



Full length article

Life cycle assessment of onshore wind power systems in China

Lei Xu^{a,b}, Mingyue Pang^a, Lixiao Zhang^{a,*}, Witold-Roger Poganietz^b, Sheetal Dattatraya Marathe^c^a State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China^b Institute for Technology Assessment and Systems Analysis, Karlsruhe Institute of Technology, Karlsruhe 76021, Germany^c Institute for Energy Economics and the Rational Use of Energy, University of Stuttgart, Stuttgart 70565, Germany

ARTICLE INFO

Keywords:

Wind power

Environmental impacts

Life cycle assessment (LCA)

China

ABSTRACT

The rapid recent economic growth in China was accompanied by a comparable demand for electricity, which is mainly provided by fossil-based power plants. Due to the impacts on climate change a switch to a more climate-friendly power system is required and part of the official policy of the Chinese Government. Wind power systems have been identified as one of the most promising technology to fulfill that goal. However, focusing only on the global warming potential of a technology could cover up other, possibly negative, environmental impacts.

The aim of the article is to learn more about the entire environmental performance of utility-scale wind power systems in China, based on a life cycle assessment for Saihan plant, a typical MW-level wind power plant in Inner Mongolia, China. The assessment results were compared to those of equivalent coal and natural gas power plants in China. Moreover, the global warming potential and ten other environmental impact indicators, differentiated by the five processes specified within the “cradle to grave” boundaries, i.e. production, transportation, installation, operation, and disposal, were calculated and analyzed by using CML 2001 method. The results show that, for producing 1 kWh of electricity, the studied wind power plant yields an 8.65E–03 kg CO₂-e global warming potential and a 9.34E–02 MJ abiotic depletion fossil, which represent 0.8% and 0.6%, respectively, of those yielded by coal power plants, and 1.2% and 0.8%, respectively, of those yielded by gas power plants in China. Further, the results show a significant reduction in the values of most of the other studied impact indicators, e.g. acidification, eutrophication, human toxicity and eco-toxicity, compared to those of coal and natural gas power plants. However, these encouraging results were accompanied by higher abiotic depletion (elements) and ozone layer depletion, which should be taken into consideration. Finally, some recommendations for technical developments and policy that would further enhance the wind power systems in China were proposed based on sensitivity and uncertainty analysis.

1. Introduction

The rapid recent economic growth in China was accompanied by a comparable demand for electricity. It is expected that during the next few decades the economic growth will continue, which will need to be supported with comparable supply of electricity, in order to meet societal demands for an improving living standard (EIA, 2012). However, switching from a coal-based energy system, which currently dominates the power generation, to an environment-friendly energy supply system to avoid the severe impacts of fossil-based energy on the climate is a huge challenge for China (Pang et al., 2013). Wind power is considered as one of the most promising renewable energy sources in China and has been rapidly developing in the recent years (Liu et al., 2017; Shen et al., 2017; Zhou et al., 2010). The total installed capacity of wind power, which has turned to be the largest installed renewable source worldwide, experienced a steady increase from 381.2 MW in 2001 to

91,413 MW by the end of 2013 (Li et al., 2014; Li et al., 2010). However, taking into account the entire life cycle of a wind power system, which would include amongst others, fossil fuels, the production and provision of construction materials and electric generation equipment, some negative impacts of wind energy on the environment can be revealed (Cambero et al., 2015; Chen et al., 2011; Coelho and Lange, 2016; Han et al., 2013; Pang et al., 2015; Shao and Chen, 2013; Wu et al., 2015, 2014, 2016). Therefore, a detailed analysis of the environmental performance of wind power should be conducted to provide scientific information to the relevant stakeholders, because it is rapidly increasing to form a significant part of the future energy system in China.

In this study, life cycle assessment (LCA), which is a quantitative method used to assess the environmental impacts during the life cycle of a product or a service starting from the extraction and processing of raw materials and through the processes of production, utilization,

* Corresponding author.

E-mail address: zhanglixiao@bnu.edu.cn (L. Zhang).

recycling, and disposal, was used in the analysis (Finnveden et al., 2009; ISO, 2006). LCA is considered a ‘cradle-to-grave’ analysis method, which addresses the environmental aspects of products in a comprehensive manner, and it is useful to avoid partial-optimization when only few processes are evaluated (Finnveden et al., 2009). Over the past two decades, LCA has been widely applied to assess the life cycle impacts of wind power plants, wind turbines or certain power system components on the environment. Jungbluth et al. (2005) established a life cycle model to assess the environmental burdens including greenhouse gas (GHG) emissions, energy consumptions, ecotoxicity, etc., of wind turbines according to the European conditions. Similarly, LCAs on the country level (e.g. Germany, Italy, France, Australia, Brazil, and Denmark) have also been conducted to evaluate the environmental performances of worldwide wind power in the recent years focusing mainly on GHG emissions and energy consumption (Ardenete et al., 2008; Crawford, 2009; Garrett and Rønde, 2013; Oebels and Pacca, 2013; Pehnt et al., 2008; Tremeac and Meunier, 2009).

Moreover, Chen et al. (2011) investigated the profile of wind power in China by assessing the energy consumption and GHG emissions for a case study of a wind power plant located in the Guangxi Province. Furthermore, Xue et al. (2015) conducted an LCA of the same wind power plant in Guangxi to evaluate the emissions of air pollutants other than GHGs. However, few studies have been carried out to evaluate the other environmental impacts of wind power in China e.g. toxicity and ozone layer depletion, which are also important and should be taken into account. Likewise, few studies have investigated this subject in the north of China, where the largest number of wind turbines has been installed with the greatest wind power potential. Thus, a study based on the north of China would be more representative of the wind power in the country. This study will fill the gap and give a complete profile of life cycle environmental impacts of the wind power in Inner Mongolia, which is a typical region for studying wind power in the north of China.

The following sections in the paper are organized as follows: Section 2 focuses on materials and methods, where first some insights regarding the case study were discussed, followed by the goal and scope definition as well as a description of the inventory of the site. Section 2 also aims to investigate the consumption of the resources and the environmental performance per kWh of electricity produced during the life cycle of the wind power plant. Section 3 presents and discusses the results of the assessment of the environmental impacts of the studied wind power plant and their comparison to those of other wind power plants as well as coal and gas power plants in China, because they represent the most important current power generation technologies. In addition, the results of the sensitivity and uncertainty of the calculations were also discussed in this section. The paper concludes with Section 4, which provides policy suggestions for sustainable development of wind power in China, aiming for environmental protection and reduction of non-renewable energy consumption.

2. Materials and methods

2.1. The case study

The investigated wind power plant is called Saihan and is located in the southern part of Suniteyou County, Saihantala Town (112°54'E, 42°24'N) in the Inner Mongolia Autonomous Region, China. It occupies an area of 24 km², and it has an average altitude of about 1140 m above the sea level. This is mainly a desert and grassland area with no groundwater underground and covered with stable sandstone, which can be used as a foundation-bearing layer. The physical geological condition is favorable, because no collapses or landslides have recently occurred in the area.

The site is equipped with 18 Goldwind GW77/1500 kW wind turbines (each with a blade diameter of 77 m and a hub height of 65 m) and 30 Goldwind S50/750 kW wind turbines (each with a blade diameter of 50 m and a hub height of 50 m). Each Goldwind GW77/

Table 1

Technical parameters of the studied power plant.

	Goldwind GW77/ 1500 kW wind turbine	Goldwind S50/750 kW wind turbine
Life time (year)	20	20
Quantity of Turbines	18	30
Turbine size (MW)	1.5	0.75
Installed capacity	27	22.5
Quantity of box-type transformers	18 (1600 KVA)	30 (800 KVA)

1500 kW wind turbine tower is connected to a 1600 KVA box-type transformer, while each Goldwind S50/750 kW wind turbine tower is connected to an 800 KVA box-type transformer. The towers and the transformers are installed on steel-reinforced concrete and concrete foundations, respectively. A 220 kV step-up transformer is installed to connect the power plant to the existing Ondor substation, which is located 18.4 km away from it. The cables are buried underground rather than above the ground for an aesthetic reason. After a one-year period of construction, the plant started to operate in May 2009 and has a designed operational life of 20 years. Technical parameters of the plant are summarized in Table 1.

The installed capacity of the studied wind power plant is 49.5 MW. The annual average wind speed is 8.3 m/s at a 70 m height, and the corresponding average annual wind power density at this height is 569.4 W/m². Electricity generation of the studied wind power plant was 130.1 GWh with a 26.1 GWh power curtailment in 2010. Due to the exceptional decrease of wind power density in 2011, the electricity generation shrank to 105.4 GWh and the power curtailment became 19.0 GWh. An average electricity generation of 130 GWh with a 20 GWh power curtailment is assumed in this study and the capacity factor is set as 30% based on the practice in the past few years.

2.2. Goal and scope definition

The goal of this study was to evaluate the environmental impacts by applying a process-based LCA model to a typical wind power plant in Inner Mongolia, China, according to the ISO guidelines. The sole function of the studied power plant is to generate electricity, and the functional unit is thus defined as 1 kWh electricity generation provided by the 220 kV step-up transformer. Because there is no data regarding the specific generation from the 1.5 MW or the 0.75 MW wind turbines, electricity generation shares were assumed to be 54.5% and 44.5%, respectively, in accordance with the installed capacity shares.

The investigated system consists of five processes including operation and maintenance, disassembly and disposal of the entire wind power plant, and up-stream and auxiliary processes, e.g., processing and production of raw materials as well as transportation and installation. Fig. 1 shows all the processes considered in this study. It is worth noting that the manufacture of equipment was neglected due to the lack of information. The data for foreground processes was site specific, whereas for the background processes average data was used (Fig. 1) (Chen et al., 2011).

2.3. Life cycle inventory

The life cycle inventory (LCI) analysis was based on a comprehensive collecting, investigating, and managing of data. The data of the foreground system, i.e. data related to the wind power plant, were mainly collected from suppliers' technical and maintenance manual (BJNEC, 2012); data of the background system, i.e. upstream and auxiliary processes, were obtained from the Eco invent 2.2 database. It is worth noting that the most important background data, e.g. electricity mix, were Chinese specific, while the data for other background processes were based on the records of global areas, such as Europe or

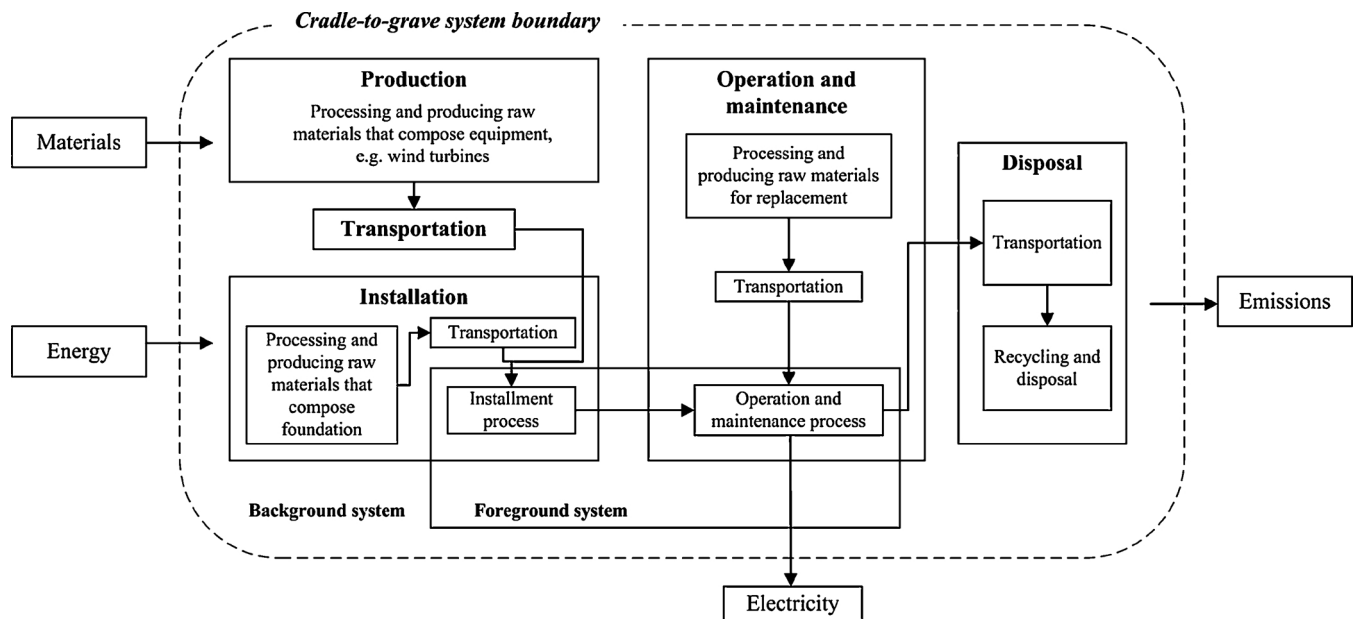


Fig. 1. The system boundary of the LCA analysis of the studied wind power plant.

globalized information, because of the lack of localized database for this information in China. In general this would lead to some uncertainties on the results, irrespective that some components are international traded. The life cycle inventory data for the production of 1 kWh of electricity were used in the analysis is listed in Table 2.

2.3.1. Production

The components mainly includes: 30 Goldwind S50/750 kW wind turbines, 30 box-type transformers (800 KVA), 18 Goldwind GW77/1500 kW wind turbines, 18 box-type transformers (1600 KVA), one 220 kV step-up transformer, and cables. Some materials and sub-components, such as lubricating oils used in wind turbines as well as lifts, lighting systems, and brakes used in wind nacelles are present in small quantities, which represent less than 1% of the total materials; and therefore were neglected.

2.3.2. Transportation

Transportation involves the transport of raw materials from factories to be processed into specific components in production plants, and the transport of components (wind turbines, towers, transformers, etc.) from the production plants of the components to the Saihan wind power plant. It is assumed that all materials and components were transported by trucks. The factories for processing of raw materials were selected either based on the cooperating raw materials production companies with the production plants of the specific components, or based on the principle of proximity, i.e. the nearest distance between the possible factories for raw materials and the components production plants, when no specific data were available. The location of the specific factories for the production of the components were obtained from the open tender information included in the post-evaluation report of the studied power plant (BJNEC, 2012).

2.3.3. Installation

The foundation of wind turbines is made of steel-reinforced concrete, where the total volume of reinforced concrete is 8526 m³ and 7,662.42 m³ for the 30 Goldwind GW77/1500 kW wind turbines and the 18 Goldwind GW77/1500 kW wind turbines, respectively. On the other hand, the foundation of the transformers is pure concrete. Additionally, power and water are used for the process of installation.

2.3.4. Operation and maintenance

During the 20-year life time of the wind turbine, it was assumed that one blade for each wind turbine and 15% of the components of the generator would be replaced (Ardente et al., 2008; Chen et al., 2011). The transportation considered in this process is limited to the raw materials and the replaced components but not the transportation of operating staff, which was assumed to have insignificant impact on the environment. Additionally, the daily water consumption of the 15 permanent personnel employed in the plant is 2.2 m³.

2.3.5. Disassembly and disposal

In this study, a scenario was created for component disposal based on other types of wind power and renewable energy projects due to the data unavailability for disposal of similar plants. In the scenario, it was assumed that foundations would be left in place (Martínez et al., 2009). Rotors from wind turbines were managed separately, the composite materials were assumed to 100% incinerated, while the rest glass contents were landfilled in the nearby disposal plant. For the treatment of the other equipment materials, it is assumed that 20% would be recycled and the rest would be sent to the nearby landfill (Ardente et al., 2008; Chen et al., 2011; Pang et al., 2015; Wang et al., 2012). Assuming that the recovered metals were included in the production of new components, the LCA was therefore credited for the recovered materials and negative values were used to represent the credit. It is also worth noting that the transport of components from the studied power plant to the final disposal plant is included in this study.

3. Results and discussion

3.1. Life cycle impact assessment

Life cycle impact assessment (LCIA) was conducted by applying the problem-oriented (mid-point) CML 2001 method (baseline) to calculate the environmental impacts. CML 2001, as an established approach, offers a consistent but also rather wide range environmental assessment with eleven indicators. CML 2001 like most other widely spread assessment model base on European conditions, which differ from the one in China. The choice of the assessment model could be crucial for the finding of the calculation. However, comparable assessment models for China are until now not available (Pang et al., 2015; Xu et al., 2013).

The calculation was performed using the software GaBi 6. The

Table 2
Overall LCI data for the production of 1 kWh of electricity.

Items	Materials	Unit	Input
Production			
750 kW wind turbine			
Rotor	Fiberglass	kg	4.71E-05
	Resin	kg	7.06E-05
	Cast iron	kg	5.19E-05
	Steel	kg	2.08E-05
Nacelle	Steel	kg	1.85E-04
	Cast iron	kg	3.69E-05
	Silica	kg	1.38E-06
	Copper	kg	1.56E-05
	Fiberglass	kg	8.08E-06
	Resin	kg	1.27E-05
Tower	Steel, low alloyed	kg	6.39E-04
1500 kW wind turbine			
Rotor	Fiberglass	kg	4.59E-05
	Resin	kg	6.89E-05
	Cast iron	kg	4.25E-05
	Steel	kg	1.33E-05
Nacelle	Cast iron	kg	3.79E-05
	Fiberglass	kg	8.31E-06
	Resin	kg	1.25E-05
	Steel	kg	1.57E-05
Generator	Magnetic steel	kg	7.71E-05
	Copper	kg	1.38E-04
	Cast iron	kg	6.33E-05
Tower	Steel, low alloyed	kg	7.03E-04
Transformers	Copper	kg	3.38E-05
	Steel	kg	1.13E-04
	Silica	kg	4.61E-06
Cables	Copper	kg	5.03E-05
Transportation	Truck transport	tkm	3.48E-03
Installation	Concrete	m3	5.99E-06
	Reinforcing steel	kg	4.70E-04
	Electricity	kWh	1.38E-04
	Reservoir water	kg	2.08E-02
Operation and maintenance	Tap water	kg	6.14E-03
	Fiberglass	kg	3.10E-05
	Resin	kg	4.65E-05
	Silica	kg	1.92E-07
	Copper	kg	2.30E-05
	Steel	kg	4.88E-06
	Magnetic steel	kg	1.16E-05
	Cast iron	kg	9.50E-06
	Truck transport	tkm	1.52E-04
Disassembly and disposal			
Resin incineration	Resin	kg	2.11E-04
Fiberglass landfill	Fiberglass	kg	1.40E-04
Cast iron landfill	Cast iron	kg	1.94E-04
Silica landfill	Silica	kg	4.95E-06
Copper landfill	Copper	kg	2.09E-04
Magnetic steel landfill	Magnetic steel	kg	7.10E-05
Steel (low alloyed) landfill	Steel, low alloyed	kg	1.07E-03
Steel landfill	Steel	kg	2.82E-04
Cast iron recycling	Cast iron	kg	-4.84E-05
Silica recycling	Silica	kg	-1.24E-06
Copper recycling	Copper	kg	-5.21E-05
Magnetic steel recycling	Magnetic steel	kg	-1.77E-05
Steel (low alloyed) recycling	Steel, low alloyed	kg	-2.68E-04
Steel recycling	Steel	kg	-7.06E-05
Transportation	Truck transport	tkm	4.55E-04

environmental impacts are based on the characterization models (ISO, 2006). The potential environmental impacts considered in this study were:

- Global Warming Potential (GWP)
- Abiotic Depletion (ADP elements and ADP fossil)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Human Toxicity Potential (HTP)
- Ozone Layer Depletion Potential (ODP)

Table 3
Characterized environmental impacts per kWh of electricity generated by the studied power plant.

Environmental impact indicators	Unit	Quantity
Global Warming Potential (GWP)	kg CO ₂ -e	8.65E-03
Abiotic Depletion (ADP elements)	kg Sb-e	2.49E-07
Abiotic Depletion (ADP fossil)	MJ	9.34E-02
Acidification Potential (AP)	kg SO ₂ -e	7.25E-05
Eutrophication Potential (EP)	kg PO ₄ -e	5.45E-05
Human Toxicity Potential (HTP)	kg DCB-e	5.46E-02
Ozone Layer Depletion Potential (ODP)	kg R11-e	3.68E-08
Terrestrial Eco-toxicity Potential (TETP)	kg DCB-e	1.30E-03
Freshwater Aquatic Eco-toxicity Potential (FAETP)	kg DCB-e	3.33E-02
Marine Aquatic Eco-toxicity Potential (MAETP)	kg DCB-e	4.78E+01
Photochemical Ozone Creation Potential (POCP)	kg C ₂ H ₄ -e	6.36E-06

- Terrestrial Eco-toxicity Potential (TETP)
- Freshwater Aquatic Eco-toxicity Potential (FAETP)
- Marine Aquatic Eco-toxicity Potential (MAETP)
- Photochemical Ozone Creation Potential (POCP)

The results of the characterized environmental impacts calculated per kWh of electricity generated by the studied wind power plant are listed in Table 3. The total non-renewable energy consumption for the 20-year operating period was found to be approximate 67 GWh. As mentioned in Section 2.1, the average annual power generation of the studied wind power plant is 130 GWh in the presence of power curtailment, i.e. the energy payback time is 0.52 years, indicating a high renewability.

A contribution analysis of the environmental impacts with regard to the life cycle processes is shown in Fig. 2. The overall environmental impacts of all eleven indicators were assumed to be 100%. A negative value, i.e. credits, was assigned to the process of disassembly and disposal, because 20% of the recycled materials were assumed to be utilized and thus included as an added value to the plant. Therefore, the share of other processes could be more than 100%. The production process is the largest contributor to all the environmental impacts, with the shares ranging between 56% (for FAETP) and 118% (for TETP). Although both transport of raw materials and components were considered, transportation had the lowest impacts in most cases (with less than 5% of the total share) except for the indicators GWP, ADP fossil, and POCP, with shares of 7%, 10%, 7% for GWP, ADP fossil, and POCP, respectively.

The environmental impacts in the processes of installation and operation were of minor importance compared to the production process, because there was no fuel consumption in the operation process while in the production process there was a large raw materials input. Whereas recycling generally results in credits, in case of FAETP and MAETP, the entire impacts of disassembly, transport and treatment of materials within the disposal process outmatches the positive impacts of recycling.

Because the production process shows the highest share of the environmental impacts, a detailed analysis of this process is important to determine the share of the different sub-processes. Fig. 3 shows a more detailed investigation of ADP fossil and GWP in the production process. In case of ADP fossil, towers (41.8%), nacelles (28.3%) and rotors (20.6%) are the largest contributors and responsible for more than 90% of the total ADP fossil potential, while transformers represent 8.9% of the total potential and cables have the lowest proportion (only 0.4%). Similar analysis was applied to the GWP, which is mainly influenced by towers (41.0%), nacelles (30.0%), and rotors (19.0%). These three components represent about 90.0% of the total GWP in the production process, while transformers and cables represent only 9.6% and 0.4%, respectively.

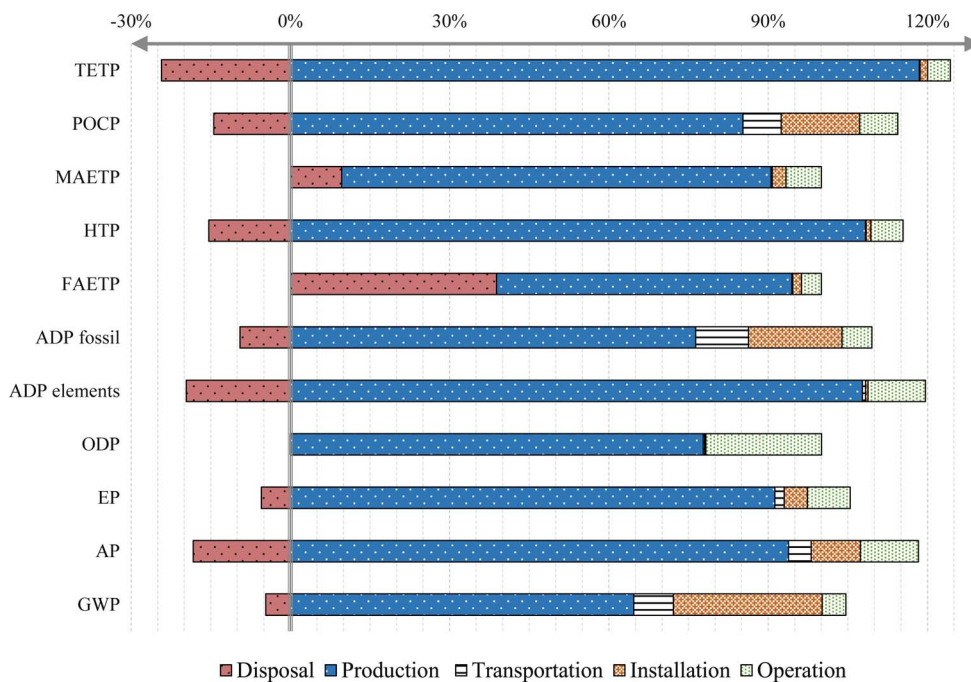


Fig. 2. Environmental impacts associated with different life cycle processes. (a) The ADP fossil in the production process (b) The GWP in the production process.

3.2. Comparison between wind power and other electricity production alternatives

3.2.1. Comparison between wind power and coal and natural gas power plant in China

The assessment results of the case study were compared to those of coal and natural gas power plants in order to establish a complete profile of the environmental impacts of wind power systems in China. For this comparison, we have calculated the environmental impacts of the average coal and natural gas power plants using the CML 2001 method, because it was difficult to obtain all the environmental impacts investigated in this study from the literature. In addition, the inventory data were derived from the Eco invent database. In order to compare the three energy technologies accordingly, the eleven environmental impact indicators were normalized by assuming that each technology produced the same amount of electricity, i.e. the share of each technology at the hypothetical electricity system was a third.

The results of this study showed that the GWP of coal power plants was more than 160 times higher than that of wind power plants, which confirmed the advantages of switching from a coal-based to a wind-based electricity system in China (Fig. 4). Additionally, wind power showed the lowest emissions per kWh regarding AP, EP, ADP fossil, and POCP, because they were 5% to 41% lower than those of coal and natural gas power plants. However, these encouraging results were accompanied by higher abiotic resource depletion (ADP elements) and higher ODP, which should be taken into account in the future development of wind power. The specific source analysis for environmental impact indicators, especially the ADP elements and the ODP, which were higher in case of wind power, can be found in the sensitivity analysis in Section 3.3.1.

The calculations regarding environmental impacts of fossil-based power plants are to some extent supported by other studies. For instance, the ADP fossil of a coal-fired power plant in China has been calculated by Wu et al. (2016) to be 2.9 kWh/kWh, while the one

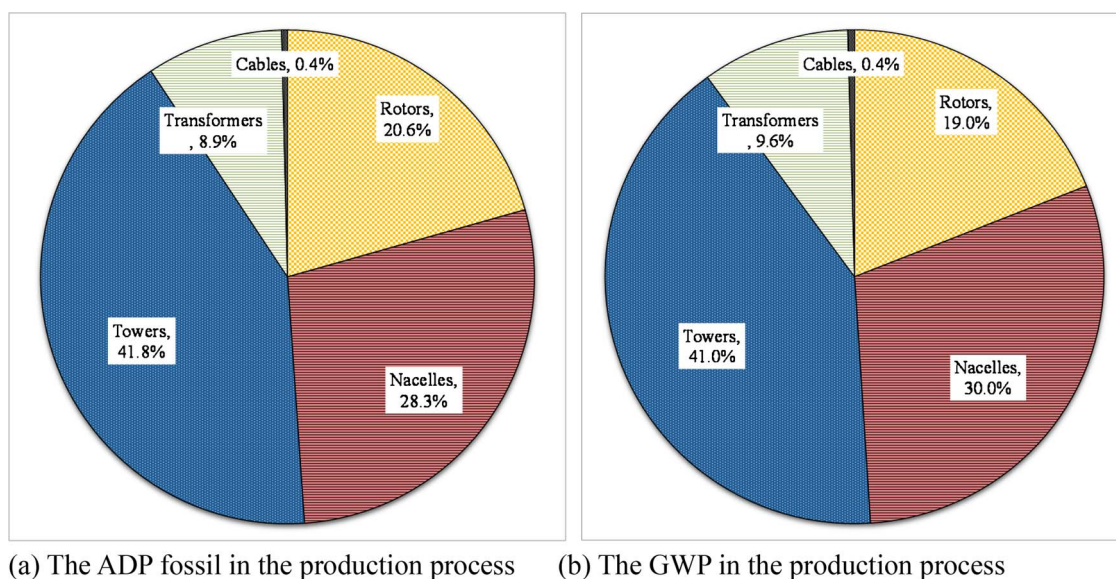


Fig. 3. Environmental impacts of (a) the ADP fossil indicator and (b) the GWP indicator on the production process.

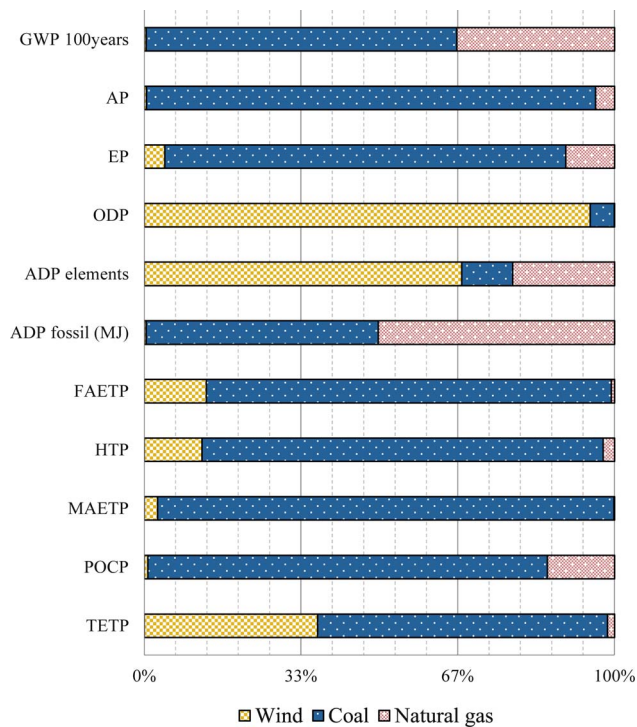


Fig. 4. Results of life cycle assessment of 1 kWh electricity production in different power plants.

calculated in this study was 3.2 kWh/kWh. Both of the results are much larger than that of the wind power plant, confirming the great reliability of the analysis conducted in this study.

3.2.2. Comparison with other wind power plants in other countries

Because ADP fossil and GWP are the most important indicators that are usually focused on in similar studies, they were used for comparison with the other wind power plants in other regions of the world.

Table 4 lists the results obtained in this study and those of several typical wind power plants that were investigated in previous studies. As shown in the table, ADP fossil ranged from 0.014 to 0.150 kWh/kWh, and GWP ranged from 7 to 440 g/kWh. Therefore, compared to the other wind power plants, the ADP fossil in this study (0.026 kWh/kWh) was within the advanced range, while the GWP (8.6 g/kWh) was within the moderate range.

When the specific sizes of wind turbines were considered in the comparison, the ADP fossil and the GWP of the Chinese 1.5 MW and

Table 4
Comparison between the studied plant and other wind power plants in other region.

Reference	Location	Turbine type	ADP fossil (kWh/kWh)	GWP (g/kWh)
This study, 2016	China	1.5 MW and 0.75MW	0.026	8.6
Garrett and Rønde (2013)	Denmark	2MW	0.028–0.036	7–10
Oebels and Pacca (2013)	Brazil	1.5MW	–	7.1
Crawford (2009)	Australia	0.85MW	0.048	10.3
		3.0MW	0.043	9.3
Tremeac and Meunier (2009)	France	250W	0.33	46.8
		4.5MW	0.08	16
Pehnt et al. (2008)	Germany	5.0MW	–	22
Kubiszewski (2010)	Worldwide	–	0.04	7.2–440
Lenzen (2002)	Worldwide	–	0.014–0.150	28.8–440

0.75 MW wind turbines were found to be close to those of the Danish 2 MW wind turbines and the Australian 3 MW wind turbines, but less than that of the 4.5 MW wind turbines in France and 5.0 MW wind turbines in Germany. However, the smaller-size wind turbines (250W turbines in France) has a much higher ADP fossil and GWP. Therefore, no direct relationship was found between the size of the turbines and the life cycle environmental impacts.

3.3. Sensitivity analysis and uncertainty

3.3.1. Sensitivity analysis

The sensitivity analysis is a method to quantify the effect of changing any component on the whole system, and it shall reveal the robustness of the results (Huang et al., 2012; Xu et al., 2013). Therefore, the effects of a 10% increase of every raw material used in the equipment fabrication on all the discussed impact indicators were investigated (Table 5).

The table lists the numerical values of sensitivity, which ranges from 0 to 100%. Standard deviations (σ) were calculated for all the environmental impact indicators to represent their variation in order to support the sensitivity analysis, and they were found significant when the material had over 50% numerical sensitivity.

The results show that ODP was significantly influenced by the resin material (> 98%), which corresponds to the highest standard deviation. Other impact indicators, such as AP, EP, ADP elements, FAETP, and TETP, were highly sensitive to one single material. For example, AP was sensitive to magnetic steel, while EP and ADP elements were easily influenced by copper; on the other hand, FAETP and TETP were significantly affected by steel. In contrast, GWP and ADP fossil were rather not sensitive to a single material, i.e., only a combination of several materials in large amounts can reduce them.

In addition, it was found that steel, copper, and resin were the most critical influencers on several multiple environmental impacts. However, fiber glass, cast iron, silica, concrete, and reinforcing steel were not imperative for yielding environmental emissions.

3.3.2. Uncertainty of wind curtailment

As mentioned in Section 2.1, the average annual electricity generation of the studied wind power plant was assumed to be 130 GWh with a curtailment of 20 GWh. The power curtailment was due to the poor power distribution capacity in North China, i.e. the extension of utility grid is not advancing at the same rate as the development of wind power. At full capacity operation, i.e., if the current wind curtailment was avoided, the entire environmental impacts of unit electricity generation would decrease by 14%. The results were obtained assuming that the use of fuels and materials in upstream sectors as well as efficiency were not related to the amount of wind curtailment. It is therefore suggested that local power grid should be developing along with building new wind power plants, which should be slowed down at the present stage to decrease the impacts on the environment. In addition, the power grid development to support large-scale power transmission from west to east is a long-term requirement for wind power systems, because the wind resources in China are mainly concentrated in the north, northeast, and northwest, while the power demand is mainly concentrated on the eastern coastal areas (Li et al., 2013; Wang et al., 2011).

3.3.3. Scenario-based uncertainty analysis due to changing the turbine size

The size of the wind turbine should have an effect on the environmental burdens of a wind power plant. In the following the environmental impacts of different average turbine sizes are analyzed, i.e. the current wind power plant with an average turbine size of about 1 MW (18 turbines of 1.5-MW and 30 turbines of 0.75-MW) is compared to a wind power plant with an average size of 1.5 MW (33 turbines of 1.5-MW), as it was originally designed.

Fig. 5 illustrates comparative results of the utilization of wind

Table 5
Sensitivity analysis on the relationship between raw materials and environmental impacts (unit: %).

	GWP	AP	EP	ODP	ADP elements	ADP fossil	FAETP	HTP	MAETP	POCP	TETP
Fiberglass	4.28	3.09	1.15	0.09	18.72	5.04	0.28	2.41	0.96	2.61	0.49
Resin	12.35	2.71	1.85	98.78	1.11	12.87	0.42	0.42	0.63	4.77	0.35
Cast iron	4.04	1.72	9.71	0.04	0.06	4.62	0.93	0.32	1.04	3.68	1.09
Steel	15.74	9.69	5.51	0.20	16.79	16.47	51.11	44.47	29.46	11.05	57.97
Silica	0.17	0.08	0.05	0.03	0.02	0.25	0.01	0.01	0.03	0.11	0.00
Magnetic steel	3.80	54.62	6.26	0.07	4.53	3.84	5.02	14.58	6.02	27.35	17.52
Steel (Low alloyed)	21.33	10.26	12.28	0.23	8.88	25.85	16.75	15.68	12.68	22.15	19.65
Copper	1.51	3.53	56.75	0.02	48.75	1.76	23.62	21.02	46.29	5.02	1.32
Concrete	18.35	3.66	1.29	0.14	0.25	6.55	0.21	0.30	0.38	4.89	0.29
Reinforcing steel	7.82	3.36	2.84	0.08	0.20	9.61	1.39	0.51	1.79	8.65	1.13
Standard deviation σ	0.07	0.16	0.17	0.31	0.15	0.08	0.17	0.14	0.16	0.09	0.18

turbines with different sizes to produce 1 kWh of electricity, which was calculated as the normalized difference between the assumed scenario and the real case. Whether the higher average size turbine (assumed scenario) produces higher or lower emissions compared to the smaller size turbine (reality) can be determined by positive or negative results, respectively, of the analysis.

The results indicate that the higher average size of the turbines improved most environmental impact indicators, which ranged between 7.5% (HTP) and 21% (TETP) below those in the case of the smaller turbine size. In contrast, AP, EP, ADP element, MAETP, and POCP showed higher environmental impacts. It should be noted that ODP was the only impact indicator with a unanimously improvement of the environmental performance over all processes.

As mentioned, a scaling up of the turbine leads to a large increase in AP and EP due to the high amount of magnetic steel and copper used in the equipment, which results in high emission-intensity and consequently higher AP and EP, respectively. The results also confirm that there is no direct relationship between the size of the turbines and the life cycle environmental impacts, which is consistent with the findings discussed in Section 3.2.2.

4. Conclusions and policy implication

As one of the most promising renewable alternatives to fossil fuels-

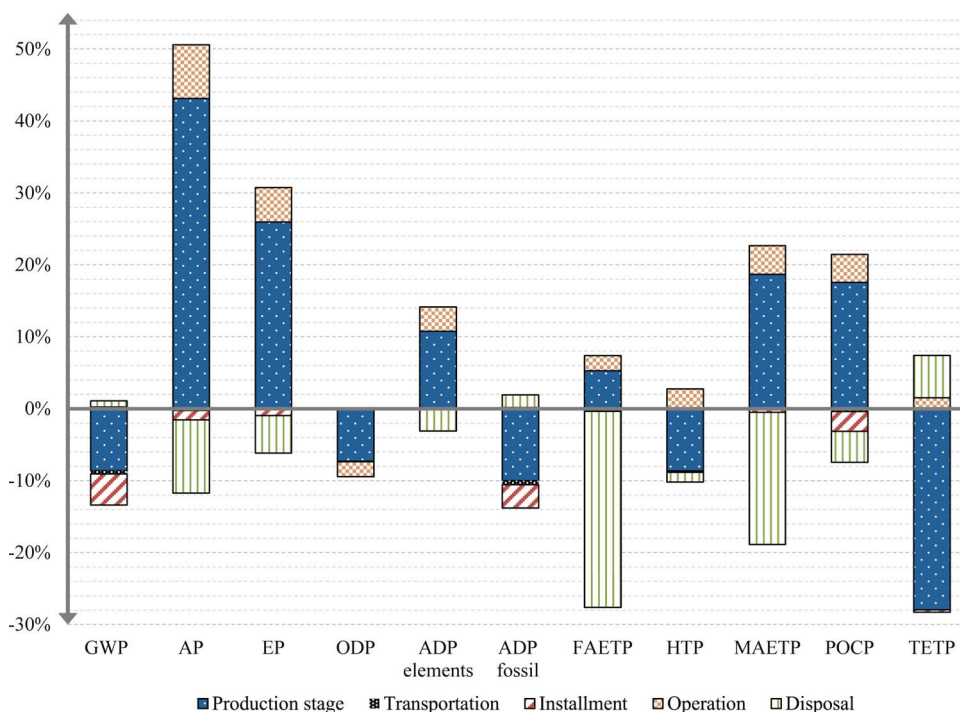


Fig. 5. The comparative results of utilizing different wind turbines for 1 kWh electricity production.

based energy systems in China, wind power has been intensively developed in the recent years. This study applied LCA to evaluate the environmental impacts of a typical wind power plant in Inner Mongolia, China, and the following results were obtained:

- (1) The results indicate high environmental performance and renewability of the studied wind power plant. In addition, the results of investigating the contributions of different processes in the life cycle revealed that the production process was the largest contributor to all of the environmental impact indicators, which can be attributed to the large input of raw materials in this process. Among the components of a wind power plant, the production of towers contributes the most to the GWP, and the production of towers and rotors were the most important contributors to ADP fossil.
- (2) Compared to coal and natural gas power plants in China, wind power exhibits a significant reduction regarding most of the impact indicators, i.e. GWP, ADP fossil, AP, EP, HTP, TEP, and POCP. In contrast, these results are accompanied by higher ADP elements and higher ODP, which should be taken into further consideration.
- (3) Sensitivity and scenario-based uncertainty analysis was applied in order to explore some technical and policy suggestions for the development of wind power in China. The results of this analysis were as follows: the optimization of the structural design and the application of raw materials is an effective measure to improve the

environmental performance of wind power in China. Moreover, the environmental performance of wind power in China is affected by the slow development of the electric grid compared to that of the wind power expansion, which resulted from the over-investment in large-scale wind power and consequently its overcapacity in the north, northeast, and northwest, which are the main areas of China's wind resources, while the high power demand is concentrated in the east. Therefore, the regional and national development of wind power should be carefully planned.

Finally, the size of the turbine did not show any clear relationship with the environmental impact indicators. In contrast, choices of materials or their substitution had a high influence from the perspective of climate change and environmental protection.

Nevertheless, it should be noted that this study was conducted under certain limitations, such as the lack of specific datasets or impact assessment models related to China. Therefore, further efforts should be undertaken to strengthen the energy-related environmental impact assessment in China.

Acknowledgements

This work was supported by the Funds for International Cooperation and Exchanges of the National Natural Science Foundation of China (Grant No. 51661125010), Fund for Innovative Research Group of the National Natural Science Foundation of China (Grant No. 51421065), and National Science and Technology Major Project of the Ministry of Science and Technology of China (2017YFC0505703). The authors thank the reviewers for their thoughtful comments and suggestions.

References

- Ardenete, F., Beccali, M., Cellura, M., Brano, V.L., 2008. Energy performances and life cycle assessment of an Italian wind farm. *Renew. Sustain. Energy Rev.* 12 (1), 200–217.
- BJNEC, B.J.N.E.C., 2012. The Post-evaluation Report of Saihan Phase I Wind Power Project (49.5 MW).
- Cambero, C., Alexandre, M.H., Sowlati, T., 2015. Life cycle greenhouse gas analysis of bioenergy generation alternatives using forest and wood residues in remote locations: a case study in British Columbia Canada. *Resour. Conserv. Recycl.* 105, 59–72.
- Chen, G., Yang, Q., Zhao, Y., 2011. Renewability of wind power in China: a case study of nonrenewable energy cost and greenhouse gas emission by a plant in Guangxi. *Renew. Sustain. Energy Rev.* 15 (5), 2322–2329.
- Coelho, L.M.G., Lange, L.C., 2016. Applying life cycle assessment to support environmentally sustainable waste management strategies in Brazil. *Resour. Conserv. Recycl.* <http://dx.doi.org/10.1016/j.resconrec.2016.09.026>.
- Crawford, R., 2009. Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. *Renew. Sustain. Energy Rev.* 13 (9), 2653–2660.
- EIA U.S., 2012. Economic Growth Continues to Drive China's Growing Need for Energy. (accessed 26.03.2017). <http://www.eia.gov/todayinenergy/detail.cfm?id=8070>.
- Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. *J. Environ. Manage.* 91 (1), 1–21.
- Garrett, P., Ronde, K., 2013. Life cycle assessment of wind power: comprehensive results from a state-of-the-art approach. *Int. J. Life Cycle Assess.* 18 (1), 37–48.
- Han, M., Chen, G., Shao, L., Li, J., Alsaedi, A., Ahmad, B., Guo, S., Jiang, M., Ji, X., 2013. Embodied energy consumption of building construction engineering: case study in E-town, Beijing. *Energy Build.* 64, 62–72.
- Huang, N., Wang, H., Fan, C., Zhou, S., Hou, P., Yang, J., 2012. LCA data quality assessment and control based on uncertainty and sensitivity analysis. *Acta Sci. Circumst.* 32 (6), 1529–1536.
- ISO, 2006. Environmental Management, Life Cycle Assessment: Principles and Framework. ISO.
- Jungbluth, N., Bauer, C., Dones, R., Frischknecht, R., 2005. Life cycle assessment for emerging technologies: case studies for photovoltaic and wind power (11 pp). *Int. J. Life Cycle Assess.* 10 (1), 24–34.
- Kubiszewski, I., Cleveland, C.J., Endres, P.K., 2010. Meta-analysis of net energy return for wind power systems. *Renewable energy* 35 (1), 218–225.
- Lenzen, M., Munksgaard, J., 2002. Energy and CO 2 life-cycle analyses of wind turbines—review and applications. *Renewable energy* 26 (3), 339–362.
- Li, J., Shi, P., Gao, H., 2010. China Wind Power Outlook 2010. Hainan Publishing House, Haikou.
- Li, J., Cai, F., Qiao, L., Gao, H., Wang, J., Tang, W., Peng, P., Li, X., 2013. 2013 Annual Review and Outlook on China Wind Power. China Environmental Science Press, Beijing.
- Li, J., Cai, F., Qiao, L., Wang, J., Gao, H., Tang, W., Peng, P., Geng, D., Li, X., Li, Q., 2014. 2014 China Wind Power Review and Outlook. Chinese Renewable Energy Industries Association, Beijing.
- Liu, C., Wang, Y., Zhu, R., 2017. Assessment of the economic potential of China's onshore wind electricity. *Resour. Conserv. Recycl.* 121, 33–39.
- Martínez, E., Sanz, F., Pellegrini, S., Jiménez, E., Blanco, J., 2009. Life cycle assessment of a multi-megawatt wind turbine. *Renew. Energy* 34 (3), 667–673.
- Oebels, K.B., Pacca, S., 2013. Life cycle assessment of an onshore wind farm located at the northeastern coast of Brazil. *Renew. Energy* 53, 60–70.
- Pang, M., Zhang, L., Wang, C., Liu, G., 2013. Energy analysis of a biomass direct-fired power plant in Inner Mongolia of China. *J. Environ. Acc. Manage.* 1 (4), 321–331.
- Pang, M., Zhang, L., Wang, C., Liu, G., 2015. Environmental life cycle assessment of a small hydropower plant in China. *Int. J. Life Cycle Assess.* 20 (6), 796–806.
- Pehnt, M., Oeser, M., Swider, D.J., 2008. Consequential environmental system analysis of expected offshore wind electricity production in Germany. *Energy* 33 (5), 747–759.
- Shao, L., Chen, G., 2013. Water footprint assessment for wastewater treatment: method, indicator, and application. *Environ. Sci. Technol.* 47 (14), 7787–7794.
- Shen, G., Xu, B., Jin, Y., Chen, S., Zhang, W., Guo, J., Liu, H., Zhang, Y., Yang, X., 2017. Monitoring wind farms occupying grasslands based on remote-sensing data from China's GF-2 HD satellite—A case study of Jiuquan city Gansu province, China. *Resour. Conserv. Recycl.* 121, 128–136.
- Tremec, B., Meunier, F., 2009. Life cycle analysis of 4.5 MW and 250W wind turbines. *Renew. Sustain. Energy Rev.* 13 (8), 2104–2110.
- Wang, Z., Shi, J., Zhao, Y., 2011. China Wind Power Development Roadmap 2050. National Development and Reform Commission Energy Research Institute.
- Wang, C., Zhang, L., Yang, S., Pang, M., 2012. A hybrid life-cycle assessment of non-renewable energy and greenhouse-gas emissions of a village-level biomass gasification project in China. *Energies* 5 (8), 2708–2723.
- Wu, X., Wu, X., Li, J., Xia, X., Mi, T., Yang, Q., Chen, G., Chen, B., Hayat, T., Alsaedi, A., 2014. Ecological accounting for an integrated pig–biogas–fish system based on emergent indicators. *Ecol. Indic.* 47, 189–197.
- Wu, X., Chen, G., Wu, X., Yang, Q., Alsaedi, A., Hayat, T., Ahmad, B., 2015. Renewability and sustainability of biogas system: cosmic exergy based assessment for a case in China. *Renew. Sustain. Energy Rev.* 51, 1509–1524.
- Wu, X.D., Xia, X.H., Chen, G.Q., Wu, X.F., Chen, B., 2016. Embodied energy analysis for coal-based power generation system-highlighting the role of indirect energy cost. *Appl. Energy* 184, 936–950.
- Xu, X., Chen, Y., Zhang, S., Zhang, Y., Song, G., 2013. Life cycle assessment of composite portland cement. *Acta Sci. Circumst.* 33 (9), 2632–2638.
- Xue, B., Ma, Z., Geng, Y., Heck, P., Ren, W., Tobias, M., Maas, A., Jiang, P., de Oliveira, J.A.P., Fujita, T., 2015. A life cycle co-benefits assessment of wind power in China. *Renew. Sustain. Energy Rev.* 41, 338–346.
- Zhou, W., Lou, C., Li, Z., Lu, L., Yang, H., 2010. Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. *Appl. Energy* 87 (2), 380–389.