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A Quantitative Analysis System for Greener Wind Turbine Concept Selection

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Abstract

This paper describes a proposed method of developing a quantitative analysis system to facilitate the comparison of different wind turbine concept designs. It is known that the manufacturing processes of making a wind turbine contribute a significant proportion of the impact of the environment, costs and energy usage. This proposed method is therefore focus on this area and developing a method to support initial assessments of multiple design concepts. This method will allow a designer to select and develop a "greener" wind turbine. Furthermore, the proposed approach could potentially be used to minimise the carbon footprints of major engineering projects such as wind farms.

1. Introduction

A horizontal-axis wind turbine (HAWT) consists of 4 major sub-systems: the foundation, tower, nacelle and rotor blades. A wind turbine is designed to produce "cleaner" energy with minimum CO_2 emissions throughout its life time of operation. However CO_2 emissions are created and energy is used throughout the product development process and this means wind turbines are not completely free of carbon footprints [1, 2]. Furthermore, Lee and Hashim [3]'s findings concluded that CO_2 emissions produced by wind turbines should be taken into account of in order to reduce global CO_2 emissions by halve in 2050 as targeted by the European commission [4].

The design process of any engineering project is arguably one of the most important stages of product development [5]. Through good design, minimal design changes can occur in decision making during the product development process. However, it is the decision made at the early design stage would contribute the largest impact of a product [5]. A method that to support accurate decision at the early design stage can minimise changes to the final design which could directly lead to reduce environmental impact, reduce cost and time. Therefore, an evaluation of the costs, carbon emission, energy consumed at the manufacturing stage and potential energy a wind turbine produced should be conducted at the early design stage so that a full impact could be evaluated. As such, a method that rapidly provides analysis of energy, carbon emission and cost of different design concepts which would lead to the improvement of designing a wind turbine to provide cleaner energy.

The objective of this study is to develop a low-cost software platform to evaluate the three important design attributes namely: energy, costs and carbon emission of a wind turbine. By selecting the right design concept may lead to minimise carbon footprints whilst also reducing costs and energy used in manufacturing, and maximising the energy output of a wind turbine. The layout of this paper is as follows: Section 2 describes the related literature. Section 3 discusses the proposed approach. Section 4 highlights the implementation and, finally, the conclusion and future work are presented.

2. Related Literature

A wide range of literatures have been reviewed on assessment methods of CO_2, manufacturing energy requirements and cost of building wind turbines. They are summarised in Table 1.

Table 1: Literature summary

Authors	Method	Product type	Findings
[2] Haapala and Prempreeda	LCA and sensitivity analysis	2.0 MW wind turbines	The environmental impacts of wind turbines are mainly occurred at the manufacturing stage of a wind turbine's tower. This is largely due to the amount of energy and steel used for producing the tower.
[6] Uddin and Kumar	-	Wind turbines	Environmental impacts of the vertical-axis wind turbine are 50% more than the impact of a horizontal-axis wind turbine.
[1] Demir and Taşkın	LCA	Wind turbine	the environmental impact of wind turbines are lower for turbines with larger hub heights
[7] Valori et al.	LCA	Micro-wind generators, vertical-axis and horizontal-axis	Environmental impacts are related to the ratio of the mass of a wind turbine.
[8] Garret and Rønde	LCA	Vestas' 2 MW horizontal-axis wind turbine	Manufacturing stage contributes the largest impact in terms of CO_2 emissions, in particularly the wind turbine tower

[9] Guezuraga, et al.	LCA	1.8 MW gearless and a 2 MW geared wind turbine	Manufacturing stage alone accounted for 80-90% of the cumulative energy requirements of both wind turbines. More than 50% of the energy used in the manufacturing process was used to manufacture the towers of both wind turbines
[10] Fleck and Huot	LCA	Small wind turbine system and home diesel generator system	Considerable environmental impact could occur at the manufacturing stage even though there are cost benefits for wind power.
[11] Martinez, et al.	LCA	2 MW wind turbine	Greatest contributor to environmental impact is the manufacturing processes of each component of a wind turbine
[12] Tremeac and Meunier	LCA and sensitivity analysis	4.5 MW and 250W wind turbines	Energy consumption are primary occurred at the manufacturing stage. The manufacturing of the systems accounted for 75% for the 4.5 MW and 96% of the 250 W wind turbines.
[13] Nalukowe et al.	LCA	Vestas V90-3 MW wind turbine	Manufacturing processes as the greatest contribution to environmental impact.
[14] Jungbluth et al.	LCA	Photovoltaic and wind power systems	Environmental impacts of such systems depend on the material and energy consumption at the construction stage
[15] Lenzen and Munksga	LCA	Wind Turbine	CO_2 emission varied depends on production methods.

Based on the findings by the above authors as shown in Table 1, they concluded that manufacturing processes contribute to majority of the environmental impact of wind turbines. Further finding from the above literature review is that the methods require detailed design and manufacturing data before an evaluation can be performed. Based on the result of the literature, a novel method for early design analysis of carbon emissions, energy and costs of horizontal-axis wind turbines has been proposed and is discussed in the next section.

3. The Proposed Method

Fig. 1 illustrates the proposed method to support decision making at the concept design stage of a HAWT. The method enables a designer to make design decision based on the evaluation of carbon emission, energy and cost of a wind turbine prior to the detail design stage. The main input parameters such as wind turbine hub height, turbine blade length, number of blades and average wind speed will be defined by the user. The proposed system will then assess the cost, energy requirements, power output, and carbon emission of a wind turbine tower. If necessary the input parameters can be changed and compared to the previous result for further comparison of different design concepts of a wind turbine.

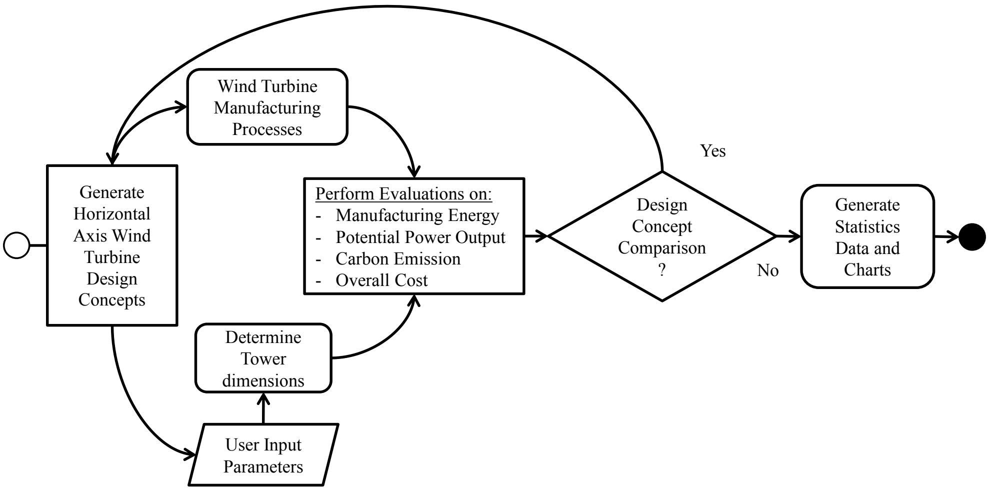

Fig. 1. The overall proposed method

3.1 Energy requirement in manufacturing

The process of manufacturing a wind turbine tower must be understood fully before calculating the energy requirements to manufacture a wind turbine tower. The proposed method has adopted the manufacturing processes by Vestas, (2006) [16] as shown in Fig. 2.

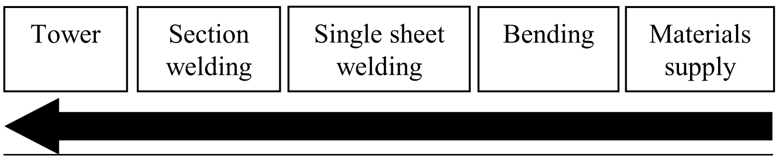

Fig. 2. Flow chart of the manufacturing process of a wind turbine tower

The method does not take into account of the energy used for mining the raw material and forming the original steel plates. It was assumed that the material was bought into the wind turbine factory and already as steel plates. The first process was rolling the steel plates into cylinders. The cylinders were then welded together by the section welding process to form the tower. The main energy consumed by the manufacturing processes of a wind turbine tower was bending (rolling), single sheet welding and section welding.

3.2 Carbon Footprint

Reducing carbon emissions is very important in nowadays product manufacturers. A method to determine carbon emissions from the electrical energy used in manufacturing processes was developed by Jeswiet and Kara, [17]. By analysing the carbon dioxide produced for each 1 GJ of heat by various primary energy production methods, the study developed the concept of a Carbon Emission Signature (CES). The findings of this analysis are summarised in Table 2. This signature, specific to each electrical energy grid was used to calculate the carbon dioxide related to the electrical energy used by the manufacturing processes.

Table 2. Heat and CO_2 released by energy production fuels [17]

Type of fuel	1 GJ of heat produced releases	ΔH (kJ)	CO_2 (kg)
Coal	$C + O_2 \rightarrow CO_2$	-394	112
Heavy oil	$C_{20}H_{42} + 30O_2 \rightarrow 20CO_2 + 21H_2O$	-13300	66
Natural Gas	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	-890	49
Biomass	$CH_2O + O_2 \rightarrow CO_2 + H_2O$	-440	100

Where ΔH = Enthalpy

The CES can be calculated using the following equation [17]:

$$CES = \frac{\eta \times [112 \times \%C + 49 \times \%NG + 66 \times \%P]}{100} \quad (1)$$

Where: CES = Carbon Emission Signature (kgCO_2/GJ)
h = Energy conversion efficiency
%C = Percentage of coal power contribution to the electrical grid
%NG = Percentage of natural gas power contribution to the electrical grid
%P = Percentage of petroleum power contribution to the electrical grid

This CES could then be used to determine the carbon dioxide associated with the consumption of a specified amount of energy by the following equation:

$$C_E = E_c \times CES \quad (2)$$

Where: C_E = Carbon emitted (kg)
E_c = Energy consumed (GJ)

Equation (2) can be used to determine carbon dioxide emitted on each of the manufacturing processes in making a wind turbine.

3.3 Costs

Ortegon et al. [18] developed several cost estimation relationships (CERs) which were used to calculate the cost of each component of a wind turbine. CER for a turbine blade is given as [19]:

$$Baseline\ cost = \frac{[BCE \times (0.4019R^3 - 955.24) + 2.7445R^{2.5025} \times GDPE]}{1 - 0.28} \quad (3)$$

Where: Baseline cost = Cost for a turbine blade (US$)
R = Rotor radius (m)
BCE = Blade material cost escalator
GDPE = Labour cost escalator

The CER of a wind turbine's hub is given as [19]:

$$M_H = 0.954 \times M_B + 5680.3 \quad (4)$$

$$Hub\ cost = 4.25 \times M_H \quad (5)$$

Where: Hub cost = cost of a wind turbine's hub (US$)
M_H = Hub mass (kg)
M_B = Single blade mass (kg)

A single blade mass is also calculated using an equation developed by Fingersh et al. [18]:

$$M_B = 0.1452 \times R^{2.9158} \quad (6)$$

Where: M_B = Single blade mass (kg)
R = Rotor radius (m)

Cost of a wind turbine's steel tubular tower can be determined by the following equation on WindPACT studies [20]:

$$Tower\ cost = [0.3973 \times A \times h - 1414] \times C_\$ \quad (7)$$

Where: Tower cost = Cost of a wind turbine's steel tubular tower (US$)
A = Swept area (m^2)
h = Hub height (m)
$C_\$$ = Cost of steel (US$)

A wind turbine foundation's CER is given by Fingersh at al. [19]. The foundation is assumed to be in the form of a hollow drilled pier.

$$Foundation\ cost = 303.24 \times (A \times h)^{0.4037} \quad (8)$$

Where: Foundation cost = cost of the wind turbine foundation (US$)
A = Swept area (m^2)
h = Hub height (m)

This investigation was therefore taken great detail into the manufacturing processes of a wind turbine due to the large contribution given to both the environmental and energy impacts.

3.4 Wind Turbine Power Calculation

The theoretical maximum power output of a wind turbine is given by the equation [21]:

$$P_{max} = \frac{1}{2} C_p \times \rho_a \times A \times V^3 \quad (9)$$

Where P_{max} = Maximum power output (W)
C_p = Power conversion efficiency
ρ_a = Air density (kg/m^3)
A = Swept area (m^2)
V = Air velocity (m/s)

The value of the power conversion efficiency (C_p) is 59.3% which defines as the maximum efficiency of converting kinetic energy from a wind turbine to electrical energy [22]. In addition to this, inefficiencies in the gearing and power generation components of a wind turbine could reduce the actual conversion efficiency. Common values used for C_p are 0.35-0.45 [6, 23]. In this study 0.4 has been chosen as the power conversion efficiency. Air density is dependent on the temperature and altitude from sea level. However, this proposed method is not intended to analyse differing locations of a wind turbine. The overall intention is to compare the effects of different conceptual design alternatives of a wind turbine and therefore the air density was chosen to be constant at sea level with an air density of 1.225 kg/m^3 [24]. The swept area of the rotor can be calculated using the blade length.

$$A = \pi \times R^2 \tag{10}$$

Where: A = Swept area of the rotor (m^2)
R = Wind turbine blade length (m)

The velocity of air is also dependent on the location and other factors. Similar to the air density, the air velocity is a constant value defined by the user.

4. Implementation of the Proposed Method

Fig. 3. illustrates the developed software system for analyses of the energy, carbon and cost calculation of designing a wind turbine at the concept design stage. The system was developed using Microsoft's Excel Visual Basic.

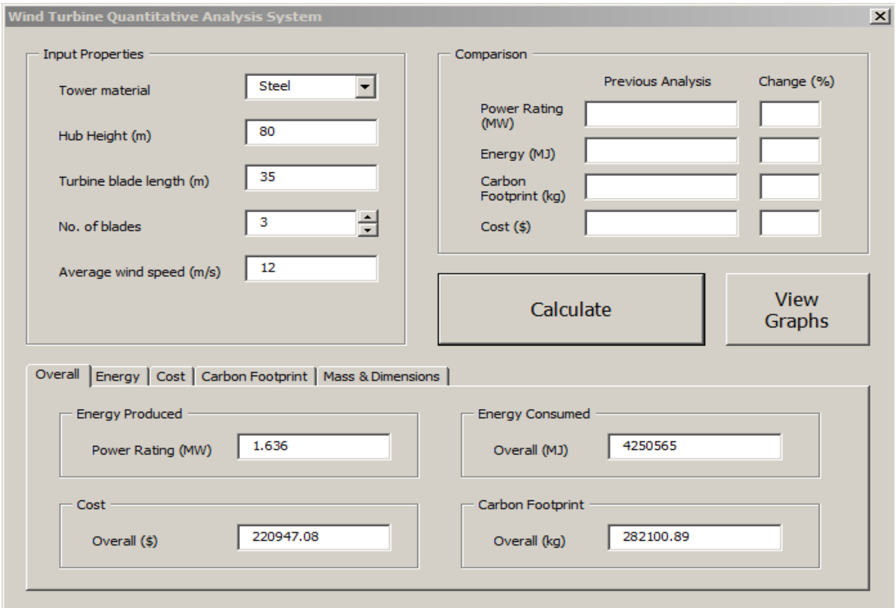

Fig. 3. The developed software system

4.1 Energy Used in Manufacturing

To calculate the energy used to manufacture a wind turbine tower, the manufacturing processes to include in the calculation were: (i) material supply, (ii) bending, (iii) single sheet welding and (iv) section welding as discussed in Section 3.1. The energy consumed in the manufacture of a wind turbine tower was taken into account of the rolling of the steel plates, the welding of edges of the rolled sections and the welding of those rolled sections to form the tower. The energy taken to roll the steel plates into the correct shape was found by using the power and time taken to roll one plate section in the following equation:

$$E = P \times t \tag{11}$$

Where:
E = Energy (J)
P = Power (W)
t = Time (s)

Once the energy required to roll one section has been calculated, the overall energy requirement could be determined by multiplying the number of plate sections needed.

4.2 Carbon Emissions Calculation

The carbon footprint was calculated using a CES. It was obtained by equation (1) and the standard values in Table 3 from the UK National grid [26].

Table 3. UK electricity fuel source contributions

Fuel Source	Electricity Supplied (TWh)	Percentage contribution (%)
Coal	135.89	37.6
Bioenergy	13.4	3.71
Gas	98.17	27.17
Hydro	5.25	1.45
Net imports	12.04	3.33
Nuclear	63.95	17.7
Offshore	7.46	2.07
Oil	2.74	0.76
Other fuels	2.71	0.75
Pumped storage	-1.02	-0.28
Wind and Solar	20.78	5.75
Total all generating companies	**361.36**	**100**

It can be seen from Table 3 that coal contributes 37.6% to the UK national power grid; oil contributes 0.76% and; gas contributes 27.17%. These values can be used to calculate the CES of the UK national power grid. The value of "η" is commonly set as 0.34 [17]. By using equation (1) the CES of National Grid is equal to 19.015 $kgCO_2/GJ$. This shows that 19.015 kg of CO_2 is emitted per GJ of energy consumed. By multiplying the CES and the energy consumed by each manufacturing process, the carbon dioxide emitted in the manufacturing process can be calculated using equation (2).

The carbon footprint of the primary material production can be calculated using the primary production carbon footprint value given in CES EduPack [26] as 1.72-1.9 kg CO_2/kg steel. The mean value of 1.81 kg CO_2/kg steel was used in the software system.

4.3 Cost Calculation

The software system has been computed to estimate a wind turbine's main components and its overall costs. The cost of blades was calculated using equation (3) and the turbine blade length was specified by the user. As the system is intended for concept design, both the blade material cost and labour cost escalators should be constant with an assigned value of '1'. This cost was then multiplied by the number of turbine blades to obtain the total cost of the turbine blades.

The cost of the hub was calculated using the equations (4); (5) and (6). The cost of the tower was calculated using equation (7). The material cost of the tower was calculated by multiplying the mass of the tower by the cost of steel/kg. The cost of steel per kilogram was taken from CES EduPack [26]. The exact material was structural steel S275N [27]. The material cost per kilogram is given as 0.39-0.434, this has been converted into US$, i.e. 0.685 US$/kg of steel. The cost of the foundation (tower base) was calculated using equation (8). The overall cost of the wind turbine is therefore equal to the sum of the cost of the blades, tower, hub and foundation.

4.4 To display results statistically from the developed software system

The user can chose a statistical display of the overall result as shown in the example of Fig. 4. Since the range of values of power rating (MW) total cost (US$), carbon footprint (kg) and energy consumed (GJ) can be very large to be represented in the statistical chart. The outputs were therefore converted to the following units. For example, power rating was converted from kW to MW. Energy consumed was converted from GJ to MWh. Carbon footprint was converted from kg to t. Cost was converted from US$ to 1,000 US$. Based on the result, a decision can be made which concept is applicable and proceed to next stage of the design.

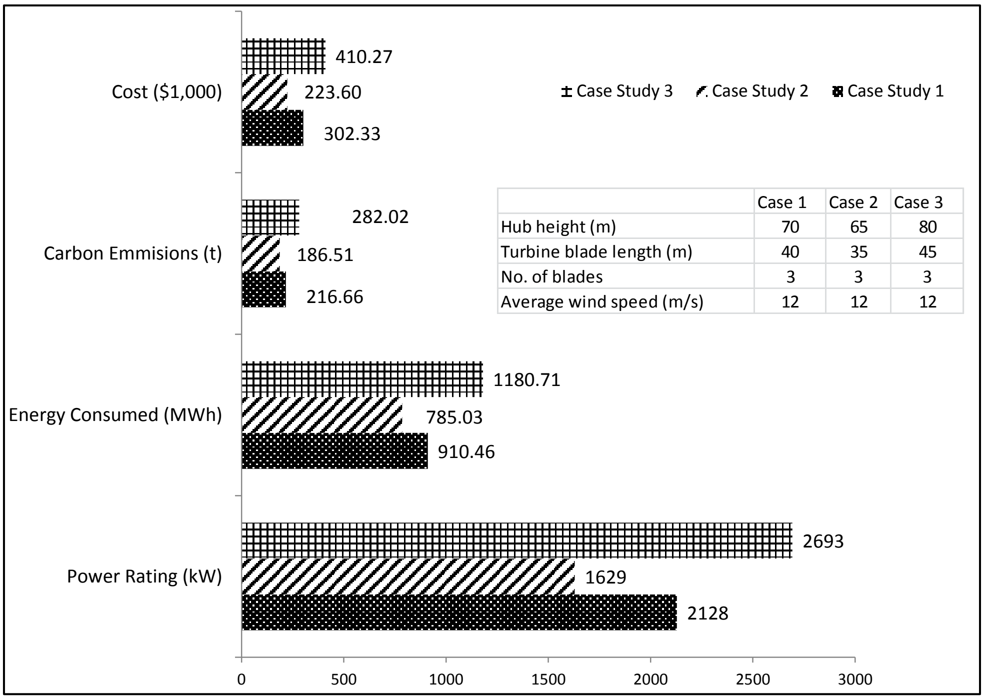

Fig. 4. Output graph data of a single dataset

5. Conclusion and future work

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The novel approach would allow for rapid initial assessment of multiple design concepts of wind turbines, enabling the “greener” concept to be selected quickly and progress to the detailed design and product development stages. A large wind farm may consist of several hundred individual wind turbines and cover an extended area of hundreds of square miles and therefore the proposed approach could potentially be used to minimise the carbon footprint of such application by selecting appropriate wind turbines from the conceptual design stage. Further work may include a proposed method of developing an additional component into the software to analysis a wind farm situation. The system could be extended to include predictions of more than one wind turbine, aiding the early design and analysis of a proposed wind farm by taking account of (1) Energy payback time, (2) carbon emission penalty cost and (3) the overall “return-on-investment”.

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