



Carbon footprint accounting of a typical wind farm in China



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HIGHLIGHTS

- Construction phase accounts for the largest share of total lifetime carbon emissions.
- The “Smelting and Pressing of Metals” sector contributes most to the carbon emissions.
- Peak regulation is incorporated into the carbon accounting of wind farm.

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ABSTRACT

The reserves and exploitable capacity of the wind power resource in China are both ranked first in the world and could be developed to strengthen China's energy security and mitigate global warming. Carbon footprint accounting of wind farms is vital for large-scale wind energy exploitation. This paper establishes a systematic accounting framework with life cycle assessment (LCA) and input–output analysis (IOA) for the overall carbon footprint of the life cycle of a typical wind farm. Carbon emissions from the construction, operation, and dismantling phases are considered in the LCA of the wind farm. Then, each expense of the wind farm is treated as a change in exogenous demand for the output of the corresponding economic sectors according to the IOA. In addition, the virtual carbon footprint from peak regulation triggered by the on-grid fluctuation of wind power is incorporated. The results show the total carbon footprint of the studied wind farm is 1.45×10^4 tCO₂ over the 21-year lifetime. The construction phase accounts for the largest fraction (76.74%), followed by the operation phase (15.32%) and dismantling phase (7.94%). According to the IOA, the indirect carbon footprint of the wind farm is greater than the direct footprint. The “Smelting and Pressing of Metals” sector that produces the steel and copper used to manufacture the wind turbines dominates the carbon footprint. The virtual carbon footprint of coal-fired power for wind power peak regulation is estimated to be 2.08×10^3 tCO₂, which is close to that of the operation phase.

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1. Introduction

China's energy and climate policy sets forth a national carbon intensity reduction target of 18% as part of the Thirteenth Five-Year Plan (2016–2020). This is consistent with the nation's commitment given at the Copenhagen climate talks to achieve a 40–45% CO₂ intensity reduction by 2020, relative to a 2005 baseline. Realizing such a target is a considerable challenge because fossil fuels with their high carbon emissions dominate China's energy mix.

The wind power resource in China has an exploitable capacity of 2380 GW on land and is considered an important clean energy option. In 2015, China installed 33.0 GW of new wind power

generation capacity, raising the total national capacity to 129.1 GW, which ranks first in the world. Currently, about 3.3% of China's national electricity consumption is contributed by wind power [1]. However, large amounts of metal and nonmetal products, buildings materials, and labor are required by a wind farm from its construction to dismantling phases. These products and processes emit carbon directly or cause carbon emissions indirectly via related activities. Thus, comprehensive carbon footprint accounting of wind farm is required.

Life cycle analysis (LCA) is one of the methods used most widely to quantify the environmental impact of a given product throughout its entire life cycle [2,3]. Process-based life cycle analysis (PLCA) on wind farms has been carried out extensively, focusing on energy demand and greenhouse gas (GHG) emissions [4–6]. Jungbluth et al. [7] showed that material consumption for the main parts of the wind turbines provided the largest contribution for the

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environmental impact of electricity production. Yang et al. [8] presented a complete process analysis for the consumption of non-renewable energy and GHG emissions that included six parts: the wind turbine components, substations, transportation, building construction, operation and maintenance, and dismantling disposal, of which 67% of GHG emissions are from the building construction, 30% from wind turbine manufacturing, and 3% from the operation and maintenance phases. Based on an environmental impact and benefit analysis of wind farms in Italy, Ardente et al. [9] also stated that most GHG emissions derive from the building construction. However, some studies have concluded that wind turbine production contributes most to the overall emissions during the entire life cycle of a wind farm [10]. For example, according to the calculation of Yang and Chen [11], emissions from the production of wind turbines contribute the largest proportion at 46.86%.

PLCA might lead to significant truncation errors due to an artificial cut-off when defining the system boundaries [12,13]. To overcome this problem, an input–output analysis (IOA), originally developed by Leontief, is introduced to improve the LCA-based framework by reflecting the inter-relationships of various sectors via the production and consumption of intermediate economic outputs. The monetary transactions flowing between the economic sectors can be transformed to physical flows (such as carbon emissions) under the assumption that all outputs of a sector are produced with the same intensity of physical flow [14]. It is assumed that each industry consumes the outputs of various other industries in fixed ratios to produce its own unique and distinct output [15]. As IOA is constrained by aggregated sector representation, the IO-LCA has been developed to reduce the limitations of each individual approach and to increase their accuracies [16,17]. Alternative models based on IO-LCA are then proposed by the selective disaggregation of aggregated input–output data or by the creation of hypothetical new commodity sectors [18].

Few studies have applied IO-LCA to evaluate wind power generation systems. For example, Davidsson et al. stated that when assessing the energy usage of the operation and maintenance phases, IO-LCA could present greater relative numbers than PLCA to avoid the underestimation of embodied energy consumption [19]. Crawford concluded that previous embodied energy assessments of wind turbines based on PLCA or IOA might be up to 78% incomplete compared with those of IO-LCA [20]. An IO-LCA model was developed to quantify the direct and supply chain related indirect environmental impacts of wind energy technologies in the United States [21]. Carbon footprint accounting of wind farms based on IO-LCA is also quite rare. Nagashima added new sectors related to wind power generation systems to IO-LCA model to analyze the carbon emissions of wind power system [22]. Wiedmann et al. used two types of IO-LCA, i.e., integrated hybrid LCA and IO-based hybrid LCA, to account for the carbon footprint of a wind farm in the UK [23]. The IO-based hybrid LCA is easier and more efficient to implement, although both methods produced similar results regarding principal yield. Li et al. [24] used the IO-based hybrid LCA to account for the carbon emissions of wind power generation in China, and determined that the electricity sector contributes 48% of the carbon emissions because of the amount of electricity consumed in turbine manufacturing and the dominance of coal in China's electricity generation mix.

The crucial weakness of wind power, which imposes the greatest restriction on its development, is the intermittent and volatile nature. To protect the electric power system from violent fluctuations with wind power on-grid, peak regulation (i.e., the way to change the generator load demand and supply of electricity to meet the balance of power [25]) in the electric power system is required. However, most previous LCA studies on wind power have not considered the carbon emissions caused by wind power connection interfaces.

This paper calculates the carbon footprint in the construction, operation, and dismantling phases of a typical wind farm in China using the IO-LCA method. In particular, the carbon footprint triggered by peak regulation is included. The remainder of the paper is organized as follows: In Section 2, the method and data sources are introduced. Section 3 shows the results of the carbon footprint accounting of each phase included in the boundary. Finally, some discussions and suggestions for sustainable wind energy development are provided in Section 4.

2. Method

2.1. System boundary

We calculate the carbon footprint of a wind farm in terms of its construction, operation, and dismantling phases. The construction phase comprises the design and management, diesel and petrol for transportation, electricity, materials, and electrical equipment for construction, and transportation of materials and equipment. In the operation phase, labor for equipment maintenance, renewal of parts, and water use in the wind farm are considered. Because the wind turbines and buildings will be decommissioned at the end of their useful life, the carbon emissions related to dismantling cannot be ignored. In addition, the virtual carbon footprint for peak regulation triggered by the on-grid fluctuation of wind power is calculated (see Fig. 1).

2.2. IO-LCA

IOA originally developed by Leontief describes how sectors are inter-related through producing and consuming intermediate economic outputs that are represented by monetary transaction flows between economic sectors, which can be transformed to physical flows such as carbon emissions under the assumption that all outputs of a sector are produced with the same physical flows intensity [14,26]. Assuming that each industry consumes outputs of various other industries in fixed ratios in order to produce its own unique and distinct output, the basic input–output model can be described as [14,15]:

$$x = (I + A + A \times A + A \times A \times A + A \times \dots) y = (I - A)^{-1} y \quad (1)$$

where x is the vector of required capital inputs of sectors, I is the identity matrix, A is the direct requirements matrix, and y is the vector of final demand. The details of IO-LCA can be referred to the work of Joshi [18], in which five alternative models are proposed according to various research objects and data accessibility. Here we modify the Model-I when approximating the product by its sector. Each expense (i.e., for equipment purchasing, labor employment, energy consuming, etc.) of a wind farm is treated as a change in the exogenous demand for the output of the corresponding economic sector according to the IOA. Then, the relations between each item of three phases and its corresponding sector are established (see Table 1). Lack of data regarding capital input for the dismantling phase, we assume the cost for decommissioning a wind farm is equal to that of the activities in the construction phase, and that the cost for waste material transportation is equal to that of the transportation in the construction phase. Consequently, the carbon footprint can be estimated by multiplying the output of each sector and its environmental impact per monetary unit of output:

$$C_i = R_i x = R_i (I - A)^{-1} y \quad (2)$$

where C_i is the vector of the carbon footprint, R_i is the matrix with diagonal elements representing the emissions per monetary unit of input for each sector, x is the vector (or list) of the required capital inputs from the sectors, I is the identity matrix, A is the technical

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