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The life-cycle energy and environmental emissions of a typical offshore wind farm in China

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ABSTRACT

China's vast untapped offshore wind energy and the concentration of electricity consumers in coastal regions make offshore wind power a promising solution to the country's cleaner power transition. However, the potential energy and environmental emissions of offshore wind farms have not been thoroughly investigated. Thus, this study employed a process-based life cycle inventory (LCI) model to calculate the life-cycle energy and emissions of offshore wind power in China based on the country's first offshore wind energy project. Results showed that the life-cycle energy of the studied wind farm was 2.28E+09 MJ, or 0.39 MJ/kwh, with emission intensities of 25.5 g CO_2-eq/kWh for GHG, 0.02 g/kWh for $PM_{2.5}$, 0.06 g/kWh for SO_2 and 0.09 g/kWh for NO_x. The life-cycle footprints are dominated by the manufacture of wind turbines and foundation materials production. Compared to onshore wind farms, offshore wind power plants usually have greater life-cycle electricity yields, but their levelized energy and environmental footprints are less favorable. The green manufacturing of China's steel sector, and scientific operation and maintenance programs of wind facilities contribute to greening offshore wind power. Results of this study facilitate robust policy making of government authorities and contribute to the green deployment of offshore wind technologies in China.

1. Introduction

Wind energy has become the second largest contributor (behind hydro) to global renewable power generation (IRENA, 2015). Worldwide, more than 54.6 GW of wind power capacity was installed in 2016 in over 90 countries. The cumulative installed capacity was nearly 487 GW in 2016, and this is projected to exceed 800 GW by 2021 (GWEC, 2017).

To address the deteriorating atmospheric quality and rising climate change challenges, the Chinese government has made great efforts to promote wind energy development. In response to enactment of the *Renewable Energy Law* in 2006, wind power has grown rapidly in China, and it has had the world's largest installed capacity since 2010. As of 2015, China's total installed capacity for wind power reached 145.4 GW (approximately 33.6% of the world total), and this value is expected to increase to 250 GW by 2020 as the country moves toward its target of 15% renewable energy consumption (CWEA, 2016). Currently, wind power accounts for 3.3% of China's total electricity consumption, or approximately 186.3 TWh in 2015.

However, wind power facilities in different regions in China show unbalanced development. Specifically, large-scale deployment is concentrated in the northeast, north, and northwest (the “Three Northern Regions”), whereas the country's electricity demand pressure mainly exists in coastal regions in the east. This mismatch between wind power generation and electric power consumption makes offshore wind a promising power source for eastern China. Indeed, China has abundant offshore wind energy resources, especially in the southeastern coastal areas, such as Jiangsu, Shanghai, Zhejiang, Fujian, and Guangdong provinces (Sun et al., 2015; Chen, 2011). Approximately 200 GW (or 300 W/m^2) of offshore wind energy could be exploited at a height of 50 m in areas with a water depth of 5–25 m (Fu and Yuan, 2012). Under the support of national policies such as *China's Wind Power Twelfth Five*

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Year Plan and the *National Offshore Wind Power Development Plan (2014–2016)*, offshore wind power in China presents a preliminary achievement; however, it is still in a nascent stage. By the end of 2015, the cumulative installed capacity of China's offshore wind power was only 657.88 MW (CWEA, 2016), which is about 0.07% of that of its coal-fired technologies. Thus, accelerating offshore wind energy utilizations is a critical strategy for renewable energy development in China.

Compared to onshore wind, offshore wind power in China has the advantage of a vast deployment area, higher and more stable wind speed, and it could be potentially more accessible for consumers (Zhang et al., 2011). However, the construction and operation of the offshore facility requires higher material and resource inputs because of the more complex environment. For example, substructures are designed with larger dimensions for enhanced stabilization of the wind tower, and the construction and maintenance of offshore wind turbines is more difficult because they necessitate on-ocean work. As a result, for an individual wind power facility, the off-shore deployment usually generates more life-cycle electricity than the output of an on-shore application, but requires higher input of materials and resources. Therefore, quantification of the life-cycle energy and pollutant emissions associated with offshore wind power utilization should be conducted to help understand the trade-offs between the on- and off-shore wind power technologies in China, and thus shed light on the deployment scheme of China's wind power systems.

Because it has the advantages of providing systematic consideration and quantitative analysis, life cycle assessment (LCA) is widely used to quantify the energy and environmental impacts across the life span of products and services (Chang et al., 2010; Xue et al., 2015; Amini et al., 2013; Boroojeni et al., 2016). Existing LCA studies have investigated the environmental impacts of on- and off-shore wind farm systems, but have mainly focused on European practices. Schleisner (2000) quantified the energy consumption and emissions of wind farms in Demark, while similar studies were conducted for wind farms in the United Kingdom (Wiedmann et al., 2011), Norway (Arvesen et al., 2013), Italy (Ardente et al., 2008), Greece (Abeliotis and Pactiti, 2014), and Germany (Wagner et al., 2011; Reimers et al., 2014). Arvesen and Hertwich (2012) presented a comprehensive review of wind farm LCA studies based on 44 wind farms in Europe, seven of which were offshore wind farms. Additionally, LCAs of on-shore wind farms in the United States (Kumar et al., 2016), Brazil (Oebels and Pacca, 2013), Japan (Hondo, 2005) and Libya (Al-Behadili and El-Osta, 2015) are also available.

Comparatively, existing literature on China's wind power life cycle assessment are relatively rare, and those that have been conducted primarily focus on the onshore technologies of the main wind farms in China (Table 1). Furthermore, existing studies have mainly adopted process-based LCI (life cycle inventory) models to calculate the life-cycle energy consumption and GHG emissions, whereas the pollutant emissions of SO_2, NO_x and $PM_{2.5}$ are not considered. Notably, Zhang et al. (2016) used the input-output (IO) LCI model to calculate the embodied energy of offshore wind farms in China, but the highly aggregated sectors in China's input-output table cause uncertainties to study estimates. Also, the wind facilities' operation was not considered.

To present a complete understanding of the energy and environmental impacts associated with off-shore wind power utilization in China, this study calculated the life-cycle energy and environmental emissions (including GHG, SO_2, NO_x, and $PM_{2.5}$) of an offshore wind farm in China. The contribution of this work includes that: (i) the study results will be useful to government authorities to evaluate the energy and emissions benefits associated with future offshore wind power projects to enable robust planning for energy infrastructure; (ii) this study unveils the trade-offs associated with the deployment of off-shore wind farms through comparison with a typical on-shore wind farm in China; (iii) results of this study will help engineers identify green opportunities in the supply chains and operation of the wind facilities, as well as help policy-makers optimize the portfolio of wind power development to advance cleaner power transitions moving forward in China.

The paper is organized as follows. In section 2, we introduce the case offshore wind farm. In section 3, we illustrate the method and date used in this study. The life cycle inventory calculations are demonstrated in section 4 followed by the results and discussion in section 5. We conclude and shed light on directions for future studies in section 6.

2. Case offshore wind farm descriptions

The studied wind farm, the Donghai Bridge Offshore Wind Farm (DBOWF), is China's first offshore wind farm within the jurisdiction of Shanghai, as well as the first offshore wind farm outside Europe. The project has two-phases of construction, located on each side of the Donghai bridge (Fig. 1). Construction of the first-phase was started in March 2009 and commissioned in 2010, while the second-phase was completed in 2013.

In this study, we used the second-phase for quantifications. The total installed capacity of the studied farm is 102.2 MW, consisting of 27 3.6-MW wind turbines and one 5-MW prototype wind turbine. The turbines are 90 m high standing in 10 m deep sea water. The center of the wind farm is 9.2 km away from the shore. The wind farm is designed with an annual on-grid power generation of 236 GWh and an annual average wind speed of 7.7 m/s. The total economic investment is 1.963 billion Yuan, with a designed operation period of 25 years.

3. Method and data

LCA is a decision-making tool that can be used to evaluate the "cradle to grave" resource and environmental impacts of renewable energy technologies (Chen et al., 2011a; 2011b; Wang et al., 2012, 2017; Masanet et al., 2013). There are three approaches for calculating the life-cycle footprints of products and services, process-based LCA (PLCA), economic input-output (EIO) LCA and hybrid LCA (Chang et al., 2010; Han et al., 2016; Wu et al., 2016). For wind power technology, the differences of each modeling approach in system boundary scope and spatial and temporal specificity of model parameters and variables would result in significant variations in footprint results. PLCA facilitates the use of physical data specific to research subjects, but is vulnerable to subjective system cut-off. EIO LCA is a top-down technique based on the monetary value of products and services at the level of economic sectors. The model overcomes the truncation errors of the PLCA, but sectors in an economic system are usually too coarse to precisely calculate the energy and emission footprints of individual products. The hybrid LCA modeling approach enables the advantages of the two approaches (Arvesen and Hertwich, 2011), but still relies on fine sector classifications in the national economy to enable the calculation of specific supply-chain footprints.

Because the material inventory of offshore wind farms has few material categories (basically steel and iron, concrete, resin and fiberglass), their corresponding sectors in China's IO table are highly aggregated, preventing specific footprint calculations for each material input. Conversely, PLCA is a bottom-up approach based on production system processes, and model results can potentially be generated with a great deal of detail and accuracy, especially when detailed process data is available (Chang et al., 2012, 2014, 2015; Wu et al., 2015). Therefore, detailed process models of China's first offshore wind farm will facilitate cross-study