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Wind Power Electricity: The Bigger the Turbine, The Greener the Electricity?

Marloes Caduff,*[,†,‡] Mark A. J. Huijbregts,[§] Hans-Joerg Althaus,[†] Annette Koehler,[†] and Stefanie Hellweg[†]

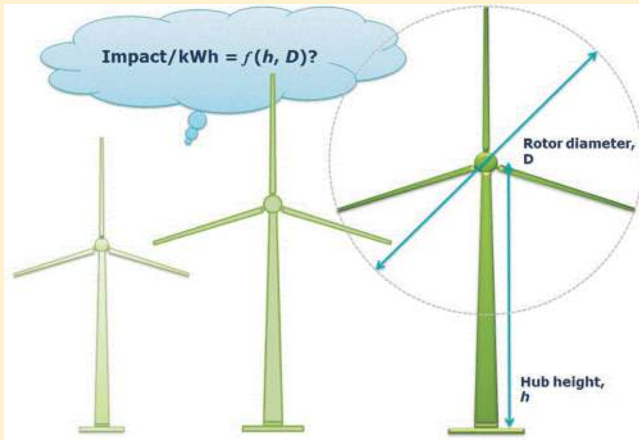
[†]ETH Zurich, Institute of Environmental Engineering, CH-8093 Zurich, Switzerland

[‡]Empa, Swiss Federal Laboratories for Materials Testing and Research, Technology and Society Laboratory, Ueberlandstrasse 129, CH-8600 Duebendorf, Switzerland

[§]Department of Environmental Science, Institute for Wetland and Water Research, Faculty of Science, Radboud University Nijmegen, P.O. Box 9010, NL-6500 GL Nijmegen, The Netherlands

Supporting Information

ABSTRACT: Wind energy is a fast-growing and promising renewable energy source. The investment costs of wind turbines have decreased over the years, making wind energy economically competitive to conventionally produced electricity. Size scaling in the form of a power law, experience curves and progress rates are used to estimate the cost development of ever-larger turbines. In life cycle assessment, scaling and progress rates are seldom applied to estimate the environmental impacts of wind energy. This study quantifies whether the trend toward larger turbines affects the environmental profile of the generated electricity. Previously published life cycle inventories were combined with an engineering-based scaling approach as well as European wind power statistics. The results showed that the larger the turbine is, the greener the electricity becomes. This effect was caused by pure size effects of the turbine (micro level) as well as learning and experience with the technology over time (macro level). The environmental progress rate was 86%, indicating that for every cumulative production doubling, the global warming potential per kWh was reduced by 14%. The parameters, hub height and rotor diameter were identified as Environmental Key Performance Indicators that can be used to estimate the environmental impacts for a generic turbine.



INTRODUCTION

Wind energy is being promoted as a promising source of renewable energy, consequently the wind energy market is growing notably both in Europe and globally. From 2006 to 2007, alone, the gross production of wind energy in the EU-27 countries grew by 21% to 99 430 GWh.[1] The trend toward more wind energy can also be observed globally. The United States for instance, have set a target for 2030 in which 20% of the electricity originates solely from wind power.[2] To reach these targets, more wind parks as well as larger turbines are built.

With an increased cumulative production of wind turbines, manufacturers gain experience with the technology, which is commonly reflected in a reduction of the investment costs. The factors responsible for the cost reduction can be grouped in size and learning effects.[3] Size effects are described in the form of a power law and are commonly developed to estimate properties at size X when no measurements or data are available.[4] Cost scaling laws estimate the costs of bigger or smaller equipment based on the costs of a known equipment size,

$$C_2 = C_1(X_2/X_1)^b \quad (1)$$

where C_2 is the investment cost of unknown equipment; C_1 is the investment cost of known equipment; X_2 is the capacity of unknown equipment; X_1 is the capacity of known equipment and b is the scaling factor. Commonly cost scaling factors between 0.5 and 1 are applied, however a scaling factor of 0.6 is recommended if no data is available, meaning that a 1% size increase, results in a 0.6% cost increase.[5,6] Scaling factors between 0.5 and 1 have also been found for the environmental impacts from the production phase of energy conversion equipment.[7]

Besides "pure" size effects, another effect causing production costs to reduce was identified by Wright, who observed that labor costs in airplane manufacturing decreased at a constant

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percentage with every doubling of the cumulative output.[8] This effect is nowadays described as the learning curve concept.

An approach quantifying both these mechanisms together, scaling and learning, is the experience curve concept, which estimates the investment costs at a certain cumulative installed capacity, without having detailed product specifications or cost indications.[3,9] Combining scaling and learning is commonly practiced due to the difficult separation of the two effects. Few studies have tried to disentangle scaling from learning, relevant examples come from photovoltaic technologies.[10,11] Experience curves are commonly derived from empirical studies and widely applied in different energy sectors.[12−15] A study for wind energy showed that due to the global cumulative experience the investment costs of a wind farm display a progress rate of 81%, meaning that costs decrease by 19% each time the cumulative production doubles.[16] An experience curve is a function of the cumulative production and if plotted on a log−log scale, the experience curve becomes linear. The formula used is

$$\log C_{cum} = \log C_0 + z \log \mathrm{Cum} \quad (2)$$

where C_{cum} is the cost per unit; C_0 the cost of the first produced unit; Cum the cumulative production; z is the experience index.[17] The progress rate (PR) describes the rate at which the costs reduce with every doubling of the production,

$$\mathrm{PR} = 2^z \quad (3)$$

Usually b is used as a notation to describe the experience factor, however to avoid confusion with the scaling factor b, we use z to describe the experience factor in this paper.

Wind parks or turbines must not only be financially competitive, but also environmentally beneficial compared to other energy sources. A method commonly used to quantify the environmental performance of energy systems is life cycle assessment (LCA). Knowledge about environmental experience curves can be advantageous for comparative LCA studies, specifically when technologies in different developmental stages are compared. An unedited comparison of these technologies does not take into account that the younger technology will still improve and grow, while the established technology will have reached its maximum learning and size. Such direct comparisons however, without incorporating experience effects have been made previously in the LCA literature.[18,19] In the past decade, the importance of incorporating experience curves in LCA has been emphasized.[20]

The aim of this study is to quantify the environmental size and learning effects for wind energy. We first give an overview of onshore wind energy systems and perform an analysis on a "micro level", examining the theoretical size effect expected from *engineering-based modeling* as well as the observed size effect for turbine components and environmental impacts (the latter called *empirical modeling* in this paper). To derive empirical scaling factors, life cycle inventories of 12 different wind turbine systems were harmonized using the same modeling principles. Combining the engineering-based modeling with the empirical modeling allows disentangling pure turbine size effects from learning effects on LCA results of the produced electricity from land-based wind energy technologies. The second part of the study quantifies environmental experience effects over time and progress rates of the wind power industry as a whole in Europe, defined as the *macro* level.

■ MATERIALS AND METHODS

Engineering-Based Size Model for Wind Electricity Production. A wind energy turbine consists of several components, such as the rotor, nacelle, tower, foundation and electrical cables (see Figure 1).

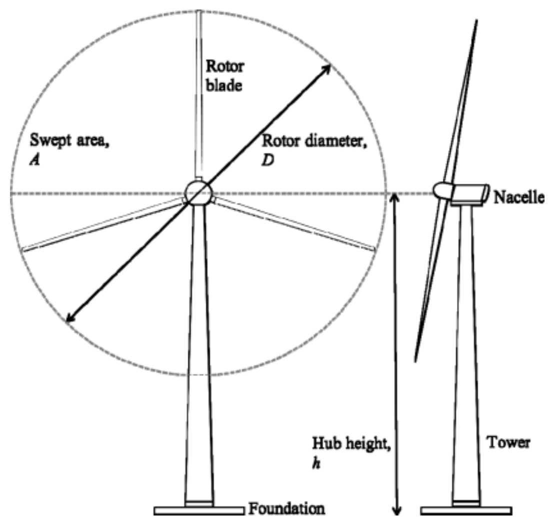

Figure 1. Wind turbine and its components.

The captured kinetic wind power depends on the air density ρ, swept area of the rotor A and the wind speed v at hub height h.[21] Average wind speed at hub height depends on height (h), swept area A, and wind shear n. As a general rule a vertical wind shear gradient described by the Hellman exponent of 1/7 is applied, which is at the lower range of wind shear gradients reported in the literature (between 0.15 and 0.25 for onshore regions).[22,23] All calculations in this paper were based on a low wind speed site with an annual wind speed of 5 m/s (v_1) at 10 m height (h_1) and a wind shear gradient n of 1/7. A generator in the nacelle converts the captured energy into electric energy with a reported average mechanical-electrical efficiency ($\eta_{generator}$) of 94%.[24] Losses due to rotor blade soiling (1−2%), wind hysteresis (1%) and losses for the grid connection (1−3%) were assumed to amount to 5% (η_{losses}).[25] An average turbine load of 8,760 h per year was assumed. To calculate the captured wind power as well as other parameters of a wind turbine system, several equations and constants were applied throughout this paper and are listed in Table 1.

Substituting swept area A and average wind speed at hub height (v_2) in eq 6 with eqs 4 and 5 (Table 1), we derive $P \propto D^2 h^{3n}$. Classical scaling implies that $M \propto V \propto L^3$, stating that mass M scales directly with volume V which scales cubic with length L. Hence, size scaling laws for the mass of the rotor, nacelle, tower and foundation are cubic, either with $M \propto D^3$ or $M \propto D^2 h$ for the tower. The tower design (and hence mass) is based on the base moment and thrust from the rotors.[40] All other factors, such material innovations and fatigue loads are not considered in these scaling laws. The cables and electronics inside the tower were assumed to scale with tower height h. The cables from the tower to the electricity grid were assumed independent from the turbine.

The environmental impact categories used in this study were mainly driven by the mass of the used materials, except for land use, hence a relation of $\mathrm{EI}_{production} \propto M_{components}{}^1$ was assumed for modeling the environmental impact (EI) since material

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Table 1. Basic Equations of a Wind Turbine System Used in This Paper[a]

parameter	unit	description	equation	equation number	sources
a	m^2	swept area	$A = 1/4\pi D^2$	(4)	
v_2	m/s	average wind speed at hub height	$v_2 = v_1/(h_1/h_2)^n$	(5)	22
P	W	kinetic power at hub height	$P = 1/2\rho_{air}\cdot Av_2^3$	(6)	21
$P_{captured,max}$	W	Betz' law	$P_{captured,max} = 16/27P$	(7)	26
$P_{electric}$	W	electric power	$P_{el} = \eta_{generator}\eta_{losses}P_{captured,max}$	(8)	
P_{cal}	Wh/a	produced electricity per year (calculated)	$P_{cal} = 8760h/a\cdot P_{el}$	(9)	

[a] $\rho_{air} = 1.2$ kg/m^3, v_1: wind speed at ground; $\eta_{generator}$=94%, η_{losses} = 95%.

production and processing as well as the transport were directly related to the mass. The use phase is primarily dominated by lubricating oil consumption and the diesel for the transport of the lubricating oil to the wind tower location. The lubricating oil consumption is expected to scale linearly with power. The transport is directly linked to the amount of oil; therefore the overall scaling for the use phase is expected to scale with $EI_{use} \propto P^1 \propto D^2 h^{3/7}$. The expected scaling factor for the disposal of the whole wind system is again linked to the mass M of the individual components; hence the factor is expected to be $EI_{disposal} \propto M_{components}$. See Table 2.

Table 2. Engineering-Based Size Scaling Laws Used in This Paper[a]

parameter	proportional to
power, p	$\propto d^2\, h^{3/7}$
M_{rotor}	$\propto D^3$
$M_{nacelle}$	$\propto D^3$
M_{tower}	$\propto D^2\, h$
$M_{foundation}$	$\propto D^3$
$M_{electronics\&cables}$	$\propto h$
EI production	$\propto M_{components}$
EI use	$\propto D^2\, h^{3/7}$
EI disposal	$\propto M_{components}$

[a] D: rotor diameter (m); h: hub height (m); M: mass (kg); V: volume (m^3); EI: environmental impact.

Empirical Modeling of Wind Energy Production. *Data Collection.* Several LCA studies on wind turbines have been published, including scientific papers, reports, and databases.[27−32] Only publications which include life cycle inventories (LCI) of the turbine (nacelle, rotor and tower) as well as the foundation were included in the current analysis. A total of 12 turbine systems from eight different sources ranging in power from 30 kW to 3 MW were included (see Table 3). The LCIs of the 12 turbine systems were not based on or extrapolated from each other. Other studies which did not include detailed LCI data or were only specifically for one element of a wind turbine were not included.[21,33,34] This paper includes two- and three-bladed onshore wind turbines, which feed electricity into the national grid. The production year was not mentioned in all 12 cases, two data points were therefore left out of the estimation of the environmental progress rate.

LCI Harmonization. To make the impact assessments results comparable, the inventories were harmonized regarding system boundaries and background processes. The harmonized system boundaries included the following the life cycle phases: resource extraction, material manufacturing and processing, production of the elements, transport to the erection site, turbine maintenance and disposal. Due to lack of data, the assembly of the turbine and the energy for decommissioning of the turbine were not included. All major elements of the turbine system were included, and these were the nacelle, rotor, turbine, foundation, cables inside the turbine, cables to the grid, and the electronic control box. Not included were roads to the turbine, cables trenches and specific infrastructure for the operation of entire wind parks, such as a main transformer room. An important factor in the life cycle of a wind turbine is the amount of electricity produced. The energy production

Table 3. Specifications of the Wind Turbines

source	rated power*, P [kW]	tower height, h [m]	rotor diameter, D [m]	construction year of turbine	calculated captured power at rotor[c], $P_{captured,\ max}$ [kW]	calculated energy generation, P_{cal} [MWh/a]
30	660	55	55	2001[b]	219	1715
29	500	41.5	39	1996[b]	98	764
37	850	60	52	n/a	203	1591
37	3000	80	90	2003[b]	689	5392
31	2000	67	78	n/a	480	3754
33	1650	80	80	2005	545	4261
34	30	22	12.5	1990	8	60
34	150	30	23.8	1994	32	248
34	600	40	43	1996	117	915
34	800	50	50	2001	174	1361
32	600	35	44	1998	116	904
38	1500	67	66	2000	344	2688

[a]Reported by the producers,. [b]Year not mentioned in the original study. [c]Power output calculated for standard site with wind speed of 5 m/s at 10 m height and a wind shear gradient of 1/7.

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however depends on many factors, such as wind conditions, exposure and location. The power output mentioned in the original publications was not used in this analysis since it could not be guaranteed that the conditions were similar in all publications. The power output was therefore recalculated under identical conditions, assuming a wind speed of 5 m/s at 10 m height and a wind shear gradient of 1/7. The equations and constants listed in Table 1 were used and the results are given in the last two columns of Table 3. The maximum calculated captured power at the rotors, $P_{captured,max}$, was calculated using eqs 4−7. Note that the calculated power is lower than the rated power, since the rated power refers to the maximum power output at which a turbine can operate. The calculated power however refers to the previously defined site conditions (v = 5 m/s at 10 m height), which is a conservative standard site. The calculated power production per year, P_{cal} was calculated using eqs 8 and 9.

A harmonization of the background processes was done for all inventories. The major adjustments were

- All metal and plastic production processes were complemented with the corresponding metal and plastic processing steps. For instance, the production process "aluminum, production mix" was complemented with "sheet rolling, aluminum" using the same material amount.
- Transport distances of the raw materials to the production plant were modeled as 100 km lorry (>32 tonnes and according to the European emission standard EURO 4) and 200 km freight train. Distances from the production plant to the erection site were modeled as 100 km lorry (>32t, EURO 4) and 800 km freight train. An exception was made for the foundation. It was assumed that the materials were provided by a local producer; hence 50 km lorry (>32t, EURO 4) for concrete, 100 km lorry (>32t, EURO 4) for plastics, steel and iron as well as 200 km freight train for plastics, steel and iron was assumed.
- Many publications did not specify whether the material was virgin or recycled material, also iron and steel were occasionally not further specified; hence material assumptions were made based on the inventories that did specify the material in more detail. For instance, aluminum was included as a mix of primary and secondary aluminum according to their share on worldwide production and the steel used in the rotors was included as chromium steel 18/8.
- In two publications the category "others" appeared. In the study by Schleisner, this involved 700 kg, which corresponds to 1.2% of the total turbine mass.[27] In the study by Martinez et al, 0.2% of the total turbine mass was declared as others.[29] Due to the low relative share, these amounts were left out in the harmonized inventory.
- The electronic control units as well as the electric cables were not included in all studies. The electronics box was considered independent of turbine size and modeled according to Martinez et al.[29] The electronic cables were divided into cables running from the hub to the tower base and from the tower base to the grid. The first set of cables depended directly on hub height, and the inventories were parametrized according to hub height. The second set was considered size independent as the distance to the grid was assumed 1000 m for all cases.
- The published studies used different sources for unit process data. The harmonized inventories all revert to unit process data available in the ecoinvent Database version 2.01.[35]

All adaptations and harmonized inventories can be found in the Supporting Information.

Life Cycle Impact Assessment. Included in the assessment are commonly used midpoint indicators from ReCiPe.[36] The LCA software SimaPro 7.3.2 was used for modeling.[37]

Environmental Size Scaling Laws. A scaling law relating size to environmental impact (EI) was derived from classical size scaling. Equation 1 was adapted by replacing costs by environmental impacts and is described as

$$\mathrm{EI}_2 = \mathrm{EI}_1(X_2/X_1)^{\mathrm{be}} \tag{10}$$

where EI_2 is the environmental impact of equipment 2; EI_1 is the environmental impact of equipment 1; X_2 is the capacity factor of equipment 2; X_1 is the capacity factor of equipment 1 and $\mathrm{b_e}$ is the environmental scaling factor.

Environmental Experience Curve Concept. The empirical size scaling was combined with the engineering-based size model. The difference between the empirical and engineering-based model was interpreted as the learning effect. Technological learning takes place by the use of other materials like fiber-reinforced blades or, for instance, by optimizing the blade design to capture more kinetic wind energy. To model the environmental experience curve and the environmental progress rate (EPR), eqs 2 and 3 were modified. The cost factors were substituted with environmental indicators (EI), resulting in

$$\log \mathrm{EI}_{\mathrm{cum}} = \log \mathrm{EI}_0 + z_{\mathrm{e}} \log \mathrm{Cum} \tag{11}$$

$$\mathrm{EPR} = 2^{\mathrm{ze}} \tag{12}$$

where $\mathrm{EI}_{\mathrm{cum}}$ is an environmental indicator, such as global warming potential per unit after cumulative units have been produced; EI_0 environmental indicator of the first produced unit and z_{e} is the environmental experience index. The reported production year of the turbines mentioned in the LCA studies was linked with the cumulative wind power production in Europe within that year.[38] This step enabled plotting the environmental impact from each turbine to the cumulative production in Europe and hence the environmental progress rate was calculated according to eqs 11 and 12. The prevented environmental impact (GWP/kWh) due to learning was calculated as the difference between the environmental impact from the engineering-based modeling and the empirical modeling.

Regression and Statistics. To enable and perform ordinary least-squares (OLS) linear regression, the results were plotted on a log−log scale. Regression analysis was performed with the Statistical Package for the Social Sciences (SPSS) statistical software for Windows, version 16.0 (SPSS, IL). The applied power law was

$$\log y = \log a + b \log x \tag{13}$$

Scaling factors were presented as b and the intercept as log a, with a 95% confidence interval (95% CI). We also reported the residual standard error (SE) and the Pearson correlation coefficient (R^2) of the regression.

RESULTS

Empirical Size Model and Learning on a Micro Level. The mass of wind turbine components scaled with rotor diameter D with scaling factors (b) between 1.58 and 2.22 (Table 4) and showed high correlations ($R^2 = 0.84 - 0.97$).

Table 4. Scaling Factor b and Intercept a for the Parameter Mass M (kg) versus Rotor Diameter D (m) and Hub Height h (m) Using OLS, Ordinary Least Squares. 95% CI: 95% Confidence Interval; R^2: Coefficient of Determination; SE: Standard Error; n: Number of Observations

relationship[a]	log a (95% CI)	b (95% CI)	R^2	SE	n
$M_{total} \propto D^2 h^{3/7}$	1.90 (1.48–2.31)	0.76 (0.67–0.87)	0.97	0.084	12
$M_{rotor} \propto D$	0.30 (−0.50–1.09)	2.22 (1.80–2.73)	0.93	0.165	10
$M_{nacelle} \propto D$	0.64 (−0.07–1.35)	2.19 (1.81–2.65)	0.95	0.147	10
$M_{tower} \propto D$	1.70 (1.27–2.13)	1.82 (1.58–2.09)	0.97	0.088	10
$M_{tower} \propto D^2h$	1.34 (0.94–1.74)	0.68 (0.60–0.76)	0.98	0.074	10
$M_{foundation} \propto D$	1.44 (0.63–2.25)	1.58 (1.20–2.09)	0.84	0.175	12
$M_{electronics\&cables} \propto h$	2.88 (2.83–2.93)	0.32 (0.30–0.35)	0.98	0.008	12

[a]Note that the scaling factors for the mass of the rotor, nacelle, tower and foundation were given as D^1, whereas in Table 2 the engineering-based scaling laws were given as D^3. This representation was chosen to state more clearly the difference between the engineering-based scaling factor of 3 and the empirical scaling factor of below 3. The difference was caused by learning.

The mass of the cables and electronics however, scaled with rotor diameter D with a scaling factor of 0.22 (Figure 2a and Table 4). The overall mass of the turbine system scaled with rotor diameter D with $b = 1.75$ (CI: 1.53 − 2.01, $R^2 = 0.96$) and with $D^2h^{3/7}$ with $b = 0.76$ (CI: 0.67 − 0.87, $R^2 = 0.97$), see Figure 2b.

The global warming potential of the produced electricity varied between 9.5 and 29.7 g CO_2-eq/kWh. The main contributors were the tower (27–39%) and the nacelle production (12–37%). The scaling factors b for all the impact categories per kWh varied between −0.55 and −0.22, with an exception of −0.87 for urban land occupation (Table 5 and Supporting Information).

Figure 2d shows the engineering-based size modeling for the relationship environmental impact of the rotor versus rotor diameter, according to Table 2 as well as the empirical model for that relationship. To display the difference between the engineering-based model and the empirical results, a reference turbine model was arbitrarily chosen with a rotor diameter of 12.5 m, which corresponds to the oldest wind turbine included in this study. The result was a lower environmental impact for the empirical model with increasing rotor size than for the engineering-based model. According to the engineering-based modeling (Table 2), the environmental impact scales according to a cubic law with rotor diameter, D^3. The empirical scaling factor found was 1.79, hence learning on a micro level took place with a value of (D^3–$D^{1.79}$).

Experience Curve and Environmental Progress Rate on a Macro Level. Both, the calculated power output P and the rotor diameter D increased strongly over the years (Figure 3a.). The global warming potential (GWP) per produced kWh electricity continuously decreased over the analyzed time period (Figure 3b). After linking the construction year with the total European wind turbine production, an environmental experience curve was established (Figure 3c). The environmental experience curve was described by GWP/kWh = 0.11 $\mathrm{Cum}^{-0.22}$, which corresponds to an environmental progress rate (EPR) of 86%, indicating that with every doubling of the cumulative production the GWP/kWh was reduced by 14%. The EPR varied per impact category between 69% and 86%, with the exception of 57% for land occupation (see Supporting Information).

The environmental experience curve and the corresponding EPR encompass both pure size scaling effects as well as learning effects due to, for instance, learning-by-doing and technological learning. As can be seen from Table 4, the empirical factors for the mass of the nacelle, rotor and tower are all clearly below cubic with values around 2. From this information, the saved GWP/kWh produced electricity per cumulative production was calculated. Figure 3d shows that with increasing experience in the form of cumulative production, the amount of prevented kg CO_2-eq./kWh could be continuously increased compared to the engineering-based scaling model, indicating that the more was learned about the technology, the more GWP per produced kWh electricity could be saved.

DISCUSSION

The results showed that the bigger the wind turbine is, the greener the produced electricity is. Two effects contributed to this result, namely pure size scaling as well as learning about the technology over time, allowing through experience and innovation that the turbines can be built bigger in the first place.

Empirical Scaling Factors. The empirical scaling factors found in this study were in agreement with values reported in literature. The empirical scaling factors for the relationship rotor mass versus rotor diameter were reported between 1.9 and 2.9 by various authors, where low values correspond to advanced rotor technology and the higher values to older technologies.[24,39−42] Empirical scaling factors of the relationship nacelle mass versus rotor diameter were reported between 1.91 and 1.95.[43] The mass of the turbine, without the foundation and grid connection was reported as $M \propto D^{2.7}$.[24] The foundation was reported to scale empirically with $M_{foundation} \propto h^{0.40} D^{0.8}$ while our values scaled with $M_{foundation} \propto (h^{0.40} D^{0.8})^{1.7}$.[40] The impact assessment results obtained after harmonization were in accordance with other published emission values, such as a review study by Kubiszewski, who reported CO_2 emissions within a wide range of 2–134 g CO_2/kWh.[44]

The parameters hub height h and rotor diameter D are easy to obtain, hence the found scaling laws can be applied directly to estimate the environmental impacts if these two parameters are given. As explained in the Introduction, scaling is commonly used to estimate parameters when only few data is available. This approach can therefore be very useful for screening LCA studies, where only limited data or time to perform a LCA study is available. Therefore hub height h and rotor diameter D could be defined as Environmental Key Performance Indicators for onshore wind energy technologies.

Environmental Experience Curve. The experience curve showed the reduction of environmental impact per cumulative wind turbine production in Europe. This curve can be extrapolated into the near future under the assumptions that

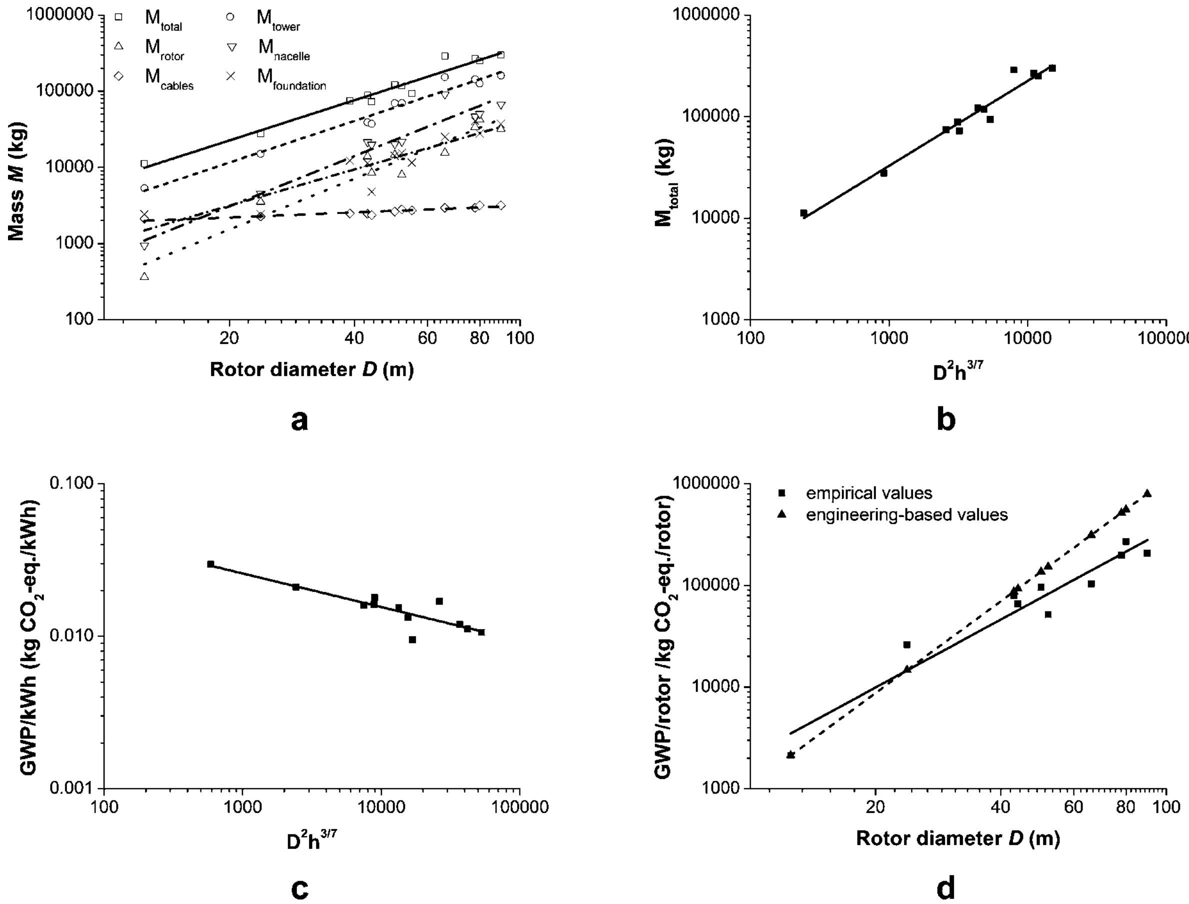

Figure 2. a. Mass M (kg) of turbine components and total mass versus rotor diameter D (m). b. Total mass M (kg) versus $D^2h^{3/7}$ c. Global warming potential per produced kWh (kg CO_2-eq./kWh) versus $D^2h^{3/7}$. d. Global warming potential per rotor (kg CO_2-eq./rotor) versus rotor diameter D (m), the dashed line presents the expected pure size scaling according to the engineering-based model, the solid line presents the empirical scaling line.

Table 5. Exponent b and Intercept a for Selected ReCiPe Impact Categories Versus $D^2h^{3/7}$ Using the Ordinary Least Squares Regression Technique[a]

impact category	unit	log a (95% CI)	b (95% CI)	R^2	SE	n
climate change	kg CO_2 eq/kWh	−0.93 (−1.27 to −0.59)	−0.22 (−0.16 to −0.31)	0.77	0.070	12
freshwater ecotoxicity	kg 1,4-DB eq/kWh	−1.66 (−2.13 to −1.18)	−0.39 (−0.29 to −0.51)	0.84	0.097	12
urban land occupation	m^2a/kWh	0.58 (0.41–0.76)	−0.87 (−0.82 to −0.91)	0.995	0.036	12
metal depletion	kg Fe eq/kWh	−0.22 (−0.68–0.23)	−0.35 (−0.26 to −0.46)	0.83	0.093	12

[a]95% CI: 95% confidence interval; R^2: coefficient of determination; SE: standard error; n: number of observations.

no major technological developments or market changes take place which influence the experience curve drastically, hence the use of the experience curve concept and EPR for long-term forecasting purposes is limited. It can be applied for short-term extrapolation of the same turbine technology, if the limitations of the experience curve are clearly communicated. In the case of a large technological innovation, the experience curve shifts down by a step function to subsequently resume on a lower level.[45] In addition, future environmental impacts, for instance caused by changes in the supply chain of scarce metals, are not covered by the EPR and might cause a change in impact in the future, not foreseen by the empirical experience curve.

Sensitivities and Limitations. Due to the harmonization of the inventories, the scaling factors in this paper are only valid for a generic location and wind regime. However, based on the equations in Table 1, this can be adapted for other locations with different wind shear factors and wind speeds. For instance, if the wind shear factor is 1/4 instead of the used 1/7, the relation global warming potential per kWh ranges from 5.4 to 23 g CO_2-eq./kWh instead of 9.5 to 29.7 g CO_2-eq./kWh, since more wind energy can be captured at higher wind shear factors and hub heights.[23] The environmental progress rate for GWP/kWh drops to 81%, hence the scaling effect is more pronounced since wind speed scales according to a cubic relation with power P. Increasing the wind speed from 5 m/s, as assumed in our study, to 15 m/s (v_1), the output power was increased by a factor of 27, according to eq 5 (v_1^3), but there was no effect on the scaling factors, only on the intercept (see Supporting Information, Table S12 and S13).

In the calculations, the generator efficiency was assumed constant. However, based on previous work, it can be assumed that efficiency may improve with size according to a power law.[46] To analyze the sensitivity of this assumption, a rough efficiency scaling law was established and the deviation of the

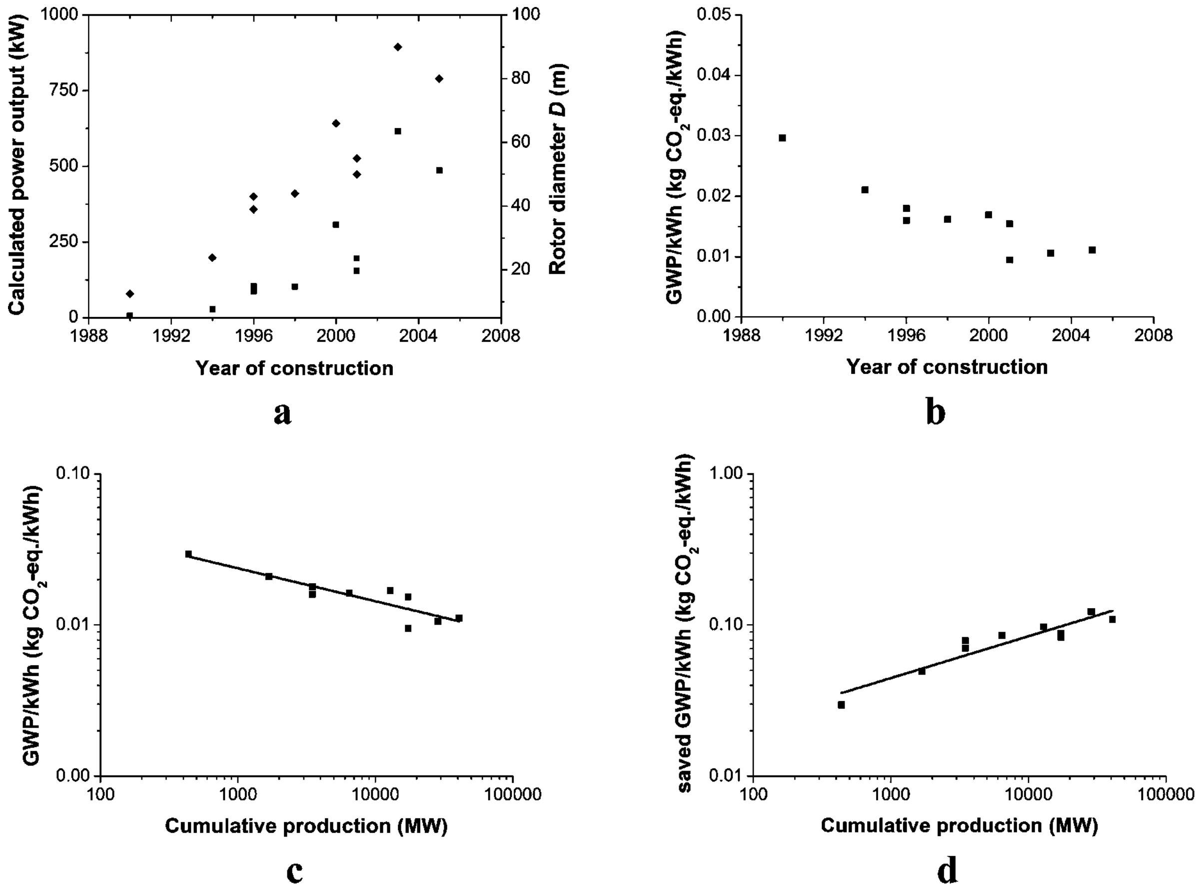

Figure 3. a. Calculated power output P versus erection year on the left axis (black squares) and rotor diameter D on the right axis (gray diamonds). b. Global warming potential (GWP) per produced kWh energy versus erection year. c. Empirical environmental experience curve for global warming potential GWP per kWh produced electricity versus the European cumulative production (MW). d. Prevented environmental impact (GWP/kWh) versus the European cumulative production (MW) compared to the engineering-based model.

calculated power output between the scaled and nonscaled efficiencies was calculated, resulting in a maximum deviation of 2.9% (see Supporting Information, Table S14).

Besides the generator efficiency, the overall turbine performance was also assumed constant at an efficiency of 53%, which resembles a best-case scenario. Turbine performances have been reported to be 35−40% in the early 1980s increasing to 48% mid-1990s.[47] To analyze the sensitivity, the efficiency of all turbines produced before 2000 was set to 48%, the modern turbine efficiency remained 53%. The power output of the older turbines decreased by 9%, resulting in an environmental progress rate (EPR) of 84%, indicating that with every doubling of the cumulative production the GWP/kWh was reduced by 16% instead of 14%.

The scaling factors b in Table 5 were evaluated against other impact methods. Both the single score results per kWh produced electricity from IMPACT 2002+ as well as the nonrenewable cumulative energy demand (CED) per kWh produced electricity were within the expected range of −0.55 and −0.22 (see Supporting Information, Table S15).

As mentioned in section "LCI Harmonization", the original studies omitted processes and materials, which were described as "others" in the used publications. These omissions might include scarce metals or hazardous chemicals. Hence, the omission of these materials might underestimate the impacts, in particular concerning impact categories such as resource consumption or toxicity.

The boundaries of the study were set by a single wind turbine and not a wind park. As turbines get larger, they need to be spaced further apart and hence occupy more land. The land use impact results in this study are therefore limited to stand-alone wind turbines only.

Because of the recalculation of the power output to a generic turbine location, it has to be mentioned that a simplification took place and the wind turbines might not be designed optimally for this "new" location, hence an over- or underestimation of the masses and respective impacts occur, resulting in larger spread in the data.

If empirical laws are not available from literature or measurements, the sole use of engineering-based scaling laws quantifies an upper boundary for the size scaling factors. Therefore, it might be possible to derive scaling relationships and upper boundaries in a similar way for other technologies as well. This suggestion, however, remains to be explored in further studies.

This paper presented how size scaling relationships, environmental experience curves and EPR can be established and used for LCA purposes. Further studies are necessary to investigate the robustness of the established relationships. In this sense, it is recommended that due to the effects of modeling assumptions such as turbine location, wind shear and wind speeds on the LCA results, they should be expressed in a transparent way in LCA reports. Furthermore, it is recommended to clearly state the year of wind turbine production or installation for which the data is valid. Though recommended by the ISO standard on life cycle assessment, this information is often lacking in LCA studies. Only with such a clear statement can reliable environmental experience curves be established in the future.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional details on raw data, life cycle inventories and results. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: +41 44 823 48 12; fax: +41 44 823 40 42; e-mail: marloes.caduff@ifu.baug.ethz.ch.

Notes

The authors declare no competing financial interest.

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