Resources, Conservation & Recycling xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

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).

http://dx.doi.org/10.1016/j.resconrec.2017.06.014
Received 19 December 2016; Received in revised form 14 June 2017; Accepted 15 June 2017

Please cite this article as: Xu, L., Resources, Conservation & Recycling (2017), http://dx.doi.org/10.1016/j.resconrec.2017.06.014

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 (Ardente 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 km^2, 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 GW77/1500 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.

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)

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 shrinked 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