2.41E+20
	Cast iron	6.55E+09	g	8.60E+08	(Odum 1996)	5.63E+18
	Aluminum	4.32E+07	g	5.73E+09	(Brown et al., 2012)	2.48E+17
	Epoxy resin	3.69E+08	g	6.22E+09	(Brown et al., 2012)	2.30E+18
	Copper	1.05E+07	g	3.36E+09	(Gurkan et al., 2006)	3.53E+16
	Fiber glass	2.33E+09	g	5.04E+09	(Ulgiati et al., 1995)	1.17E+19
	Carbon fiber	5.63E+08	g	2.30E+09	(Brown and Ulgiati 2004)	1.29E+18
	Silicon	5.62E+07	g	1.68E+09	(Odum 1996)	9.44E+16
	Plastic	3.05E+07	g	3.80E+08	(Brown and Ulgiati 2004)	1.16E+16
	Coating	1.82E+08	g	6.22E+09	(Brown et al., 2011)	1.13E+18
	Lubricant	3.05E+07	g	6.22E+09	(Brown et al., 2011)	1.90E+17
	Diesel	2.00E+11	J	1.11E+05	(Odum 1996)	2.22E+16
Construction	Steel	9.61E+09	g	7.80E+09	(Brown and Ulgiati 2004)	7.50E+19
	Aluminum	5.94E+08	g	5.73E+09	(Brown et al., 2012)	3.40E+18
	Epoxy resin	6.45E+08	g	6.22E+09	(Brown et al., 2012)	4.01E+18
	Copper	1.16E+08	g	3.36E+09	(Gurkan et al., 2006)	3.90E+17
	PVC	1.12E+06	g	3.80E+08	(Brown and Ulgiati 2004)	4.26E+14
	Concrete	1.54E+11	g	2.27E+09	(Haukoos 1995)	3.50E+20
	Steel bar	6.50E+03	t	4.82E+15	(Yang et al., 2010)	3.13E+19
	Land loss	1.46E+08	m^2	8.00E+10	(Yang et al., 2010)	1.17E+19
Operation and maintenance	Wind	1.14E+16	J	2520	(Odum 1996)	2.87E+19
	Steel	4.15E+08	g	7.80E+09	(Brown and Ulgiati 2004)	3.24E+18
	Cast iron	3.52E+08	g	8.60E+08	(Odum 1996)	3.03E+17
	Aluminum	1.12E+05	g	5.73E+09	(Brown et al., 2012)	6.42E+14
	Epoxy resin	7.22E+07	g	6.22E+09	(Brown et al., 2012)	4.49E+17
	Copper	3.33E+06	g	3.36E+09	(Gurkan et al., 2006)	1.12E+16
	Fiber glass	7.63E+08	g	5.04E+09	(Ulgiati et al., 1995)	3.85E+18
	Carbon fiber	1.88E+08	g	2.30E+09	(Brown and Ulgiati 2004)	4.32E+17
	Silicon	4.21E+06	g	1.68E+09	(Odum 1996)	7.07E+15
	Plastic	2.29E+06	g	3.80E+08	(Brown and Ulgiati 2004)	8.70E+14
	Coating	1.37E+07	g	6.22E+09	(Ulgiati et al., 1995)	8.52E+16
	Lubricant	1.80E+06	g	6.22E+09	(Ulgiati et al., 1995)	1.12E+16
	Diesel	1.08E+10	J	1.11E+05	(Odum 1996)	1.20E+15
	Gasoline	2.34E+07	g	2.92E+09	(Bastianoni et al., 2009)	6.83E+16
	Electricity	2.21E+11	J	1.85E+05	(Ulgiati and Brown 2002)	4.09E+16
	Land loss	1.88E+06	m^2	8.00E+10	(Yang et al., 2010)	3.16E+18
	Investment in Restoration	4.12E+06	$	5.87E+12	(Yang et al., 2010)	2.42E+19
Disassembly and recycling	Landfill	1.72E+05	t	3.18E+13	(Almeida et al., 2012)	5.47E+18
	Diesel	6.70E+11	J	1.11E+05	(Odum 1996)	2.34E+16
Total emergy (without wind)						7.81E+20

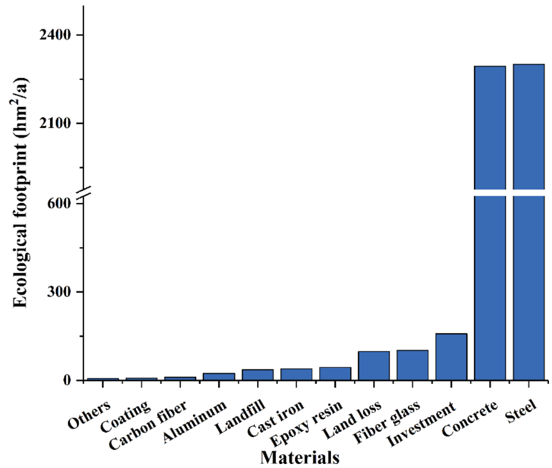

Fig. 2. Ecological footprint of different components of the wind farm.

According to Eqs. (2) and (6), the ecological footprint of the wind farm is shown in Table 3. The emergy carrying capacity of the wind farm was 3879.57 hm^2/a, while the emergy ecological footprint was 5117.59 hm^2/a. And Flux was -1238.02 hm^2/a (<0), so the wind farm was in an unsustainable state. In addition, EFI of the wind farm was 1.32 (>1), indicating that the ecological pressure of the wind farm was greater than the capacity it can carry, and it was in an ecological insecurity state.

In the ecological footprint of the wind farm, steel and concrete were the main contributors, accounting for 44.93%, 44.80% respectively, followed by ecological protection investment, fiber glass, land occupation and epoxy resin. Other materials accounted for a small proportion (Fig. 2). Other materials refer to copper, lubricant, silicon, diesel, gasoline, electricity, plastic, PVC. Therefore, reducing the use of steel and concrete would play a major role in decreasing the ecological footprint of the wind farm.

Fig. 3 shows the proportion of ecological footprint for the different phases of the wind farm, in the phase of production and transportation, construction, operation and maintenance, and disassembly and recycling, the ecological footprint was 1727.97 hm^2/a, 3118.40 hm^2/a, 235.03 hm^2/a and 36.18 hm^2/a, respectively, and accounts for 60.93%, 33.77%, 4.59%, 0.71%, respectively. The high contribution of construction phase to the ecological footprint of the wind farm is corresponding to the results from Fig. 2. Materials consumed in construction phase are mainly steel and concrete. In the disassembly and recycling phase, all wind turbines and infrastructure must be dismantled. Due to the lack of actual reference data, it is assumed that the recoverable metal materials are transported to the wind turbine production plant for subsequent processing, and all non-recyclable materials and wastes are transported to the local landfill to be landfilled. According to the research results of Almeida et al. (2012), the emergy transformity of landfill is 3.18E+13 sej/t, so the emergy of this stage is the waste consumption of landfill and transportation.

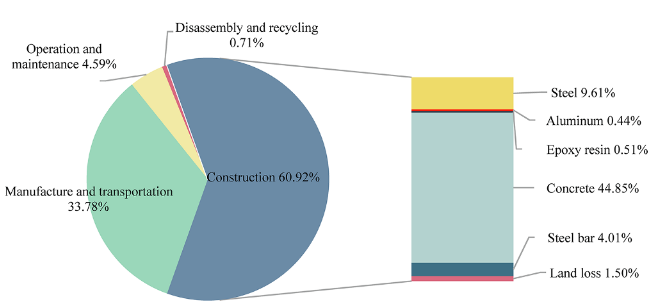

Fig. 3. Ecological footprint of different phases of the wind farm.

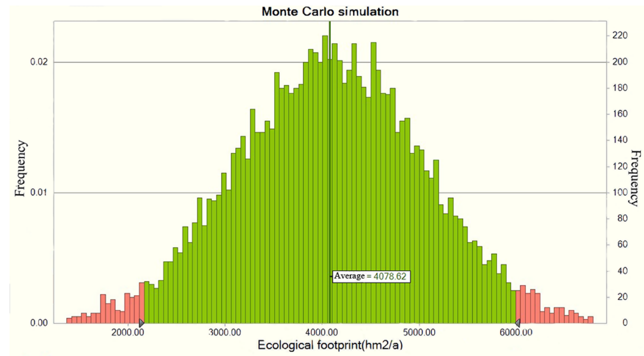

Fig. 4. Results of ecological footprint of the wind farm with Monte Carlo simulation.

3.2. Uncertainty analysis

The ecological footprint of wind farms is uncertain. Due to the inherent vulnerability of the energy flow path, the UEV also has uncertainty (Yi and Braham, 2015). This study conducted an uncertainty analysis of the ecological footprint of the wind farm.

The uncertainty of UEVs was first proposed by Odum (1996). Ingwersen (2010) used Monte Carlo simulation to estimate the uncertainty of UEVs, and proposed an analysis method that incorporates uncertainty into emergy. Yi and Braham (2015) introduced the uncertainty analysis of UEVs in building emergy analysis using Monte Carlo simulation and fuzzy logic theory. Based on the published literatures, this paper used the EXCEL plug-in to perform Monte Carlo simulation on the uncertainty of UEVs involved in the ecological footprint of the wind farm. The number of iterations was set to 10,000 times, and the confidence interval is 95%. The UEVs of steel, concrete and PVC obey normal distribution. The UEVs of other materials such as glass fiber, epoxy resin, aluminum and copper are subject to triangular distribution due to the limited data. The final results is shown in Fig. 4. The results showed that the average ecological footprint was 4078.62 hm^2/a, and the standard deviation was 968.29 hm^2/a. In the 95% confidence interval, the ecological footprint ranged from 2497.36 hm^2/a to 5670.15 hm^2/a. The results calculated in Table 3 were in this extent. In addition, in the sensitivity analysis, as shown in Fig. 5, the largest variations in the ecological footprint occurred when the solar transformity of steel and concrete were perturbed, and the sum of that accounted for 99.4% of the total uncertainty. Therefore, if the uncertainty of UEVs of steel and concrete become smaller, the ecological footprint calculation of the wind farm would be more accurate and reliable.

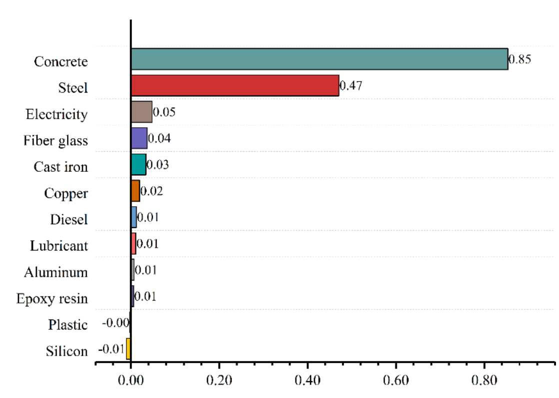

Fig. 5. Sensitivity of different materials' UEVs.

Table 4
Recovery rate of some metal materials of the wind farm.

Material	Steel	Cast iron	Aluminum	Copper
Recovery rate	0.85	0.5	0.72	0.9
Recovery amount (t)	3.80E+04	3.45E+03	4.59E+02	7.82E+01

3.3. Scenario analysis

Based on the above results, measures should be made to promote the wind farm sustainability.

To explore the optimal direction of wind farms in the future, three scenarios which focused on materials input were set. The specific assumptions are as follows:

Scenario I: In the phase of dismantling of wind farms, some metal materials can be recycled and reused. As shown in Table 4, the average recovery rate of scrap steel in China is about 85% Xie (2012), and the average recovery rate of aluminum is about 72% Yue et al. (2015). The recovery rate of copper during the wind turbine dismantling process is generally 90%, and that of cast iron is about 50%. Other materials such as concrete, waste resin, and scrapped blades are generally filled (Guezuraga et al., 2012). If the materials in the waste phase of the wind farm were recycled for the production of new wind turbines, it would greatly affect the ecological footprint of the wind farm, and produce an effect on the sustainability judgment of the wind farm.

How many materials in the wind turbine production is derived from recycled materials, rather than new mining materials, which will have a great impact on the final accounting of the wind farm's ecological footprint. At present, there is no actual data in this respect, so this study assumed that 10%, 20%, 30%, 40%…100% of the recycled materials are applied to the production of wind turbines to observe the ecological footprint change of the wind farm, respectively.

As shown in Fig. 6, there is a linear correlation between the ecological footprint of wind farms and the recovery rate of recycled materials. As the proportion of recycling materials is increasing, the ecological footprint of the wind farm is getting smaller. The dark area in Fig. 4 indicates the state of ecological deficit, and the light area indicates the state of ecological surplus. When the recovery rate is lower than 62%, the wind farm is in an ecological deficit and not sustainable. When the recovery rate is higher than 62%, the wind farm is in an ecological surplus and sustainable development. When the recovery rate is 62%, the wind farm is in an ecological balance. Therefore, in the view of the current unsustainable condition of the wind farm, applying recycled materials as many as possible to the wind turbine production process is an effective method to solve that.

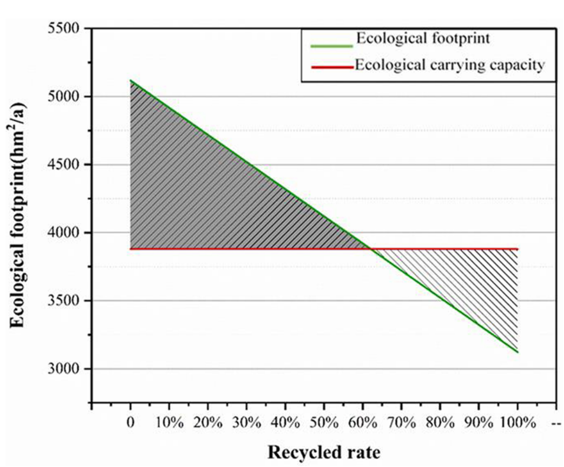

Fig. 6. Changes in ecological footprint of different recycling rates.

Table 5
Changes of the different indices under different scenarios.

	EEF (hm^2/a)	Flux (hm^2/a)	EFI (hm^2/a)
baseline	5117.59	−1238.02	1.32
Scenario II	4870.40	−990.83	1.26
Scenario III	4622.92	−743.35	1.19

Scenario II: In the Fig. 2, steel, concrete, investment in restoration projects, fiber glass and land loss are the most contributors to the ecological footprint. It is assumed that these five kinds of materials are reduced by 5% in this scenario. Ecological footprint responds to this change, which results in the fluctuation of other indices.

Scenario III: Steel, concrete, investment in restoration projects, fiber glass and land loss are assumed to be reduced by 10% in this scenario. Then changes are compared with baseline.

According to the scenario analysis, as shown in Table 5, when the main materials input reduced by 5%, EEF, Flux and EFI of the wind farm reduced by 4.83%, −19.97% and 4.55%, respectively. When the main materials input reduced by 10%, EEF, Flux and EFI of the wind farm reduced by 9.67%, −39.96% and 9.85%, respectively. It reflects that technology innovation should be made to reduce materials input of the wind farm.

4. Conclusion

As a key renewable energy resource, mastering wind power's sustainability has a certain reference value and guiding significance for national policy-making. In this paper, the ecological footprint method based on emergy analysis was used to study the sustainability of a wind farm in Dalian, China. The whole life cycle of the wind farm was divided into four phases: wind turbines production and transportation, construction, operation and maintenance, and disassembly. The results showed that the emergy carrying capacity of the wind farm was 3879.57 hm^2/a, and the ecological footprint was 5117.59 hm^2/a, which was in an unsustainable state. In the ecological footprint, the main contribution was steel, concrete, ecological protection investment, fiber glass, and land occupation. Among them, the ecological footprint of the wind farm in the infrastructure construction phase accounted for the largest proportion, making up 60.93% of the total ecological footprint. This results are similar to the carbon footprint studied by Ji and Chen (2016).

The results demonstrated the demand to achieve sustainability of the wind farm that concentrate on: a) Reducing the use of new steel and concrete in the construction phase by using more efficient technologies. b) Avoiding the waste and emissions during production and construction phase. c) Using more materials with lower solar transformity instead of steel. d) Reusing metal materials from waste and applying them to the wind turbines production as many as possible. If reuse rate reaches 62%, the wind farm would be in an ecological balance. Moreover, after uncertainty analysis of the UEVs of materials, the uncertainty of UEVs of steel and concrete has a significant influence on the uncertainty of ecological footprint, reaching 99.4%. So increasing the accuracy of the UEVs of materials input will enhance the accuracy the ecological footprint calculating.

This study showed that emergy accounting coupled with ecological footprint can be a holistic and simple method to sustainability assessment. Compared with the traditional ecological footprint method, emergy ecological footprint simplifies the calculating steps of six kinds of land use types and is easier to understand. At present, the emergy ecological footprint methods are applied widely, but it has rarely been used in the wind farm research, and it could be further improved in the future. Given the rapid expansion of China's wind power market, it is recommended that more attention should be paid to future wind power development to facilitate sustainability.

CRediT authorship contribution statement

Xiao-qin Zhang: Conceptualization, Methodology, Validation, Formal analysis, Writing - original draft, Visualization. **Ling Xu:** Conceptualization, Resources, Supervision, Project administration. **Yu Chen:** Resources, Writing - review & editing. **Ting-ting Liu:** Writing - review & editing.

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