Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power

Systematic Review and Harmonization

Stacey L. Dolan and Garvin A. Heath

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Supporting information is available on the *JIE* Web site

Summary

A systematic review and harmonization of life cycle assessment (LCA) literature of utility-scale wind power systems was performed to determine the causes of and, where possible, reduce variability in estimates of life cycle greenhouse gas (GHG) emissions. Screening of approximately 240 LCAs of onshore and offshore systems yielded 72 references meeting minimum thresholds for quality, transparency, and relevance. Of those, 49 references provided 126 estimates of life cycle GHG emissions.

Published estimates ranged from 1.7 to 81 grams CO_2-equivalent per kilowatt-hour (g CO_2-eq/kWh), with median and interquartile range (IQR) both at 12 g CO_2-eq/kWh. After adjusting the published estimates to use consistent gross system boundaries and values for several important system parameters, the total range was reduced by 47% to 3.0 to 45 g CO_2-eq/kWh and the IQR was reduced by 14% to 10 g CO_2-eq/kWh, while the median remained relatively constant (11 g CO_2-eq/kWh). Harmonization of capacity factor resulted in the largest reduction in variability in life cycle GHG emission estimates.

This study concludes that the large number of previously published life cycle GHG emission estimates of wind power systems and their tight distribution suggest that new process-based LCAs of similar wind turbine technologies are unlikely to differ greatly. However, additional consequential LCAs would enhance the understanding of true life cycle GHG emissions of wind power (e.g., changes to other generators' operations when wind electricity is added to the grid), although even those are unlikely to fundamentally change the comparison of wind to other electricity generation sources.

Introduction

Electricity generation accounted for approximately 40% of energy-related carbon dioxide (CO_2) emissions in the United States in 2008 (EIA 2009). Interest in technologies powered by renewable energy sources such as the wind and sun has grown partly because of the potential to reduce greenhouse gas (GHG) emissions from the power sector. However, due to GHG emissions produced during equipment manufacture, transportation, on-site construction, maintenance, and decommissioning, wind and solar technologies are not GHG emission-free. Life cycle assessment (LCA) is particularly well suited for comparing conventional power generation systems to renewables because it accounts for GHG emissions across the full life cycle of each technology, and therefore helps to inform decision makers of the attributable environmental impacts of energy technologies.

Address correspondence to: Garvin Heath, National Renewable Energy Laboratory, 1617 Cole Blvd. Golden, CO 80401, USA. *E-mail*: garvin.heath@nrel.gov

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Hundreds of LCAs have been published on various solitary wind turbines and wind farms over the past several decades, as well as two articles reviewing the wind power LCA literature (Lenzen and Munksgaard 2002; Varun et al. 2009) and one meta-analysis, which focuses on energy return on investment (Kubiszewski et al. 2010). Lenzen and Munksgaard (2002) investigated the effects capacity factor, lifetime, power rating, method, scope, country of manufacture, and vintage have on energy and CO_2 emission intensities of 72 previously published analyses of wind turbines taken from 32 LCAs. They also performed a multivariate regression normalizing the capacity factor to 25% and lifetime to 20 years, resulting in a decrease in the range of energy intensities from almost two orders of magnitude to one.

In contrast, objectives of the present meta-analysis include identifying, explaining, and, where possible, reducing variability in estimates of life cycle GHG emissions through a meta-analytical process called "harmonization." The purpose of this analysis and its umbrella project, the LCA Harmonization Project, which examines other electricity generation technologies such as coal and natural gas, is to inform decision making and future analyses that rely on such estimates. (Articles from the LCA Harmonization Project appearing in this special issue on meta-analysis of LCAs perform similar analysis on crystalline silicon photovoltaic [Hsu et al. 2012], thin film photovoltaic [Kim et al. 2012], coal [Whitaker et al. 2012], concentrating solar power [Burkhardt et al. 2012], and nuclear [Warner and Heath 2012].)[1]

Variability exists in estimates of life cycle GHG emissions even between studies performed on the same technology. Differences can be attributed to several factors, including specifics of the particular model, configuration and operating conditions of the system studied, methodological decisions and assumptions made by those conducting the study, variability in data sources, and LCA approach (e.g., consequential or attributional, process chain or economic input-output). To better understand the extent to which some of these sources of variability affect the overall results of a study, the present research systematically reviews previously published wind power LCAs and harmonizes their GHG emission estimates by establishing more consistent methods and assumptions, including characteristics of system performance, system boundaries, and global warming potentials (GWPs) of the individual GHG species.

Methods

An exhaustive literature search of the English-language literature was performed to compile a database of published wind LCAs. Studies were initially screened out if they did not meet the following criteria: published as a scholarly journal article, trade journal article greater than three published pages in length, conference proceeding greater than five double-spaced pages in length, books or chapters, theses, dissertations, or reports; were published after 1980; were written in English; and evaluated electricity as an end product. This preliminary screen reduced the number of references from 237 to 175. The database was structured to record certain defining characteristics of each study, such as whether it is an empirical or theoretical study. Specific study information extracted included publication year, reference type, onshore or offshore technology, vertical- or horizontal-axis turbines, utility-scale or distributed generation, manufacturer, tower type, publication date, which GHG species were inventoried, and vintage of the GWPs used. Several quantitative system parameters were also recorded, such as capacity, capacity factor, lifetime, and lifetime power output.

An LCA's system boundary is the choice of the researcher, so there may be considerable differences in scope across studies. To allow for comparison of studies in a common framework, our research defines the wind power life cycle as comprising three generalized life cycle phases illustrated in figure 1 and described below:

One-time upstream emissions, which includes emissions resulting from raw materials extraction, materials manufacturing, component manufacturing, transportation from the manufacturing facility to the construction site, and on-site construction.

Ongoing emissions during the turbine's operating phase, which includes emissions from maintenance activities such as replacement of worn parts and lubricating oils, and transportation to and from the turbines during servicing.

One-time downstream emissions, which includes emissions resulting from turbine and site decommissioning, disassembly, transportation to the waste site, and ultimate disposal and/or recycling of the turbines and other site materials.

Transmission and distribution (T&D) of electricity is sometimes included within the scope of LCAs, either through accounting for construction of the infrastructure or the loss of generated electricity in delivery to the consumer, or both.

Screening of the Literature

After the preliminary screen, a quality screen consistent with the general principles of the umbrella LCA Harmonization Project was applied to each estimate of life cycle GHG emissions, as many references produced more than one estimate because they evaluated multiple scenarios. Although a reference wasn't necessarily eliminated if only one of its estimates was screened out, most screening criteria applied to the reference as a whole; the results of screening are therefore reported at the level of the reference.

The pool of references was reduced from 175 to 72 upon applying the following minimum screening criteria:

1. LCA method:
   a. Employed a currently accepted LCA method (e.g., following guideline 14040 from the International Organization for Standardization [ISO 2006a, 2006b]).
   b. Included the upstream life cycle stage, as this stage is known to be the largest contributor to total GHG emissions for wind power systems.

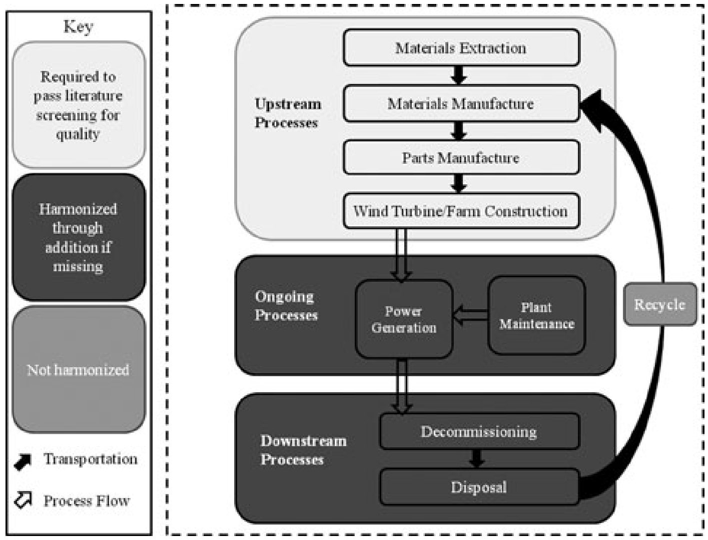

Figure 1 Process flow diagram illustrating the life cycle stages of wind power systems. Inclusion of at least one or more upstream life cycle stage was required for passing the screening process. Transportation between life cycle stages was not harmonized.

2. Transparency and completeness of reporting:
   a. Reported a reasonably descriptive method (e.g., scope and boundaries of study) and set of assumptions (e.g., capacity factor, system lifetime, recycling in end-of-life scenario).
   b. Cited primary or secondary data sources used for the analysis.
   c. Described, numerically where possible, characteristics of the wind power system studied (e.g., turbine model, capacity, site description or location, wind class, single turbine, or wind farm).
   d. Reported the name of software or database, if used, (e.g., SimaPro, Ecoinvent) as well as input parameters for the modeling (e.g., a material requirements list).
3. Relevance of the evaluated technology to modern, utility-scale wind power systems:
   a. Excluded wooden, steel, and aluminum rotor blades.
   b. Excluded non-three-bladed turbines.
   c. Excluded vertical-axis turbines.
   d. Excluded turbines with a rated capacity of less than 150 kilowatts (kW).

All estimates passing the above screening criteria were categorized as onshore, offshore, or a mix of the two, and are listed in table 1 along with important characteristics of the study and technology evaluated.

Harmonization Process

For the LCA Harmonization Project as a whole, two levels of harmonization were devised. The more resource-intensive level was envisioned as a process similar to that employed by Farrell and colleagues (2006) to harmonize the results of LCAs of ethanol. In that process, a subset of the available literature estimates of life cycle GHG emissions was carefully disaggregated. This process produced a detailed meta-model based on factors such as adjusted parameter estimates, realigned system boundaries within each life cycle phase, and a review of all data sources. A less-intensive and therefore grosser approach is more appropriate for the harmonization of a large set of literature estimates of life cycle GHG emissions. The less-intensive approach was chosen as the appropriate level of harmonization for wind power LCAs. The decision-making process for the level of harmonization is discussed in the supporting information available on the Journal's Web site.

This less-intensive harmonization process was performed by proportional adjustment of the published estimates of life cycle GHG emissions in grams CO_2-equivalent per kilowatt-hour (g CO_2-eq/kWh) to consistent values of two influential performance characteristics (capacity factor, system lifetime) and then, by addition or subtraction, to a consistent system boundary at the level of major life cycle stage.[2] GWPs were also harmonized where possible.

In keeping with the less-intensive harmonization approach, estimates were not audited for accuracy; published GHG emission estimates were taken at face value and converted to consistent units prior to being harmonized. Additionally, no exogenous assumptions were employed; if a reference did not report the information required for harmonization or conversion to the common functional unit, no assumptions were made. In those cases, that particular step of harmonization was not applied to that specific published GHG emission estimate, or the estimate wasn't included for harmonization, respectively. For instance, several estimates reported on a damages basis (e.g.,

Table 1 Studies and technologies that passed the screening criteria and produced an estimate of life cycle greenhouse gas (GHG) emissions, including key harmonization parameters

Author	*Year*	*Technology type*	*Turbine capacity (MW)*	*Lifetime (years)*	*Capacity factor (%)*	*Wind farm name, location*	*Study type*	*Notes*
Ardente et al.	2008	Onshore	0.66	20	19%	Italy (Sicily)	Empirical	
Berry et al.	1998	Onshore	0.3	—	31%	Penryddlan and Llidiartywaun, Wales	Empirical	
Chataignere and Le Boulch	2003	Onshore	0.6	20	29%		Theoretical	(1) Vestas 600 kW turbine
Chataignere and Le Boulch	2003	Onshore	2.5	20	34%		Theoretical	(1) Nordex 2.5 MW turbine
Chataignere and Le Boulch	2003	Offshore	2.5	20	46%		Theoretical	(50) Nordex 2.5 MW turbines, cassion
Chataignere and Le Boulch	2003	Offshore	2.5	20	46%		Theoretical	(100) Nordex 2.5 MW turbines
Chataignere and Le Boulch	2003	Offshore	2.5	20	46%		Theoretical	(50) Nordex 2.5 MW turbines, monopile
Chataignere and Le Boulch	2003	Onshore	1.5	20	29%		Theoretical	(1) Enercon 1.5 MW turbine
Crawford	2009	Onshore	3	20	33%		Theoretical	
Crawford	2009	Onshore	0.85	20	34%		Theoretical	
Dolan	2007	Offshore	1.8	20	30%	U.S. (Florida)	Theoretical	
Dones et al.	2005	Onshore	0.8	20/40	20%	Germany	Empirical	Turbine parts assume different lifetimes
Dones et al.	2005	Offshore	2	20	30%	Middelgrunden, Germany	Empirical	
Dones et al.	2007	Onshore	0.8	20/40	20%	Europe	Empirical	Turbine parts assume different lifetimes
Dones et al.	2007	Offshore	2	20	30%	Europe	Empirical	
Dones et al.	2007	Onshore	0.8	20/40	14%	Mont Crosin, Switzerland	Empirical	Turbine parts assume different lifetimes
DONG Energy	2008	Offshore	2	20	46%	Horns Rev, North Sea	Empirical	
Enel SpA	2004	Onshore	0.66	20	18%	Sclafani Bagni, Italy	Empirical	
European Commission	1995	Onshore	0.4	20	30%	Delabole, Penryddlan and Llidiartywaun, UK	Empirical	
Frischknecht	1998	Onshore	0.15	20	9.0%	Switzerland	Empirical	
Hartmann	1997	Onshore	1	20	19%		Theoretical	Process chain analysis
Hartmann	1997	Onshore	1	20	19%		Theoretical	EIO analysis
Hondo	2005	Onshore	0.4	50	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.4	30	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.3	50	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.4	20	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.3	30	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.3	20	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.4	10	20%	Japan	Theoretical	

(*Continued*)

Table 1 (*Continued*)

Author	*Year*	*Technology type*	*Turbine capacity (MW)*	*Lifetime (years)*	*Capacity factor (%)*	*Wind farm name, location*	*Study type*	*Notes*
Hondo	2005	Onshore	0.3	10	20%	Japan	Theoretical	
Jacobson	2009	Onshore	5	30	43%		Theoretical	
Jacobson	2009	Onshore	5	20	43%		Theoretical	
Jacobson	2009	Onshore	5	30	29%		Theoretical	
Jacobson	2009	Onshore	5	20	29%		Theoretical	
Jungbluth et al.	2005	Onshore	0.8	20/40	20%	Europe	Theoretical	Turbine parts assume different lifetimes
Jungbluth et al.	2005	Offshore	2	20	30%	Middelgrunden, Baltic Sea	Theoretical	
Khan et al.	2005	Onshore	0.5	20	—	Canada (Newfoundland)	Theoretical	
Krewitt et al.	1997	Onshore	0.25	20	25%	Northfriesland, Germany	Empirical	1990 technology vintage
Kuemmel and Sørensen[a]	1997	Mix	1.3	25	29%	Denmark	Theoretical	
Kuemmel and Sørensen	1997	Onshore	0.4	20	23%	Denmark	Theoretical	
Lee and Tzeng[b]	2008	Onshore	0.6–1.75	20	33%	Mailiao, Jhongtun and Chunfong, Taiwan	Empirical	
Lenzen and Wachsmann	2004	Onshore	0.6	20	68%	Manufactured and operated in Brazil	Theoretical	Recycled steel, coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	71%	Manufactured and operated in Brazil	Theoretical	Recycled steel, coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	55%	Manufactured and operated in Brazil	Theoretical	Recycled steel, near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	68%	Manufactured and operated in Brazil	Theoretical	Coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	71%	Manufactured and operated in Brazil	Theoretical	Coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	55%	Manufactured and operated in Brazil	Theoretical	Near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	42%	Manufactured and operated in Brazil	Theoretical	Recycled steel, inland, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	46%	Manufactured and operated in Brazil	Theoretical	Recycled steel, inland 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	42%	Manufactured and operated in Brazil	Theoretical	Inland, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	46%	Manufactured and operated in Brazil	Theoretical	Inland, 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	68%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	71%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	55%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	46%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Inland, 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	42%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Inland, 55 m hub height

(*Continued*)

Table 1 *(Continued)*

Author	*Year*	*Technology type*	*Turbine capacity (MW)*	*Lifetime (years)*	*Capacity factor (%)*	*Wind farm name, location*	*Study type*	*Notes*
Lenzen and Wachsmann	2004	Onshore	0.6	20	68%	Manufactured in Germany, operated in Brazil	Theoretical	Coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	71%	Manufactured in Germany, operated in Brazil	Theoretical	Coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	55%	Manufactured in Germany, operated in Brazil	Theoretical	Near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	46%	Manufactured in Germany, operated in Brazil	Theoretical	Inland, 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	42%	Manufactured in Germany, operated in Brazil	Theoretical	Inland, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	25%	Manufactured and operated in Germany	Theoretical	Coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	26%	Manufactured and operated in Germany	Theoretical	Coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	20%	Manufactured and operated in Germany	Theoretical	Near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	17%	Manufactured and operated in Germany	Theoretical	Inland, 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	15%	Manufactured and operated in Germany	Theoretical	Inland, 55 m hub height
Liberman and LaPuma[c]	2003	Onshore	0.75–1.3	Various	—	U.S. (Arkansas)	Empirical	
Martínez et al.	2009	Onshore	2	20	23%	Munilla, Spain	Empirical	
Martínez et al.	2009	Onshore	2	20	23%	Munilla, Spain	Empirical	
Martínez et al.	2009	Onshore	2	20	23%	Munilla, Spain	Empirical	
McCulloch et al.	2000	Onshore	0.6	25	20%		Theoretical	
Nadal	1995	Onshore	0.225	20	20%		Theoretical	
Pacca and Horvath	2002	Onshore	0.6	20	24%		Theoretical	
Pacca	2003	Onshore	0.6	40	24%	U.S. (Southern Utah)	Theoretical	
Pacca	2003	Onshore	0.6	30	24%	U.S. (Southern Utah)	Theoretical	
Pacca	2003	Onshore	0.6	20	24%	U.S. (Southern Utah)	Theoretical	
Pacca	2003	Onshore	0.6	10	24%	U.S. (Southern Utah)	Theoretical	
Pehnt	2006	Offshore	2.5	—	—	Germany	Theoretical	2010 technology vintage
Pehnt	2006	Onshore	1.5	—	—	Germany	Theoretical	2010 technology vintage
Pehnt et al.	2008	Offshore	5	—	—	North Sea	Theoretical	
Proops et al.	1996	Onshore	6.6	20	29%	UK	Theoretical	Used 1989 EIO tables
Proops et al.	1996	Onshore	6.6	20	29%	UK	Theoretical	Used 1989 EIO tables
Proops et al.	1996	Onshore	6.6	20	29%	UK	Theoretical	Used 1989 EIO tables
Rule et al.	2009	Onshore	1.65	100	39%	Te Apiti, New Zealand	Empirical	
Rydh et al.	2004	Onshore	0.225	30	26%	Gronhogen, Sweden	Empirical	End-of-life scenario: renovation
Rydh et al.	2004	Onshore	2	20	35%	Gronhogen, Sweden	Empirical	End-of-life scenario: replacement
Rydh et al.	2004	Onshore	0.225	20	26%	Gronhogen, Sweden	Empirical	End-of-life scenario: relocation

(*Continued*)

Table 1 (*Continued*)

Author	*Year*	*Technology type*	*Turbine capacity (MW)*	*Lifetime (years)*	*Capacity factor (%)*	*Wind farm name, location*	*Study type*	*Notes*
Rydh et al.	2004	Onshore	0.225	20	26%	Gronhogen, Sweden	Empirical	End-of-life scenario: recycling
Schleisner	2000	Onshore	0.5	20	25%	Tuno Knob, Denmark	Empirical	
Schleisner	2000	Offshore	0.5	20	29%	Fjaldene, Denmark	Empirical	
SECDA	1994	Onshore	0.3	40	24%	Canada (Saskatchewan)	Theoretical	
Spitzley and Keoleian	2004	Onshore	0.5	30	36%	Western U.S.	Theoretical	Ridge site, class 6 winds
Spitzley and Keoleian	2004	Onshore	0.5	30	26%	Western U.S.	Theoretical	Plains site, class 4 winds
Tremeac and Meunier	2009	Onshore	4.5	20	30%	Southern France	Theoretical	Transport by train
Tremeac and Meunier	2009	Onshore	4.5	20	30%	Southern France	Theoretical	Transport by truck
Tremeac and Meunier	2009	Onshore	4.5	20	30%	Southern France	Theoretical	Doubling transport distance
Uchiyama	1996	Onshore	0.4		20%	Japan	Theoretical	Micon 400/100 kW two-speed turbine
Uchiyama	1996	Onshore	0.3		20%	Japan	Theoretical	Mitsubishi 300 kW turbine
van de Vate	1996	Onshore	0.3	20	23%		Theoretical	
Vattenfall[d]	2003	Onshore	0.225–1.75	25	21%	Various wind farms, Sweden	Empirical	
Vattenfall[e]	2010	Mix	0.6–3	20	29%	Denmark, UK, Poland, Sweden, Germany	Empirical	Does not include T&D grid
Vattenfall[e]	2010	Mix	0.6–3	20	29%	Denmark, UK, Poland, Sweden, Germany	Empirical	Includes T&D grid
Vestas Wind Systems	2006a	Onshore	1.65	20	41%		Theoretical	
Vestas Wind Systems	2006b	Onshore	3	20	54%		Theoretical	
Vestas Wind Systems	2006b	Offshore	3	20	54%		Theoretical	
Voorspools et al.	2000	Onshore	0.6	20	34%	Belgium (coastal)	Theoretical	EIO analysis
Voorspools et al.[f]	2000	Onshore	0.15–1.5	20	34%	Belgium (coastal)	Theoretical	Process chain analysis
Voorspools et al.	2000	Onshore	0.6	20	11%	Belgium (inland)	Theoretical	EIO analysis
Voorspools et al.[f]	2000	Onshore	0.15–1.5	20	11%	Belgium (inland)	Theoretical	Process chain analysis
Waters et al.	1997	Onshore	0.15	25	23%	Baix Ebre, Spain	Empirical	
WEC	2004	Onshore	0.23	—	35%	Greece	Theoretical	
WEC	2004	Onshore	0.6	—	23%	Finland	Theoretical	
WEC	2004	Onshore	0.6	—	21%	Australia	Theoretical	
WEC	2004	Onshore	0.5	—	25%	Denmark	Theoretical	
WEC	2004	Offshore	0.5	—	29%	Denmark	Theoretical	
Weinzettel et al.	2009	Deep offshore	5	20	53%		Theoretical	With end-of-life scenario
Weinzettel et al.	2009	Deep offshore	5	20	53%		Theoretical	Without end-of-life scenario
Weinzettel et al.	2009	Offshore	2	20	30%		Theoretical	Ecoinvent database process
White	2006	Onshore	0.3425	25	26%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Update to 1998 publication estimate
White	2006	Onshore	0.75	30	29%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Update to 1998 publication estimate
White	2006	Onshore	0.6	20	20%	Glenmore, U.S. (Wisconsin)	Empirical	Update to 1998 publication estimate

(*Continued*)

Table 1 *(Continued)*

Author	Year	Technology type	Turbine capacity (MW)	Lifetime (years)	Capacity factor (%)	Wind farm name, location	Study type	Notes
White and Kulcinski	1998	Onshore	0.75	30	35%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Zond Z-46 turbines
White and Kulcinski	1998	Onshore	0.3425	25	24%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Kenetech KVS-33 turbines
White and Kulcinski	1998	Onshore	0.6	20	31%	Glenmore, U.S. (Wisconsin)	Empirical	Tacke 600e turbines
White and Kulcinski	2000	Onshore	0.3425	25	24%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Update to 1998 publication estimate
Wibberly	2001	Onshore	0.6	30	21%	Crookwell, Australia	Empirical	

Notes: One meter (m, SI) ≈ 3.28 feet (ft); MW = megawatts; kW = kilowatts.
[a]This data point represents a mix of 1 megawatt (MW) onshore and 3 MW offshore turbines. Therefore a mean capacity of 2 MW listed here was assumed for plotting in figure 2. Because the proportion of onshore to offshore turbines in the mix is unknown, this estimate could not be harmonized by capacity factor.
[b]This data point represents a mix of (4) 660 kilowatt (kW), (4) 600 kW, and (2) 1.75 MW turbines. Therefore the average was assumed for plotting purposes in figure 2. A weighted average was also used for capacity factor to allow harmonization by this parameter.
[c]This data point represents a mix of various turbines for which only the capacity range of 750 kW to 1.3 MW was reported; therefore a mean capacity of 1.025 MW was assumed to include this data point in the scatter plots in figure 2.
[d]The capacity listed represents a weighted average of (1) 225 kW, (2) 500 kW, (7) 600 kW, and (1) 1.75 MW turbines. The capacity factor also represents a weighted average based on the reported power outputs of the 11 turbines.
[e]The capacity listed represents a weighted average of the mix of (7) 600 kW, (4) 850 kW, (10) 1.5 MW, (63) 2.0 MW, (50) 2.3 MW, and (30) 3 MW turbines. The capacity factor is also an average weighted by the reported capacity factors of the groups of turbines.
[f]This data point represents a range of turbine capacities for which only the endpoints of the range were given. Therefore the mean of the endpoints was assumed as the capacity to include this point in the scatter plots in figure 2.

milliperson-equivalents/kWh) could not be back-calculated to the common functional unit and thus were not retained. Only nonduplicative estimates were included; however, any estimate that adapted previous work in a way that resulted in an estimate different from the original was accepted. Only the latest publication from authors who published the exact same estimates in multiple papers was retained for further analysis. Finally, GHG emission estimates had to be reported numerically (not just graphically) for inclusion.

Harmonization Parameters

Life cycle GHG emission estimates for wind power systems are calculated as follows:

$$\frac{CO_2 + \left(CH_4 * 25 \frac{\text{g } CO_2\text{-eq}}{\text{g } CH_4}\right) + \left(N_2O * 298 \frac{\text{g } CO_2\text{-eq}}{N_2O}\right)}{\textit{Capacity factor} * 8760 \frac{\text{hours}}{\text{year}} * \textit{Lifetime} * \textit{Nameplate capacity}}.$$

This equation allows for clear identification of the potential magnitude for adjustment that each of the harmonization parameters has in the life cycle GHG emission estimates. The numerator represents the total emissions over the life cycle, while the denominator represents the lifetime power output of the system. The GWP harmonization step adjusts two of the values in the summation in the numerator; however, the CO_2 portion of the emission estimates remains unchanged. Both the capacity factor and system lifetime harmonization steps scale the denominator in its entirety, and therefore have a larger potential than GWP harmonization to adjust the life cycle GHG emission estimates. The system boundary harmonization step adds additional emissions onto the numerator to account for life cycle stages that were not included in the scope of the original analysis. Thus this harmonization step has a potential for adjustment of the life cycle GHG emission estimates similar to that of the GWP harmonization step.

Statistical Assessment

Central tendency and variability in life cycle GHG emission estimates passing our screens are described using several statistical metrics. The key statistical metric chosen to characterize central tendency is the median value. The arithmetic mean is also reported but, due to the slight positive skew of the dataset, the median is preferred. Variability is discussed mainly in terms of interquartile range (IQR = 75th percentile − 25th percentile), which represents the spread of the middle 50% of estimates. Total range is also a key metric for expressing variability, as IQR only summarizes variability in the central half of the estimates. Standard deviation, as well as minimum and maximum values, is also reported. For each harmonization step, changes in central tendency and variability are compared with published estimates to describe the impact of the harmonization step. Decreases in measures of variability indicate effective harmonization in terms of a tightened IQR or range of life cycle GHG emissions from the evaluated technology.

These statistics are meant to summarize the current state of LCA literature of utility-scale wind power technologies. Although the studies and estimates that we selected were reasonably large in number and high quality, the available studies might not cover all possible cases of manufacture, deployment, or use. Thus the range exhibited in this article may not represent the true minimum, maximum, or central tendency for wind power GHG emissions, the current state of the technology as deployed or anticipated, or the inclusivity of all relevant contributions with regard to the depth and breadth across the supply chain. For example, the difference in results generated using process chain compared to hybrid economic input-output methods indicates that system boundary truncations can have significant impacts (Suh et al. 2004). In this respect, the upper end of the range exhibited in this article may be closer to the true life cycle GHG emissions than those estimates at the lower end.

The distribution of our results also cannot be considered a distribution of likelihood for actual life cycle GHG emissions for current or future applications of the technology. The precision and range of results are improved with the large sample size evaluated here, but sample limitations impact the accuracy of the results compared to the "true" life cycle GHG emission range and central tendency of wind power under all potential conditions. Confidence in the results for onshore wind is higher than for offshore owing to the larger sample size.

Finally, the impact on variability reduction of harmonizing a particular parameter is an indicator of the influence that parameter exerts on life cycle GHG emissions for wind, but is not a formal sensitivity analysis.

Harmonization of Global Warming Potentials

Per the screening criteria, the pool of articles ranged in publication year from 1980 to 2010, with several updates to GWPs published by the Intergovernmental Panel on Climate Change (IPCC) during this time. Therefore, because various GWPs were utilized in the literature, wherever mass emissions of individual GHGs were reported the GHG emission estimates were updated to reflect the most recent 100-year time horizon GWPs published by the IPCC (Forster et al. 2007) of 25 g CO_2-eq/g methane (CH_4) and 298 g CO_2-eq/g nitrous oxide (N_2O).

Harmonization of Operating Lifetime

Life cycle GHG emission estimates were also harmonized by assumed operating lifetime of the wind turbine and its components. Reported lifetimes ranged from 10 to 100 years, 20 years being the most commonly cited. Since 20 years is also a common design life for modern turbines (Vestas Wind Systems 2006a, 2006b), all GHG emission estimates were harmonized to a 20-year life span by proportionally scaling the lifetime power output while holding the life cycle emissions estimate constant. This assumes that emissions resulting from maintenance are not changed when a different lifetime is assumed. Operational maintenance, however, was the life cycle stage with the least coverage in the literature, and because its emissions are small relative to the other life cycle stages, any errors resulting from this assumption are likely small in magnitude. Several publications (Dones et al. 2005, 2007; Jungbluth et al. 2005; Rule et al. 2009) assumed lifetimes longer than 20 years and included a certain amount of parts replacement after the 20-year point, but did not separately report the emissions resulting from the refurbishing process. These estimates could not be harmonized by lifetime because the emissions from parts replacement could not be subtracted out. It is worth noting that different wind turbines or farms will have different lifetimes in practice. These depend on various factors—the length of the operating contract with the utility company, the lease on the land where the turbine is sited, parts failure and replacement with new turbines instead of repowering—and it is the nature of LCAs to be context specific. However, harmonization of assumed lifetime was nonetheless performed to demonstrate the effect that system lifetime has on wind power's life cycle GHG emissions, and to assess the degree to which harmonizing by this parameter tightens the range of estimates.

Harmonization of Capacity Factor

For wind power, capacity factor is the ratio of actual electricity generated to the maximum potential electricity generation (nameplate capacity multiplied by 8,760 hours per year). For a given wind resource, turbines operating at a higher capacity factor produce more electrical output than those with lower capacity factors by operating for longer periods of time over the course of the year.

In practice, different wind farms will operate at different capacity factors for several reasons, for instance, the specific wind conditions experienced at the site and the frequency and duration of maintenance. However, the purpose of harmonizing the GHG emission estimates is not to suggest that all LCAs of wind turbines or farms should assume a consistent nominal capacity factor, but to observe how large a role differences in assumed capacity factor play in the variability of published GHG emission estimates. The mean assumed capacity factor for onshore turbines in the pool of literature passing the quality and relevance screens was, after rounding, 30%, while the mean assumed capacity factor for offshore wind turbines was 40%. The latest survey of deployed turbines (Wiser and Bolinger 2010) suggests that the capacity-weighted average in 2009 is very close to these literature averages. Therefore GHG emission estimates that assumed alternative capacity factors were adjusted to these values. Modern turbines deployed in high wind class zones can reach 35% for onshore turbines and 45% for offshore turbines. In 2008, capacity-weighted average capacity factors for onshore wind reached 34%, owing to 2008 being a better wind resource year and having less curtailment than 2009. An additional contributing factor to the reduction in average capacity factor from 2008 to 2009 is the recent trend of wind installations in lower-quality wind resource areas because of transmission and other siting constraints (Wiser and Bolinger 2010). The effect of the higher capacity factor benchmarks on life cycle GHG emission estimates is provided in the supporting information on the Web.

Harmonization of System Boundary

The quality screen required that studies include an estimate for upstream GHG emissions because wind turbine operation has no direct combustion emissions. To improve consistency and reduce sources of variability, the median estimate of GHG emissions for operational or downstream life cycle phases from studies that included those phases were added to studies whose scope did not include one or both of those phases. When testing the effect of harmonization by system boundary independently, the median was calculated using published GHG emission estimates; when performed cumulatively with the other harmonization steps, the GHG emission estimates for studies that included these life cycle phases were harmonized by the other parameters first, and then the median of those harmonized estimates (per phase) was calculated. The rationale for employing these methods is further described in the supporting information on the Web.

Cumulative Harmonization of All Parameters

The last harmonization step was to harmonize by GWP, lifetime, capacity factor, and system boundary consecutively. As some harmonization steps may counteract previous ones, this represents the final results of the complete harmonization process.

Results

Summary of the Published Literature

The 126 estimates from 49 studies of wind power life cycle GHG emissions display a median of 12 g CO_2-eq/kWh, IQR of 12 g CO_2-eq/kWh, and a range of 79 g CO_2-eq/kWh. The IQR shows that the central 50% of the estimates lie within only 12 g CO_2-eq/kWh of each other, which is a relatively tight range when compared to the magnitude of other power technologies such as coal, for which life cycle GHG emission estimates are on the scale of 1,000 g CO_2-eq/kWh (Whitaker et al. 2012).

While the onshore studies are far greater in number than the offshore studies and have a larger total range of values, the IQR for the onshore group is only 13 g CO_2-eq/kWh, ranging from 7.3 to 20 g CO_2-eq/kWh. The published offshore studies are even tighter, with a smaller total range, and the central 50% of estimates within less than 5 g CO_2-eq/kWh of each other, lying in the range of 9.4 to 14 g CO_2-eq/kWh.

Cumulative installed wind capacity in the United States gradually grew from nearly zero in the early 1980s to roughly 3,000 megawatts (MW) by the year 2000, followed by exponential growth over the past decade to more than 35,000 MW in 2009.[3] The average turbine size in 1999 was 0.71 MW and the average price of wind energy was $65/megawatt-hour (MWh) expressed in 2009 U.S. dollars.[4] In 2009 the average turbine size had more than doubled to 1.74 MW while the average price had reduced to $45/MWh (Wiser and Bolinger 2010). These trends suggest that considerable learning has taken place in the industry. One might expect the increasing scale and industrial learning to reduce materials usage, which could reduce embodied GHG emissions. Figure 2 explores these potential trends, but neither is found, suggesting that with regard to GHG emissions, wind power has been stable over time and scale. This constancy may not remain into the future, but given the already low life cycle GHG emissions, even if relative reductions were to be achieved, they might not appreciably affect the magnitude.

Harmonization Results

The harmonization process was performed in a stepwise fashion, illustrated in figures 3 and 4 for onshore and offshore wind, respectively. In both figures, frame (a) displays the published estimates and frames (b) through (e) display the results of applying each harmonization step independently. Frame (f) is the final result of harmonizing by all factors cumulatively. Estimates are displayed in an ordinal ranking (from lowest to highest) that remains constant through all frames such that the effect of harmonization can be seen in the vertical translation of a given point. If a point remains in the same position after a given step, either the value of the harmonization parameter in the publication was already the same as the benchmark value chosen for harmonization, or the value for the harmonization parameter was not reported so harmonization of the estimate could not be performed.

Table 2 reports summary statistics for the onshore, offshore, and total pool of estimates passing the screens for each harmonization step. Life cycle GHG emission estimates that could not be harmonized in any given harmonization step due to missing data remain unchanged in the harmonization plots and the calculation of summary statistics from published values so that all of the summary statistics for each harmonization step are based on the same number of estimates (n = 126 for all values, n = 107 for onshore, and n = 16 for offshore). The three life cycle GHG emission estimates that were reported for an aggregated mix of both onshore and offshore technologies (Kuemmel and Sørensen 1997; Vattenfall 2010) were included in the harmonization process and the summary statistics for all technology types only. The individual GHG emission estimates from each publication for each harmonization step are also reported numerically in table S3 of the supporting information on the Web.

Harmonization of Global Warming Potentials

Only six estimates were harmonized in this step because most references do not report both the GWPs used and mass emissions of individual GHGs. All adjustments were less than 1 g CO_2-eq/kWh, resulting in an insignificant (less than 1%) change in variability and central tendency as a result of this harmonization step (figures 3b and 4b).

Harmonization of System Lifetime

Of the 126 estimates evaluated, 107 report system lifetimes; 80 were already at the benchmark value selected for harmonization, that is, 20 years. Therefore the effect of this harmonization step was relatively small, with a 2% increase in the median value, an 11% increase in the IQR, and a less than 1% reduction in total range (figures 3c and 4c).

Harmonization of Capacity Factor

Of the 126 GHG emission estimates in the pool, 118 report capacity factors. Because the assumed capacity factors of the literature vary considerably more than the assumed lifetimes, harmonizing by capacity factor reduced variability significantly

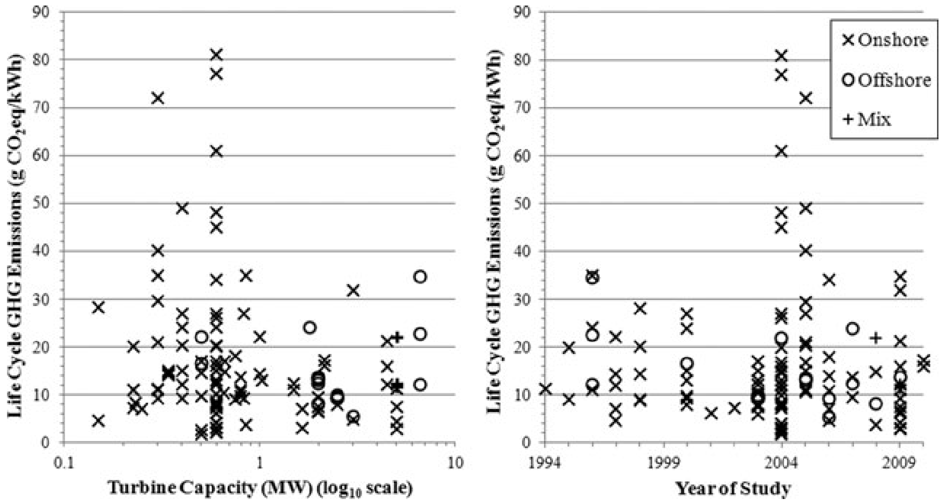

Figure 2 Published life cycle greenhouse gas (GHG) emissions of utility-scale wind power technologies by rated capacity (left) and year of study (right) for estimates that pass screening.

more. This harmonization step reduced the IQR by 14% and the total range by 42%. Figures 3d and 4d display that, on average, low-end GHG emission estimates increased while high-end estimates decreased as a result of this harmonization step. These results suggest that the value chosen for capacity factor in wind power LCAs significantly influences resulting estimates of life cycle GHG emissions.

Harmonization of System Boundary

Sixty-seven estimates of life cycle GHG emissions from 24 references disaggregated GHG emissions into life cycle phases. However, the system boundary for only 22 of those 67 estimates included all three previously defined life cycle stages: upstream, ongoing, and downstream. For the remaining 45 estimates, the median values for the missing life cycle stages, reported in table S2 in the supporting information on the Web, were added. Two sets of median add-on values were used, one for onshore and one for offshore technologies.

Harmonizing for system boundary logically resulted in an increase in the median estimate for both onshore and offshore studies, as add-on values were applied. Harmonization by system boundary did not, however, reduce the variability in life cycle GHG emission estimates. The IQR remained constant and the total range increased by 2.1%. Plots of this harmonization step (figures 3e and 4e) illustrate the small vertical translation of the individual estimates that were harmonized ($n = 45$), only two of which were offshore estimates. The majority of the life cycle GHG emission estimates remained constant because they either did not report disaggregated emissions or because, although disaggregated GHG emissions were reported, they already accounted for all three life cycle stages.

Cumulative Harmonization of All Parameters

Harmonizing for GWPs, system lifetime, capacity factor, and system boundary resulted in a significantly tighter distribution than the published GHG emission estimates for wind power systems (figures 3f and 4f). The published GHG emission estimates ranged from 1.7 to 81 g CO_2-eq/kWh, whereas harmonized estimates comprised a much smaller range of 3.0 to 45 g CO_2-eq/kWh, a decrease of 47% in the total spread of the data. The IQR decreased from 12 to 10 g CO_2-eq/kWh, a 14% reduction. The central tendency remained fairly constant through the harmonization process, with the median value decreasing from 12 to 11 g CO_2-eq/kWh. The change in IQR being considerably less than the change in total range implies that the lowest and highest 25% of the GHG emission estimates were more affected by the harmonization process than the middle 50% of the estimates. Harmonization of capacity factors resulted in a 42% reduction in total range, compared to the 47% reduction resulting from cumulative harmonization of all parameters. This effect implies that variability in assumed capacity factor is the largest contributor—of the harmonization parameters investigated—to variability in published estimates of life cycle GHG emissions of wind power systems.

These findings suggest that the harmonization process, through systematically adjusting estimates to reflect a consistent set of several important parameters, increased the precision of life cycle GHG emission estimates in the literature while having little effect on published central tendency. Figure 5 provides a side-by-side comparison of the published data and the harmonized data, which demonstrates the central tendency and variability of the data.

Overlay plots presenting the progression from published estimates to harmonized estimates showing each successive

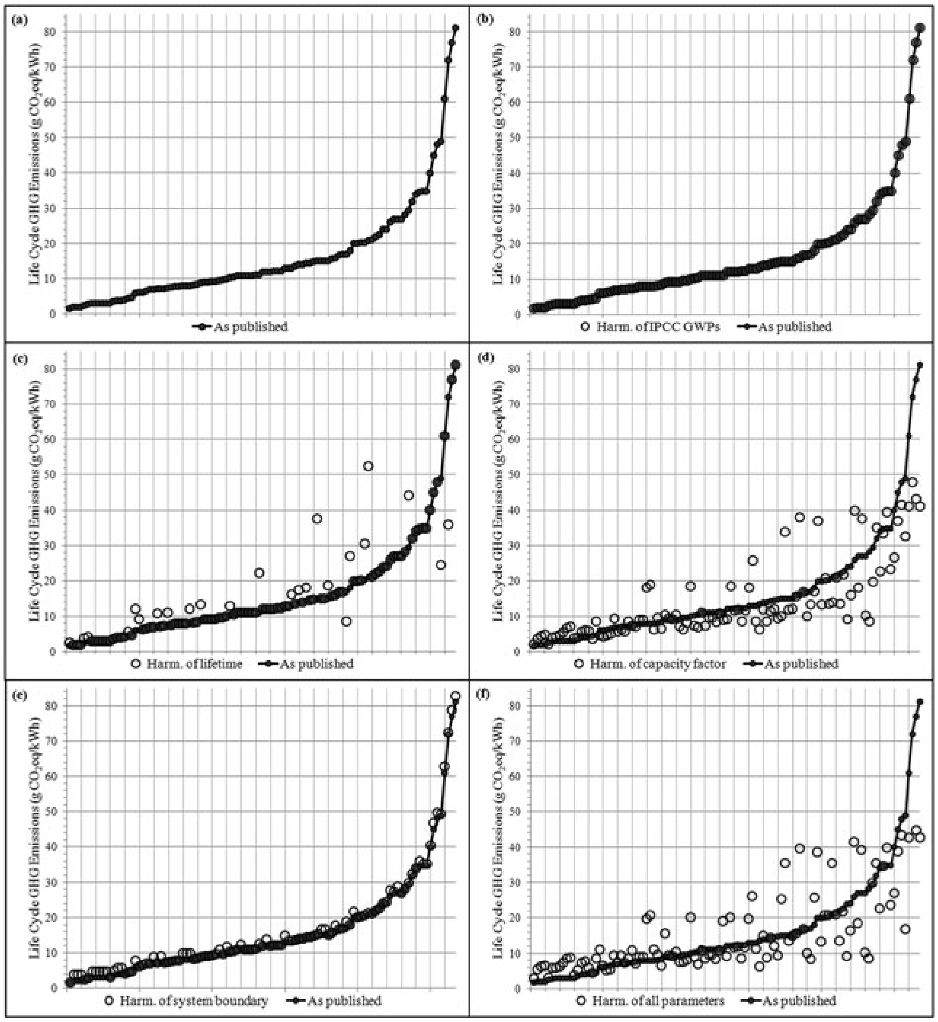

Figure 3 Life cycle greenhouse gas (GHG) emission estimates for onshore wind power from literature passing the screening criteria, ordinally ranked from smallest to largest published value. Frame descriptions: (a) published GHG emission estimates, (b) harmonization of global warming potentials to the most recently published values (Forster et al. 2007), (c) harmonization of operating lifetime to 20 years, (d) harmonization of capacity factor to 30%, (e) harmonization of system boundary to include the ongoing and downstream life cycle stages, and (f) cumulative harmonization of all parameters.

harmonization step (building upon the prior step) are given for onshore and offshore wind on a common set of axes in figures S1 and S2, respectively, in the supporting information on the Web.

Discussion

Comparing Onshore and Offshore

Based on the available literature, the range and IQR for onshore is considerably larger than for offshore, which may reflect the difference in the number of references or might reflect a true wider variability for this class of wind power technologies from range of siting circumstances, turbine size, turbine/wind farm design, and other factors. However, the median life cycle GHG emission estimates for onshore and offshore technology types are both 12 g CO_2-eq/kWh, as published, and 11 g CO_2-eq/kWh after harmonization. This similarity, combined with the tight distribution for both technology types in an absolute sense, suggests that the two technology types may not have significantly different life cycle GHG emissions. However, it should be remembered that these summary statistics reflect the technologies as they are represented in the

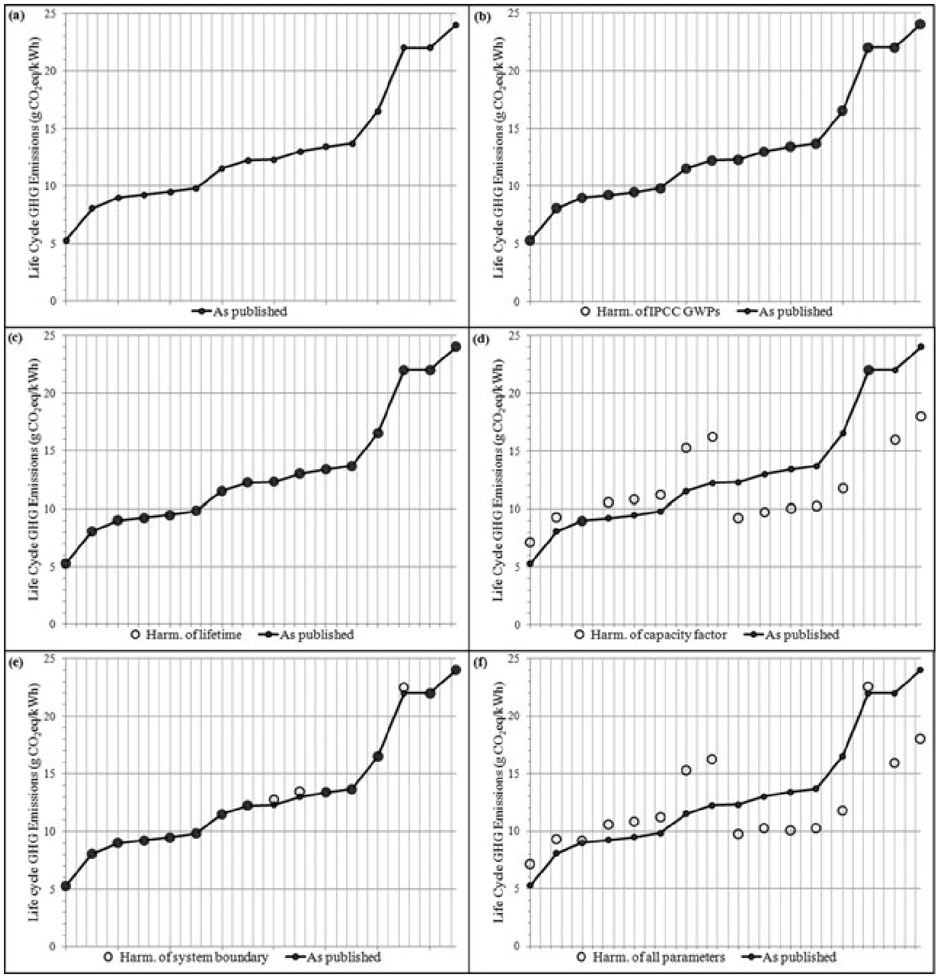

Figure 4 Life cycle greenhouse gas (GHG) emission estimates for offshore wind power from literature passing the screening criteria, ordinally ranked from smallest to largest published value. Frame descriptions: (a) published GHG emission estimates, (b) harmonization of global warming potentials to the most recently published values (Forster et al. 2007), (c) harmonization of operating lifetime to 20 years, (d) harmonization of capacity factor to 40%, (e) harmonization of system boundary to include the ongoing and downstream life cycle stages, and (f) cumulative harmonization of all parameters.

literature and perhaps not the true distribution of deployed technologies.

Limitations of this Analysis

Focus on Life Cycle Greenhouse Gas Emissions

The broad goal of the current phase of the LCA Harmonization Project is to clarify estimates of life cycle GHG emissions and better inform decision making and future analyses, where such estimates would be useful. However, to provide a more comprehensive perspective of the environmental and social impacts of power-generating technologies, other parameters, such as human health impacts, water consumption, and jobs created, should also be assessed.

Pooling Empirical and Theoretical Data

Some practitioners only consider empirical LCAs valid for current technologies because of the potential for modeled estimates to differ from measurements of the same parameter (e.g., Kubiszewski et al. 2010). Table 1 characterizes each study as either empirical or theoretical on balance, despite this characteristic being a continuum rather than a dichotomous choice. (In truth, almost all LCAs have some modeled estimates because empirical data are not always available for every process in the life cycle.) LCAs based on both types of data were included in this analysis. Including studies that are based, at least in important aspects, on parameters not empirically grounded could contribute some additional uncertainty to the results. However, given the similarity of results for GHG emission

Table 2 Summary statistics for each harmonization step, grouping the two system boundary harmonization steps (addition of ongoing and downstream life cycle stages) into one

Statistical measure	*As-published life cycle GHG* (*g* CO_2*-eq/kWh*)	*Harmonized by GWPs* (*g* CO_2*-eq/kWh*)	*Harmonized by lifetime* (*g* CO_2*-eq/kWh*)	*Harmonized by capacity factor* (*g* CO_2*-eq/kWh*)	*Harmonized by system boundary* (*g* CO_2*-eq/kWh*)	*Harmonized by all* (*g* CO_2*-eq/kWh*)
All values						
Mean	16	16	16	14	16	15
SD	14	14	13	10	14	10
Minimum	1.7	1.7	2.0	2.1	1.7	3.0
25th percentile	7.9	7.9	8.1	7.2	8.1	8.5
Median	12	12	12	10	12	11
75th percentile	20	20	21	17	20	18
Maximum	81	81	81	48	83	45
IQR	12	12	13	10	11.6	10
Range (maximum–minimum)	79	79	79	46	81	42
Change in mean (%)[a]	n/a	<1%	3.3%	−12%	3.4%	−5.6%
Change in SD (%)[a]	n/a	<1%	−5.6%	−27%	<1%	−28%
Change in median (%)[a]	n/a	0%	2.0%	−15%	1.5%	−10%
Change in IQR (%)[a]	n/a	0%	11%	−14%	0%	−14%
Change in range (%)[a]	n/a	<1%	<−1%	−42%	2.1%	−47%
Count of estimates[b]	126	6	109	118	82	126
Count of references[b]	49	3	42	44	26	49
Onshore						
Mean	16	16	17	14	17	15
SD	15	15	14	11	15	11
Minimum	1.7	1.7	2.0	2.1	1.7	3.0
25th percentile	7.4	7.4	7.9	7.0	7.9	8.4
Median	12	12	13	9.8	12	11
75th percentile	20	20	22	18	21	20
Maximum	81	81	81	48	83	45
IQR	13	13	14	11	13	11
Range (maximum–minimum)	79	79	79	46	81	42
Change in mean (%)[a]	n/a	<1%	3.5%	−13%	3.8%	−5.7%
Change in SD (%)[a]	n/a	<1%	−5.8%	−27%	<1%	−29%
Change in median (%)[a]	n/a	0%	4.6%	−18%	1.2%	−9.4%
Change in IQR (%)[a]	n/a	0%	12%	−13%	0%	−10%
Change in range (%)[a]	n/a	<1%	<−1%	−42%	2.1%	−47%
Count of estimates[b]	107	5	93	104	74	107
Count of references[b]	44	3	35	41	22	44
Offshore						
Mean	13	13	13	12	13	12
SD	5.2	5.2	5.2	3.9	5.3	3.9
Minimum	5.3	5.3	5.3	7.2	5.3	7.2
25th percentile	9.4	9.4	9.4	9.6	9.4	10
Median	12	12	12	11	13	11
75th percentile	14	14	14	15	14	15
Maximum	24	24	24	22	24	23
IQR	5.0	5.0	5.0	5.8	5.0	5.5
Range (maximum–minimum)	19	19	19	15	19	15
Change in mean (%)[a]	n/a	<1%	<−1%	−7.2%	<1%	−6.4%
Change in SD (%)[a]	n/a	<1%	<1%	−25%	1.2%	−24%
Change in median (%)[a]	n/a	0%	0%	−13%	2.0%	−13%
Change in IQR (%)[a]	n/a	0%	0%	17%	0%	10%
Change in range (%)[a]	n/a	0%	0%	−21%	0%	−18%
Count of estimates[b]	16	1	16	14	8	16
Count of references[b]	12	1	11	10	6	12

Notes: Statistics are reported to two significant digits with the exceptions of changes that are less than 1%, or if there is no change 0% is reported. GHG = greenhouse gas; g CO_2-eq/kWh = grams carbon dioxide equivalent per kilowatt-hour; GWP = global warming potential; SD = standard deviation; IQR = interquartile range.

[a]Percent change statistics were calculated with all references in the category (all values, onshore, or offshore) whether harmonized or not.

[b]Counts of estimates and references for each harmonization step only include the estimates that were harmonized for that step. The counts for the "harmonized by all" column include estimates that were harmonized by at least one parameter.

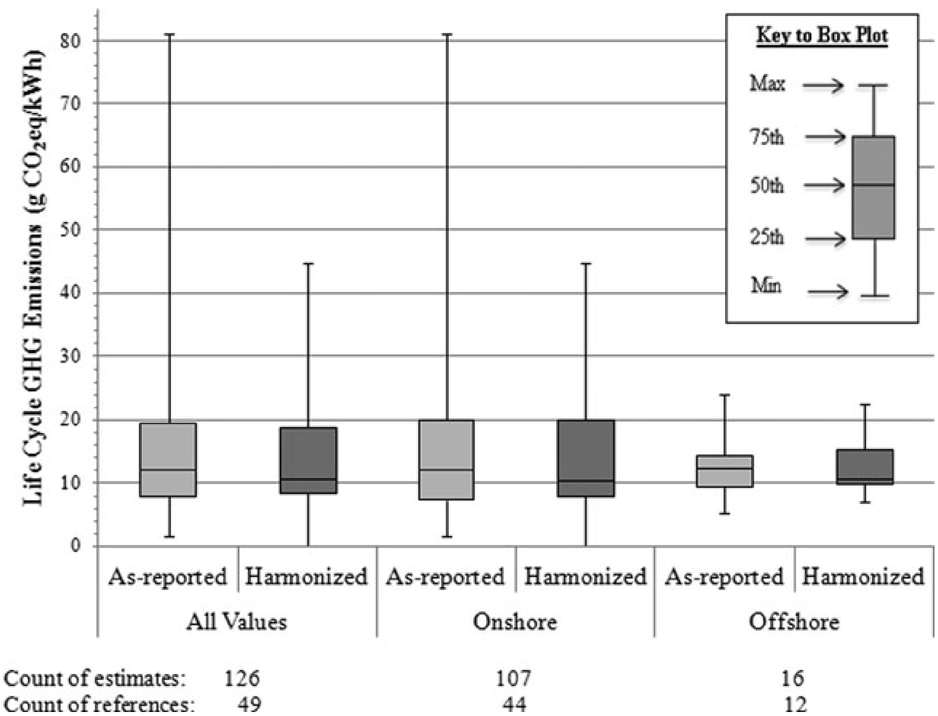

Figure 5 Side-by-side comparison of central tendency and spread of published greenhouse gas (GHG) emission estimates passing our screening criteria and the corresponding harmonized estimates.

estimates of wind power systems between studies characterized as empirical and theoretical, any additional uncertainty from combining the two types of studies is likely insignificant.

Remaining Dimensions of Inconsistency

The light level of harmonization performed for life cycle GHG emission estimates for wind power technologies included harmonizing system boundaries at the level of major life cycle phase, GWPs, system lifetimes, and capacity factors for the pool of estimates that passed the screening criteria. This extent of harmonization was deemed sufficient for reducing variability in published life cycle GHG emission estimates of wind power systems, as the published estimates already comprise a relatively tight dataset. However, additional dimensions of inconsistency across studies are known. Harmonization along these dimensions could potentially further reduce the variability in published estimates. Remaining parameters not harmonized here include upstream electricity mix used in the manufacturing processes (which determines the GHG emission intensity of input electricity); a more detailed system boundary harmonization to account for each individual subprocess that comprises the more general upstream, ongoing, and downstream life cycle stages used in this analysis; harmonization to either include or exclude transmission and distribution infrastructure for all estimates so that individual turbines can more accurately be compared to wind farms; and wind power class. Transmission and distribution losses (typically 5% to 10% of generated electricity) are also excluded, which could increase life cycle GHG emissions by a similar magnitude if the functional unit is chosen as delivered electricity rather than the more common generated electricity. Another effect of harmonization by additional parameters could be to alter the central tendency of life cycle GHG emission estimates, for instance, as has been shown in Lenzen and Wachsmann (2004) and Pehnt (2006) regarding changes to the GHG intensity of background energy systems.

Accuracy of the Central Tendency of Literature Estimates to True Life Cycle Greenhouse Gas Emissions

The literature collected consists solely of attributional LCAs, which evaluate the technology in isolation, with few exceptions such as Pehnt (2006). Consequential LCAs consider impacts to other systems caused by the studied technology. Potential consequential effects not covered in the reviewed literature include changes in consumption owing to changes in the retail price of electricity from the addition of wind power; lowering the GHG intensity of the electrical grid, which reduces embodied GHG emissions of industrial products, including newly manufactured wind turbines; GHG emissions caused by changes in land use to accommodate wind farms; and the combustion-based technologies in the electrical grid having to respond to accommodate the intermittency and nondispatchable nature of wind power. The thermal efficiency of fossil-based power plants is reduced when operated at fluctuating and suboptimal loads to supplement wind power, which may degrade, to a certain extent, the GHG benefits resulting from the addition of wind to the grid. A study conducted by Pehnt and colleagues (2008) reports that a moderate level of wind penetration (12%) would result in efficiency penalties of 3% to 8%, depending on the type of conventional power plant considered. Gross and colleagues (2006) report similar results, with efficiency penalties ranging from nearly 0% to 7% for up to 20% wind penetration. Pehnt and colleagues (2008) conclude that the results of adding offshore wind power in Germany on the background power systems maintaining a level supply to the grid and providing enough reserve capacity amount to adding between 20 and 80 g CO_2-eq/kWh to the life cycle GHG emissions profile of wind power, depending on the various conditions of the energy economy that determine the grid's composition. Thus, considering consequential effects on the background energy system can be significant relative to the attributional life cycle GHG emissions of wind power, as well as for the comparison of wind to other renewable electricity generation technologies (which themselves should be considered on a consequential basis), but should not fundamentally alter the comparison to fossil fuel-based technologies.

Some consequential effects of wind power systems listed above could improve the life cycle GHG emissions profile while others increase it, and all are dependent on specific circumstances of the systems in which wind power is embedded. Thus the answer could change depending on how the question is asked. Therefore the estimates found through this meta-analysis aren't necessarily any more accurate than the underlying LCA literature regarding true (and complete) life cycle GHG emissions, although, for many purposes, knowing the GHG emissions of this technology in isolation, which this study clarifies, could be desirable.

Clustering Bias

This study analyzed 126 distinct life cycle GHG emission estimates of wind power systems. However, these 126 estimates were generated from only 49 different studies and were produced by only 42 different primary authors (not accounting for additional overlap in authors where primary authors were also coauthors of other studies). Thus, there is potential bias in the results of this meta-analysis from clustering, such as multiple scenarios produced within the same study or multiple studies published by the same author(s). In both of these cases, estimates are more likely to be similar to one another than to the rest of the pool of estimates due to commonalities in methods, assumptions, the particular system studied, and data sources. The extent to which these two types of data clustering could cause bias in the results was not quantitatively accounted for or examined. Each of the 126 estimates was treated as independent throughout the analysis. As a result, large clusters within the dataset have potentially caused the summary statistics to be somewhat skewed in their direction. The cluster with the greatest potential to cause bias, due to the largest number of estimates produced from just one study (Lenzen and Wachsmann 2004), generated 25 GHG emission estimates that ranged from 2 to 81 g CO_2-eq/kWh. Given the breadth and even distribution of the range of estimates from this reference, author-based clustering from this study likely does not significantly skew the distribution of results found from harmonization. Other potential clusters in the dataset are considerably smaller in the number of estimates and thus would appear to present a small risk of potential bias.

There is also a third type of clustering bias inherent to LCAs, which is overlap in data sources. LCAs of any one type of system or product that employ common databases or software packages are more likely to have similar results than those using different data sources. The pool of publications that passed the screening criteria contains articles that used common data sources, for example, the Ecoinvent database. One might be able to quantitatively assess the influence of clustering by data source by defining a hierarchical influence tree for each article, statistically evaluating the extent of correlation and then perhaps using the correlation metric to weight the calculation of means. However, because of the large number of data sources for any given LCA, questions of cut-off in modeling data source influence, the subjective nature of assigning a quantitative measure of influence to each source, and other issues such an analysis were beyond the scope of this study. Nevertheless, given the tight distribution of published results, any bias in the distribution is not likely consequential when considering contexts of decision making and comparisons to other electricity generation technologies.

Sample Sizes

Another limitation of this analysis is the relatively small number of offshore wind studies compared to the much larger pool of onshore studies. There were only 12 publications producing 16 life cycle GHG emission estimates for offshore turbines that passed the screens for quality. With such a small dataset, summary statistics can easily be skewed by one or two outlying values. However, the published offshore GHG emission estimates fell within such a tight range that an outlier estimate causing biased results was not a serious concern. Additionally, only one study passing our screens considered deep offshore wind (Weinzettel et al. 2009), so this is a technology for which additional LCA studies are required to be able to assess with any amount of confidence how its life cycle GHG emission profile compares to onshore and shallow offshore wind technologies.

Conclusions

Life cycle GHG emissions of wind-powered electricity generation published since 1980 range from 1.7 to 81 g CO_2-eq/kWh. Although this is already a tight range, upon harmonizing the data to a consistent set of GWPs, system lifetime, capacity factors, and gross system boundary, the range of life cycle GHG emission estimates was reduced by 47%, to 3.0 to 45 g CO_2-eq/kWh. The first and third quartiles stayed relatively constant through the harmonization process, revealing that the middle 50% of the data did not change nearly as much as the lowest 25% and highest 25% of the estimates. The parameter found to have the greatest effect on reducing variability is capacity factor.

The extensive overlap in the distributions of estimates for onshore and offshore technologies suggests that their life cycle GHG emissions may not be notably different. An exception to this may be deep offshore wind technology, for which the literature provided only one estimate. Therefore, with deep offshore wind being a nascent technology on which there is sparse LCA literature to date, as well as a technology that may have considerably different material requirements due to design differences, this may be an area where life cycle GHG emissions of wind power systems have the potential to significantly differ from previously published studies and warrants further investigation.

The harmonization process decreased the variability and increased the precision of the previously published estimates by systematically aligning common system parameters across studies to a consistent set of values. However, improved precision does not imply improved accuracy. There are many consequential effects of deployment of wind power not typically considered in the majority of wind LCAs, which are attributional in nature, and these effects could increase or decrease previously published estimates of life cycle GHG emissions. Another issue is truncation error often inherent in process-based LCAs, which form the majority of LCAs considered in this article. In this respect, the upper end of the range exhibited in this article may be closer to the true life cycle GHG emissions than those estimates at the lower end.

This study ultimately concludes that, given the large number of previously published life cycle GHG emission estimates of wind power systems and their narrow distribution, it is unlikely that new process-based LCAs of similar wind turbine technologies will greatly differ. Additional consequential LCAs would enhance understanding of the true life cycle GHG emissions of wind power, although even those are unlikely to fundamentally change the comparison of wind to other electricity generation sources.

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Notes

1. Results from the whole LCA Harmonization project, including this article, can be visualized and downloaded at http://openei.org/apps/LCA.
2. One gram (g) = 10^{-3} kilograms (kg, SI) ≈ 0.035 ounces (oz). One kilowatt-hour (kWh) ≈ 3.6×10^6 joules (J, SI) ≈ 3.412×10^3 British thermal units (BTU). Carbon dioxide equivalent (CO_2-eq) is a measure for describing the climate-forcing strength of a quantity of greenhouse gases using the functionally equivalent amount of carbon dioxide as the reference.
3. One megawatt (MW) = 10^6 watts (W, SI) = 1 megajoule/second (MJ/s) ≈ 56.91×10^3 British thermal units (BTU)/minute.
4. One megawatt-hour (MWh) ≈ 3.6×10^9 joules (J, SI) ≈ 3.412×10^6 British thermal units (BTU).

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About the Authors

Stacey Dolan was an analyst at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, USA, during the time of this research. **Garvin Heath** is a senior scientist at NREL.

Supporting Information

Additional supporting information may be found in the online version of this article:

Supporting Information S1: The supporting information provides further detail on the screening process, GHG emissions by life cycle and harmonization stage, and rationale for the system boundary harmonization approach.

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