Comparative life cycle assessment of 2.0 MW wind turbines

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Abstract: Wind turbines produce energy with virtually no emissions, however, there are environmental impacts associated with their manufacture, installation, and end of life. The work presented examines life cycle environmental impacts of two 2.0 MW wind turbines. Manufacturing, transport, installation, maintenance, and end of life have been considered for both models and are compared using the ReCiPe 2008 impact assessment method. In addition, energy payback analysis was conducted based on the cumulative energy demand and the energy produced by the wind turbines over 20 years. Life cycle assessment revealed that environmental impacts are concentrated in the manufacturing stage, which accounts for 78% of impacts. The energy payback period for the two turbine models are found to be 5.2 and 6.4 months, respectively. Based on the assumptions made, the results of this study can be used to conduct an environmental analysis of a representative wind park to be located in the US Pacific Northwest.

Keywords: life cycle assessment; LCA; wind turbine; wind park; environmental impact; energy payback; sustainable manufacturing; transportation; installation; maintenance; end of life.

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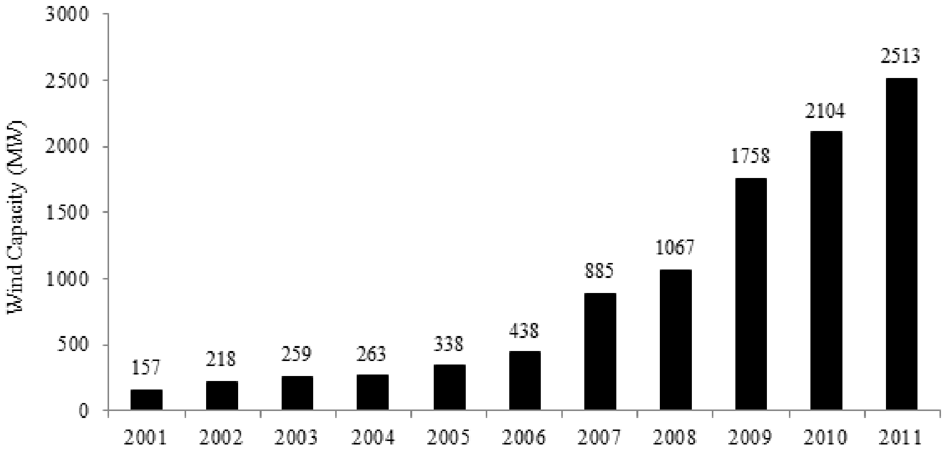
1 Introduction

Due to fossil fuel-based electricity production, greenhouse gases and carbon dioxide emissions are released into the environment (Jeswiet and Hauschild, 2008). A 2012 report from the US Energy Information Administration (EIA) showed that 3.6 Gt of carbon dioxide was released in 2011, primarily from the combustion of fossil fuels, a 2.0 Gt increase from 2009 (USEIA, 2011). Increasing concerns and awareness of carbon emissions as well as costs and security issues surrounding fossil-based energy have led to the exponential growth of renewable energy, including wind energy generation (USEIA, 2012). The USEIA has predicted that renewable energy consumption in the electric power sector will grow from 1,477 PJ in 2010 to 3,587 PJ in 2035, with wind accounting for 44% of the growth (USEIA, 2011). Figure 1 shows the growth of installed wind energy capacity in Oregon from 2001 to 2011 (Hook et al., 2011).

Figure 1 Wind capacity from 2001 to 2011 in Oregon



Source: Hook et al. (2011)

Wind energy is a promising source of alternative energy generation. During operation, wind turbines are environmentally responsible, releasing no direct emissions and requiring little energy consumption. It has been shown that the majority of environmental impacts of wind power plants result from the manufacture and installation processes (Pehnt, 2006). As all forms of energy generation require the conversion of natural resource inputs, they are attendant with environmental impacts. Thus, consistent means for assessing and comparing energy generation types is crucial to ensuring that decisions for energy system investment, planning, and development are made in the most informed manner (Varun et al., 2009).

Life cycle assessment (LCA) offers such an approach to identifying the potential environmental impacts associated with energy systems and to improve their sustainability performance from the early development phases (Li et al., 2010). LCA is a method to assess the environmental impacts of a product from raw material extraction through production, use, and end of life (Pennington et al., 2004; Rebitzer et al., 2004). LCA guidelines have been set forth by the International Organization for Standardization (ISO) (2006) in the ISO 14040 standard. The guidelines are not described in detail herein, but rather adopted in this study as presented in Section 2. The following section will briefly review prior LCA studies related to wind energy.

LCA studies for wind energy have been conducted to investigate many aspects (Table 1). Modernised turbines were examined for an offshore project, for example (Weinzettel et al., 2009). The authors used the CML 2 baseline 2000 V2.03 method and presented the environmental impacts for eight different impact categories. The main focus was on marine eco-toxicity. Generic capacity factors were assumed to estimate energy production. Lenzen and Wachsmann (2004) reported the only work identified in a review of the literature that focused on transportation of wind turbine components from the manufacturer to a specific wind park location in the analysis. For in-depth analysis, the reader may refer to prior literature, which has examined numerous LCA studies of wind energy systems (Kubiszewski et al., 2010; Lenzen and Munksgaard, 2002; Price and Kendall, 2012).

Prior studies have considered various environmental impacts. Some present only greenhouse gas emissions (Ardente et al., 2008; Kabir et al., 2012; Raadal et al., 2011). Ardente et al. (2008) investigated the air and water emissions, and solid wastes for an Italian wind farm, and compared to other energy generation systems. Schleisner (2000) reported on the energy and emissions for the production of the materials required for Danish onshore and offshore wind farms. Tremeac and Meunier (2009) examined four damage types (climate change, resources, ecosystem quality, and human health) resulting from 14 midpoint impacts for a large (4.5 MW) and small (250 kW) wind turbine using the Impact 2002+ method. Methodology dependence was investigated for the same study assumptions by using different impact assessment methodologies, giving significantly different results. Martinez et al. (2009a, 2009b) conducted two studies with same wind turbine by using different methods. One used the Eco-indicator 99 method, which considers 11 different impact factors (Martinez et al., 2009a), while the other used the CML method, which considers ten impacts, normalised as equivalent emissions (Martinez et al., 2009b).

It is recognised that LCA methods are evolving and can generate widely varying results (Davidsson et al., 2012). Thus, use of the different methodologies makes it difficult to compare assessment results and raises questions about whether studies using different methodologies should be compared at all. In addition, it is difficult to assess the breadth of technical improvements driven by LCA results due to the fact that LCA results are often used for internal decision making or to support specific goals, e.g., preparing an environmental product declaration (Elsam, 2004).

In Table 1, it can be seen that there is a limited number of LCA studies of wind turbines in the United States of America (USA). Most wind energy LCA studies are based in Europe, which has likely been a direct consequence of the higher number of wind energy installations in Europe – approximately 50% more than in the USA. Thus, a key motivating factor for the research reported herein is to address the limited amount of reported LCA studies for wind turbines installed in the USA.

Table 1 Summary of prior wind energy LCA studies by location

Location	*Study goal*	*Sources*
The Americas	Compare three wind turbine models	Kabir et al. (2012)
	Compare environmental impacts and net-energy inputs of two stand-alone wind turbines	Fleck and Huot (2009)
	Determine GHG emissions of onshore and offshore wind power	Dolan and Heath (2012)
	Determine GHG emissions of a wind-fuel cell integrated system	Khan et al. (2005)
	Determine the impact of geographical variation of a wind turbine production's location	Lenzen and Wachsmann (2004)
	Determine the environmental impacts of a wind farm using Eco-indicator 99 method	Hapke et al. (2010)
	Determine the environmental impact of an offshore wind farm in Florida	Dolan (2007)
Europe	Compare offshore and onshore wind farms to assess energy use	Schleisner (2000)
	Compare photovoltaic and wind power for the production of energy	Jungbluth et al. (2005)
	Evaluate the environmental burden of floating offshore wind turbine	Weinzettel et al. (2009)
	Study CO_2 emissions of offshore wind energy	Pehnt et al. (2008)
	Study the environmental impact of a wind turbine from cradle to grave	Elsam (2004)
	Determine CO_2 emissions of wind turbines using LCA	Lenzen and Munksgaard (2002)
	Determine the environmental impact of a 2 MW wind turbine using the CML method	Martinez et al. (2009b)
	Review LCA studies of wind turbines to identify research need	Davidsson et al. (2012)
	Determine environmental impact of wind turbines using Eco-indicator 99 method	Hassing and Varming (2001)
	Determine environmental impacts of a 2 MW wind turbine	Martinez et al. (2009a)
	Perform sensitivity study on LCA result of 2 MW wind turbine	Martinez et al. (2010)
	Compare two different 2 MW wind turbines to determine the environmental impacts	Guezuraga et al. (2012)
	Compare two models of wind turbines	Tremeac and Meunier (2009)
	Compare GHG emissions of wind and hydropower	Raadal et al. (2011)
	Determine the environmental impacts of a wind farm and identify energy consumption	Ardente et al. (2008)
	Determine the environmental impacts and cumulative energy demand of a wind turbine	Allen et al. (2008)

Table 1 Summary of prior wind energy LCA studies by location (continued)

Location	*Study goal*	*Sources*
Europe	Determine the environmental impact of a 150 MW offshore wind park	Properzi and Herk-Hansen (2002)
	Compare the environmental impact of an offshore wind park to that of the electricity mix in Germany	Wagner et al. (2011)
Asia	Determine the environmental impact of a wind park in Fuzhou, China	Songlin et al. (2011)
	Determine CO_2 emissions of a wind park	Wang and Sun (2012)
	Review LCA studies of wind turbines to determine the LCIA method used	Leung and Yang (2012)

The objective of the work reported herein is to perform a comparative LCA for two potential wind turbines to be deployed in a representative wind park located in the Columbia River gorge, which forms the border between the US states of Oregon and Washington. First, the goal and scope of the study are presented. Next, supporting life cycle inventory (LCI) data and process models are reported. Then, the results of the life cycle impact assessment are presented and discussed. Finally, based on this study, several conclusions are drawn.

2 Research methodology

As mentioned above, to assess relative environmental impacts and identify potential future research needs of wind energy generation, the LCA method was applied. The LCA study was facilitated using a commercially available software tool, SimaPro 7.3 (PRe Consultants, 2012). In general, an LCA study is completed in four stages:

1. define the goal and scope
2. conduct a LCI analysis
3. conduct a life cycle impact assessment
4. interpret the results (Pennington et al., 2004; Rebitzer et al., 2004).

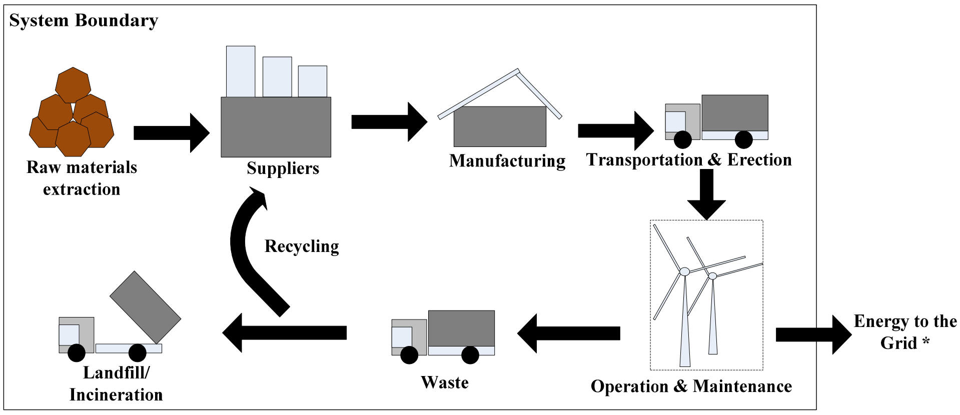
These stages are described below in the context of the current study.

2.1 Goal and scope definition

The goal of this study is to compare the life cycle environmental impacts of two wind turbine designs. This study would assist in determining and quantifying the impacts of a hypothetical wind park to be located in the Columbia River gorge. The two turbines explored are 2.0 MW onshore wind turbine models, referred to as model 1 and model 2. Both models have similar function and technical specifications, but differ in design and performance characteristics, as detailed below.

The scope definition of an LCA provides a description of the product system in terms of the system boundaries. The scope of this study is from cradle to grave and considers the raw material extraction, wind turbine manufacturing, transportation of the wind turbine components to the wind park site, operation and maintenance, and dismantling and recycling (Figure 2). Transformers and substations are not considered in this study, which are key components of a wind park. The functional unit must be defined, which provides a clear description of the function of the product, system, or service under study so that alternatives can be compared in a meaningful way. Thus, the functional unit for this LCA study is defined as a 2.0 MW wind turbine, which assumes the two models considered are functionally equivalent. The energy payback comparison additionally considers the amount of energy generated over their assumed 20 year lifetime.

Figure 2 Scope of the LCA (see online version for colours)



Note: *Considered in energy payback analysis.

2.2 Life cycle inventory

Wind turbines consist of many mechanical and electrical assemblies, which are comprised of many sub-components. Therefore, it is a challenge for practitioners to gather the information from all suppliers that provide the wind turbine components. Information contained in the LCI is described below:

- Wind turbine characteristics: model 1 is a 2.0 MW, three bladed, upwind pitch regulated wind turbine with active yaw control (Gamesa, 2007). The blades are 39 m in length with full span control and a four-part modular tower of 78 m in height. The rotor operates with a speed of 1,900 rpm. Model 2 is also a 2.0 MW turbine and has been designed for medium and low wind sites (Vestas, 2012). The blade is 40 m in length and the design employs a three-part modular tower that is 78 m in height.
- Wind turbine components: The rotor assembly is the key module of the wind turbine, and comprised of the blades, hub, nose cone, and bearing (Elsam, 2004). The rotor assembly is connected to the nacelle assembly, which is attached at the top of the tower with a large, framed steel structure – necessary to survive the extreme wind loads. The nacelle assembly is comprised of a fibreglass housing that protects the gearbox, generator, hydraulic system, main shaft, and yaw/pitch system from the weather. The tower is made of large tubular steel sections that are painted, sealed, and bolted together. The tower is attached to a reinforced concrete foundation with large threaded rods, or is embedded into the concrete.

To compile the LCI for the wind turbines, the systems were decomposed into their major assemblies, sub-components, and respective materials. As specific information was not available, the paint and minor components such as bolts, fasteners, and internal wires were neglected. Information about the various components considered is provided in Table 2.

- Wind turbine operation and maintenance: Regular inspection visits with a diesel truck are assumed three times a year (Dolan and Heath, 2012; Elsam, 2004). In addition, maintenance activities include transportation and oil and lubricant changes, while rotor blade, gearbox, and generator replacements are assumed to be required once within a 20-year lifetime. These assumptions likely under predict actual maintenance impacts, as a reliability study of smaller turbines indicated significantly higher failure rates, in some cases (Echavarria et al., 2008).

Table 2 Wind turbine materials and masses

Components	*Model 1 (Gamesa, 2007)*		*Model 2 (Vestas, 2012)*	
	Material	*Total mass (tons)*	*Material*	*Total mass (tons)*
Rotor Assembly	Steel	5.00	Steel	5.40
	Fibreglass	7.50	Carbon fibre	3.69
	Epoxy	5.00	Fibreglass reinforced plastic	7.96
	Cast iron	8.50	Cast iron	8.50
Tower	Steel	200.00	Steel	165.00
Nacelle Assembly	Steel	12.27	Steel	25.63
	Copper	2.50	Copper	2.34
	Silica sand	0.15	Aluminium	0.54
	Cast iron	35.92	Cast iron	16.47
	Fibreglass reinforced plastic	2.00	Fibreglass reinforced plastic	6.40
	Lubricant (20 years)	300.80	Lubricant (20 years)	601.60
Foundation	Steel	35.00	Steel	38.00
	Concrete	775.00	Concrete	750.00
Total mass		1,389.64		1,631.53

- Transportation: Transportation impacts result from emissions caused by the extraction and production of fuel and its combustion during transport operations. Each component is assumed to be transported to the wind park site from the component manufacturer by road truck, measured in ton-kilometres (tkm). The unit tkm is equivalent to the transport of one ton (1,000 kg) product over one kilometre. A 50% load factor is used to account for trucks transporting turbine parts to the wind site and returning to the manufacturer empty. Table 3 presents the distance from the wind turbine component suppliers to the wind park location (assumed to be the Augspurger area in Washington State). Transportation of materials, components, and assemblies to the turbine manufacturer has been neglected due to the inability to trace the complete supply chain.

Table 3 Transportation distances from supplier to wind park site

Component	*Model 1 supplier (distance to site)*	*Model 2 supplier (distance to site)*
Blades	Edensburg, PA (4,229 km)	Windsor, CO (1,945 km)
Rotor	Fairless Hills, PA (4,200 km)	Brighton, CO (1,931 km)
Gearbox	Verona, VA (4,464 km)	Lake Zurich, IL (2,782 km)
Generator	Raleigh, NC (3,826 km)	Raleigh, NC (3,826 km)
Yaw/pitch system	Andalucia, Spain (8,722 km)	Hebron, KY (3,181 km)
Tower	Fairless Hills, PA (4,200 km)	Pueblo, CO (2,205 km)
Nacelle	Fairless Hills, PA (4,200 km)	Brighton, CO (1,931 km)

- Dismantling and recycling: The end of life stage is an important aspect of the LCA. The recycling rates of materials are adopted from previous studies (Elsam, 2004; Martinez et al., 2010; Tremeac and Meunier, 2009; Wagner et al., 2011; Wang and Sun, 2012). Steel, copper, aluminium, and cast iron recycling rates are at 90%, and non-recyclable waste is transported to a landfill. Concrete is not recycled, so it assumed to be landfilled entirely (left in ground). It is assumed that the recycling location is 50 km from the wind park. Material end of life treatment strategy is shows, in Table 4.

Table 4 End of life treatment

Material	*End of life treatment*
Concrete	Landfill 100%
Copper	Recycling with a loss of 5%
Fiberglass	Landfill 100%
Iron	Recycling with a loss of 10%
Oil	Incinerated 100%
Plastics	Incinerated 100%
Rubber	Incinerated 100%
Steel	Recycling with a loss of 10%

Source: Elsam (2004), Martinez et al. (2009a), and Properzi and Herk-Hansen (2002)

2.3 Life cycle impact assessment method

The life cycle inventories for the two 2.0 MW wind turbine models were used to support life cycle impact assessment using two methods: ReCiPe 2008 and energy payback analysis. Commercial LCA software (SimaPro 7.3) was used to assist the analysis. The environmental impacts of wind turbines were compared using ReCiPe 2008 version 1.03

with a world weighting set across three different archetypical perspectives (i.e., egalitarian, hierarchist, and individualist). The ReCiPe method evaluates the impact to 18 midpoint categories as follows: fossil depletion (FD), metal depletion (MD), natural land transformation (NT), urban land occupation (UO), agricultural land occupation (AO), marine ecotoxicity (ME), freshwater ecotoxicity (FE), terrestrial acidification (TA), climate change-ecosystems (CCE), terrestrial ecotoxicity (TE), ionising radiation (IR), freshwater eutrophication (FEU), particulate matter formation (PM), photochemical oxidant formation (PO), water depletion (WD), human toxicity (HT), ozone depletion (OD), and climate change-human health (CCH). WD category is not taking into consideration in SimaPro software, so this category will be represented as zero herein. In the method, one thousand points is equivalent to the environmental impact generated by one European citizen over the course of a year (Goedkoop et al., 2009).

Energy payback is used to measure how long a system must operate to generate sufficient energy to offset the amount of energy required during its entire life (Guezuraga et al., 2012). Life cycle energy requirements are considered to include those for each of the activities described above (production, transportation, operations and maintenance, and dismantling and recycling). Thus, energy payback, P, for a wind turbine can be calculated using equation (1) (Weinzettel et al., 2009):

$$\mathrm{P} = \sum\nolimits_{k=1}^{n} E_k / E_{annual} \tag{1}$$

where E_k is the energy required for life cycle stage k and E_{annual} is the annual electricity generated by the wind turbine. The foregoing information can now be used to complete the LCA study.

3 LCA study results

Impact assessment is conducted using the ReCiPe 2008 method and evaluated with sensitivity analysis. Energy payback period is then calculated. Figure 3 compares environmental impact of both models for varying cultural perspectives to elucidate the effect of different decision maker valuation. Model 1 has significantly higher environmental impact than model 2 for each perspective. Thus, concerns of the uncertainty for applying different importance weightings to the various impact categories are reduced. The ensuing analysis only applies the hierarchist perspective, which offers the most balanced view of damage types (Goedkoop and Spriensma, 2001). Hierarchists place higher importance on resources and ecosystem quality than individualists, and less importance on human health. They place lower importance on ecosystem quality, greater importance on resources, and the same for human health as egalitarians.

As seen in Figures 4(a) and 5(a), the environmental impacts of the wind turbines are mainly due to the manufacturing stage, which includes material extraction, manufacturing, and transport of components to the wind park. Impacts of the maintenance stage are 5.8% of the manufacturing stage for model 1 and 3.2% for model 2. This compares well with the result of 4.3% obtained for the assessment of a 2 MW turbine (Guezuraga et al., 2012). The end of life stage produces negative environmental impact, reflecting a benefit to the environment of recycling iron, steel, and copper. These results reiterate the importance on focusing on sustainable design and sustainable manufacturing efforts early in the wind park development process.

Figures 4(b) and 5(b) show the relative environmental impacts of the wind turbine components. It is seen that the relative impacts are similar for both models. The tower is the key contributor to the environmental impact, followed by the rotor, nacelle, and foundation, respectively. These results are shown in Figure 6, along with two other studies that provided this information for studies of 2 MW turbines. Significant proportions of impact for several components are due to FD. Steel is the primary material in the tower, and the majority of FD results from steel processing for the tower. Despite the significant amount of materials used in both models, overall impact is reduced by 28% because of material recycling.

Figure 3 Comparison of environmental impacts under different archetypes

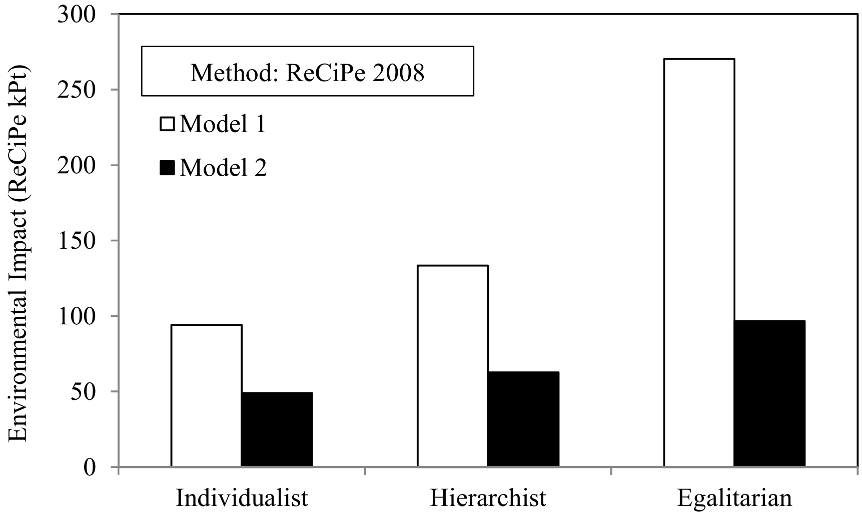
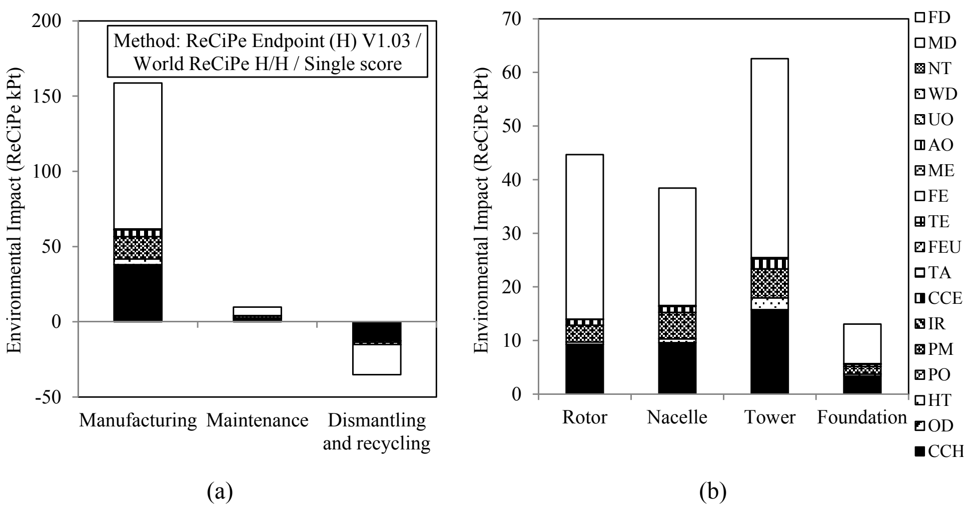


Figure 4 Environmental impact of model 1 for (a) cradle-to-grave life cycle stages and (b) major components



The environmental impact assessment proceeded by examining the impact contributions of the material inputs using ReCiPe 2008. Figure 7 reveals that steel is the predominant material in terms of environmental impact. It can be noted that model 1, the four-section tower design, has higher impacts due to steel. While model 2 has higher impacts due to reinforcing steel in the foundation, overall foundation impacts are similar due to a reduced use of concrete. In addition, model 2 has lower associated particulate matter (PM) impacts due to reduced use of concrete.

Figure 5 Environmental impact of model 2 for (a) cradle-to-grave life cycle stages and (b) major components

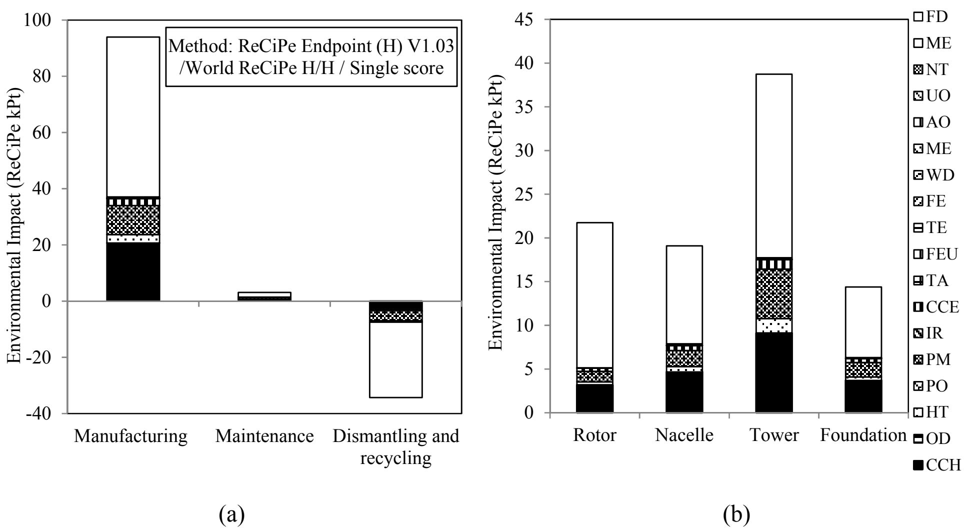
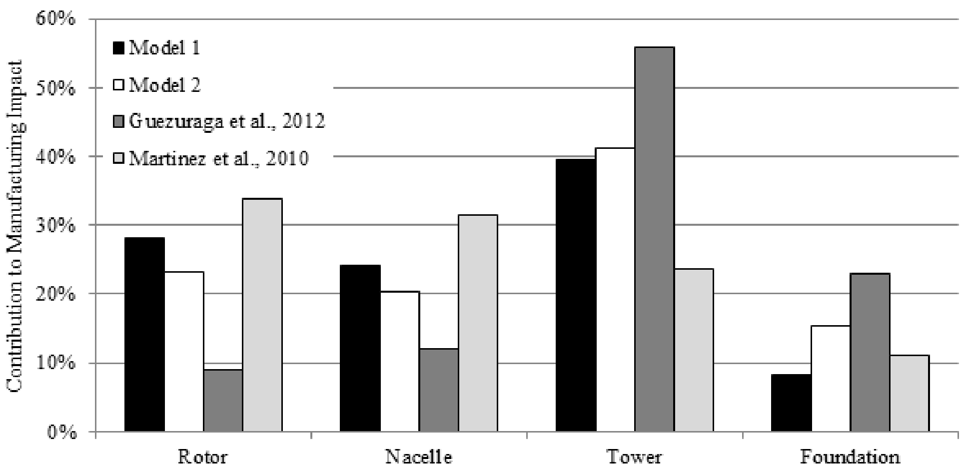


Figure 6 Contribution of wind turbine components to impacts from cradle to construction



4 Interpretation

Inventory data are critical in determining the success of an LCA study. To assess the sensitivity of the environmental impacts to the assumptions made in each stage, scenario analysis can be conducted. The uncertainties arising from the assumptions made during the development of the LCA were analysed using three scenarios: SC 1 assumes an increase in maintenance over the wind turbine lifespan, SC 2 assumes an increase in the percentage of material recycling to 100%, and SC 3 assumes a change in transportation type from road truck to freight rail.

Figure 7 Environmental impact of major material inputs for each wind turbine model

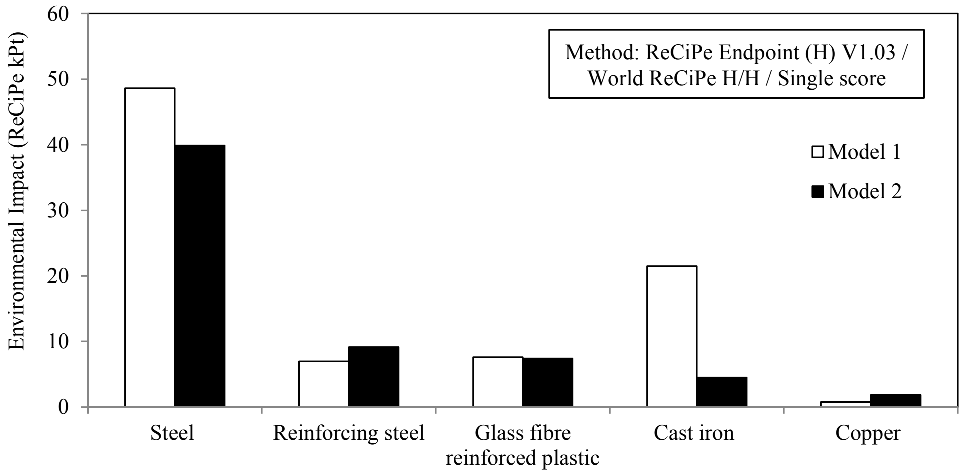
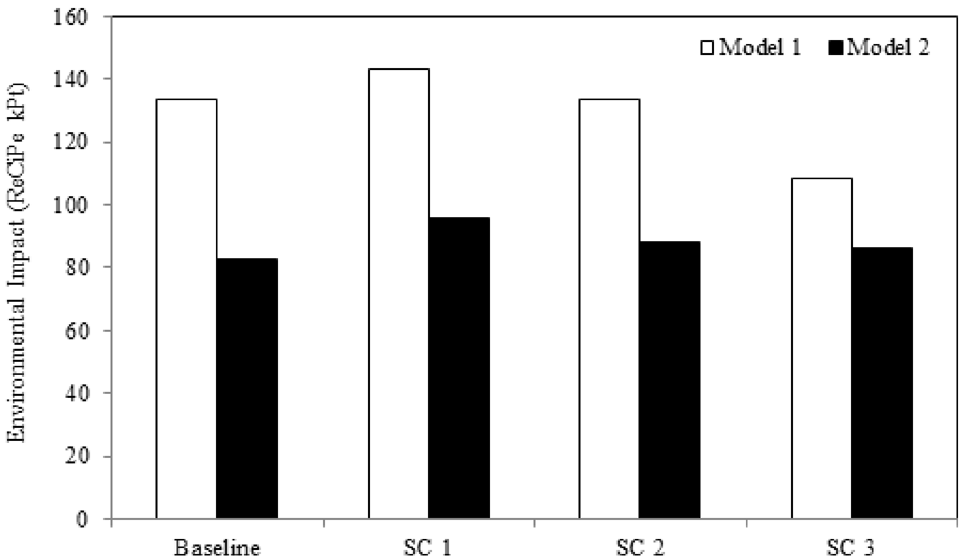


Figure 8 Environmental impacts of each scenario for each wind turbine model



The sensitivity analysis conducted found only slight variations in the predicted overall impact (Figure 8). Increasing maintenance (SC 1) has the greatest effect on the overall environmental impact, resulting in an increase of 7.2% (model 1) and 12.5% (model 2). The environmental impact of freight rail transportation (SC 3) increases impacts by 6% for model 2, which contrasts with model 1 (a reduction of 5%). Surprisingly, increasing the percentage of material recycling (SC 2) did not significantly affect the environmental impact for either wind turbine. Moreover, variation in the results was less than typical uncertainty in LCA studies (20%). Thus, the conclusion that model 2 is the superior option holds.

The energy payback time is an important indicator for renewable resources. For this purpose, the cumulative energy demand impact assessment method was used to calculate life cycle energy requirement. A 2.0 MW wind turbine would generate 6.12 GWh per year, assuming a 35% capacity factor. Analysis revealed that energy payback time would be 0.43 years and 0.53 years for model 1 and model 2, respectively, which compares with studies of other multi-megawatt turbines of 0.58 to 0.65 years (Elsam, 2004; Guezuraga et al., 2012; Tremeac and Meunier, 2009). This indicates that model 1 would be selected as the better option when considering life cycle energy use, in contrast to the ReCiPe 2008 method.

5 Conclusions

This LCA study compared the environmental impacts of two 2.0 MW wind turbines using two methods (ReCiPe 2008 and energy payback). The tower, rotor, and nacelle are found to have the greatest contribution to the environmental impact in each case. For the tower, the large amount of steel required is the major contributor to cradle-to-grave environmental impact. One of the outcomes from this LCA study is the confirmation that the main life cycle environmental impacts of a wind turbine originate from the manufacturing stage. When compared to prior work, the results lead to a similar conclusion that environmental impacts are driven by the material consumption, especially steel.

It was shown that the use stage has an almost negligible environmental impact due to maintenance activities. In addition, the transportation distances of wind turbine components to the wind park site influenced environmental impact. The travel distance of model 1 is longer than model 2 by 16,000 km (approximately 50%), and some components for model 1 are transported from other continents. It was found that recycling is important to the environmental profile of the turbine, while transportation type can have a profound effect on life cycle impacts when components must travel relatively longer distances.

It can be concluded that model 2 is superior in terms of broad environmental performance and is suitable for analysis of a representative wind power plant to be located in the Columbia River gorge. A key difference between the two models is the design of the tower. Model 1 is a four-part modular tower, while model 2 uses a three-part tower module. Thus, model 1 requires 35 tons more steel than model 2. In addition, it is shown that the major components all outperform those for model 1, except the foundations exhibit similar impacts.

This study investigated the life cycle environmental impacts of wind turbines in the USA, which addresses a limitation of prior studies in capturing supply chain, manufacturing, and end of life phases, simultaneously. The results of this study are in agreement with prior studies that have reported similar analysis. A limitation faced by this study, as well as others, is the knowledge regarding specific manufacturing processes and supply chain entities. Since the materials and manufacturing phase has been revealed as a significant source of life cycle impacts for wind turbines, future work must better understand the sources of these impacts and identify opportunities for improvement. In addition, as energy demand has grown rapidly in recent years, it is becoming increasingly important for utility companies to invest in alternative energy technologies to ensure long-term reliability and sustainability. The results from this study can aid in promoting sustainable energy technologies and policies to support wind turbine manufacturing and wind park development. Specifically, it is shown that engineering decision makers should consider not only the functional characteristics of a wind turbine, but also the materials, component and system design, and the supply chain needed to manufacture, construct, and decommission a wind turbine.

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