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ScienceDirect

Energy Procedia 88 (2016) 250 – 256

Energy Procedia

CUE2015-Applied Energy Symposium and Summit 2015: Low carbon cities and urban energy systems

LCA-based Carbon Footprint of a Typical Wind Farm in China

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Abstract

Wind power resources are abundant in China, with the reserves and exploitable capacity ranking the first in the world. The carbon footprint is used to provide an expending scale accounting of carbon emission embodied in relative phases and sectors. In order to account the carbon footprint of wind farm, this paper introduces a method combining the Life Cycle Assessment and Input-Output analyses to calculate the overall carbon footprint in the construction, operating and dismantling phases of a typical wind farm in China on the basis of the latest acquirable input-output table of province level and province energy statistic. As a result, the total carbon footprint of the case wind farm is 14,490 tCO2 all over the 21 years lifetime. Due to a mass of steel and copper was consumed to manufacture the wind turbines, the 'Smelting and Pressing of Metals' sector discharged the largest amount of CO2among all economic sectors. Considering the character of wind farm, IO-LCA is an appropriate method to analyze the overall direct and indirect carbon emissions of wind farm.

Peer-review under responsibility of the organizing committee of CUE 2015

Keywords: IO-LCA; Carbon footprint; wind farm

1. Introduction

Countries over the world have devoted to developing low-carbon economies with the main feature of low power consumption and low pollution so as to alleviate global climate change and achieve sustainable development [1]. Therefore, it's of great significance to set up low carbon power systems, which

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Peer-review under responsibility of the organizing committee of CUE 2015
doi:10.1016/j.egypro.2016.06.160

specifically means to promote large-scale grid integration of renewable energy such as wind power [2]. Wind power has experienced the greatest growth worldwide in the past several decades, e.g., during the period 2004 to 2013, the average annual compound growth rate of China's wind power installed capacity is 61.8%. By the end of 2013, China has ranked first for four consecutive years in the world for the cumulative installed capacity, which accounted for 28.8% of the global total capacity [3].

Numerous studies have indicated that the use of wind power can reduce carbon emissions and other environmental impacts as well compared to conventional energy. Some studies considered the life cycle environmental impacts considering the stages including manufacture of each of wind turbines' component, transport to the wind farm, installation, start-up, maintenance and final decommissioning with its subsequent disposal of waste residues [4, 5]. Yang and Chen presented a whole process evaluation of the GHG emission of a wind farm in China, the construction phase makes up the largest proportion of GHG emission. As for dividing by inputs, 46.87% due to wind turbine manufacturing, 36.64 % of greenhouse gas emissions are from the building materials. [6]. Ardente et al. derived a range of similar conclusions on the environmental impact and benefits analysis of wind farms in Italy [7]. Guo et al. found that the energy consumption and CO2 emissions in wind turbines production phase took the largest proportion in the total life cycle of a wind farm [8]. Regarding the important carbon emissions and energy consumption stages like wind turbines manufacturing phase, recycling phase is often suggested expanding the system boundary and highlighting the low-carbon characteristic of wind power [9, 10]. To some extent, wind energy has become one of the best ways to mitigate climate change and to provide electricity in rural zones not connected to the grid [11].

Life Cycle Assessment (LCA) is one of the most widely used methods for quantifying the environmental impacts of product throughout its entire life cycle [12, 13]. There are three methodological variants of LCA: Process Life Cycle Analysis (PLCA), Input-Output based Life Cycle Analysis (IO-LCA) analysis and hybrid LCA. PLCA is often employed to establish the indirect environmental impacts associated with production processes. However, this method can lead to significant truncation errors in the calculations due to an artificial cut-off when defining the system boundaries [14, 15]. Besides, a focus on emissions associated with physical processes could overlook important factors that emerge from the interaction among the multiple firms or sectors that constitute each supply chain. Thus, the limitation of PLCA has led to a combination of Input-output (IO) and LCA analysis in this paper to analyze the overall direct and indirect carbon emissions of wind farm.

The concept of carbon footprint originated from the ecological footprint also provides a guideline to scale up the carbon accounting framework. As Wiedmann and Minx defined, carbon footprint is a measure of the exclusive total amount of CO_2 emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product [16].

In this paper, carbon footprint is used to provide an expending scale accounting of carbon emissions embodied in relative phases and sectors based on IO-LCA. The main objectives of this paper are as follows: (1) Introduce a systems accounting method in terms of combination of PLCA and IO analyses to account the overall embodied carbon for wind farm; (2) calculate the overall carbon footprint in the construction, operating and dismantling phases of a typical wind farm on the basis of the latest acquirable input-output table of province level and province energy statistics to get the emission intensity; and (3)promote suggestions for wind energy development and the further research about carbon footprint of wind farm.

2. METHODOLOGY

2.1. Study Site

The total installed capacity of concerned wind farm is 48 MW, having 24 wind turbines, each of 2000 kW capacity. Based on the characteristic power curve and hourly wind resource data from the study site, annual optimal gross electricity output is calculated to be 127.28 GWh and on-grid power 95.97 GWh. The construction of the wind farm takes 12 months from 2013 while the operation period is expected to be 20 years.

2.2. Input-Output Analysis

The emission equations are derived from the literature of economic IO-LCA [17] and applied to carbon footprint calculations [17, 18].

The basic input-output model derives the total economic purchases (i.e., supply chain) across an economy required to make a vector of desired output $\mathbf{y}$, commonly called "final demand". In this paper, $\mathbf{y}$ is defined as the capital input of items as below:

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

where $\mathbf{x}$ is the vector (or list) of required capital inputs of sectors; $\mathbf{I}$ is the identity matrix;$\mathbf{A}$ is the direct requirements matrix; and y, is the vector of capital input of items. Terms in Eq. 1 represent the capital input itself ($\mathbf{I} \times \mathbf{y}$), contributions from the first level costs ($\mathbf{A} \times \mathbf{y}$), and those from the second level indirect costs ($\mathbf{A} \times \mathbf{A} \times \mathbf{y}$).

Once the supply chain is calculated, carbon footprint can be estimated by multiplying the output of each sector by its environmental impact per monetary unit of output:

$$\boldsymbol{C}_i = \boldsymbol{R}_i(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \quad (2)$$

where $\boldsymbol{C_i}$ is the vector of carbon footprint, and R_i is a matrix with diagonal elements representing the emissions per monetary unit of input for each sector.

2.3. Corresponding Relation

The corresponding sector and phase for each item of the wind farm fix assets can be identified in Table 1. Because of the deficiency of capital input in dismantling phase, we assume the cost for pull down project is equal to the construction project in construction phase, and the cost for transport the waste material is equal to the transportation in construction phase.

Table 1 The matchup of items, sectors and phases

Categories	Items	Sectors	Sector No.
		Construction	
Labor	Construction Project	Construction	24
Transportation	Transportation	Freight Transport and Warehousing	25
Equipment	Electric Equipment	Electric Equipment and Machinery	18
Electricity	Electricity	Electricity and Heating Power Production and Supply	22
Oil	Diesel and Petrol	Petroleum Processing and Coking	11
Materials	Construction Materials	Construction	24
Scientific Services	Designation and Management	R&D	29
Others	Others	Other Services	30
		Operating	

Labor	Staffs Wages and Welfares	R&D	29
Maintenance	parts	Electric Equipment and Machinery	18
Water	water	Gas and Water Production and Supply	23
	Dismantling		
Pull down	Pull Down	Construction	24
Transportation	Transportation	Freight Transport and Warehousing	25

3. Results and discussions

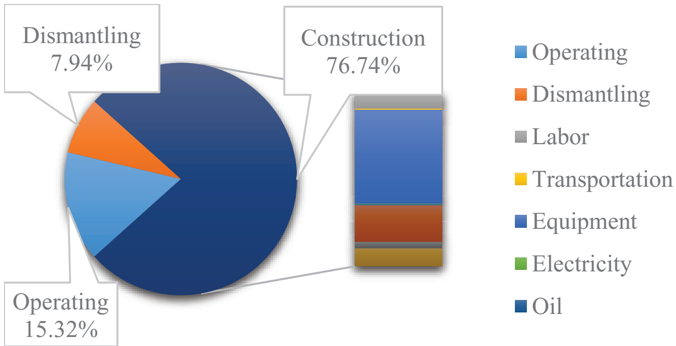

Fig. 1. Carbon footprint of various inputs

The total carbon footprint of the case wind farm is calculated to be 14,490 tCO_2 all over the 21 years lifetime. The construction phase discharges 11,120 tCO_2, accounting for 76.74%, of the total carbon footprint (see Fig.1). Followed is the operating phase with 2,220 tCO_2 emissions and a proportion of 15.32%, which has been considered to have no emissions or environmental impacts. Dismantling phase has a small emission of 1,150 tCO_2 and a proportion of 7.94%. The carbon footprint in construction phase is larger than those in operating phase and dismantling phase.

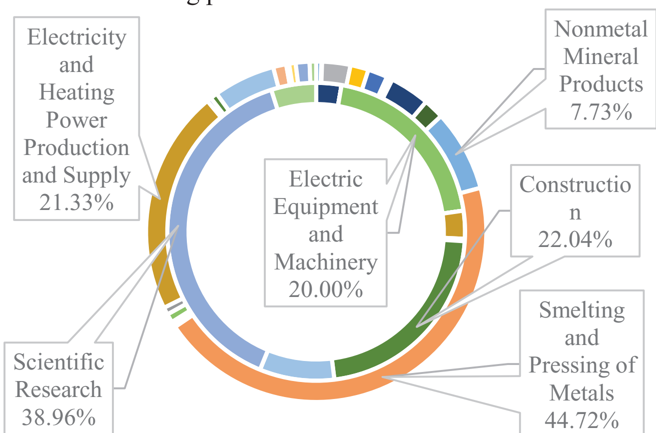

Fig. 2. The carbon footprint composition of direct emissions and total emissions

Fig. 2 illustrated the composition of direct emissions (the inner circle) and total emissions (the outer circle). Regarding direct emissions, three sectors, 'Scientific Research', 'Construction', 'Electric Equipment and Machinery', took the large three fractions of 38.96%, 22.04% and 20.00%, respectively. After multiplying by the Leontief inverse matrix, the real major emission sectors, i.e., 'Smelting and Pressing of Metals', 'Electricity and Heating Power Production and Supply' and 'Nonmetal Mineral Products', are identified.

4. Conclusion

In this study, a new carbon footprint accounting framework as a combination of process analysis and input–output analysis is presented in context of ecological economics for an environmental assessment of wind farm. According to the results, the direct carbon footprint is below 10% of the embodied carbon for the three phases, indicating the significant role of indirect carbon emission in the overall carbon footprint analysis.

The carbon footprint in the construction phase is larger than those of other phases. The carbon footprint of equipment made from Electric Equipment and Machinery sector derived indirectly and mostly from Smelting and Pressing of Metals sector as the largest carbon source of the construction phase of wind farm. Some technical improvements should be made, e.g., prolonging the wind turbines life span, advancing the technology in Smelting and Pressing of Metals industry, to mitigate the overall carbon emissions of wind farm.

In addition, uncertainty from the deficiency of temporal information cannot be ignored. By incorporating time-dependent technical parameters of material inputs, the DLCA proposed by Pehnt [19] and Yang and Chen [20] may help improve the accuracy of the conventional life cycle inventory for wind farms.

5. Copyright

Acknowledgements

This work was supported by the Fund for Innovative Research Group of the National Natural Science Foundation of China (No. 51421065), the China Sustainable Energy Program of Energy Foundation (G-1407-21749), Major Research Plan of the National Natural Science Foundation of China (No. 91325302), National Natural Science Foundation of China (Nos. 71573021, 41271543), and Specialized Research Fund for the Doctoral Program of Higher Education of China (No. 20130003110027).

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Biography

Bin Chen is a professor of energy science at Beijing Normal University. Dr. Chen has published over 200 peer-reviewed papers in prestigious international journals. He is also serving as subject editor of Applied Energy and editorial board member of more than ten journals.