ELSEVIER

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 20 (2012) 402 – 413

Energy Procedia

Technoport RERC Research 2012

Influence of site specific parameters on environmental performance of wind energy converters

Till Zimmermann[a*], Stefan Gößling-Reisemann[a]

[a]*University of Bremen, Enrique-Schmidt-Straße 7, D-28259 Bremen, Germany*

Abstract

Wind energy is supposed to provide the world with “clean” energy, reducing the emission of anthropogenic greenhouse gases and other environmental impacts. While the energy produced in the use phase of wind energy converters (WEC) is as good as carbon neutral there are environmental impacts coming from production, transport and disposal of the WEC. Here the question about the WEC's energy and CO_2 balance comes up.
For different converters, indicators like the CO_{2e} emissions per kWh (i.e. the carbon footprint), the energetic payback time and the harvest factor can be found in the literature. Since the underlying assumptions, boundary conditions, etc. will –in most cases- differ from each other, the results have only very limited comparability and allow drawing only general conclusions. Key indicators like the mentioned CO_{2e} emissions per kWh, the energetic payback time, etc. will vary for each of the assessed converters individually, depending on the respective site.
Factors like length of access roads and grid connection, size and depths of foundation, or wind conditions have an influence on the LCA results. Here, an assessment of a 2.3 MW wind energy converter at different sites will be presented, demonstrating which site specific factors are negligible and which are crucial for the environmental performance. Each aspect will be varied ceteris paribus showing the impact of every parameter individually.

Keywords: Wind energy; site influence; LCA; energy balance; CO2 balance; harvest factor

* Corresponding author. Tel.: +49 (0) 421-218-64893; fax: +49 (0) 421-218-98 64893.
E-mail address: tillz@uni-bremen.de.

1876-6102 © 2011 Published by Elsevier Ltd. Selection and/or peer-review under responsibility of the Centre for Renewable Energy.
Open access under CC BY-NC-ND license. doi:10.1016/j.egypro.2012.03.039

1. Introduction

The motivation of the increasing expansion of wind energy is to provide green (i.e. low carbon) energy. However, there are still environmental impacts like energy consumption and CO_{2e}-emissions etc. arising from resource production, manufacturing, transport, installation, dismantling and final disposal; but also from the use phase – due to energy consumption from grid to maintain certain functionalities in times without wind and due to service and maintenance. There are also some environmental impacts like land use, noise emissions, bird strike, and shadow casting that arise to a large share or even exclusively within the use phase. With an increasing share of renewable energy generation, the conflicts between different renewables and other land uses will become more prevalent. The choice between renewable technologies will have to include local and site-specific information as to optimize resource use and environmental performance.

The formerly mentioned environmental impacts (energy consumption, CO_{2e}-emissions, etc.) and resulting indicators like the energetic payback time, the harvest factor and the carbon footprint have been assessed in various studies (cf. [1–11]). Many studies focus on these indicators and neglect others since providing clean energy and saving CO_{2e} are the main reasons why wind energy converters (WEC) are built. Other 'classic' LCA impact categories like ozone depletion potential or acidification potential are sometimes also included in these assessments; however currently they are not in the focus of ongoing discussions around WECs.

Within the various studies assessing CO_{2e} emissions and energy balance, the results vary considerably and would also vary for each converter type individually – depending on the respective site – if site specific parameters would have been included in the assessment. However, site influence, as crucial as it is, is usually not explicitly discussed. Of course, wind conditions are an important aspect that differs from site to site. But there are other aspects, too, like length of access roads and grid connection, size and depth of foundation or service and maintenance intensity influencing the environmental performance. Based on previous works (cf. [3, 12, 13]) the influence of these site specific factors has been assessed and quantified within this study for a 2.3 MW onshore WEC.

2. Method

The influence of the site specific parameters has been assessed using a parameterized model within the LCA software GaBi 4.4. The WEC assessed within this model is a 2.3 MW converter with a pre-cast concrete tower and a hub height of about 98 meters which is located onshore. The inventory data used for this generic converter is mainly based on previous studies [3, 13]. Where necessary this data has been completed with data from LCA databases [14]. Within [3, 13] an extensive collection of primary data has been carried out in collaboration with Enercon as industry partner. Enercon's high in-house production depths granted access to production data for all major components and their respective production processes. Also, assistance was provided in identifying relevant site specific parameters. Raw material production, energy supply, transport to the site, production logistics and some pre-products (bearings, screws etc.) have been modeled using datasets from the GaBi (or PE International, respectively) database [14]. 500km of transport per truck and 200km per train from manufacturing to the site have been assumed.

Additional studies of 1.8 to 3 MW WEC have been used for validating collected data, identified relevant parameters, system boundaries and assumptions [1, 2, 9].

End-of-life has been modeled using system expansion and crediting. Based on primary data and literature [14–17] recycling rates of 80% have been assumed for steel and cast iron, and 95% for aluminum and copper at end-of-life. Incineration with energy recovery has been assumed for the rotor blades, and use as filling material in road construction has been assumed for the tower.

The result is a material flow model of the assessed 2.3MW converter with a parameterization that allows varying selected site specific factors. These factors include length of access roads and grid connection, foundation size, service intensity, and wind conditions. Table 1 shows the underlying inventory data on an aggregated level. The rotor blades of the assessed product system have a length of about 40m and consist mainly of glass fiber reinforced plastic (GRP). The nacelle includes the generator of the WEC as well as different cast iron parts like the rotor hub, axle pins, blade adapter and main carrier. Its casing is made of aluminum. The generator is an annular generator without gear. The assessed WEC uses a precast concrete tower with pre-stressed steel reinforcements. The electrics include components like printed wiring boards but also power cabinets etc. that are made of steel. The foundation consists of concrete as well as steel reinforcements.

For the required materials and involved processes connected to the site specific parameters (e.g. excavation for road building and foundation, production of cables, steel reinforcement and concrete) PE datasets have been used, too [14].

Table 1. Aggregated inventory details for assessed 2.3 MW converter

Material	**total [t]**	**rotor blades [t]**	**nacelle [t]**	**tower [t]**	**electrics [t]**	**foundation [t]**
steel	~246	~1.1	~53	~103	~37	~52
cast iron	~73		~72.5		~0.5	
aluminum	~1.3	~0.1	~1.2			
copper	~11		~10		~1	
GRP	~29	~29				
concrete	~1,880			~790		~1,090
Total	**~2,240**					

Each of the site specific factors has been varied ceteris paribus within the parameterized model to assess its influence on the environmental performance; the harvest factor (net energy production divided by cumulated energy demand) and the specific carbon footprint (grams CO_{2e} per kWh) have been chosen as indicators, here.

The influence of the parameter variations are shown relatively to a base scenario whose configuration is being shown in **Feil! Fant ikke referansekilden.**.

Table 2. Parameter settings for base scenario

WEC type	generic 2.3 MW WEC
annual full load hours	2,425
length access roads [m]	150
length grid connection [m]	150
service trips per year	5
distance to service station [km]	150
power consumption (from grid; kWh/a)	3.500
life span [a]	20

2.1. Performance indicators: harvest factor and carbon footprint

Two indicators have been chosen for describing the energetic performance and the environmental load: the harvest factor and the (specific) carbon footprint.
The harvest factor is the ratio of the energy fed into the grid by the WEC and the cumulated energy demand, i.e. the electricity output minus the power consumption divided by the cumulated energy demand:

$$harvest\ factor = \frac{net\ energy\ production}{cumulated\ energy\ demand}$$

The specific carbon footprint indicates the CO_{2e} emissions per kWh, i.e. the global warming potential over the life cycle (in grams of CO_2 equivalents) is divided by the net energy production (i.e. the net electricity output):

$$specific\ carbon\ footprint = \frac{global\ warming\ potential}{net\ energy\ production}$$

In the result section both indicators will be given as percentage values for each parameter variation emphasizing the change compared to the basic scenario.

2.2. Length of access road

Access roads are required to transport components, equipment etc. to the site. Depending on the location of the site, the length of these access roads varies for each site. A generic access road with a depth of 0.5 meters and a width of 4 meters with adjustable length has been used in the model.

For this study, the length of access roads has been varied from 0 to 4,000 meters which is considered as a range covering most onshore sites in northern Germany based on information from the industry partner [13]. Varying just the length is, of course, a simplification since depending on the size of the WEC freights of up to some hundred tons need to be transported requiring different depths of the road in dependence of the condition of the soil. Also, it could be considered in a more detailed assessment that one road might be used for constructing multiple WEC. This would reduce the influence of road building on the individual WEC and should be considered especially for assessments of wind parks. However, the distance between the different WECs in one park is usually at least 3 or 4 times the rotor diameter equaling about 250m to 330m for the assessed 2.3 MW converter and requiring access roads of at least corresponding length. Against this background, varying the length of access roads regarding one converter is considered to be sufficient to demonstrate the potential influence of road building on the overall LCA results.

2.3. Length of grid connection

Just like the length of the access roads the grid connection depends on the location of the WEC's site. It influences the LCA results by two means: by additional environmental burdens arising from production, installation and disposal and by additional grid losses. But since only onshore sites are within the scope of this study the latter has not been regarded. For most sites in Europe grid connection will have a maximum length of a few kilometers and grid losses can be considered as marginal. In compliance with the access roads, length of grid connection has been varied from 0 to 4,000 meters given the same limitation that multiple converters might use a joint grid connection (with regard to their minimum distance) which was not considered here, either, but could of course be included in a subsequent, more detailed assessment.

2.4. Foundation size

Foundations for onshore WECs are usually made from concrete with steel reinforcements. Their diameter and depth depend on WEC and tower type as well as the soil condition, i.e. they also vary depending on the site. On the basis of a base scenario with 460 m^3 of concrete and 40 tons of steel reinforcement four alternative scenarios with +- 10% and +-50% of material have been assessed. This parameter range covers most sites in Western and Central Europe [13].

2.5. Service and maintenance intensity

Service and maintenance, e.g. the required number of service trips per year and the need of repairs, depends to some extent on the site, too. WEC that are exposed to rather turbulent wind conditions have, for example, a higher need of repairs then WEC at sites with lower and more constant wind speeds. Another factor is the distance to the nearest service station which affects the emissions caused by each trip.

To assess the influence of service and maintenance, different scenarios will be assessed, showing the influence of the number of service trips and the distance to the nearest service station. Five, seven and ten service trips as well as distances of 150km, 300km and 450km have been chosen, resulting in nine different scenarios. Each trip is considered with an average maintenance effort that is based on primary data [13] that refers to about 60% of installed WECs in Germany. Due to the use of average values for the maintenance effort, individual needs of repair, e.g. the replacement of major components due to turbulent wind conditions at a particular site are not considered; still, the chosen approach should be sufficient to give an impression of the average potential impact of service and maintenance on the overall results.

2.6. Wind conditions

Besides service intensity the wind conditions on the particular site evidently influence energy production as well as energy consumption. The wind conditions are usually measured with the number of full load hours per year. These are varied within the study from 2,000 to 3,600 hours per year, representing a range of medium-profit inland sites to high-profit near-shore sites.

The power consumption, i.e. power consumption for operation of control systems, pitch and yaw motors, obstruction lights, etc., in times of standstill depends obviously on the wind conditions, too. In accordance with primary data from the industry partner (Enercon, cf. [13]) valid for the 2.3MW converter E-82 E2 the power consumption has been varied from 800 kWh per year to 4,000 kWh. It can be assumed that the vast majority of onshore sites is covered by this range.

2.7. Tower heights and wind condition

When looking at one particular site, the number of full load hours is not a fixed figure. Depending on the hub height of the installed converter different numbers of full load hours can be achieved due to different wind conditions in different heights. This means, installing a higher tower which leads to an increase of the CED, results in an increased energy production at the same time. This influence has been assessed, too, comparing three hub heights (84m, 98m, 108m) and the resulting energy production for the converter type E-82 E2. Based on the wind conditions at 84 meters, the wind conditions in 98m and 108m are calculated using the Helman or power law [18, 19]:

$$v_2 = v_1 (\frac{h_2}{h_1})^{\alpha}$$

Here, v_2 and v_1 are the (average) wind speeds in heights h_2 and h_1, respectively, and α being the Helman (or power law/ friction) exponent [18, 19] which depends on the specific site. To analyze this aspect of site influence, different values (0.19; 0.33; 0.53) for α have been assessed, based on empirical values presented in [18]. Based on an average wind speed of 7.5m/s for a hub height of 84 meters resulting in 1,600 full load hours per year, the average wind speeds in 98 and 108 meters have been calculated according to the formula for different values of α. The results of this calculation are given in Table 4.

3. Results

The described parameters have been varied as described above showing their individual impact on the overall environmental performance. This impact is here analyzed by the two described indicators, harvest factor and specific carbon footprint. All results are compared to the described base scenario (see Table 2). The results for this base scenario are shown in Table 3.

Table 3. Results for base scenario

CED	2,881	[MWh]
global warming potential	901	[t CO_{2e}]
net energy production	113,905	[MWh]
harvest factor	39.5	[-]
energetic payback time	6,1	[months]
carbon footprint	7.9	[g CO_{2e}/kWh]

3.1. Variation of length of access roads

The variation of the length of the access roads shows an increase of the carbon footprint of up to 6.6% for 4,000 meters of access roads compared to the basic scenario. The harvest factor on the other hand is decreased by up to 7.6 percent. The results are also shown in Fig. 1.

However, this provides only an indication of the potential influence of road building on the WEC's environmental performance. Structuring etc. can be very different from case to case – leading to different environmental burdens. However, it can be said that this is an aspect that needs to be included in an assessment.

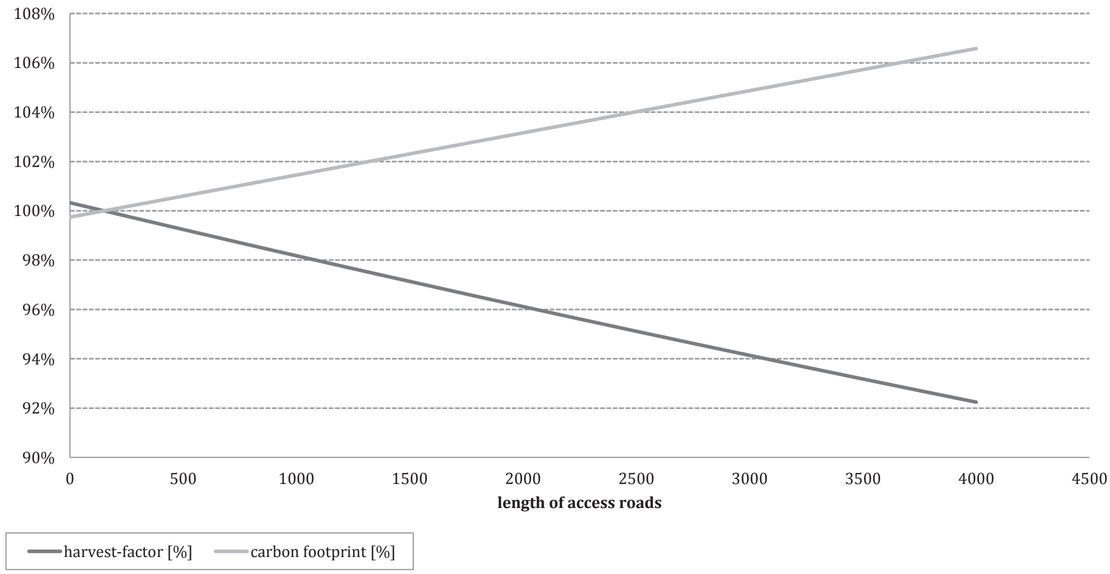

Fig. 1: Variation of length of access roads

3.2. Variation of length of grid connection

Varying the length of the grid connection shows only marginal impacts on the analyzed indicators. The carbon footprint is increased by 0.45 percent for 4.000 meters of grid connection, the harvest factor decreased by 0.65 percent.

3.3. Variation of foundation size

Analyzing different scenarios for the size of the foundation leads to an increase of the carbon footprint of up to 8.6 percent and a reduction of the harvest factor of over five percent. A smaller foundation shows the inverse effect. Fig. 2 gives an overview of the results for the assessed scenarios.

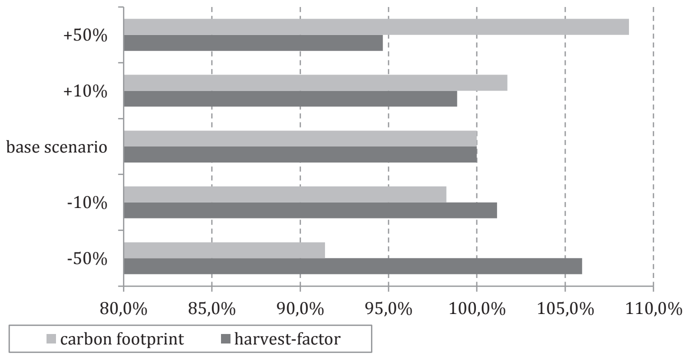

Fig. 2: Results for different foundation-scenarios

3.4. Variation of service and maintenance intensity

The service intensity appears to have only a little impact on the environmental performance. Only the scenarios with more than seven service trips per year and a distance of at least 300km to the nearest service station influences the carbon footprint by more than 2% and the harvest factor by more than 3%. However, it has to be noted that only averaged service trips are taken into account here. If larger components, like for example rotor blades, gear box or generator, need to be replaced this would lead to a significant increase of the environmental impacts. An overview of the results for the variation of the service intensity is given in Fig. 3.

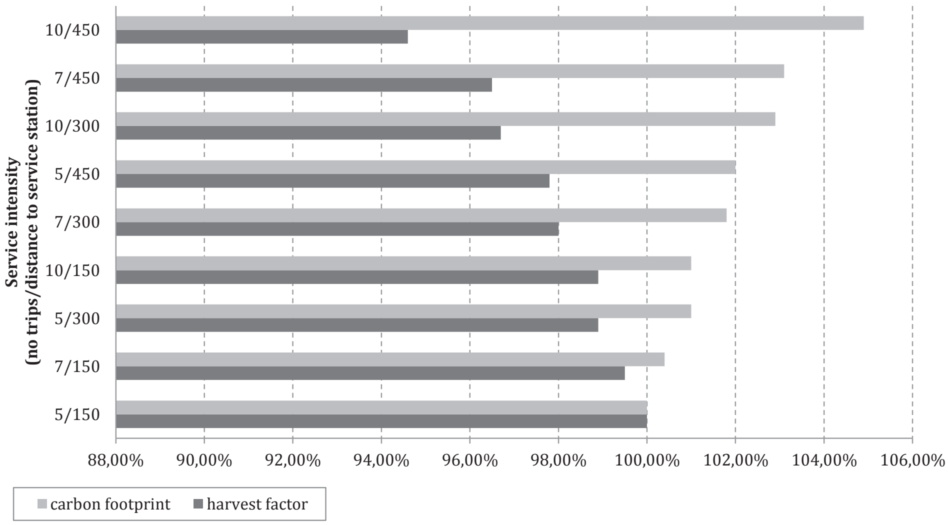

Fig. 3: Results for different service intensity scenarios

3.5. Variation of wind conditions

Not surprisingly, varying the number of annual full load hours leads to the most significant changes to the two indicators. The harvest factor decreases by almost 18 percent for 2,000 full load hours and increases by about 49 percent for 3,600 full load hours. With constant CED and GWP, the carbon footprint, as the reciprocal of the harvest factor increases by over 21 percent for 2,000 full load hours and decreases by 32.6 percent to 67.4 percent for 3,600 full load hours accordingly. The impacts of the variation of annual full load hours are also shown in Fig. 4.

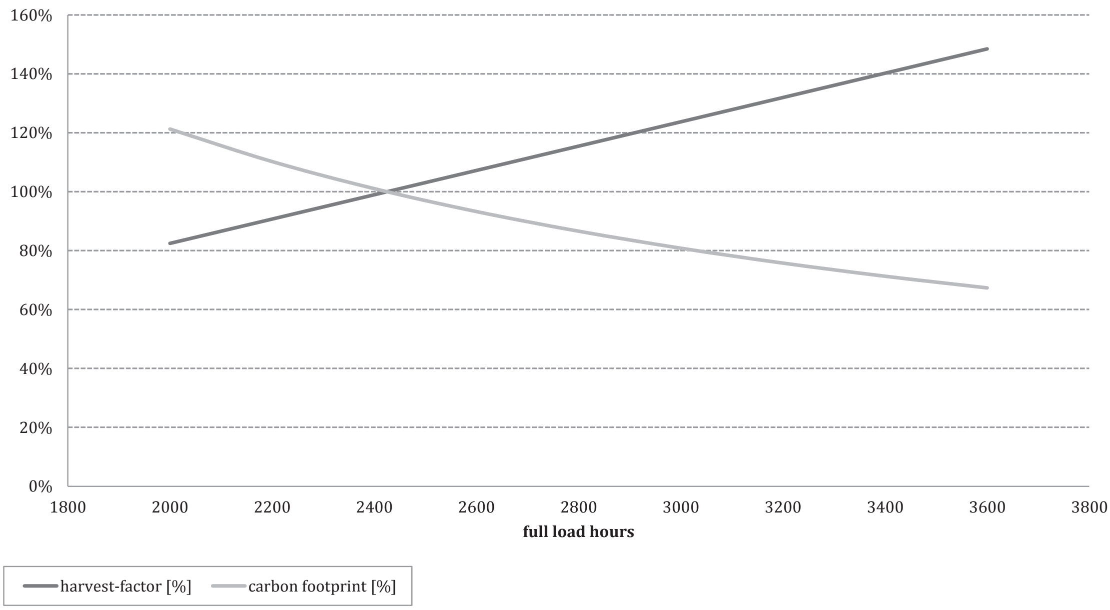

Fig. 4: Variation of annual full load hours

The other wind related parameter variation, i.e. the variation of the converter's energy consumption, shows an increase of the harvest factor of 6.5 percent for an energy consumption of 800 kWh per year and a decrease of the carbon footprint of 4.3 percent (see Fig. 5).

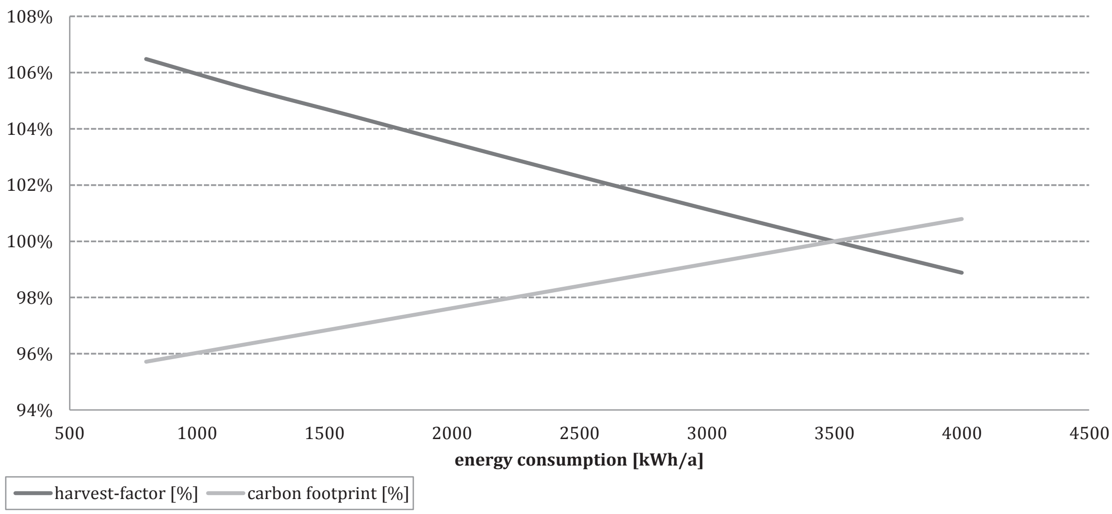

Fig. 5: Variation of converter's energy consumption

3.6. Variation of tower height and resulting wind conditions

Varying the tower height (and the hub height, respectively) results in changes of the number of full load hours. The results are given in Table 4. The table shows the results for different values of the power law exponent alpha.

It can be seen that in the assessed exemplary scenarios the (same) additional energetic investment of using a higher tower leads to quite different results in terms of the indicators of harvest factor and energetic payback time due to differences in the calculated wind conditions and the resulting energy production. While for $\alpha = 0.19$ the higher towers cause only a slight increase of the harvest factor of 0.9 and 1.7 respectively, the increase shown for $\alpha = 0.53$ appears to be much more significant with a value of 6.6 for 98 meters hub height and 12.5 for 108 meters hub height. This shows the influence of site specific aspects represented by the exponent α on the environmental profitability of choosing a higher tower.

Table 4. Different tower heights and resulting energetic performance

alpha	Hub height	average wind speed [m/s]	full load hours [h/a]	net energy production [%]	CED [%]	payback time [months]	harvest factor	carbon footprint [g CO_{2e}/kWh]
0.19	84m	7.5	1,600	100.0	100.0	9.6	25.1	12.5
	98m	7.72	1,752	109.4	105.3	9.2	26.0	12.0
	108m	7.9	1,942	121.3	109.4	8.6	27.8	11.2
0.33	84m	7.5	1,600	100.0	100.0	9.6	25.1	12.5
	98m	7.9	1,942	121.4	105.3	8.3	28.9	10.8
	108m	8.15	2,152	134.5	109.4	7.8	30.8	10.1
0.53	84m	7.5	1,600	100.0	100.0	9.6	25.1	12.5
	98m	8.14	2,133	133.3	105.3	7.6	31.7	9.8
	108m	8.57	2,625	164.3	109.4	6.4	37.6	8.3

4. Conclusion

The study assessed the impact of several site specific parameters on two selected indicators, harvest factor and carbon footprint. These indicators describe the CO_{2e} emissions as well as the energy balance which can be considered as the most important categories according to ongoing discussions. However, including more result indicators in the assessment like acidification potential, ozone depletion potential or abiotic depletion potential would be quite straight forward and would provide a broader picture of the site influence on the overall environmental performance of WEC. The so derived site-specific LCA can complement the usually mandatory site specific environmental impact assessment by adding information on life-cycle impacts away from the site. Both assessments together then give a rather complete picture of the environmental burdens of the WEC plant or park.

The underlying parameterized LCA model that has been used in this study allows flexible variations of the assessed site specific parameters and hereby serves as an adjustable tool for performing site specific life cycle assessments. Application of this tool is not restricted to single sites. Given the necessary site-specific parameters, e.g. from GIS (geographic information system) databases, it can be used to assess life-cycle impacts for wind expansion scenarios in larger regions, from counties to countries.

The results of the performed analysis show that the wind conditions on the site have by far the biggest influence on harvest factor and specific carbon footprint. This is, of course, not very surprising since the energy production depends almost exclusively on the wind conditions. However, some of the other assessed parameters influencing cumulated energy demand and global warming potential can have a significant impact on the results, too.

Access roads and foundation that depend strongly on the condition on site, as well as energy consumption of the converter and service intensity can each have an influence of around five percent or more on harvest factor and carbon footprint, which means a significant potential change of these figures of around 20 percent in a worst case scenario. Still, the described limitations regarding access roads and grid connection (see sections 2.2 and 2.3) need to be considered here, too. While the influence of grid connection appears to be marginal, access roads contribute more. Validating the conclusions by assessing different wind parks in different regions should be considered here in the next steps for increasing validity of the results. The same applies to service intensity (see section 2.5). Here, performing a couple of assessments for specific converters with their actual requirements of spare parts and potential replacements of main components instead of average values could provide a broader picture on the actual influence of this parameter.

Furthermore, it has been demonstrated that choosing between different tower heights is subject to site specific factors, too. The environmental profitability of investing in a higher tower does not necessarily pay off equally (e.g. in terms of a higher harvest factor or lower carbon footprint) for different sites and site specific assessments should be performed here as well.

To conclude, it can be said that including site specific aspects in the environmental life cycle assessment helps to complete the picture of the environmental performance of WEC and allows quantifying positive or negative influence of the parameters. However, this does not mean that sites with a comparatively "negative" influence of the mentioned indicators should not be considered as WEC sites. Rather, awareness of this influence should be part of the process of prioritizing sites for use for wind energy and other purposes (photovoltaics, biomass, food, etc.).

References

[1] Guezuraga B, Zauner R, Pölz W. Life cycle assessment of two different 2 MW class wind turbines. *Renewable Energy* 2011;**37**(1):37–44.

[2] d'Souza N, Gbegbaje-Das E, Shonfield P. Life Cycle Assessment of Electricity Production from a V112 Turbine Wind Plant. Copenhagen; 2011.

[3] Zimmermann T. Fully parameterized LCA tool for wind energy converters. Life Cycle Management (LCM) Conference 2011 Berlin; 2011. Available from: www.lcm2011.org/papers.html?file=tl_files/pdf/poster/day2/Zimmermann-Fully_parameterized_LCA_tool_for_wind_energy_converters-567_b.pdf.

[4] Weinzettel J, Reenaas M, Solli C, Hertwich EG. Life cycle assessment of a floating offshore wind turbine. *Renewable Energy* 2009;**34**(3):742–7.

[5] Tremeac B, Meunier F. Life cycle analysis of 4.5MW and 250W wind turbines. *Renewable and Sustainable Energy Reviews* 2009;**13**(8):2104–10.

[6] Crawford RH. Life-Cycle energy analysis of wind turbines: an assessment of the effect of size on energy yield; 2007.

[7] Vestas Wind Systems A/S. Life cycle assessment of offshore and onshore sited wind power plants based on Vestas V90-3.0 MW turbines. 2nd ed. Randers, Denmark; 2006.

[8] Kaltschmitt M, Streicher W, Wiese A. Erneuerbare Energien: Systemtechnik, Wirtschaftlichkeit, Umweltaspekte. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg; 2006. doi:10.1007/3-540-28205-X.

[9] Elsam Engineering A/S. Life Cycle Assessment of offshore and onshore sited wind farms. 2004.

[10] Geuder M. Energetische Bewertung von WEA: Was man über Stoff- und Energiebilanz von erneuerbaren Energien wissen muss. *Erneuerbare Energien* 2004(8):25–9.

[11] Bunk O. A positive environmental balance: Converters amortize within a few month. *Windblatt* 2002(3):12–3.

[12] Zimmermann T, Gößling-Reisemann S. Optimal repowering of wind energy converters: Energy demand and CO2 intensity as indicators. Life Cycle Management (LCM) Conference 2011 Berlin; 2011. Available from:

www.lcm2011.org/papers.html?file=tl_files/pdf/poster/day2/Zimmermann-Optimal_repowering_of_wind_energy_converters-601_b.pdf
[13] Zimmermann T. Entwicklung eines Life Cycle Assessment Tools für Windenergieanlagen. Thesis. Bremen; 2011.
[14] PE, LBP. GaBi 4: Software-System and Databases for Life Cycle Engineering. Stuttgart, Echterdingen; 1999-2008.
[15] European IPPC Bureau. The European IPPC Bureau: Joint Research Center. [September 09, 2010]; Available from: http://eippcb.jrc.es/.
[16] Worldsteel Association. Worldsteel Recycling Methodology: Application of the worldsteel LCI data to recycling; 2008.
[17] vkn SAAR - Gesellschaft für die Verwertung von Kraftwerksnebenprodukten und Ersatzbrennstoffen. Kesselsand. [September 23, 2010]; Available from: http://www.vkn-online.de/vkn_smartm/html/f/19/prod_strahl.html.
[18] Lackner MA, Rogers AL, Manwell JF, McGowan JG. A new method for improved hub height mean wind speed estimates using short-term hub height data. *Renewable Energy* 2010;35(10):2340–7.
[19] Gualtieri G, Secci S. Methods to extrapolate wind resource to the turbine hub height based on power law: A 1-h wind speed vs. Weibull distribution extrapolation comparison. *Renewable Energy* 2012;43:183–200.