A REVIEW OF LIFE CYCLE ASSESSMENTS OF RENEWABLE ENERGY SYSTEMS

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ABSTRACT

A review of life cycle assessments (LCAs) of wind energy published in the past few years are presented in this paper. The aim is to identify the differences of the developed methodologies, in particular, the factors such as methods used, energy performance and influence of uncertainty. Each of the factors is addressed to highlight the shortcomings and strengths of various approaches. Potential issues were identified regarding the way LCA is used for assessing environmental impact and energy performance of wind energy. It is found that the potential of incorporating the quantification of uncertainty in the manufacturing phase has not been studied elaborately. A framework methodology has been proposed in this paper to address this issue.

Keywords: uncertainty, LCA, manufacturing processes.

1 INTRODUCTION

Prompted by current problems of energy supply and the implementation of commitments in climate change awareness, the world is searching for renewable energy sources (Ometto et al., 2009). At the end of 2009, 1.8% of global electricity demand was met by wind energy with almost 160 GW of installed capacity (Davidsson et al., 2012). This makes wind energy an important future energy option. Wind and other renewable energy systems are often assumed to be environmentally friendly and sustainable energy sources in much of main stream debate. All energy systems however have various environmental impacts and a consistent method of evaluation for analysing all aspects of a given source of energy is required as without such a method, it will be difficult to compare them and make the right decisions when planning and investing in future energy systems (Davidsson et al., 2012). Life Cycle Assessment (LCA) is a popular way of measuring the energy performance and environmental impacts of wind energy. Many researchers have attempted to resolve these issues associated with wind energy using various approaches. This paper will focus on how uncertainty can be incorporated into LCA for the manufacturing phase of wind energy systems. This will be followed by a proposed methodology incorporating uncertainty with LCA in developing renewable energy systems.

2 LITERATURE REVIEW

Padey et al. (2012) presents a methodology that offers an alternative to detailed LCA of wind electricity. A detailed analysis of the origin of wind turbine impacts provided through the assessment of one wind turbine inventory from the Ecoinvent database and survey of literature highlighted the importance of three types of parameters namely: a geographical dimension, directly related to wind conditions through the load factor (L); a technological dimension, with parameters related to the type of technology and materials used for the wind turbine; and a methodological dimension with the lifetime parameter. Sensitivity studies were then performed for the greenhouse gas (GHG) impacts, then for GHG performance, varying these three parameters to identify which is most influential. The findings from the sensitivity analysis lead to the definition of a regression from the sample relating the wind electricity GHG performance to a single parameter: wind speed. Davidsson et al. (2012) has identified an example of dependence on methodology implemented by Martinez et al., (2009 a and b). The same authors perform an LCA on the same model of wind turbine, at the same wind farm with the same assumed production, but using different impact assessment methodologies giving significantly different results. Martinez et al. (2009 a) uses Eco-Indicator 99 method using 11 different impact factors while Martinez et al. (2009 b) uses CML (Centre of Environmental Science of Leiden University) methodology presenting environmental impacts in 10 different impact categories presented as equivalents of different emissions as well as cumulative energy demand. It is noted that for the resulting energy performances, Martinez et al. (2009 a) presented an energy payback time of 0.4 years while Martinez et al. (2009 b) presented an energy payback time of 0.58 years. Therefore, the levels of uncertainty in the different impact assessment methodologies affect the energy performances hence the need to quantify this uncertainty.

Fleck and Huot (2009) employs LCA to compare the environmental impacts, net energy inputs and life cycle cost of two systems: (1) a stand-alone small wind turbine system and (2) a single home diesel generator system. Life cycle cost methodology was used to account for the time value of money on an investment. The net energy input of a unit process was calculated based on the energy inputs and outputs of a process. Results showed considerable environmental and net energy input benefit for wind power while in terms of cost, the results were comparable. Uncertainty was calculated for the key environmental impacts using a Monte Carlo simulation in order to determine their expected range. Pehnt (2006) investigated a dynamic LCA approach for renewable energy technologies with respect to change of technology, processes, electricity mix etc. extrapolating these context dependent parameters into the future. With this approach, environmental problem areas, which are inevitably connected with renewable energies, are analytically distinguished from those imported into the system by the background system, i.e. supply of energy and materials. In a sense, this could be referred to as a sensitivity analysis with respect to technological change, processes or transportation. Merugula et al. (2012) evaluated the effect on life cycle energy return-on-investment (EROI) and emissions of incorporating carbon nanofibre in wind turbine blades. The benchmark life cycle inventory from Ecoinvent and its modifications to include upstream carbon nanofibre production were evaluated for energy intensity and midpoint impacts. This highlighted the design of the analysis showing the variations imposed against the established LCA which could be referred to as a sensitivity analysis with respect to materials used for production. A step change in comprehensiveness is employed by Garret and Ronde (2012) by conducting LCAs whereby the wind turbine’s entire bill of materials is assessed, accounting individually for around 25,000 parts that make up the wind turbine and, in total, around 99.95% of the total mass of the entire power plant. The LCAs assess all stages in the life cycle from cradle to grave. Also, in the manufacturing stage, the LCA considers information from all Vestas’ global sites, and the use phase relies on Vestas’ real-time performance data of over 20,000 monitored wind turbines around the world, covering around 20% of the current worldwide installed wind capacity (Garret and Ronde, 2012). This level of detail and reliability in data represents a state-of-the-art approach to LCA modelling of wind power reducing the levels of uncertainty that could affect results.

Environmental impacts of wind energy are still a matter of controversy as Tremeac and Meunier (2009) points out. For several reasons, some of which are addressed in this paper, the results vary widely for different wind power assessments and even the type of results that are presented. It could be added that LCA methodology during the course of these studies has been and is still evolving. The critique expressed here is not directed towards the specific assessments but rather, attempts to address the need for discussion on how the manufacturing processes should be quantified and assessed. The manufacturing phase usually has the highest impact on the environment. This raises the following research questions to be addressed in this research, for example, "how can the manufacturing processes for energy producing facilities like wind turbines be optimized?" and "what are the best methods to achieve this?" For future long term planning, this will assist in optimizing the impact of design variations of renewable systems. A summary of the above reviews is highlighted in Table 1.

Paper	**Authors**	**Aim**	**Method**	**Gaps**	**Geographical location**	**Product type**
Life cycle assessment of wind power: comprehensive results from a state-of-the-art approach	Garret and Ronde (2012)	Paper aims to present a transparent and robust approach to LCA modelling of wind power systems	GaBi DfX software, Vestas internal master-data systems, CML impact assessment method	Recommendation that wind turbines are compared within equal wind classes and appropriate sensitivity analysis included to assess primary assumptions and uncertainties	Worldwide	2MW Grid streamer turbine
A simplified life cycle approach for assessing greenhouse gas emissions of wind electricity	Padey et al. (2012)	Study aims to develop a methodology towards a simplified approach as an alternative to performing a full LCA	Ecoinvent database, regression, Sensitivity analysis	Quantifying the influence of technological parameters on GHG performance for low wind speeds	USA	Various wind turbines systems
Comparative life cycle assessment of a small wind turbine for residential off-grid use	Fleck and Huot (2009)	Direct comparison of the environmental impacts, net-energy inputs and life-cycle cost of a stand-alone small wind turbine and a single home diesel generator	Monte Carlo simulation, Life cycle costing	Comparison of grid-tied small wind turbines to grid provided electricity on both a GHG and economic level	Canada	Stand-alone small wind turbine
Dynamic life cycle assessment (LCA) of renewable energy technologies	Pehnt (2006)	An investigation of the environmental performance of renewable energy systems in view of future developments	Umberto software/database, parameters extrapolated into the future (2030)	Extrapolating the various manufacturing processes into the future taking into account uncertainties in various manufacturing processes	Germany	Renewable energy technologies
Reinforced wind turbine blades – An environmental life cycle evaluation	Merugula et al. (2012)	Paper aims to assess the incorporation of carbon nanofibre in wind turbine blades	Ecoinvent database, energy return on investment	Continued investigation if the results will leads to more efficient operation and higher deployment rates	USA	Reinforced wind turbine blade

3 METHODOLOGY

According to Malca and Freire (2011), uncertainty analysis is a systematic procedure to determine how uncertainties in data are propagated throughout the life cycle of a model and how they affect the reliability of the life cycle's outcomes. Malca and Freire (2011) identified the following sources of uncertainty in LCA; parameter uncertainty which arises from lack of data, empirical inaccuracy (e.g. imprecise measurements), and unrepresentativeness of data that are incomplete or outdated; scenario uncertainty, which reflects the inherent dependence of the outcomes on normative choices in the modelling procedure for example, choice of functional unit, definition of system boundaries, or selection of allocation methods; model uncertainty, which is due to the use of mathematical relationships between model inputs and outputs that simplify real-world systems. In this paper, a robust approach is proposed to address and incorporate uncertainty in the manufacturing phase of wind turbine systems. The main steps of this approach are summarized as follows:

- A sensitivity analysis will be conducted in which the variation in a single parameter (e.g. manufacturing process) is tested to see how the results are affected. This aims to identify parameters with the highest impact on the output of the model;
- A more complete approach for compiling life cycle inventory (LCI) data for the manufacturing phase. For example, (1) recording enough observations for each process to characterize probability distributions, (2) the use of formal expert elicitation to develop distributions based on expert's estimates of possible and probable values and (3) a literature review to identify variation ranges and assign appropriate probability distributions for the most influential parameters;
- Monte Carlo simulation will be used for calculating probability distributions of the output variables based on the uncertainty within selected input parameters to determine confidence intervals and other indicators of robustness;
- An uncertainty importance analysis will be conducted in order to identify parameters that contribute most to the overall output variance and hence, guiding further research to reduce their uncertainty.

Plevin (2010) opines that single sensitivity analysis generally underestimates the uncertainty in a model. The proposed methodology requires that sensitivity is assessed with parameters varying simultaneously i.e., using Monte Carlo simulation. Figure 1 below provides an overview of this research.

4 DISCUSSION

The goal of modelling uncertainty in the input variables of LCI and LCA models is to better understand a range of results to associate with environmental impacts. To reduce uncertainty in the definition of probability distributions, best practice should be developed as regards to the definition of appropriate probability distribution types as well as uncertainty ranges. It is infeasible to comprehensively model all sources of uncertainty in complex systems by LCA. Due to the complexity of wind turbine LCA models, including all types of uncertainty will be difficult if not impossible. In the current research, these appear to be the different sources of parameter uncertainty shown in various studies, as well as specific sources of model or scenario uncertainty that are exceptionally relevant to the study (Lloyd and Ries, 2007). It may however be sufficient to consider only the most important sources of uncertainty. The type of uncertainty that will be included in the proposed methodology should be explicitly defined, and the potential implications and reasons for omitting other types should be discussed. Strategies for identifying the types of uncertainty that are considered as important contributors to the overall uncertainty need to be researched further. Although LCA databases such as Ecoinvent contain a significant amount of data and provide information on uncertainty, the lack of widely available LCI data beyond the European and American context will impede quantitative uncertainty analysis. International agreement on the best life cycle impact assessment (LCIA) methods to be used can assist in clarifying which uncertainty should be considered depending on the goals of specific case studies.

For routine LCA applications, models and choices should reflect preferences of decision makers. The significance of the results depends on the choice of methods, which in itself depends on goal and scope definition. For assessments that might prompt high financial investments, a confidence interval of 95% is appropriate. In cases where alternatives that have been investigated perform relatively equally with respect to other criteria, lower confidence levels may be sufficient. Failing to analyse the variation in the different manufacturing processes could lead to misleading or biased estimates that would impose unnecessary costs without accruing the benefits that motivate the current debate about renewable energy technologies.

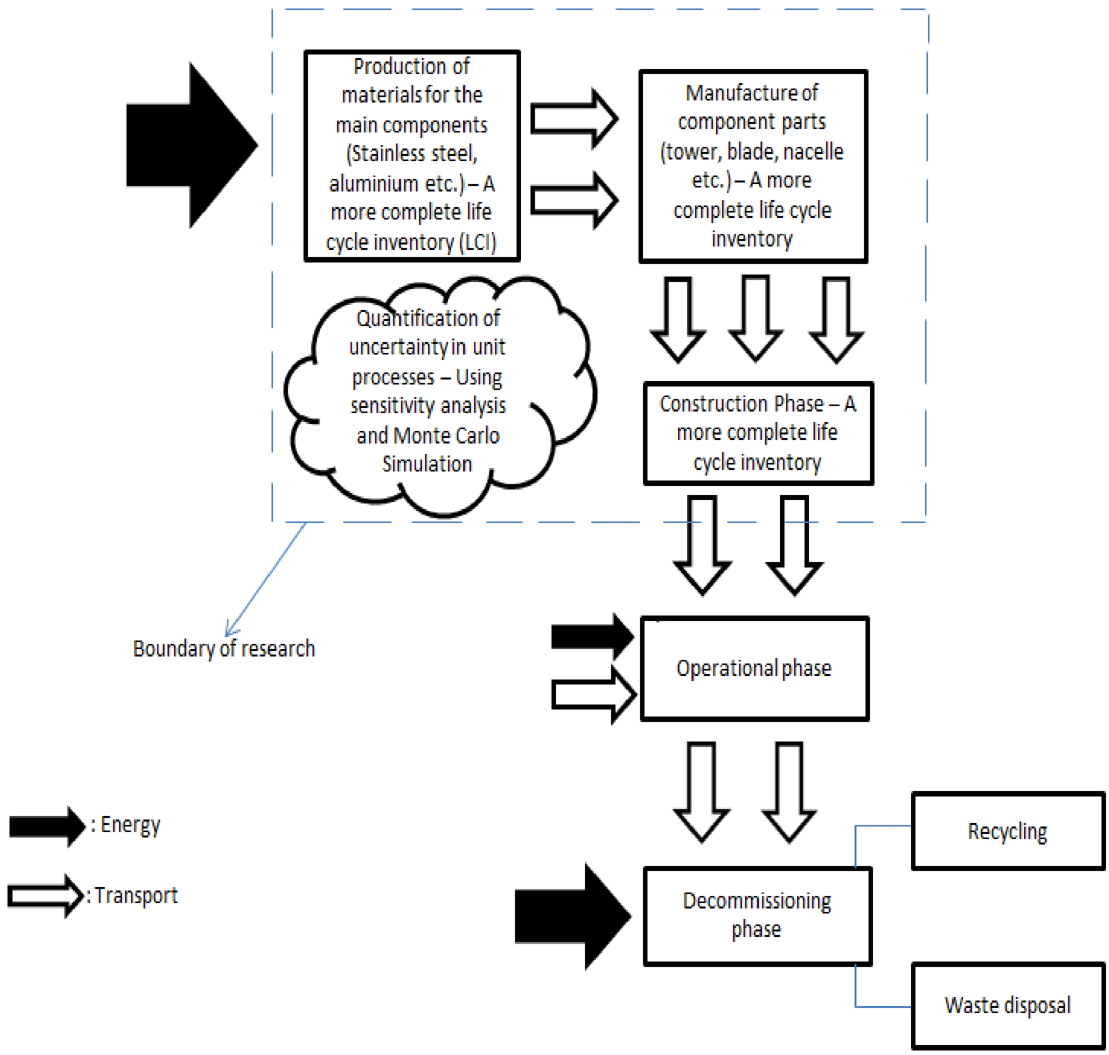

Figure 1: Diagram giving an illustration of the overview of this research.

5 CONCLUSION/FURTHER WORK

Understanding uncertainty in the manufacturing phase is a critical requirement for the sound investment, policy and environmental decisions about renewable energy. In this paper, uncertainties encountered during modelling the life cycle in the manufacturing phase are outlined and a guide to model these uncertainties is presented. The technique described in the paper can be used to improve the understanding and representation of uncertainties associated with manufacturing processes, thus enabling to improve decision making with respect to the use of LCA at the early design stage of renewable energy system. To aid in enabling reliable quantitative uncertainty analysis, the LCA community should develop a better understanding of the importance of different types of uncertainty and develop protocols for reliably characterizing and analysing uncertainty in LCA.

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