Valuing the Greenhouse Gas Emissions from Wind Power

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***Abstract*-The growth in both onshore and offshore wind power has been rapid over the past few decades and has led to a need for comparable, consistent and reliable life cycle carbon assessment of wind power in order to provide decision-makers with robust information. The current published estimates for wind power range from 2 to 81 gCO_2e/kWh. This study reduces this range through a meta-analysis of 82 estimates gathered from 17 independent studies. Through harmonisation of lifetime, capacity factor and recycling, the published range of life cycle carbon emissions estimates is reduced by 56% to between 2.9 & 37.3 gCO_2e/kWh. Average values for onshore and offshore wind power are estimated as 16 & 18.2 gCO_2e/kWh respectively after harmonisation and onshore and offshore wind power technologies exhibit similar characteristics in relation to their life cycle carbon emissions. Key differences with previous studies are that this study benefits from inclusion of data from a recently published comprehensive offshore wind farm assessment, and harmonisation is conducted for recycling procedures which results in an increase in the lower band of the range of life cycle carbon emissions estimates.**

This study concludes that much can be gained from harmonisation of historic life cycle estimates and moving towards a standard approach for carbon assessment of given technologies should be seen as an industry imperative. Wind power estimates lying within the interquartile range of meta-analyses such as presented in this paper and elsewhere should be considered to be reliable. However, the effects of wind generation intermittency on the carbon efficiency of thermal generation plant elsewhere in a supply network is not fully quantified and must be investigated to improve our knowledge of the overall carbon emissions produced by the deployment of wind generation plant.

Keywords*- *Life Cycle Assessment; Wind Power; Harmonisation; Meta-Analysis

I. INTRODUCTION

The global wind power industry has grown relentlessly in recent decades particularly in affluent economies such as the European Union and where political concerns over future Anthropogenic Global Warming (AGW) are greatest. The ability of the technology to generate electricity and feed it into a national grid has been apparent for some time and, as with all energy sources its true success will ultimately be judged on its ability to produce a reliable and inexpensive resource. In addition, due to the environmental concerns over AGW that contributed to its development, it will also be judged on its ability to produce low carbon energy. It is therefore important that a reliable and consistent method is developed to assess the wind power industries whole life cycle greenhouse gas (GHG) emissions.

European wind power capacity has been growing at a dramatic rate since its beginnings as a commercial source of power generation in the 1980s. The reasons for this have been numerous and include: depletion of fossil fuel reserves; environmental concerns, particularly with respect to AGW; and heightening energy demands across the globe [1]. In the EU in particular, ambitious GHG emissions reductions targets have led to the rapid deployment of renewable technologies and especially wind power generation since it is currently the most technologically and commercially viable option. In 2006 installed capacity of wind power was 48,027 MW [1], some 28 times greater than that in 1994. At the end of 2011 it was reported by the Global Wind Energy Council [2] that the total capacity stood at 96,616 MW for Europe (93,957MW of this within the EU). It has also been reported that based on the rate of deployment of the technology recorded in 2010, EU targets of 20% renewables by 2020 should be exceeded by 0.7% [3]. This is in contrast to many earlier reports that suggested that these targets would be difficult, if not impossible to reach [4]. However, it is also important to acknowledge that some analysts forecast wind power to produce a total energy of 495TWh in 2020, which equates to only 14% of EU electricity demand [5]. While there are several limiting issues associated with extensive use of wind power, such as grid balancing and responding to rapid variations in supply, it is undeniable that the development of wind power has exceeded expansion expectations through one of the most difficult economic climates in recent history (Figure 1).

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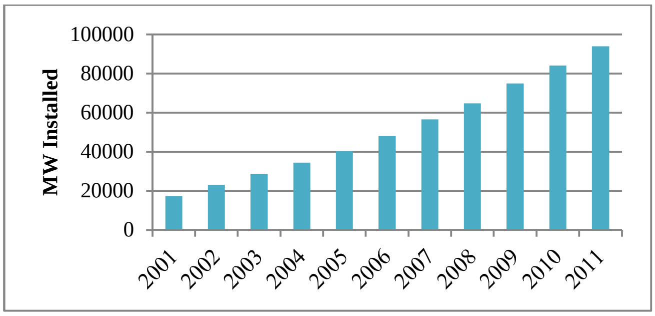

Figure 1 Wind energy installed in the EU in the last decade [2, 3]

One particular reason for the recent growth in installed wind capacity is its potential to reduce the GHG emissions associated with the electricity generation industry. However although the wind power industry does not directly contribute to GHG emissions by burning fossil fuels to generate electricity, it does contribute to other GHG emissions and analysts must consider those incurred during all parts of its life cycle including materials production, manufacturing, construction, transportation, maintenance and decommissioning activities. A lifecycle assessment such as that proposed by the International Organization for Standardisation's (ISO) Life Cycle Assessment approach [6] is appropriate for assessing the wind industries total GHG emissions. If the wind power industry is to demonstrate significant reductions in GHG emissions through its widespread use, then a LCA approach should be adopted so that a fair comparison can be made between the total emissions resulting from the activities of the industry and those of alternative generation technologies can be made.

This paper sets out to systematically review and harmonise published emission studies of the wind generation industry. This follows on from previous reviews of wind farm LCAs [7] and particularly that of Dolan and Heath [8], who use a harmonisation process to characterise and adjust system performance, system boundaries and global warming potentials (GWPs) of the individual GHG species. This paper will provide further suggestions for best practice in LCAs of wind power with the intention of reducing the large variation present in previously published LCAs [9] in future studies of wind industry activity. The objective of the paper is to identify and explain the variability in the results of published LCAs, suggest improvements to the harmonisation process and hence improve the reliability of future LCAs.

The LCA process can produce differences greater than an order of magnitude in estimates of wind farm carbon emissions, and it is clear that the method requires clearer definition for the sake of consistency and credibility of the results. A meta-analysis provides the advantage of being able to combine several studies to address unresolved issues, such as lack of consistency in system boundaries, that result from using the International Standards Organization (ISO) life cycle assessment methodology (ISO 14040-44). This has been highlighted in at least one previous study [9], and this paper adopts a similar approach applied with some variation in to attempt to improve further the reliability of the results.

Finally, this paper utilises the results of the harmonisation method employed to relate the average figure of lifecycle GHG emissions to those of gas-fired power generation. A discussion of the complex interaction between the two technologies in a typical power network mainly due to the intermittent generation of the wind industry is also included and the need for a greater understanding of this interaction emphasised.

II. METHOD OF REVIEW

A. Screening of Literature

A search of the current literature was conducted in order to find published wind LCAs. In line with the approach taken by Dolan and Heath [8] only papers that were published as scholarly journal articles, trade journal articles, conference proceedings, books or chapters, theses, dissertations, or reports, and were written in English and evaluated electricity as a product were included. In addition to the inclusion criteria outlined above, LCAs published before 2000 were excluded, as were articles that were not free of charge to researchers. This initial search yielded 82 estimates for wind power from 17 references. Following the methodology used elsewhere [8], the defining characteristics of each study were recorded as were other relevant study specific information. Important system parameters for wind power were also recorded, namely capacity, capacity factor, estimated system lifetime and total lifecycle emissions. This is summarised in Table I.

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TABLE I STUDIES INCLUDED WITHIN THIS HARMONISATION STUDY

Study	Wind System	Turbine Capacity (MW)	Capacity Factor	Life-time (Year)	GHG Esti-mate	Study Type
[12]	onshore	0.66	19%	20	14.8	empirical
[13]	onshore	3	33%	20	32	theoretical
[13]	onshore	0.3	17%	30	35	theoretical
[14]	onshore	3	43%	20	7	theoretical
[14]	onshore	3	43%	20	7.4	theoretical
[14]	onshore	3	35%	20	8.6	theoretical
[14]	offshore	2.5	40%	20	9	theoretical
[15]	onshore	1.8	21%	20	8.8	empirical
[15]	onshore	2	34%	20	9.7	empirical
[15]	onshore	2	20%	20	16.7	theoretical
[15]	onshore	2	34%	20	17.4	theoretical
[15]	onshore	2	34%	20	23.3	theoretical
[15]	onshore	2	34%	20	38.3	theoretical
[16]	onshore	0.3	20%	50	15	theoretical
[16]	onshore	0.4	25%	30	16	theoretical
[16]	onshore	0.4	23%	30	18	theoretical
[16]	onshore	0.4	20%	30	20.3	theoretical
[16]	onshore	0.4	20%	50	21	theoretical
[16]	onshore	0.4	17%	30	24	theoretical
[16]	onshore	0.3	25%	30	24	theoretical
[16]	onshore	0.3	23%	30	26	theoretical
[16]	onshore	0.3	20%	20	27	theoretical
[16]	onshore	0.4	15%	30	27	theoretical
[16]	onshore	0.3	20%	30	29.5	theoretical
[16]	onshore	0.85	34%	20	35	theoretical
[16]	onshore	0.3	15%	30	39	theoretical
[16]	onshore	0.4	20%	20	40	theoretical
[16]	onshore	0.3	20%	10	49	theoretical
[16]	onshore	0.4	20%	10	72	theoretical
[17]	onshore	0.8	20%	20	11	theoretical
[17]	offshore	2	30%	20	13	theoretical
[18]	onshore	0.6	55%	20	2	theoretical
[18]	onshore	0.6	68%	20	2	theoretical
[18]	onshore	0.6	71%	20	2	theoretical
[18]	onshore	0.6	42%	20	3	theoretical
[18]	onshore	0.6	46%	20	3	theoretical
[18]	onshore	0.6	55%	20	3	theoretical
[18]	onshore	0.6	68%	20	3	theoretical
[18]	onshore	0.6	71%	20	3	theoretical
[18]	onshore	0.6	42%	20	4	theoretical
[18]	onshore	0.6	46%	20	4	theoretical
[18]	onshore	0.6	68%	20	8	theoretical
[18]	onshore	0.6	71%	20	8	theoretical
[18]	onshore	0.6	55%	20	10	theoretical
[18]	onshore	0.6	46%	20	12	theoretical
[18]	onshore	0.6	42%	20	13	theoretical
[18]	onshore	0.6	68%	20	15	theoretical
[18]	onshore	0.6	71%	20	16	theoretical
[18]	onshore	0.6	55%	20	20	theoretical
[18]	onshore	0.6	46%	20	26	theoretical
[18]	onshore	0.6	42%	20	27	theoretical
[18]	onshore	0.6	25%	20	45	theoretical
[18]	onshore	0.6	26%	20	48	theoretical
[18]	onshore	0.6	20%	20	61	theoretical
[18]	onshore	0.6	17%	20	77	theoretical
[18]	onshore	0.6	15%	20	81	theoretical
[19]	onshore	3.6	35%	20	24.6	empirical
[20]	onshore	2	23%	20	6.2	theoretical
[20]	onshore	2	23%	20	6.6	empirical
[20]	onshore	2	23%	20	9.3	theoretical
[21]	onshore	3	43%	20	9	theoretical
[21]	onshore	1.5	30%	20	11	theoretical
[22]	onshore	0.5	25%	20	9.7	empirical
[22]	offshore	0.5	29%	20	17	empirical
[23]	onshore	4.5	30%	20	12.1	theoretical
[23]	onshore	4.5	30%	20	15.8	theoretical
[23]	onshore	4.5	30%	20	21.2	theoretical
[24]	onshore	1.65	41%	20	7.1	theoretical
[25]	onshore	3	54%	20	4.9	theoretical
[25]	offshore	3	54%	20	5.5	theoretical
[26]	offshore	5	45%	20	24.1	theoretical
[26]	offshore	5	45%	20	28.0	theoretical
[26]	offshore	5	45%	20	29.2	theoretical
[26]	offshore	5	48%	20	29.7	theoretical
[26]	offshore	5	45%	20	32	empirical
[26]	offshore	5	41%	20	34.6	theoretical
[27]	offshore	3	54%	20	5.0	empirical
[27]	onshore	3	30%	20	6.0	empirical
[27]	onshore	1.65	41%	20	8.2	empirical
[28]	deep offshore	5	53%	20	11.6	theoretical
[28]	deep offshore	5	53%	20	12.2	theoretical
[28]	deep offshore	2	30%	20	13.7	theoretical

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The scopes of LCAs in the wind industry have differed considerably to date from one study to another. It was suggested as long ago as a decade that uncertainties in lifecycle studies could be reduced by standardising assessment practice [7]. It is particularly difficult to compare lifecycle studies as a result of the different methodologies employed by individual researchers. Therefore, this paper uses the following definitions of the phases of the wind power life cycle:

1. Production: This includes extraction of raw materials, manufacturing of the foundation, tower, nacelle and blades as well as manufacturing of the transmission grid. Transportation of the raw materials and components to the site is also included.

2. Construction: This includes on-site construction and transport as well as civil works such as access roads and hardstandings. Grid connection should also be included, particularly for offshore installations. Environmental disturbance is also included where appropriate.

3. Operation: This includes all emissions from maintenance such as change of oil, lubrication and transport to and from the turbines. Furthermore, renovation of the turbines is also included.

4. Disposal: This includes dismantling and transport to the final disposal site (recycling, incineration or deposit). At recycling, it is limited to the point where the material is ready for reuse.

A variety of papers have been considered that include both the whole lifecycle of a wind farm project as well as studies that consider only part of the lifecycle such as the turbine manufacture for example. This approach is taken because complete wind farm lifecycle studies are still few and useful information that can be taken from studies involving particular lifecycle stages within the whole lifecycle of a project. Figure 2 illustrates the process of wind power systems LCAs and can be applied to either wind turbines or whole wind farms. While others [8] use three main process groups (upstream, ongoing and downstream), this paper splits upstream processes into production and construction and includes the need for transport to be considered where possible, both as its own process and as a unit process within system processes. This is shown in the key in Figure 2. The processes are divided in this way in an attempt to better utilise life cycle GHG assessment as a tool for identifying emissions in individual parts of the system as well as simply providing the life cycle GHG estimate. This is supported for GHG assessment of macro systems [10] and could be developed for micro systems in order to generate improvements and “upgrades” to the system.

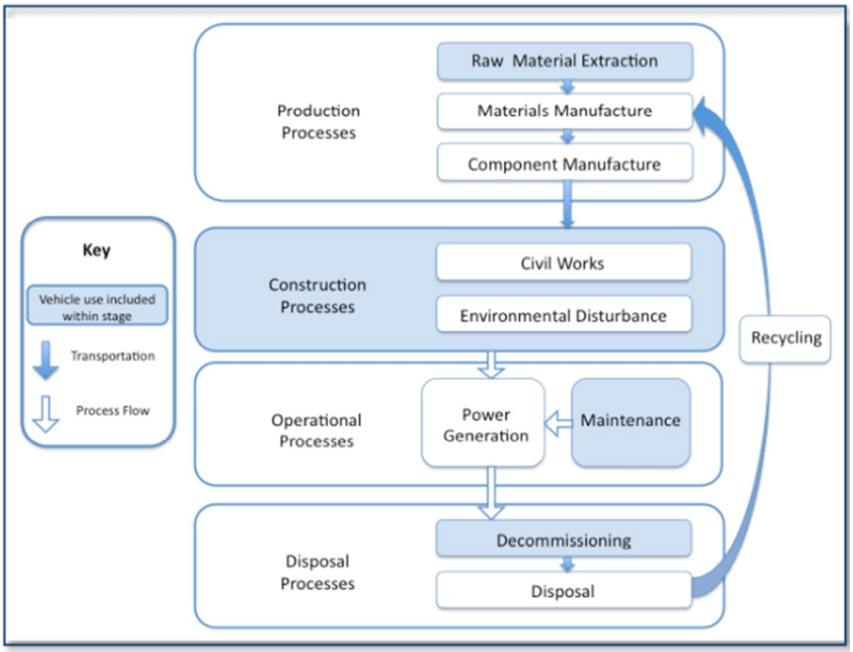

Figure 2 Process flow diagram for wind power systems LCAsProduction and Construction processes should be included as a minimum in order to pass the screening process for inclusion
Transport is included both as an individual process, shown by solid arrows and also within specific processes, shown by filled boxes.

The difference between this paper’s process allocation and Dolan and Heath [8] demonstrates how variability can easily be created when comparing processes that are upstream in nature or even when deciding which individual processes are captured within each system process, for instance by choosing whether or not to include turbine maintenance. This has consistently made it difficult to use GHG estimates to reduce emissions in wind power system since more detail about the processes that are included or excluded is required for each individual estimate.

In order to improve this current situation, this paper moves from the traditional approach to improving estimates through critical surveys, such as that of a review for nuclear power [11] to utilising a systematic review and meta-analysis such as is employed by Dolan and Heath [8]. The intention is to create more detailed guidance for production of GHG emissions

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estimates which offer comparability and consistency while also being useful for improvement and upgrading of both the system and the process of estimation.

B. Harmonisation Process

The harmonisation process used in this paper is partly derived from [8] and from the LCA Harmonisation Project developed by the National Renewable Energy Laboratory [29]. The less-intensive (or light) method of harmonisation is used herein in order to align with the Dolan and Heath study [8] for ease of comparison, however there are some reasoned differences which will be outlined in the following sections. The light harmonisation was used for wind power due to the range of published emissions estimates being up to 10% of the mean value for pulverised coal generation [30], illustrating that published variability should be considered significant. This is further outlined by Dolan and Heath [8] in their supporting information and is considered sufficient here for use in this comparable study. The standard deviation (SD) and interquartile range (IQR) of published estimates of life cycle GHG emissions in gCO_2e/kWh were both greater than 50% of the mean value of published estimates. As regional grids de-carbonise and renewable power systems increase in capacity, more extensive harmonisation will be desirable in order to improve accuracy and confidence in LCAs.

Published GHG emission estimates were taken as reported in their source publication. Estimates were included only if published in milliperson-equivalents/kWh, or equivalent units, and if the calculation steps were detailed within the published study. Estimates published in the common functional unit found within the literature of grams of carbon dioxide-equivalents per kilowatt-hour (gCO_2e/kWh) were most applicable to this review. This is generally true for power generation estimates but could be made a standard requirement throughout the power sector for GHG emission estimates. Finally, the GHG emission estimates should be reported numerically in preference to graphically for use in this paper and indeed for future standardisation of the GHG emission estimation procedure. These rules were applied by the previous study [8] and are recommended here as a significant move towards standardisation.

C. Harmonisation Parameters

Following Dolan and Heath's method [8], the equation below was used for calculating life cycle GHG emission estimates for wind power systems:

$$\text{Life Cycle GHG Emissions} = \frac{gCO_2e}{\text{Capacity factor} \times 8760 \text{ hours/year} \times \text{lifetime} \times \text{Nameplate capacity}}$$

Grams of carbon dioxide equivalent includes methane (CH_4) and nitrates (N_2O). The global warming potential (GWP) of these gases are not individually assessed in this study since previous results show that this parameter had an insignificant (less than 1%) effect on variability and central tendency after harmonisation.

The equation provides a clear representation of how lifetime and capacity factor affect the life cycle GHG emission estimates by scaling the denominator. Any addition or subtraction resulting from system boundary harmonisation affects the numerator directly. The two sets of parameters, lifetime and capacity factor, and system boundary, will be used for harmonisation in this study. Lifetime and capacity factor are grouped together since results for these parameters are presented individually by Dolan and Heath [8] who calculated that a 2% reduction in the median value, and less than 1% reduction in the total range of published GHG emission estimates. This study will yield different estimates, resulting from grouping these two parameters into a single combined harmonisation step.

Statistical measures are used to assess the results of harmonisation in order to remain consistent with previous studies. The median value is the key metric for presenting central tendency. The mean is also shown in some results but the median is preferred due to the positive skew of the dataset, as found by Dolan and Heath [8]. The interquartile range (IQR = 75^{th} percentile – 25^{th} percentile) is also presented in order to show variability but the full range is also presented in the results in order to fully characterise the variability of results. A decrease in these two measures presents effective harmonisation for GHG emission estimates for wind power and so is expected in these results. Standard deviation of estimates is also recorded in both the previous study and this paper for comparison between results and to characterise them more clearly.

It should be noted that the majority of the references used in this study employ process analysis for life cycle GHG emission estimates. This tends to mean that estimates are lower than those of hybrid economic input-output methods due to system boundary truncation [31] in life cycle assessment. More specifically in wind power assessment, this can result in underestimation of wind turbine GHG emission estimates of up to 50% [13] and so the upper range of GHG emission estimates is more likely to be representative of the actual life cycle GHG emissions of wind power.

D. Harmonisation of Operational Life and Capacity Factor

Life cycle GHG emission estimates were harmonised for the parameters, lifetime of wind power generation and capacity factor of generation. Lifetimes ranged from 10 - 50 years in the literature but 20 years was the most regular lifetime considered

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and is the recommended design lifetime for wind farms ([1]' [14]) and so should be considered the standard lifetime to be used in GHG emission estimates. This also aligns well with the process of GHG emission estimation resulting from the life cycles of photovoltaic (PV) systems or battery systems for instance. Certain studies use lifetime as a parameter in their sensitivity analysis [16] but a baseline lifetime of 20 years is recommended for standardisation and is being used by wind industry assessors and companies [24]. GHG emission estimates were harmonised by proportionally scaling the lifetime power output while holding the life cycle emissions estimate constant to maximise synergy with previous studies [8]. Maintenance-related emissions are not considered when the harmonisation process causes changes to the lifetime of the wind power system. Maintenance procedures would undoubtedly change if a wind farm were to remain operational for longer than the design life (20 years) of components, but due to the uncertainty in how these procedures may alter, it is not considered in this study or previous similar studies.

The capacity factor of wind power is the ratio of actual electricity generated to the maximum potential electricity generation (nameplate capacity multiplied by 8760 hours per year). The more operational hours a turbine/farm can generate electricity per year, the higher the capacity factor. In reality, wind farms will have different capacity factors due to local and regional environmental factors [18], maintenance variations and possible generation degradation and grid curtailment [15]. However for the purpose of this study, capacity factors are averaged for onshore and offshore sites in order to assess the impact of assuming capacity factors on the GHG emission estimate if the specific capacity factor for a site is not known. Indeed, since LCA is context-specific, it is not possible to know the exact capacity factor of a wind turbine/farm before obtaining operational information; this could be considered too late for the decision making process. The assumed capacity factors for Dolan and Heath [8] were 30% for onshore and 40% offshore, while they also carried out harmonisation of 35% and 44% in their supporting literature since it is difficult to assume an average figure for wind power systems from global sources. In contrast this study assumes the average capacity factor from the selected studies in order to offer a different dataset of results for this harmonisation step. The mean capacity factor for the studies is equally representative of likely capacity factors for onshore and offshore sites, while also still being equally susceptible to the same lack of specific characteristics for individual GHG emission estimations. Dolan and Heath [8] also suggest figures close to these for "modern turbines deployed in high wind class zones" but other references also suggest some individual capacity factors as high as 71% [18]. Therefore, those estimations that specified different capacity factors to those outlined for this study were changed through this harmonisation process, along with the lifetime of the system if it was also different to the specified 20 years. This process is less time consuming than that used in previous studies.

E. Harmonisation of System Boundary

Life cycle GHG emission estimates were harmonised for the recycling phase of the wind power life cycle. Where individual turbines were analysed (7 references) as opposed to whole wind farms, downstream emissions were accounted for generally as a result of using databases such as Ecoinvent [32] for primary information. Hence it was also difficult to deduce how extensively emissions were covered and it was decided that recycling should only be harmonised where it was missing from both the system processes, and individual unit processes, and was not included within the available data. Some references consider different scenarios that remove end of life credits resulting from recycling. Where this is the case, these estimates have not been harmonised since recycling has been included in an estimate specific to that reference's scenario. When databases are used, it should be explicitly noted whether recycling is included for each substantive material and whether this detail is specific for wind power systems or specific for the material in question since these may be different numbers.

Life cycle emission estimates are not generally displayed in a common format and life cycle processes are often not clearly defined in the published literature. While Dolan and Heath's study [8] adds to a number of studies for ongoing and downstream processes, it may be too difficult to acheive this given the incomplete nature of many of the current studies. However, there may be a need for some studies to be harmonised for recycling where no recycling has been accounted for in the analysis of life cycle impacts. The mean recycling life cycle emissions is expected to be a negative number as it represents carbon emissions saved by recovering materials to avoid the requirement of new raw materials into the upstream processes of future wind power systems. The results will not use a singular figure as an arbitrary add-on (or in this case subtraction) value because the recycling life cycle is proportional to the total material requirements for the wind power system and therefore is proportional to the whole system size and the materials used for individual case studies.

F. Cumulative Harmonisation of all Parameters

Life cycle GHG emission estimates were harmonised for the recycling phase. The final harmonisation procedure used in this study was to harmonise the lifetime, capacity factor and system boundary parameters consecutively. This was to assess whether some harmonisation procedures counteracted each other in their combined effect.

III. RESULTS

A. Summary of Published Literature

The 82 life cycle GHG emission estimates used in this study are extracted from 17 references and show a median of 15

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gCO_2e/kWh, IQR of 19 gCO_2e/kWh, and a range of 79 gCO_2e/kWh. These figures are similar but not equal to those found by previous harmonisation studies [8]. The difference is assumed to be due to the more exclusive selection criteria used to identify the samples included in this study. The range of values, however, remains the same, suggesting that this study included a reasonable number of estimates within the bounds of previous work. This is also characterised by the slightly larger IQR (7 gCO_2e/kWh). This number represents the middle 50% of the published estimates lying within 19gCO_2e/kWh of each other. This can be compared to the mean for nuclear power of 66 gCO_2e/kWh [11] with a range of 286.6 gCO_2e/kWh and other traditional technologies, such as coal-fired power generation in the region of 1000 gCO_2e/kWh [30].

Considering onshore and offshore wind power systems independently, it can be seen that while onshore estimates are far more numerous in the literature, both systems exhibit similar statistical characteristics. Of the 68 estimates for onshore systems, the median is 15 gCO_2e/kWh and IQR is 18.7 gCO_2e/kWh. Of the 14 estimates for offshore systems, the median is 15.3 gCO_2e/kWh and the IQR is 19.2 gCO_2e/kWh. This supports the hypothesis that while offshore wind power systems are currently more complex in relation to their upstream engineering, maintenance procedures and decommissioning, the total life cycle GHG emissions are comparable due to the increased power output from offshore sites. This study's IQR and range were both larger than those of Dolan and Heath [8] which appears to be due to the inclusion in this study of a recent study [26] which estimates life cycle GHG emissions from a real site located off the coast of Germany and has larger estimates than other previous studies.

The range for offshore systems is far smaller than that of onshore systems which could be due to the smaller number of estimates for offshore systems, but may also be due to the improved development of life cycle GHG emission estimation over the more recent period during which offshore wind power systems have also developed.

A number of studies include analyses that could be considered more frequently in life cycle GHG emission estimates, for instance, power generation degradation and grid curtailment [15], environmental disturbance upstream [19] and differing downstream scenarios [14], [18]. These will be returned to in the discussions section since it is believed that lessons can be taken from these particular studies in relation to any standardisation or guidance for future wind power system life cycle GHG emission estimation.

B. Harmonisation Results

The harmonisation process was performed in a series of steps. These steps can be seen in Figures 3 and 4 for onshore and offshore systems respectively. Each step is shown independently and represents the effect that harmonisation category has on the published estimates while the final step is a cumulative harmonisation whereby the steps are conducted consecutively. Table II shows the statistical data obtained from the harmonisation process. Changes relate to each step's effect on the estimates from published data. It can be seen that harmonisation for variations in capacity factor and lifetime has the greatest effect on the published data, reducing the range and SD by 57% and 37% respectively for all estimates.

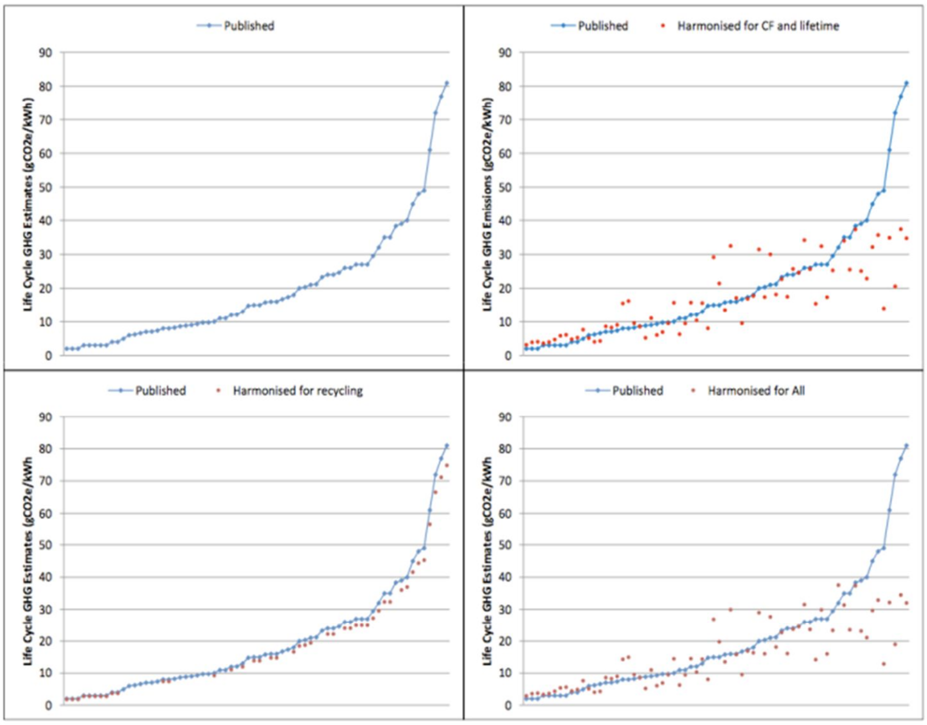

Fig. 2 Life cycle GHG emission estimates for onshore wind farms

(a) all published estimates, (b) harmonised for capacity factor to 35% and lifetime of 20 years,
(c) harmonised for missing system boundary to include recycling and (d) cumulative harmonisation of all previous parameters.

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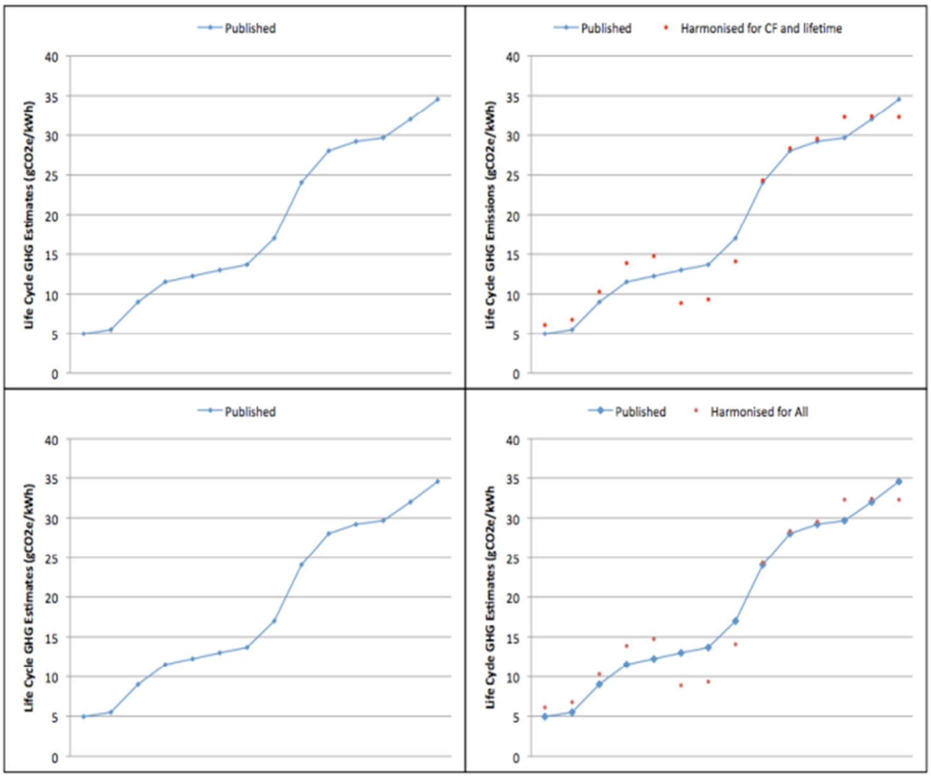

Fig. 3 Life cycle GHG emission estimates for offshore wind farms
(a) all published estimates, (b) harmonised for capacity factor to 44% and lifetime of 20 years,
(c) harmonised for missing system boundary to include recycling (not required here) and (d) cumulative harmonisation of all previous parameters.

TABLE II REDUCTION FACTOR FOR HARMONISATION OF SYSTEM BOUNDARY (RECYCLING) AND FOR FINAL HARMONISATION STEP, CUMULATIVE HARMONISATION

%	All estimates	Onshore	Offshore
Harmonisation for system boundary	-7.45	-7.55	-7.14
Harmonisation for all	-8.60	-7.70	-7.18

A. Harmonisation of Operating Life and Capacity Factor

Of the 82 estimates considered in this study, all but one were harmonised for both onshore and offshore mean capacity factors. For the lifetime of the wind power system, 14 estimates were corrected to the proposed 20 years. Both corrections were made in a single combined step. These harmonisation categories had the tendency to reduce the range of estimates significantly, in agreement with previous studies. Figures 3 & 4 show this reduction for onshore and offshore systems respectively. The range reduced by 57% for all estimates while the IQR reduced by 5.8% to 17.9 gCO_2e/kWh. Hence, the capacity factor and lifetime chosen by the assessor has a significant impact on total life cycle GHG emission estimates. It can also be deduced by separating the effect of harmonising capacity factor from harmonising lifetime that the capacity factor choice has a larger effect on life cycle emissions estimation.

B. Harmonisation of System Boundary

Of the 82 estimates considered in this study, 43 were corrected for recycling processes in the life cycle. This is related to 3 references ([13], [16], [18]) and resulted in a decrease in the range and IQR of estimates by 8% and reduction in the mean of 6%. Only onshore systems were corrected since this study found that all offshore studies contained allowances for the recycling processes. Onshore estimates showed an increase in IQR of 19% but showed the same decrease in range of 8%. The mean recycling life cycle emissions was -1.47 gCO_2e/kWh. Table II below summarises the reduction factor for harmonisation for all estimates, for onshore and offshore systems.

Estimates were harmonised by the above factors where recycling was not considered. These figures represent the average saving of carbon emissions by recycling materials at the end of the life cycle of wind power systems. The cumulative harmonisation factors shown were also used in the final step, as outlined below.

C. Cumulative Harmonisation of All Parameters

The final combined harmonisation procedure for capacity factor, lifetime and recycling processes reduced the distribution of all estimates considerably. This can be seen in Figure 5. The range of estimates has reduced by 56% to 34.5 gCO_2e/kWh.

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This is still approximately double the mean of the data (16.2 gCO_2e/kWh) but is considerably less than before harmonisation. The IQR reduced by 17% to 15.8 gCO_2e/kWh. The median value reduced only slightly from 15 to 14.3 gCO_2e/kWh, supporting Dolan and Heath's [8] results that the central tendency of estimates stayed reasonably constant. It can be seen from the individual harmonisation steps that capacity factor and lifetime were the main contributors to these changes and capacity factor appears to be the most influential when considering Dolan and Heath's [8] results for their individual steps alongside these results. While this study uses a similar approach to previous studies [8], it does have some differences in approach. However the results of both studies support each other's methodology and provide further evidence that harmonisation increases the accuracy of life cycle GHG emission estimates without dramatically changing the central tendency of results. This is shown in Figure 5. Figures 3 & 4 illustrate the reduction in the range of estimates for each step and clearly demonstrate the individual effects of the chosen parameters.

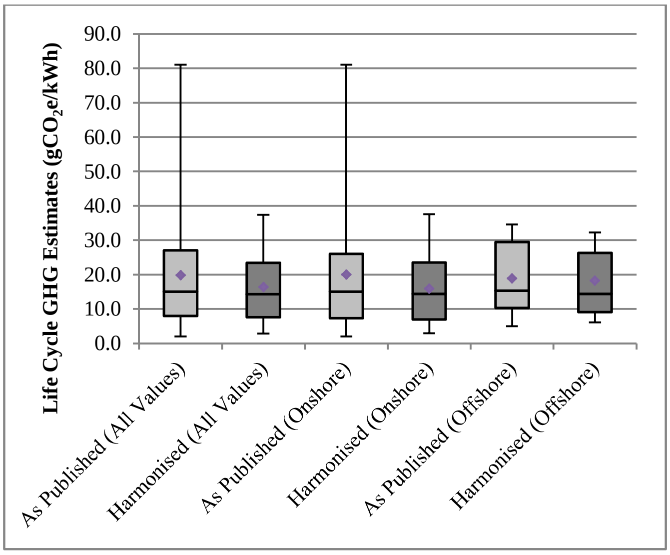

Fig. 5 Comparison of central tendency and spread of published life cycle GHG emission estimates and final harmonised estimates

A key difference in these results to Dolan and Heath [8] is seen in the narrowing of the total range which can be seen in Figure 5 due to an increase in the minimum values after harmonisation for both onshore and offshore systems. This is unlike the previous study which shows an increase in range at the system boundary harmonisation level. This is shown in numerical form in the summary statistics in Table III and can be compared with Dolan and Heath's [8] Table II below.

TABLE III SUMMARY STATISTICS FOR HARMONISATION PROCESS FROM COMPARATIVE STUDY

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

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This difference is due to this papers attempt at harmonisation of system boundaries and including recycling as a proportion of the total life cycle emissions estimate. Indeed in Figure 5 of the study [8], the minimum values become smaller total life cycle estimates after harmonisation for all values and onshore value estimates which seems counter intuitive.

The lower line represents the minimum, the lowest edge of the box is the 25th quartile, the middle line of the box is the median, the top edge of the box is the 75th quartile and the top line is the maximum. The diamond represents the mean value.

TABLE IV SUMMARY STATISTICS FOR EACH HARMONISATION STEP

Statistical Measure	As Published life cycle GHG (gCO_2e/kWh)	Harmonised by capacity factor and lifetime (gCO_2e/kWh)	Harmonised by system boundary (gCO_2e/kWh)	Harmonised by All (gCO_2e/kWh)
All Values				
Mean	19.8	17.1	18.7	16.4
SD	16.7	10.6	15.6	10.1
Minimum	2.0	3.1	1.8	2.9
25th percentile	8.0	7.6	7.4	7.6
Median	15.0	15.4	13.9	14.3
75th Percentile	27.0	25.5	25.0	23.4
Maximum	81.0	37.4	74.9	37.3
IQR	19.0	17.9	17.6	15.8
Range	79.0	34.3	73.0	34.5
Change in mean (%)	n/a	-14%	-6%	-17%
Change in SD (%)	n/a	-37%	-7%	-40%
Change in Median (%)	n/a	3%	-8%	-5%
Change in IQR (%)	n/a	-6%	-8%	-17%
Change in range (%)	n/a	-57%	-8%	-56%
Count of estimates	82	81	43	82
Count in references	17	15	3	17
Onshore				
Mean	20.0	19.6	22.5	16.0
SD	18.0	10.7	19.1	10.1
Minimum	2.0	3.1	1.8	2.9
25th percentile	7.4	6.9	7.4	6.9
Median	15.0	15.7	19.1	14.4
75th Percentile	26.0	25.3	29.6	23.5
Maximum	81.0	37.4	74.9	37.6
IQR	18.7	18.4	22.2	16.6
Range	79.0	34.3	73.0	34.7
Change in mean (%)	n/a	-2%	12%	-20%
Change in SD (%)	n/a	-41%	7%	-44%
Change in Median (%)	n/a	4%	27%	-4%
Change in IQR (%)	n/a	-2%	19%	-11%
Change in range (%)	n/a	-57%	-8%	-56%
Count of estimates	68	67	43	68
Count in references	15	14	3	15
Offshore				
Mean	18.9	18.8	18.9	18.2
SD	10.3	10.4	10.3	9.8
Minimum	5.0	6.1	5.0	6.1
25th percentile	10.3	9.1	10.3	9.1
Median	15.3	14.4	15.3	14.4
75th Percentile	29.4	28.9	29.4	26.3
Maximum	34.6	32.4	34.6	32.3
IQR	19.2	19.8	19.2	17.2
Range	29.6	26.3	29.6	26.2
Change in mean (%)	n/a	0%	0%	-4%
Change in SD (%)	n/a	1%	0%	-5%
Change in Median (%)	n/a	-6%	0%	-6%
Change in IQR (%)	n/a	3%	0%	-10%
Change in range (%)	n/a	-11%	0%	-11%
Count of estimates	14	14	0	14
Count in references	7	7	0	7

IV. DISCUSSION

A. *Comparison of Onshore and Offshore*

The results of the harmonisation suggest a close relationship between onshore and offshore systems with regard to a number of statistical indicators. While onshore systems have a larger range, due in part to the age of the technology, wind site variability, system design and also perhaps due to some studies reporting relatively large numbers of estimates [16], [18] both technology types exhibit similar IQRs both before and after harmonisation. These are 16.6 gCO_2e/kWh and 17.2 gCO_2e/kWh for onshore and offshore types respectively, representing a change of -11% and -10% of IQR respectively. The median for both types is 14.4 gCO_2e/kWh after harmonisation. This agrees with Dolan and Heath's [8] suggestion that the two system types are not dramatically different in relation to their life cycle GHG emissions. This study contains data for offshore systems [11] that is not available to the previous harmonisation study [8] and provides larger than average estimates for offshore wind systems.

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While offshore systems are behind in their development, relative to onshore systems, they are able to deliver greater capacity factors meaning that life cycle GHG characteristics are comparable. This suggests that one standard life cycle GHG emission estimation tool could be developed for both technologies. While this study can only speak for the references included within it, there appears from this harmonisation that there is closer agreement within the literature, as well as literature reviews, as to the life cycle GHG emission range of wind power systems, allowing for more confidence in the reliability of advice to informed decision making. However the range of values for emissions remains high relative to the median and mean values.

B. Limitations

A study of this nature inevitably restricts its scope to avoid overly complex results. Accordingly, in this study, life cycle GHG emissions are the only environmental effect considered for wind systems. However, since ISO-LCA considers other impact categories, future studies should be developed in order to evaluate other environmental effects of wind farms.

A meta-analysis uses specific information from available studies in order to identify common trends. While this harmonisation process offers a tighter range of estimates, it does not necessarily offer insight into common trends or aid in the development of a standard framework for conducting life cycle GHG emission estimates. This study suggests a framework based on its results and lessons gained from reviewing individual estimates at the end of this section. This will improve future estimations as well as future harmonisation studies.

Dolan and Heath [8] provide a number of insights into the potential issues surrounding the harmonisation process used in this paper such as clustering bias from large numbers of estimates coming from single references, or sample size limitations, especially with respect to offshore systems due to the relatively recent nature of the technology. If the two references that provide the most estimates are removed ([16]' [18]) the mean for all harmonised estimates reduces to 15.28 gCO_2e/kWh, a drop of 6.5%. While this is significant it is small in comparison to the range of emissions estimates, and suggests that the results for all estimates are conservative in relation to the carbon reduction potential of wind power for power generation. These issues will not be further covered in this study. The harmonisation process does not check for accuracy within each individual estimate. As a result of such an harmonisation process, an evaluation tool for new estimates should be developed in order to more rapidly assess their reliability.

C. Pooling Theoretical and Empirical Estimates

Due to the nature of life cycle assessment, it is not always clear in the literature whether a study should be considered empirical or theoretical. It may be more accurate to see the majority of studies as part theoretical, part empirical. This is especially true with the technologies and materials specified within studies since specific data are not always available for either unit processes of the life cycle or system processes. While this, and the previous harmonisation attempts, list studies as one or the other it may not be entirely valid for all parts of the life cycle assessment.

It may be better to review future wind system studies at other scales such as on an individual turbine or wind farm basis. 43 estimates in this study are from turbine studies, while the remaining 39 are farms. Farms have mean life cycle GHG emissions of 17.7 gCO_2e/kWh while turbines have mean emissions of 15 gCO_2e/kWh. This is not considerably different but does show that wind farms have higher life cycle emissions per kWh as would be expected. As harmonisation develops, it may be more suitable to harmonise for onshore and offshore farms separately to individual turbines. However for the time being it remains prudent to group onshore and offshore farms and turbine studies together and will remain so until more results are available.

D. Accuracy of the Central Tendency of Literature Estimates to True Life Cycle GHG Emissions

Assessing wind power with regards to its life cycle GHG emissions presents the technology as very favourable compared to more traditional technologies, especially fossil fuel generation [33]. However, this does not consider the consequences of adding intermittent power generation to a regional power supply network in sufficient depth. More analysis should be undertaken in order to assess how wind power systems affect the other technologies currently installed in supply networks. In particular thermal plants produce less gCO_2e/kWh at higher operating loads [34] so that reducing their operational load in response to wind generation surges should be accounted for in a comprehensive study of wind power emissions. Increasing wind power capacity in a supply network will reduce the operational hours or operating loads of thermal plants in the medium term while also fluctuating their efficiencies in the short term as they respond to intermittency. This can be seen in a study that suggests that offshore wind in Germany could result in up to 70 gCO_2/kWh ([35]; Figure 6) due to operating the supply network with offshore wind being integrated at a low carbon dioxide price scenario in a carbon trading market. At a high scenario, this would be reduced to 18gCO_2/kWh. These figures are important in comparing with total life cycle GHG emissions for wind power systems prior to integration. More research is needed in this area if the global impact on generating network CO_2e emissions of increased wind generation deployment is to be fully understood.

E. Developing a Standard Assessment Framework

This paper calls for standardisation in order to facilitate improvements to the technologies and processes under consideration as well as to ensure consistency and a reduction in variability of life cycle estimates of a given technology. The

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harmonisation process described in this paper illustrates that a number of important parameters have a large influence on total life cycle GHG emission estimates. In particular, capacity factor choice is highly influential as seen herein and in previous studies. However, little work has been done to propose a framework that supports continued improvement of the estimation process. It is suggested that all life cycle GHG emission estimates should include the life cycle phases present in Figure 2. This will allow for more accurate harmonisation of system boundaries in future studies and also provide more useful data for technological improvements through GHG assessment of individual life cycle phases. Also noted from the literature are important areas that require estimation in the life cycle GHG estimation process. These are:

1. Clarity in published estimates. This refers to all areas of estimation. Data origins should be clearly shown, as well as all assumptions made throughout the assessment. Results should be given in gCO_2e/kWh for all wind power generation technologies as standard over the lifetime of 20 years or in an alternative standard unit.

2. Environmental disturbance. While this may not be relevant for all wind power systems, it should be addressed in order to ensure completeness. For instance, peat disturbance [19] may be present, resulting in higher life cycle GHG associated emissions.

3. Degradation of power generation and grid curtailment may present a 2% annual degradation of power generation from wind power systems as well as 30% reduction due to grid curtailment [15]. These effects may increase life cycle GHG emissions by up to 43% and should be considered in all future estimates, using region-specific information where possible.

V. CONCLUSIONS

Life cycle GHG emissions of wind power systems assessed in this study range from 2 to 81 gCO_2e/kWh. While this could be considered a small absolute range for a power generation technology, it represents a difference of almost two orders of magnitude from the smallest to the largest value. It is made much smaller through applying the harmonisation process for capacity factor and lifetime, and recycling processes (2.9 to 37.3 gCO_2e/kWh). The IQR for estimates reduced by 17% following harmonisation that is much lower than the decrease in range, suggesting that average estimates in the IQR were relatively reliable. This is an important result for decision making. Capacity factor and lifetime are seen to cause the largest effect on total life cycle GHG emission estimates, with capacity factor choice being particular influential.

Harmonisation of life cycle GHG emission estimates is shown to decrease the variability of estimates. However, accuracy of estimates is not assessed and there are other factors that should be considered when reviewing their reliability.

There was relatively close agreement between onshore and offshore wind power systems in relation to their life cycle GHG emissions. This suggests that emissions from onshore and offshore installations are not substantially different. However, with offshore installations currently being the fastest area of development in wind power, particularly in Northern Europe, more studies will be required to further support or refute this claim. In particular, the additional life cycle stages involved with offshore installations such as the civil works required for grid connection and power transmission via direct current, if further than 50 km from shore, should be focussed on to align GHG estimation with development in the wind industry.

There are too great a number of process-based LCAs in relation to wind power systems which are in conflict with LCA practitioners' suggestions [13] and could result in large truncation errors. Further studies should be conducted by hybrid economic LCA as well as consequential LCAs in order to better understand the interaction of wind power with the rest of the power supply technologies currently available on distribution networks. In particular the effects of intermittency on thermal generation plants should be studied further.

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