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Life cycle assessment of CO_2 emissions from wind power plants: Methodology and case studies

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A B S T R A C T

Wind energy plays an increasingly important role in the world's electricity market with rapid growth projected in the future. In order to evaluate the potential for wind energy to mitigate the effects of climate change by reducing CO_2 intensity of the energy sector, this study developed a new direct and simple method for estimating CO_2 emissions per kWh produced during the life cycle of four representative wind power plants (three in developed countries and one in China). The life cycle analysis focuses on the wind power plant as the basic functional object instead of a single wind turbine. Our results show that present-day wind power plants have a lifetime emission intensity of 5.0–8.2 g CO_2/kWh electricity, a range significantly lower than estimates in previous studies. Our estimate suggests that wind is currently the most desirable renewable energy in terms of minimizing CO_2 emissions per kWh of produced electricity. The production phase contributes the most to overall CO_2 emissions, while recycling after decommission could reduce emissions by nearly half, representing an advantage of wind when compared with other energy generation technologies such as nuclear. Compared with offshore wind plants, onshore plants have lower CO_2 emissions per kWh electricity and require less transmission infrastructure. Analysis of a case in China indicates that a large amount of CO_2 emissions could be saved in the transport phase in large countries by using shorter alternative routes of transportation. As the world's fastest growing market for wind power, China could potentially save 780 Mtons of CO_2 emissions annually by 2030 with its revised wind development target. However, there is still ample room for even more rapid development of wind energy in China, accompanied by significant opportunities for reducing overall CO_2 emissions.

1. Introduction

In the past several years renewable sources of energy have won the support of governments in several countries, which has taken the form of various legal frameworks with stable and lasting premiums [1]. Wind energy, together with hydroelectricity, solar energy and biomass, is one of the most promising renewable energy sources. During operation, wind power plants are friendly to surrounding environments, releasing no direct emissions, harmful pollutants or CO_2. Newer technologies have made the utilitization of wind energy much more efficient and cost-effective. Wind is arguably the most convenient method to generate electricity in remote locations. Wind turbines use less space than an average coal-fired power station. With these advantages, wind power is playing an increasingly important role in the global electricity market. In 2009, global cumulative installed capacity reached 158,505 MW (MW $= 10^6$ W), eleven times of that in 1996 [2]. Recent developments in wind energy have been particularly rapid with the annual growth rate of global installations reaching 29% and 32% in 2008 and 2009 respectively [2,3].

The total electricity generation from wind turbines installed globally reached 340 TWh (TWh $= 10^{12}$ Wh) by the end of 2009, contributing 2% of the global electricity supply [4]. Denmark generates 20% of its electricity using wind. In Portugal, this figure is 15%, followed by 14% in Spain [2,4]. China doubled its capacity from 12.2 GW (GW $= 10^9$ W) in 2008 to 25.8 GW in 2009, becoming the world's largest market for wind energy [2]. About 1.4% of the total electricity consumption in China is now supplied by wind [5,6]. Current forecasts predict that annual growth rates from 2009 to 2014 will average 20.9% in terms of total installed capacity. These rates are modest compared to past developments: in the last ten years, we have seen an average increase of over 28% for both total and annual capacity additions [2].

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The process of converting the kinetic energy of the wind into electricity directly creates no forms of pollution or CO_2 emissions. But if one takes the whole life cycle of wind turbines into consideration, the manufacturing, transport and disposal of wind turbines do have quantifiable environmental impacts. If the current growth rates of wind energy are maintained in the future, as forecasted by various projections [2], it becomes crucial to understand and quantify the full extent of wind energy's impact on the climate, especially for those countries which already have relatively low carbon emissions per kWh or possess great wind resources. Only by quantifying the environmental impact of wind energy throughout the entire life cycle will we be able to evaluate the true potential of wind energy to mitigate climate change. This study thus aims to analyze the environmental impact of wind energy with respect to CO_2 emissions, considering the whole life cycle of wind power plants.

There are three differences between our study and previous academic studies published. First is on the scope of analysis. In previous life cycle analyses of wind energy, the focus has mainly been on individual wind turbines with rated power outputs ranging from 100 kW to 4.5 MW rather than on entire wind power plants [2,7–9]. Only two studies surveyed have considered wind power plants, but these plants consisted only of wind turbines with relatively small rated power outputs ($\leq$500 kW) [10,17]. As the wind power plant is in fact the smallest and most basic functional object and turbines of larger rated power outputs become more and more common, there is a need to update these studies. In this study, we discuss the differences in CO_2 emissions between wind turbines and wind power plants. The second difference concerns methodology. Previous studies of this topic have depended mostly on Life Cycle Assessment (LCA) software [1,7,8,10,12,13,17–20]. In this study, a simple method that adopts the same basics of LCA but avoid using an LCA software for better transparency in calculation processes has been developed and evaluated to calculate the direct and indirect CO_2 emissions related to wind energy. Third, our study provides data from a real case study of a wind power plant in China, and in particular those CO_2 emissions associated with the transport phase. This study assesses the potential for reducing CO_2 emissions from turbine transport and suggests greater implications for wind energy development in large developing countries.

Four cases of wind power plants are studied in this paper. Among the three general cases in developed countries, two use 3.0 MW wind turbines and the third uses 1.65 MW wind turbines. The fourth case is a wind farm in China installed with 800 kW turbines. Three of the four cases are onshore wind power plants and one is offshore.

2. Methodology

In this study, the amount of CO_2 emitted per kWh of electricity generated was selected as the indicator of the environment impact of wind energy. First, raw material consumption and electricity production during the lifetime of individual wind power plants within the system boundary was collected. Then, the emission factor provided by in the IPCC Guidelines for National Greenhouse Gas Inventories [11] was adopted to calculate CO_2 emissions from different materials. Finally, the CO_2 emission per kWh electricity produced was evaluated. An advantage of this calculation is the transparency of the whole calculation process and associated results. Besides the material consumption statistics from the turbine producer (Vestas in this study) and the emission factor from IPCC, other data or particular software is needed for the study.

2.1. CO_2 emission calculation

The calculation of CO_2 emissions is based on the following formula:

$$\begin{aligned}\text{Emission} &= \sum_{i=1}^{n} \text{Emission}_i \\ &= \sum_{i=1}^{n} \text{Activity Level}_i \times \text{Emission Factor}_i \qquad (1)\end{aligned}$$

Emission_i: Amount of CO_2 emitted from the consumption of material *i* (e.g. iron).

Activity Level_i: Material consumption for material *i*.

Emission Factor_i: Consumption of material *i*'s emission factor.

In this study, the Activity Level is the quantity of the material and energy consumed during the process of production, transport, operation and disposal in the life cycle of the wind turbine and wind power plant. The Emission Factor related to a certain kind of consumption was selected from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* [11].

2.2. System boundary

For this study, the limits of the system include the following four phases in the life cycle of the wind power plant: the production and transport of the components of the power plant, the operation of the wind plant which includes reconditioning and renewal of the components, and finally, the disposal (including recovery) of the material consumed over its lifetime.

As far as the research object is concerned, each wind power plant includes two parts: wind turbines (foundation, tower, nacelle, and rotor) and transmission (internal cables, transformer stations and external cables).

2.3. Functional unit

The kWh electricity produced by the wind power plant was selected as the functional unit for the evaluation of CO_2 emissions. A relationship will be developed between the CO_2 emissions of the plant and the electricity it generates. In this way it is possible to make a posterior comparative study with regards to other kinds of energy producing technology. The outcome of the calculation will be presented in the form of g CO_2/kWh, also called 'intensity index' in other studies [7].

3. Case studies

3.1. Basic information

This study focused on four cases, in which the research subjects are three wind power plants in developed countries (1–3) and one typical plant (4) in Chifeng, Inner Mongolia, China. As mentioned in the methodology section, each wind power plant basically includes wind turbines and transmission equipment. Table 1 shows the basic information and energy production of these farms.

The 1.65 MW wind turbine is a Vestas V82 model, of which there are currently 2733 installed globally, and the 3.0 MW turbine is a V90 model, of which 1560 have been installed [14]. These two types of wind turbines account for 11.8% and 12.2% of the total global installed capacity of Vestas turbines respectively. Vestas has the largest market share globally of wind turbine manufacturers and has the largest installed capacity of an international companies working in China. The wind power plant in China uses Vestas V52 model 850 kW wind turbines, which is currently the most common type of turbine in China's wind power market.

The focus of case 1, 2 and 3 is on the amount of CO_2 emissions during the lifetime of wind power plants. The study of case 4 focuses on emissions during the transport phase.

Table 1
Basic information of the four wind power plants [12,13,16].

Wind power plant number	Type of wind power plant	Type and number of wind turbine	Capacity factor %	Life time/ year	Electricity production/ GWh/year
1	Onshore	186*1.65 MW	40.7	20	1073
2	Offshore	100*3.0 MW	54.16	20	1423
3	Onshore	100*3.0 MW	30.02	20	789
4	Onshore	116*850 kW	23.0	20	198

3.2. Material consumption and emission factors

The material consumption during the different phases in the lifetime of the three target wind farms is represented in the Activity Level in equation (1). Table 2 shows the overall material consumption of wind power plant 1 in detail.

According to 2006 IPCC Guidelines for National Greenhouse Gas Inventories [11], the production process of eight types of materials and their chemical components listed in Table 2 will cause direct or indirect CO_2 emission during the lifetime of the wind turbine. We hereafter refer to them as *related materials* in the CO_2 calculation. Table 3 lists the consumption level of related materials for wind power plants 2 and 3.

Hard coal, crude oil, lignite and natural gas are the energy resources used primarily in the production of the materials and components used in the wind power plant. Iron and limestone are the main materials used in the production of steel. Furthermore, crude oil is used as transformer oil and as well as in the production of plastics among epoxy for the blades. Besides iron, aluminum is the most commonly used metal in the wind power plant, employed, for example, in the plat former of the towers and cables. Zinc is also used in the metalizing of the tower and offshore foundations of the wind turbine. The material consumption in the transmission represents the basis for the difference in CO_2 emissions between the wind power plant and wind turbine. The statistics in Table 3 shows that this difference is significant in the case of offshore power plants, in which the fraction of the transmission materials accounts for 15.5% of the total mass. This fraction is less than 1% for onshore wind plants.

Table 4 shows the mass of the components for wind power plant 4 and the amount of diesel consumed during transportation from the manufacturer to the site of the power plant. The course of transportation in this case is illustrated in Fig. 1. The amount of diesel fuel consumed during the transport phase depends on the weight of the transported materials and the distance traveled. Two courses are involved in this case, illustrated in Fig. 1. The rotor and nacelle are transported through course 1, while the tower and foundation of the turbines are sent via course 2 [16]. Transport routes for other components were not available, and so we give a range of associated emissions instead of one specific quantity.

Corresponding emission factors for the materials are chosen from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, as shown in Table 5. Vestas has manufacture factory around Asia, North America, Europe and other places in the world. Therefore, the default emission factor of IPCC is applied in our paper. Energy, mineral industry and metallurgy are three main sources of CO_2 emissions, and energy holds the biggest emission intensity. Although emission factors may vary by industrial process, we chose the same default value for different cases in order to compare the environmental impact of different wind power plants.

4. Results and discussion

4.1. Calculation results

CO_2 emissions could be calculated from the activity level and emission factor, the results of which are shown in Table 6 and Fig. 2.

For wind power plant 1, energy and metallurgy contributes over 98% of total lifetime CO_2 emissions, which is attributed to the large amount of material consumption and high emission factors (Fig. 2a). Among the four phases in the life cycle, the production phase produces the most emissions, followed by the transport phase. The operation phase has very little impact (Fig. 2b). These results are generally acknowledged in previous studies [1,7,10,20]. Due to the expectation that much of the plant will be recycled, the disposal phase will recover about half of the amount of CO_2 emitted from the production phase. Although there may be some negative impact involved in the recycling process (such as the necessary transportation of materials), the disposal phase ultimately presents net positive effects, which is one advantage of wind energy in comparison to nuclear, a point that should not be underestimated. Without disposal, the environmental impact of wind power plants will increase by approximately 87.6%.

Previous studies indicate that the wind turbines with higher rated power have lower CO_2 emissions [7,12,13,17]. This finding is reiterated in this study through the comparison of wind plant 1 with plants 2 or 3. This is due primarily to economies of scale: small wind turbines require more life cycle energy per unit of power generated than larger ones. This phenomenon will be more pronounced the larger the difference in the rated power between the two wind turbines.

Table 2
Consumption of materials in wind power plant 1.

Materials of wind power plant/kg	Total/kg	Production/kg	Transport/kg	Operation/kg	Disposal, incl. recovery of metals/kg	Involved in CO_2 emission
Water (fresh)	7.43E+08	1.32E+09	1.33E+06	2.60E+03	−5.81E+08	×
Stone	7.03E+07	7.03E+07	0.00E+00	3.14E-03	7.68E−06	×
Inert rock	4.08E+07	3.80E+07	0.00E+00	0.00E+00	2.80E+06	×
Hard coal	2.16E+07	4.33E+07	2.91E+04	3.55E+03	−2.17E+07	√
Iron	1.95E+07	7.85E+07	5.72E+02	4.68E+00	−5.91E+07	√
Crude oil	1.40E+07	1.06E+07	5.93E+06	1.98E+05	−2.75E+06	√
Natural gas	1.03E+07	9.55E+06	3.55E+05	2.79E+03	4.10E+05	√
Limestone	6.39E+06	6.44E+06	1.25E+03	8.29E+01	−4.62E+04	√
Lignite	4.40E+06	5.10E+06	5.22E+02	2.23E+01	−7.01E+05	√
Sodium chloride (rock salt)	2.72E+06	2.76E+06	8.20E+02	2.09E+00	−4.71E+04	×
Quartz sand	2.41E+06	2.42E+06	8.59E+00	2.45E+01	−1.09E+04	×
Soil	6.73E+05	6.71E+05	0.00E+00	0.00E+00	1.28E+03	×
Kaolin	3.88E+05	3.88E+05	0.00E+00	0.00E+00	8.09E−01	×
Gypsum	2.82E+05	2.82E+05	0.00E+00	0.00E+00	3.03E+01	×
Dolomite	2.17E+05	6.70E+05	0.00E+00	0.00E+00	−4.53E+05	√
Colemanite	2.16E+05	2.16E+05	0.00E+00	0.00E+00	4.51E−01	×
Aluminum	1.62E+05	1.74E+05	4.57E+02	1.87E+00	−1.28E+04	√

Note: The statistics directly adopted from Vestas' report [12].

Table 3
CO_2 emission from related material in wind power plant 2 and 3.

Wind power plant 2 (offshore)			Wind power plant 3 (onshore)		
Material of wind power plant involved in CO_2 emission	Turbine/kg	Transmission/kg	Material of wind power plant involved in CO_2 emission	Turbine/kg	Transmission/kg
Hard coal	1.86E+07	1.65E+06	Hard coal	9.67E+06	0.00E+00
Crude oil	9.94E+06	6.65E+06	Crude oil	7.94E+06	1.07E+04
Natural gas	8.75E+06	1.35E+06	Natural gas	6.22E+06	3.39E+03
Lignite	7.63E+06	1.16E+06	Lignite	5.15E+06	4.30E+02
Limestone	3.40E+06	1.14E+05	Limestone	1.48E+06	3.02E+02
Iron	1.17E+07	4.84E+04	Iron	6.23E+05	3.17E+01
Zinc	1.12E+06	2.44E+04	Zinc	2.08E+05	0.00E+00
Aluminum	1.95E+05	1.22E+05	Aluminum	7.81E+04	1.29E+02
Lead	4.33E+02	8.60E+04			

Note: The statistics directly adopted from Vestas' report [13].

4.2. *Onshore and offshore*

Since the ocean in general provides better wind conditions, offshore wind power plants typically have higher capacity factors than those onshore (Table 1; Fig. 3). This is why offshore wind farms are currently favored despite higher costs. However, the comparison between plant 2 and 3 shows the ultimate advantage of onshore wind power plants with respect to CO_2 emissions. Better wind conditions experienced by offshore power plants cannot cover the higher environmental costs created by the additional efforts in construction, such as boat landing platforms, external sea cables and offshore transformer stations. Therefore, offshore power plants have higher CO_2 emission per kWh. This conclusion is consistent with previous studies [17–19]. However, compared with the CO_2 emission per kWh produced from traditional energy sources, the offshore wind farms still create significantly less CO_2 emissions.

4.3. *Wind turbines and wind power plants*

To date, most studies have focused mainly on the wind turbine itself and have failed to discuss the differences between the turbine and power plant. An entire wind power plant is in fact the smallest and most basic functional object in assessing the environmental impact of wind power. Each wind power plant includes wind turbines and transmission parts (internal cables, transformer stations and external cables). Thus, CO_2 emissions from a wind power plant will be higher than the sum of the individual wind turbines installed in the plant as there are additional emissions from the transmission parts. However, the difference between them varies from case to case. Fig. 3 shows CO_2 emissions per kWh attributed to turbines and transmission in case 2 and case 3. The transmission parts play a relative more important role in the offshore power plant, which accounts for up to 19.34% of total emissions. In contrast, for the onshore farm, transmission parts represent less than 1% of total emissions. To better assess CO_2 emissions from offshore wind, it is important to focus on the whole plant instead of the individual turbines. For the onshore plant, however, this difference can be ignored. This result also demonstrates how the system boundaries of a study have definitive influences on the results.

4.4. *Emissions from transport*

Since many countries with high potential for wind power have large amounts of land, such as China, Russia and Canada, the transport-related emissions involved in the utilization of wind power can be significant and thus deserve careful analysis. We gave a range of CO_2 emissions per kWh electricity from the transport phase for a wind farm in inland China (case 4), which is lower than the corresponding value in case 1. This difference could be due to the difference in components' mass between the two cases: the total mass of case 1 is around ten times of that in the case 4 which is likely due to the large foundations (832 ton) of the turbines in case 1, which have with higher rated power [12]. The higher mass results in more oil consumption during the transport phase. However, a large amount of CO_2 emissions can still be saved by charting shorter transportation routes. We can see from case 4 using shorter transportation routes can reduce related emissions by 33%, with total savings of 346 ton CO_2 for this 116*850 kW scale wind power plant. Therefore, it is important for large countries to build distributed manufacturers of wind turbines near wind resources and potential locations of wind power plants. Whenever possible, transport by boat or train is preferred to trucks to reduce the carbon intensity in long distance transport [7].

4.5. *Comparison with other energy sources*

Table 7 compares CO_2 emissions per kWh of electricity produced by different energy resources [19]. Previous estimates for wind power ranged by more than a factor of 10, from 10 to 124 g CO_2/kWh, due to the smaller and less efficient wind turbines included in studies. With more advanced technology, the efficiency of wind power has increased and old types of turbines with lower rated

Table 4
Mass of individual components of wind power plant 4 and diesel consumption [15].

Case 4	Component	Mass/ton	Percent (%)	Diesel consumption/L
Wind Turbine	Tower	5.97E+03	31.8	4.73E+04
	Nacelle	2.73E+03	14.5	5.20E+04
	Rotor	1.28E+03	6.8	5.20E+04
	Foundation	5.97E+02	3.2	6.30E+03
	Total (turbine)	1.06E+04	56.4	1.58E+05
Other component of wind power plant	Internal cables[a]	4.69E+02	2.5	6.30E+04 ~ 1.73E+05
	Transformer station	4.69E+02	2.5	
	External Cables[a]	6.57E+03	34.9	
	Total (other components)	8.18E+03	43.5	6.30E+04 ~ 1.73E+05
Total		1.88E+04	100.0	2.21E+05 ~ 3.31E+05

[a] Masses of internal and external cables are not available from the reference. We estimate them by their ratio to the mass of the transformer in case 1.

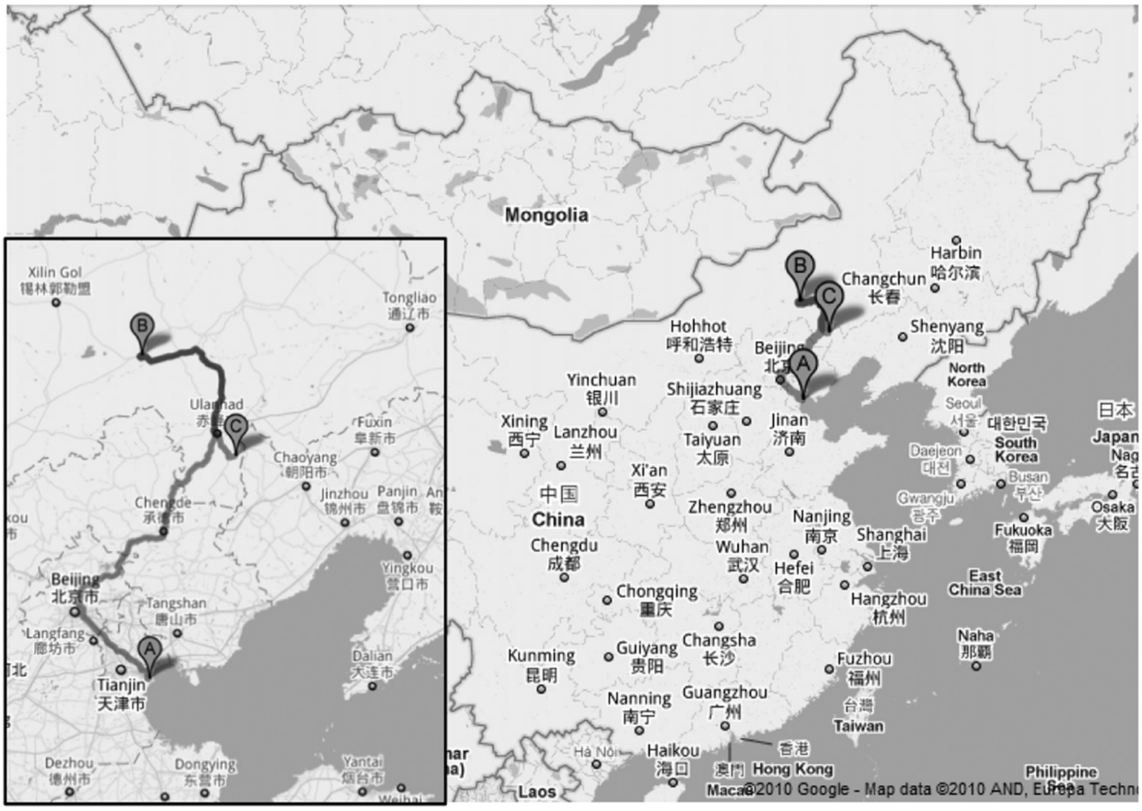

Fig. 1. The transport courses of case 4. Inset shows the zoom map of the courses. A: manufacturer of the rotor and nacelle; B: wind power plant; C: manufacturer of tower and foundation. Course 1: A–B 817 Km, course 2 C–B 297 Km.

power have become less common. Our study represents an important update to previous estimates and gives a more specific range, from 5 to 9 g CO_2/kWh. This places wind as the most environmentally desirable renewable energy, with the lowest amount of CO_2 emissions per kWh of produced electricity.

Compared with fossil fuel, it is obvious that renewable energy, especially wind energy, has significant potential to mitigate climate change. For every kWh of electricity generation, the amount of CO_2 emitted from coal-, oil- and gas-fired power plants is 154, 117 and 96 times that of wind power respectively, taking average emissions of 6.3 g CO_2/kWh for wind.

4.6. *Benefits of wind power in China*

The demand for electricity in China is currently increasing at an annual rate of ~10% [23] and China reached a total electricity generation of 3.66 PWh ($P = 10^{15}$) in 2009 [6]. It is estimated that China's production of electricity will increase to 9.24 PWh by 2030 [6,23]. If this additional electricity is supplied mainly by coal, CO_2 emissions are expected to increase by as much as 5.6 Gtons of CO_2 per year by 2030. China is now the world's fastest growing market

Table 5
Emission factors from the 2006 IPCC Guidelines for national Greenhouse gas Inventories [11].

Material of wind power plant involved in CO_2 emission	Emission factor
Hard coal, kg CO_2/TJ	98,300
Crude oil, kg CO_2/TJ	73,300
Diesel oil, kg CO_2/TJ	74,100
Natural gas, kg CO_2/TJ	56,100
Lignite, kg CO_2/TJ	10,100
Limestone, ton CO_2/ton	0.44
Dolomite, ton CO_2/ton	0.48
Iron, ton CO_2/ton	1.35
Zinc, ton CO_2/ton	1.72
Aluminum, ton CO_2/ton	1.65
Lead, ton CO_2/ton	0.52

Table 6
Breakdown CO_2 emissions from the life cycle assessment of the four wind power plants.

Wind power plant	Item	CO_2 emission/g/kWh	Percent (%)
Case 1186*1.65 MW Onshore (by material)	Hard coal	2.84	34.6
	Crude oil	2.21	26.9
	Natural gas	1.37	16.7
	Lignite	0.354	4.3
	Iron	1.28	15.6
	Aluminum	0.013	0.2
	Limestone	0.137	1.7
	Dolemite	0.005	0.1
	Total	8.21	100.0
Case 1186*1.65 MW Onshore (by phase)	Production	14.40	175.4
	Transport	0.99	12.0
	Operation	0.03	0.4
	Disposal	−7.20	−87.7
	Total without disposal	15.40	187.6
	Total	8.21	100.0
Case 2100*3.0 MW Offshore	Turbine	4.86	81.27
	Transmission	1.12	18.73
	Total	5.98	100.00
Case 3100*3.0 MW Onshore	Turbine	4.96	99.94
	Transmission	0.003	0.06
	Total	4.97	100.00
Case 4116*850 kW Onshore	Transport	0.19–0.28	

Note: CO_2 emissions from the 186*1.65 MW power plant (wind power plant 1) are given in two forms by different materials and by different life cycle phases.

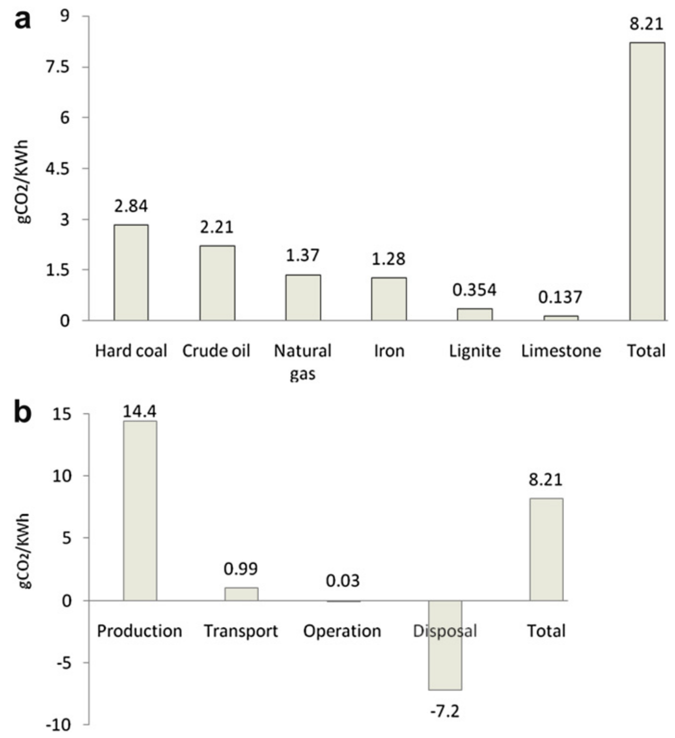

Fig. 2. CO_2 emissions per kWh in lifetime of wind power plant 1. (a) CO_2 emissions per kWh attributed to consumption of different materials; (b) CO_2 emissions per kWh attributed to different life cycle phases.

Table 7
CO_2 emissions per kWh electricity from different energy sources [19].

Power systems	CO_2 emission/g/kWh
Coal-fired	975.3
Oil fired	742.1
Gas fired	607.6
Nuclear	24.2
Solar PV	53.4–250
Solar thermal	13.6–202
Biomass	35–178
Hydro	3.7–237
Wind	9.7–123.7
Wind (This study)	4.97–8.21

for wind power and has large potential for wind electricity. Previous analysis indicated that a network of wind turbines operating at as little as 20 percent of their rated capacity could provide as much as 24.7 PWh of electricity annually, or more than seven times China's current consumption [23]. In 2007, China set a goal of installing 30 GW of wind energy by 2020, as elaborated in the central government's Plan of Long-term Development for Renewable Energy. In 2009, the installed capacity in China has already passed 25 GW [21]. It is anticipated that China will extend the target to a total installed capacity of 300 GW by 2030 [22]. With this new target, if the average capacity factor for wind turbines in China is assumed to be 30%, wind could provide 0.79 PWh of electricity annually, theoretically reducing 780 Mtons of CO_2 emissions that would have been generated by coal-fired power plants. In this case, however, wind electricity would supply 8.5% of China's total electricity demand in 2030, still below that of present-day conditions in some European countries. There is ample room for faster development of wind energy in China accompanied by larger CO_2-saving potential. The current challenges facing China include efficient connection of wind electricity to existing electricity grid, improvement of turbine quality, and development of an integrated national grid with management protocol suitable for taking renewable electricity supplies that are intrinsically variable.

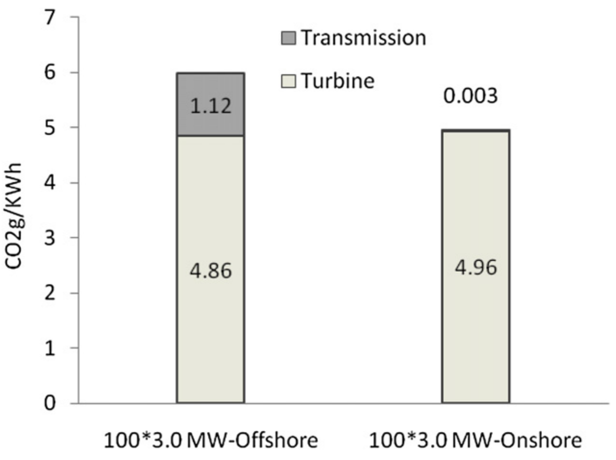

Fig. 3. CO_2 emissions per kWh attributed to turbine and transmission.

4.7. Sensitivity analysis and method testing

Sensitivity analysis helps investigate how the variation (or uncertainty) in the output of a mathematical model can be apportioned, qualitatively or quantitatively, to different sources of variation in the input parameters of a model. Put differently, it is a technique for systematically changing parameters in a model to determine the effects of such changes [24]. In this study, the capacity factor (CP) could be influenced by wind conditions, turbine technology, rated power and many other factors, so it is crucial in this calculation as it determines the quantity of electricity generation from wind power plants. In case 1, whose CP = 40.7%, a 10% increase of CP will result in 8% decrease in CO_2 emissions per kWh. This means that the sensitivity of the CP to the result is about −0.8. The sensitivity of a 10% CP increase for other cases is shown in Table 8. The case with higher original CP would have higher sensitivity of CP, which means the marginal benefit on CO_2 emissions will increase with increasing CP. Therefore, the measures taken to increase the CP would be more rewarding.

Table 9 compares our results with those derived from LCA for the same cases [12,13]. Compared with the range of estimates for renewable energy listed in Table 7, the difference between our method and LCA is small and could be attributed to different assumptions and the choice of emission factors used in the calculation. Emission factors embedded in LCA are mostly European or Danish averages, therefore representing state-of-the-art wind power technologies. Our choice of emission factors is based on the international default values recommended by IPCC, which are always higher than LCA's. The methods used in this study are general but simple and can directly present emissions from different material consumption and from different phases.

Table 8
Sensitivity of capacity factor.

Case	Capacity factor	Sensitivity
1	40.7	−0.80
2	54.16	−0.84
3	30.02	−0.75

Table 9
Results of LCA and of this study.

Wind power plant	LCA result from Veatas g [CO_2]/kWh	Result in this study g [CO_2]/kWh
Case 1186*1.65 MW Onshore	6.59	8.21
Case 2100*3.0 MW Offshore	5.23	5.98
Case 3100*3.0 MW Onshore	4.64	4.97

Admittedly, the emission factors and results may vary case by case. However, the results could still give us useful information about the environmental impact of wind power plants.

5. Conclusions

This study developed a new simple and direct method for calculating CO_2 emissions per kWh electricity produced by wind power plants. The results obtained herein confirm that wind energy produces the lowest CO_2 emissions per kWh of electricity compared to fossil fuel and other renewable sources. Energy and metallurgy dominate CO_2 emissions from material consumption. Among the four phases of the wind power plant's life cycle, the production phase of wind turbines contributes most to the total emissions. Recycling during decommission is an important step, which theoretically can decrease the impact from the production phase by nearly half. Optimal management in the transport phase could reduce overall CO_2 emissions by as much as 12% of the total emissions of a power plant, even with recycling. For countries with large wind potential and large territories, a large amount of CO_2 emission could be saved in the transport phase. The result of a real case in China shows that with reasonable shorter transport routes, the related emissions could be reduced by 33%.

Compared with offshore wind plants, onshore ones have lower CO_2 emissions per kWh electricity produced. The difference in CO_2 emissions between wind turbines and wind power plants is significant and should not be ignored when considering the CO_2 emissions related to offshore power plants.

If China can reach a total installed capacity of 300 GW in 2030 as predicted, annual savings of CO_2 emissions could amount to 780 Mtons. In this case, however, wind electricity would supply just 8.5% of China's total electricity demand in 2030, lower even than present-day condition in Europe where wind electricity accounts for 4.8% of the total energy consumption. There is ample room for more rapid development of wind energy in China accompanied by larger CO_2-saving potential. Compared with other energy sources, wind power has the greatest potential to reduce CO_2 emissions, especially through onshore, large rated power turbines that have low emission per functional unit. Sensitivity tests show that the measures taken to increase the CP would result in significant emissions reductions. Obviously, the use of wind to produce electricity constitutes an environmental improvement, and more research on this technology is needed.

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