A REVIEW OF LIFE CYCLE IMPACT ANALYSIS OF WIND TURBINES

Agne Bertasiene[a], Ruben Paul Borg[b], Brian Azzopardi[c, d]

[a] *Faculty of Electrical and Electronic Engineering, Kaunas University of Technology, Lithuania;*
[b] *Faculty for the Built Environment, University of Malta, Malta;*
[c] *Institute of Electrical & Electronics Engineering, Malta College of Arts, Science and Technology, Malta;*
[d] *Faculty of Technology, Design and Environment, Oxford Brookes University, United Kingdom*

Abstract: Renewable Energy (RE) sources, such as wind energy, are preferred over non-renewable sources, due to the potential reduction in greenhouse gas (GHG) emissions. On the other hand, large scale Wind Turbines (WTs) also present significant challenges as discussed in this paper. Meanwhile, recent developments in micro-generation and hence small scale WTs, through state-of-the-art technologies effectively manage the demand, load and instabilities with effective planning, control and efficiency yield. A life cycle assessment (LCA) allows for environmental impact evaluation during the whole life cycle stages from production, to operation and generation of energy on site. In this way a LCA leads to a comprehensive evaluation of performance of a technology. This paper presents a comprehensive LCA review of WT technologies.

1 Introduction

Society is affected by climate change through the impacts on various social, cultural, and natural resources. Climate change could affect human health, infrastructure, and transportation systems, as well as energy, food, and water supplies. The use of non-renewable resources has a negative effect on the environment as a result of emissions into the atmosphere. This supports the drive in Europe and other regions around the World to use renewable energy (RE) such as wind energy. RE reduces the reliance of remote regions and states on the main suppliers. In addition near-zero energy and zero-energy buildings relying on the energy produced on site have been demonstrated and developed for different climatic regions. Micro-scale systems which are either stand-alone or grid-connected via smart energy dispatch have made the development of urban sites with a local energy unit feasible. Micro-generation has therefore evolved through different stages in planning, control and efficiency yield, through state-of-the-art technologies which are designed to manipulate the needs, loads and instabilities.

Globally electricity demand is on the increase despite large portions of the world population still being without access to electricity. Moreover, the use of non-renewable sources of energy is significant and directly linked to GHG emissions. RE sources, such as wind energy, are an important field for investigation and their importance will be even more evident in the future. RE sources have significant advantages over non-renewable energy sources as a result of the production of clean energy. However a comprehensive assessment based on a life cycle analysis is necessary in order to assess the true impact on the environment. A comprehensive assessment is based on the determination of use of resources, emissions and evaluation of all environmental impacts during the various stages in the life cycle up to operation and generation of energy on site.

A comprehensive analysis can be conducted through a Life cycle assessment (LCA), addressing the various stages throughout the life cycle of the system. A LCA is the assessment of the environmental impact of a given product throughout its lifespan. The aim of LCA is to compare the environmental performance of products in order to be able to choose the least burdensome. The term life cycle of a product refers to the notion that for a fair, holistic assessment the raw material production, manufacture, distribution, use and disposal (including all intervening transportation steps) need to be assessed. The LCA approach can also be used to optimise the environmental performance of a single product (eco-design) or that of a system or organisation [1, 2].

An LCA includes resource and material use and energy needs in the production of the wind harvesting systems through manufacture and assembly. It also includes construction and site works, and further, the use, harvesting of energy and end of life scenarios including reuse. LCA presents a systematic approach for the evaluation of impacts, addressing environmental, social and economic aspect. LCA is based on defined and quantifiable indicators and has a broad field of application for manufacturers, scientists and experts concerned with sustainability. The tool helps develop options for an increased sustainability of the system through the definition of the impacts at different stages of the life cycle. Eventually, environment-friendly materials, state-of-the-art technologies and high efficiency smart systems lead to a reduction in emissions into the atmosphere and result in improvements in the system.

The scope of the review is to define common trends in the analysis and factors investigated in initial LCA studies, and to compare to more recent LCA studies with reference to inputs and outputs in the system. This investigation is intended to highlight gaps in information, assumptions taken, selection of impact categories and interpretation aspects, merits and drawbacks of overall procedures. Therefore this paper investigates the environmental impact of WTs through a comprehensive literature survey. The survey establishes the relative environmental impact of various Wind Turbine Technologies at various scales, through a comparison. In addition, results of sustainability criteria such as Energy Pay-back Time (EPB-T), greenhouse gas (GHG) emissions and energy intensity are compared. The methodology used in the analysis is based on a review of LCA reports as presented by several authors in order to define the limits and emerging key indicators for evaluation.

In the past the overall growth of installed capacity of large-scale WTs have underestimated small to medium-scale ones which are today considered to have a significant potential particularly in urban areas, even though limitations exist as a result of lower efficiencies due to the large velocity threshold, weak torque and large inertia. Inevitably, a very clear definition of Small Scale WTs should follow but regrettably is still not quite properly expressed [3]. Basically, Small Scale WTs are associated with WT rotors of less than 100 cm, capable of extracting power up to 50 kW [4, 5]. Small-to-medium scale WTs, encompass units up to 350 kW depending on the adoption of EU standards in the particular country.

This comprehensive review makes reference to various types of WTs. The paper consists of 3 main parts: (i) literature review with the definition of the key indicators, (ii) analysis and discussions, and (iii) conclusions of analysis and recommendations for further investigations.

2 Literature survey

Since the 1960's, LCA has developed significantly, starting with the assessment of raw material and energy use, estimation of costs and environmental impact. It is a standardised and globally accepted tool [1, 2]. LCA is based on different steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation. LCA also includes sensitivity assessment and uncertainty analysis with weighted indices that go beyond the ISO standards and also the improvement assessment [6]. During the last decades, LCA has been applied to distinct applications. All LCA studies have provided a wide range of assumptions and boundaries to their studies and therefore lack a coherent comparable approach. This is also in the case of Wind Energy technologies LCA studies. However this paper collects a comprehensive review on Wind Energy technology LCA to highlight the trends in performances and gaps in research.

LCA results for Wind Turbine Technologies provide relevant broad information about the systems. However the interpretation of the results offers challenges due to the variations with regards types of turbines, size, power rating and technology of WTs, their locations and installation. LCA studies are in general mostly dealing with the assessment of embodied energy, consumed energy in the long chain of services and production. In turn this process will translate into the embodied emissions and greenhouse gases related to CO_2-equivalent emissions during all stages from material extraction, service life and up to end of life including recycling. These impact assessments are then interpreted into energy cost and energy payback time for example.

Lenzen et al (2002) present the development in LCA with reference to 72 research papers [7]. The authors consider energy and emission parameters as well as methodology and scope definition and the estimation of uncertainties in embodied energy. The authors reported a significant scatter in results for the energy intensities that amounted in a difference of two orders of magnitude for large scale Wind Turbines with a power rating of 0.3-3000 kW. This scatter in results was due to the technical parameters of the WT themselves, differences in technologies, place of manufacture and economies of scale. The variation in CO_2 intensity was up to 16 times and partly because of differences in the regional fuel mix ratios. Indeed, the scatter might have possibly also been due to the scope definition and principles and boundaries set for the analysis.

The study presented by Lenzen et al [7] covered the period 1982-2001, and the state of LCA at the time was limited with studies addressing single aspects or parameters. Improvements in LCA methodology were reported in 1991, 1993 and in 1997 when refinements and expansion in the procedures were presented by the Society of Environmental Toxicology and Chemistry (SETAC) and through Standardization by ISO in 1997 – 2002 [6]. This explains why after 1991 and up to early 2000s, extended analysis as presented in literature was performed with the assessment of uncertainties and errors involving indirect factors, introducing various types of methods comprising interpretation of comprehensive list of indicators. Older technologies in manufacture, embodied energy for various processes, materials, production and transportation of the reviewed large scale WTs (above 300 kW) or wind farms, resulted in quite low energy intensities. However, the capacity factors have been assumed to be quite low with the mean value at around 20-30 %. This may possibly be due to the significantly low heights of wind capture (30-50 m) as well as small swept areas (30-40 m). In comparison the swept area of state-of-the-art WTs rated at 10 MW has today already reached 190 m [8]. However, these WTs have still not been extensively analysed since they are relatively new on the market [9]. Lenzen et al (2004) present a summary of a number of German studies highlighting the specific energy relations of components produced for WTs [10]. Such relations indicate separate and different requirements for the optimisation of distinct materials. The comprehensive assessment of components led to the definition of the main requirements of the WT components. The analysis indicated a small scatter in the normalised energy intensity caused by the dominating market and safety policy [7]. It was concluded that energy intensity increases in cases of sites which have a higher wind probability, with increase in the capacity factor. A decrease of Wind Turbine rated power was linked to a significant energy intensity dependency on production and material recycling considered by the particular country [7].

Another significant research was presented by Arvesen et al (2012) for the period 2000 to 2012 [11]. The research outlines the qualitative analysis of scope, methodology and limits in LCA, together with key stressors and indicators towards environmental sustainability in a much broader approach, than in previous studies. A significant development in Wind Energy Technology and LCA is reported at this point in time. The authors [11] report that the amount of emissions is comparable for both, on-shore and off-shore wind farms, independent of size (MW). They concluded that the bulk emissions are due to the component production stage. Information related to the implementation of more recent technologies such as floating wind turbines and deep – ocean wind farms is limited. Among all the stages of the LCA, the end of life phase has been lacking detail. However, this latter phase supports the reuse of resources and better management of wastes to reduce emissions and consumption of new resources.

Haapala et al (2014) assessed various LCA studies from different regions of the world, in America, Europe and Asia for the period 2001-2012 [12]. A hypothetic 2 MW onshore wind farm was analysed with reference to the performance characteristics, using different design models. The environmental impact was compared for different scenarios with different policies in order to assess distinct variations as a result of the different decision makers. Weights and normalisation of impact categories with varying importance were selected using the damage oriented method reported by Goedkoop et al (2000), with three main endpoints namely human health, ecosystem quality and resources [13].

Using this method, authors reduced the uncertainty level, since all data and model uncertainties were clearly characterised as short, Individualist; long, Egalitarian and balanced time, Hierarchist, perspectives. Hierarchists placed higher importance on resources and ecosystem quality and less importance on human health; Individualists placed lower importance on ecosystem quality but greater importance on resources; and Egalitarians placed higher importance on human health. The assessed end of life stage reflected a benefit to the environment with recycling. Significance was given to the sustainability at design and manufacturing levels.

Glassbrook K A et al (2014) present a hypothetical assessment of different scale of Wind Technology in Thailand [14]. The region, having small to moderate wind capabilities, was defined to have potential for small-scale WTs to meet the goals of the government strategy plan. Therefore the study assessed several WTs in a range of 400 W, 2.5 kW, 5 kW and 20 kW with regards to economic and environmental issues. The analysis indicated a relatively low intensity of CO_2 and embodied energy in comparison to diesel generators and the Thai grid, but implementation of such WTs was found not to be economically feasible without incentives from the government. These rated WTs were selected to cover rural house needs only since the energy demand of urban houses is very high, amounting to over 80 kWh/month. Wind availability was listed for 7 classes. The classification was not in accordance to the International Electro-Technical Commission standard IEC 61400-1 (2005), dividing wind turbine classes into I-IV (High-low wind speeds) [15]. Here extended divisions were used namely 1.1, 1.2, 1.3, 1.4, 2, 3, 4, 5, 6 and 7, which do not reflect the wind speeds directly but refer to power densities [16].

Table 1: Analysis of LCA outputs

Ref., date	Technology	C_p	Size, kW	A, m^2	Site	LFT, yrs	EPB-T, mths	Energy intensity	CO_2 intensity
[14], 2013	N/A	0.2	0.4 2.5 5 20	1.08 19.6 31.9 70.9	Thailand, *On*	20	1.2-0.7 2.3-1.0 7.6-2.1 11-2.3	29.75-3.59 2.89-0.24 3.62-0.19 2.15-0.09	36.06-5.11 2.59-0.29 1.94-0.15 1.09-0.057
[17], 2009	*H*	0.33-0.34	850 3000	2123.72 6361.74	Australia, *On*	20 / 30	12	N/A	23-26
[7], 2002, [10], 2004	N/A		S; M; L	1.77-283.5; 707-3217	Brasil/ Germany	N/A	6-49	0.09-0.77	2-81
[11], 2012	N/A	0.18; 0.22; 0.31; 0.43 *Off*	S; M; L	N/A	*On* *Off*	15-30	N/A		16-12
[18], 2014	*V*; *H*;	0.35	0.3-0.5	N/A	Thailand	20	0.08-0.25	0.01-0.05	5-12
[12], 2014	upwind pitch regulated	0.35	2×2000	Blade length 39 and 40	US Pacific Northwest, *On*	20	0.43-0.53	N/A	
[19], 2012	N/A		>1000	N/A	Various regions: USA, EU, East sites	N/A	1.3-20.4-49	N/A	2-20.2-46.4-81-168-185
[20], 2009	*V*; *H*; gearbox, grid	0.3	0.25 4500	N/A 132.73	France	20	2.29 0.58	0.3 1.2	46.4 15.8
[21], 2008	N/A		11×660	N/A	Italy	N/A	<12; (3-6.5)	0.04-0.07	8.8-18.5
[22], 2015	N/A	0.19-0.53	250-6000	N/A	Italy	N/A	2.4-27.5	0.01-1.2	6.2-46
[23], 2011	N/A	0.21	15133	N/A	Spain	20	N/A	0.0573 0.0691	8.7-12

Table 1: Analysis of LCA outputs

Ref., date	Technology	C_p	Size, kW	A, m^2	Site	LFT, yrs	EPB-T, mths	Energy intensity	CO_2 intensity
[24], 2010		0.29 0.45	100× 3000	N/A	China; *On;Off*	20	N/A	0.18 0.12	15.83 10.74
[25], 2008			N/A		Taiwan		1.3	0.05	3.6
[26], 2006	*H*; plants; gearbox; grid;	0.30 0.54	2000 3000	N/A	Denmark; *On;* *Off*	20	9; 6.6 6.8	0.098 0.102	4.64 5.23
[27], 2013	N/A	0.34	141500	N/A	Brasil; *On*		N/A		7.1
[28], 2009	Scenario 2000-2030	0.375	60×5000		Scandinavia; *Off*	25	N/A		16.5+/- 1.3
[29], 2009	Off-grid; Batteries	0.17	0.4	1.08	Canada; *On*	20	N/A		11.43
[30], 2013	N/A		330 500 810 2050 3020	876 1560 2198 5281 5281	Turkey	20	35.6 14.6	N/A	15.1-38.3
[31], 2013		0.2	25×2000		Denmark; *On*	20	8-11	N/A	7-10
[32], 2012	Grid;	0.23 0.22 0.24	20×5 or 5×20 or 100	23.75 70.14 346.4	Canada	25	16.8 9.6 7.2	0.424 0.221 0.133	42.7 25.1 17.8
[33], 2012		0.23 0.4 0.3 0.54	800 1650 3000	N/A	China, *On;* *Off*	20	N/A		0.28 8.21 5 6
[34], 2012	Gearless; geared		1800 2000	3848; 6362	Europe	20	7.7 7.8	N/A	8.82 9.73

Ref. – reference, c_p – capacity factor, A – Swept area, *On* – Onshore, *Off* – Off-shore, S<30 kW, M∈[100 kW÷1 MW], L – >1 MW, H – horizontal, V – vertical, LFT – Lifetime, yrs- years, mths – months, EPB-T – energy payback time.

All the output quantities were obtained using this scaling in a thorough manner. Swept areas were mentioned to be as most important factors to determine the energy potential, apart from wind speed and the overall efficiency. Due to the lack of real data, the efficiency of the WTs for the near best case scenario was assumed to be 20 %. However it was emphasised that small scale WTs are not capable to return this efficiency consistently. The energy payback time indicated that the technical capabilities of almost all WTs could cover the embodied energy, over the course of a functional unit, which was set at 50 kWh/month. As expected, all indices were reported to decrease with increase in wind speed.

The authors reported significant differences in all output units for different classes of wind. The levelised cost of electricity (LCOE) was very dependent on wind classes and showed a linear dependency with WT efficiency. With increase in efficiency, LCOE decreases. Consequently, it was confirmed that WTs' LCOE is much lower than in the case of diesel, though investments are less for these latter systems. However, WTs' investments were reported to be too high for rural communities. The analysis showed that the decrease in the efficiency of WTs, has a more significant impact on global warming potential (GWP), payback time and embodied energy but is less pronounced for the GWP value.

On the other hand, a comprehensive test was done on large-scale WTs using VESTAS V90-3 MW models for onshore and offshore plant applications (VESTAS, 2006) [26]. The goal of this LCA was to gain life cycle assessments for environmental improvement and product development as well as to use LCA data to document the environmental performance of the turbine. The study involved all basic stages from manufacturing of WT parts to transportation, mounting, grid connection and operation, dismantling and waste management. Toxicity and waste measures were involved in the evaluation of environmental impact as well as basic metrics – GWP, ozone depletion, eutrophication and acidification potential. Environmental impacts were divided into LCA stages where manufacture and recycling stages showed the highest impact on the results. For the offshore plant, operation was also significant due to the emissions into water. The transport stage and the operation stage for onshore WTs were considered as insignificant. Environmental impacts per kWh_{el} generated by these power plants were close and within the expected uncertainties of the results. Naturally, the resource consumption by the offshore plant was significantly higher than for the onshore one. However, increased energy output by the offshore WTs outweighed the increased inputs. An improvement in environmental impact was evident when comparing to older VESTAS WT V80-2.0 MW model as EPBT was noted to decrease from 9 to 6.8 months for the offshore case. Guezuraga et al (2012) defined a similar time of 7.2 months, for 1.8 MW gearless and 2 MW geared WTs [34].

3 Analysis and Discussion

A large number of life cycle analysis (LCA) studies on WTs, have been presented in the scientific literature mostly concerning MW-size. Table 1 summarises the most recent WT LCA studies. The technical noted details of WT technology include the capacity factor (c_p), site, rated power, swept area and lifetime are summarised in the table. Meanwhile the comparable outputs are the GHG emissions in $CO_{2\text{-eq}}$ intensity, Energy Payback Time (EPBT) and energy intensity. Energy payback is used to measure the time during which a system must operate to generate sufficient energy to offset the amount of energy required during its entire life [34]. Energy intensity is considered to by the amount of embodied energy in MJ to yield a certain amount of kWh of electricity (kWh_{el}); CO_2 intensity is equivalent to CO_2 in g per kWh_{el}. The significant deviation in final outputs was evident in many reviews and singular specific analysis. This supports the need for a comprehensive research with comparable and measureable conditions, inputs and methodologies.

Methodologies are structured clearly in general but the outcome and results show significant scatter which is undesirable. The reason for this is rarely highlighted but may arise due to inconsistency in many stages which includes differences in procedures and sources for input assessments, access to and limitations of real data or site-specific assumptions. Differences were expressed very clearly with regards energy intensities for different regions and even continents taking similar rated power. The differences amounted to one or even two orders of magnitude both for small scale WTs and even for farms with large scale WTs. Differences in models, sizes and technology of WTs, local market impact and installation sites and heights lead to variations in results and it is difficult to determine which of these may have the most significant impact and carries most weight on the results. $CO_{2\text{-eq}}$ intensity variation varied less and was often related to regional fuel mix ratios. In general, the analysis of older WTs and known technologies indicated that despite these being less developed, lower CO_2 impact and lower energy intensity were reported. This is taken to be mainly due to the lower installation heights and smaller dimensions inherent for older systems at the time of their installation. Environmental metrics may be issued due to regional requirements of safer technologies and materials used in manufacture and recycling options. Economies of scale also play an important role on environmental impact and energy consumption.

The varying boundary conditions, different assumptions considered, inconsistent inputs and outputs both in quantity and quality, all increase the uncertainty levels in interpretation of results and preclude further development and possible replication of the analysis.

Assumptions lead to overestimation of impacts and do not reflect the real case scenarios and the unique characteristics of specific locations, especially in the case of offshore structures. The near best scenario is not an optimal solution. However, there seem to be little possibilities for improvements for the state-of-the-art wind farms in this regard, since there are ongoing developments in technologies adopted, lack of complete data leading to inaccuracies of the assessments. Small scale WTs are of less interest due to cost issues and very broad spectrum of technologies adopted. However smart city strategies lead to an increased interest in Built Environment Wind Technology and in urban applications.

4 Conclusions

A comprehensive review of LCA studies for Wind Technology is presented. Comparable sustainability metrics were reviewed and analysed for efficiency and lifetime considerations, as related to environmental issues. The following main conclusions are drawn:

1. Due to the recent increase in size of WTs and rated power as a technological improvement, the trade-off of required energy to yield these factors namely size and energy output require further asssessment. This further assessment is required to determine whether it covers and compensates for the embodies energy requirements.
2. Variability of a number of LCA studies lead to difficulties in the comparison of results. It is difficult to assess whether results are comparable with distinct assumptions and boundaries
3. LCA studies differ from very simple to very detailed ones, going into different aspects. Therefore while some studies base their analysis on assumptions and published results, others refer to up to date and actual data. Thus, the uncertainty of results offers significant challenges in comparative assessments.
4. Economies of scale play a vital role in energy intensity and system outputs.
5. Small to Medium-scale units are not adequately covered in literature.

On the basis of the data presented in this paper it is shown that developments and improvements in WT lead to an improved environmental performance. The cost and technical limitations suggest that future WT systems can be well integrated into the market with favourable conditions for reasonable energy prices and improved environmental performance.

Acknowledgments

The investigation was performed under the framework of the COST Project TU1304, WINERCOST: *Wind energy technology reconsideration to enhance the concept of smart cities.* The research was supported through the Post-doctoral fellowship funded through European Union Structural Funds; "Postdoctoral Fellowship Implementation in Lithuania".

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