Towards Greener Horizontal-Axis Wind Turbines: Analysis of Carbon Emissions, Energy and Costs at the Early Design Stage

Raymond Aso, Wai Ming Cheung[1]
Faculty of Engineering and Environment
Department of Mechanical and Construction Engineering
University of Northumbria
Newcastle Upon Tyne
NE1 8ST, UK

Abstract

This paper describes the development of a quantitative analysis system as a platform for rapidly estimate energy, costs and carbon emission to facilitate the comparison of different wind turbine concept designs. This system aimed specifically at wind turbine manufacturing processes due to the fact that a large proportion of the environmental, costs and energy impacts would occur at this stage. The proposed method supports an initial assessment of multiple design concepts which allows the selection and development of a "greener" wind turbine. The developed system enables concept design of commercial wind turbine towers of hub heights between 44 to 135 m. The method supports an accurate estimation in regards to the dimension, energy consumed, maximum power output, costs and carbon emission in the early design phases of a wind turbine. As a result of the development, the proposed approach could potentially be used to minimise the carbon footprints of major engineering projects such as wind farms.

Keywords: Carbon Emission; Carbon Footprint, Energy; Cost; Manufacturing; Wind Turbine Design Concept

Please cite this article as: Aso, R. and Cheung, W.M., 2015. Towards greener horizontal-axis wind turbines: analysis of carbon emissions, energy and costs at the early design stage. *Journal of Cleaner Production*, *87*, pp.263-274.

[1] Corresponding author
wai.m.cheung@northumbria.ac.uk
+44(0)191 243 7584

Nomenclature

%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
A	Swept area (m^2)
BCE	Blade material cost escalator
C_E	Carbon emitted (kg)
C_p	Power conversion efficiency
$C_\$$	Cost of steel (US$)
CES	Carbon Emission Signature (kg CO_2 / GJ)
D_b	Base Diameter (m)
D_t	Top Diameter (m)
E	Energy (J)
E_c	Energy consumed (GJ)
GDPE	Labour cost escalator
h	Hub height (m)
m	Mass of steel used (kg)
M_B	Single blade mass (kg)
M_H	Hub mass (kg)
P	Power (W)
P_{max}	Maximum power output (W)
R	Rotor radius (m)
rpm	Revolutions per minute
T_r	Taper ratio
t	Time (s)
t_b	Base wall thickness (mm)
t_t	Top wall thickness (mm)
V	Air velocity (m/s)
V_i	Inner conical volume (m^3)
V_o	Outer conical volume (m^3)
V_T	Total volume of a wind turbine tower (m^3)
η	Energy conversion efficiency
ρ_a	Air density (kg/m^3)
ρ_s	Density of steel (kg/m^3)

Abbreviations	
CER	Cost Estimation Relationship
CO_2	Carbon dioxide
D	Diameter
ErP	Energy-related Products
LCA	Life Cycle Assessment

1. Introduction

In compliance with Cellura et al. (2013), Energy-related Products (ErP) account for a large proportion of European energy and natural resource consumption. In order to reduce the energy and environmental impacts of these products, the European Commission published the Ecodesign Directive 2009/125/EC, (2009) as a key component for improving the energy and environmental performances of ErP. The focus of this article is therefore to discuss a proposed approach to evaluate the environmental, energy and cost impacts of horizontal-axis wind turbines from an early design perspective. This method could potentially lead to the development of a 'greener' wind turbine.

A horizontal axis wind turbine consists of 4 major sub-systems: the foundation, tower, nacelle and rotor blades. A wind turbine is designed to produce "cleaner" energy without producing CO_2 emissions during operation. However CO_2 emissions are created and energy is used throughout the manufacturing, logistical and decommissioning processes (Demira and Taskin, 2014; Haapala and Prempreeda, 2014). This means wind turbines are not completely without carbon footprints. Furthermore, CO_2 emissions of renewable energy sources such as wind turbines during operation are almost negligible in comparison to fossil fuels and are recognised as essential in aiming to reduce the global CO_2 emissions (Lee and Hashim, 2014). 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 design process of any engineering project is arguably one of the most important stages of product development (Ulrich and Eppinger, 2011). 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 (Newnes et al. 2008). Therefore, an accurate decision at the early design stage can minimise changes to the final design which could directly lead to reduce cost and time.

The objective of this study is to develop a low-cost software platform for managing engineering data to evaluate the three important design attributes namely: energy, costs and

carbon emission of a wind turbine. The approach allows wind turbine designers to make design decision at the early design stage without spending too much time and effort prior to the next phrase of a full detailed wind turbine design. 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 case studies for validating the approach are based on data obtained from published journals and commercial wind turbine brochures. The layout of this paper is as follows: Section 2 describes the related literature. Section 3 discusses the proposed approach and its background theory. Section 4 discusses the implementation and Section 5 describes a case study and data analysis and, finally, the conclusion and future work are presented.

2. Related Literature

This literature review is focused on relevant research in assessment methods of CO_2, manufacturing energy requirements and cost of building wind turbines. This review found that many researchers used LCA as their assessment technique in their approach. The discussion of the research approaches are summarised as follow.

Martinez, et al. (2009), investigated a 2 MW wind turbine using Life Cycle Assessment (LCA) approach and they concluded that the greatest contributor to environmental impact is the manufacturing processes of each component of a wind turbine. Tremeac and Meunier, (2009) applied LCA and sensitivity analysis to compare a 4.5 MW and 250W wind turbines. They concluded that 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. Fleck and Huot (2009) deployed LCA to compare the environmental impacts, net energy inputs and life cycle cost of two systems: (1) a standalone small wind turbine system and (2) a single home diesel generator system. The net energy input of a unit process is calculated based on the energy inputs and outputs of a process. The results show that considerable environmental impact could occur at the manufacturing stage even though there are cost benefits for wind power. Demir and Taşkın, (2013) conducted another investigation using LCA into a large variety of wind turbines with varying hub heights between 50 to 100 m. They concluded that the environmental impact of wind turbines are lower for turbines with larger hub heights as a taller tower can accommodate longer turbine blades, thus this can increase the maximum power available from a wind turbine. The location of a wind turbine

also has a significant contribution to its environmental impact, as it was found that installing a wind turbine in optimum wind speed locations also reduces the environmental impact.

A study into the energy, emissions and environmental impact of a vertical and a horizontal wind turbine was undertaken by Uddin and Kumar, (2014) and they established that the energy and environmental impact of the vertical-axis wind turbine are 50% more than the impact of a horizontal-axis wind turbine. Lenzen and Munksgaard, (2002) conducted an LCA on a wide variety of wind turbines, focussing on the energy requirements and CO_2 emission. The result of the investigation shows that small wind turbines of 1 kW power output required three times more of life cycle energy per unit power than 1 MW wind turbines. As can be expected, it was also found that the CO_2 emission varied depends on production methods. A study by Maki et al. (2012) focused on optimising the cost of a wind turbine using a multi-level system to optimise the system design of a 3 bladed horizontal-axis wind turbine. The cost of energy in production is the ultimate factor and the result indicates that the cost of energy in the production process is lower with a larger hub height, for rotor diameters about 60 m and with 32 rpm. It was also found that the cost of energy increases with a wind turbine's power rating. Furthermore, Valori et al. (2013) performed a LCA comparison of two types of micro-wind generators, vertical-axis and horizontal-axis respectively. Both of the small scale generators are capable of generating 1 kW. They concluded that environmental impacts are related to the ratio of the mass of a wind turbine.

Jungbluth et al. (2005) performed LCA for photovoltaic and wind power systems. They concluded that environmental impacts of such systems depend on the material and energy consumption at the construction stage. For example, the air emissions from different types of steel in the tower, the nacelle and the concrete in the foundation are the main contributors of environmental impacts. Nalukowe et al. (2006) also conducted a LCA of the Vestas V90-3 MW wind turbine and compared its environmental impacts with other sources of power. This study also highlighted that manufacturing processes as the greatest contribution to environmental impact. Recycling the components of the wind turbine was found to significantly reduce the environmental impact of wind turbines. In another LCA carried out by Guezuraga, et al. (2012) on a 1.8 MW gearless and a 2 MW geared wind turbine were compared. The study evaluated the CO_2 emissions and energy payback time of the two wind turbines and further investigated the implications of varying recycling scenarios and

manufacturing locations. It was concluded that the 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. Garret and Rønde, (2012) conducted a LCA on one of Vestas' 2 MW horizontal-axis wind turbine. The evaluation has been carried on all components of the wind turbine. They concluded that the manufacturing stage contributes the largest impact in terms of CO_2 emissions, in particularly the wind turbine tower. The end of service life of wind turbines was studied by Ortegon et al. (2013) and they found that very few LCA of wind turbines covered the end of service life. This is due to the fact that end of service life of this area is largely unexplored because of lack of data. However, they concluded that through remanufacturing and recycling of wind turbines, the environmental impact could be reduced. Haapala and Prempreeda, (2014) also conducted a comparative study of 2.0 MW wind turbines using LCA and sensitivity analysis. They concluded that 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.

To summarise this review, it was found 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. This conclusion is also supported by Davidsso's finding (Davidsson et al. 2012) in reviewing of LCA on wind energy system. 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 developed and is discussed in the next section. This method utilized an insufficient statistically significant data approach for the early stages of product development process (Cheung et al. 2011).

3. The Proposed Method and its Theoretical Background

Fig. 1 illustrates the proposed method for evaluating the cost, energy and carbon emission of a wind turbine at the concept 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

According to the authors Guezuraga et al. (2012); Tremeac and Meunier, (2009) that about 84% of the energy was consumed for producing a 1-3 MW wind turbines, among these, 55% was used for producing the tower alone, 20% for a nacelle and about 10% for the blades; the rest of the 16% energy was used in transportation, the foundation, maintenance and dismantling. Haapala and Prempreeda, (2014) and Jungbluth et al. (2005) also claimed that the environmental impacts of wind turbines are mainly occurred at the manufacturing stage of a wind turbine's tower and this is largely due to the amount of energy and steel used. Based on these findings, this proposed work is therefore focused on a wind turbine's tower.

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) as shown in Fig. 2.

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

The material was bought into the 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

Several academics at some of the world's top climate research institutes reported that, global carbon emissions have reached record high with 36 Gt in 2013 (The Carbon Brief, 2013). Europe emerged as the third biggest polluter and produced nearly 6 Gt of CO_2. Asia, the

highest overall emitter, produced 16 Gt of CO_2 while North America emitted just over 6 Gt. The rest of the world produced about 8 Gt.

The definition of a carbon footprint was discussed by Qi and Chang, (2012); Wiedmann and Minx, (2007); they stated that a carbon footprint is the total amount of greenhouse gases (GHGs) produced to support a specific activity, and is usually equated as tonnes of CO_2. A specific activity such as manufacturing processes can have its own carbon footprint. Carbon footprints can be referred as carbon emissions in the manufacturing process from energy supply to end-use (Čuček et al. 2012; Scipioni et al. 2012). Carbon footprints show where energy is used and lost; and the associated GHGs that are emitted. Each carbon footprint indicates the flow of energy (in the form of fuel or electricity) to major end-uses in manufacturing, including boilers, power generators, process heaters, process coolers, machine-driven equipment, facility and lighting (Domer et al. 2013).

Reducing carbon emissions is therefore 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, (2008). 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 1. 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 1. Heat and CO_2 released by energy production fuels, where ΔH = Enthalpy (Jeswiet and Kara, 2008)

The CES can be calculated using the following equation (Jeswiet and Kara, 2008):

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

Where:
- CES = Carbon Emission Signature ($kgCO_2/GJ$)
- η = 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

From the equation, it can be seen that the coefficients were derived from the results in Table 1. The energy conversion efficiency η is commonly given the value of 0.34 (Jeswiet and Kara, 2008). 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:

$$C_E = E_c \times CES \tag{2}$$

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. Another method to determine carbon emissions of a product is detailed by Chen et al. (2011), by using a carbon intensity to determine the carbon footprint in using separate intensity factors for each material used in the manufacture of a wind turbine. This method however is a broad overview of the entire process and is not suitable to be used in the authors of this article's proposed method.

3.3 Costs

Ortegon et al. (2012) conducted a study of the end of service life of wind turbines. They concluded that 81% of the total cost was due to installation of a wind turbine's tower, nacelle, blades and foundation. A study by Fingersh et al. (2006) investigated the costs of wind turbines, detailing the contribution of each main component such as the tower, foundation and turbine blades towards the final cost. Their study developed several cost estimation relationships (CERs) which were used to calculate the cost of each component of a wind turbine. Fingersh et al. (2006)'s CER for a turbine blade is given as:

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

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 (Fingersh et al. 2006):

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

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

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. (2006):

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

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 (Malcolm and Hansen, 2002; Smith, 2001):

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

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. (2006). 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 (Manwell et al. 2009):

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

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 (Wu at al. 2011). 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 (Uddin and Kumar, 2014; Patel, 2012). 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 (Rogers and Mayhew, 1995). 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. Sections 4.1 to 4.4 discuss the detailed implementation of each of the attributes.

Fig. 3. The developed software system

4.1 Dimensional Approximation

In order to calculate the energy required to manufacture a wind turbine, the total mass of the wind turbine's tower needs to be determined. To calculate the tower mass, a dimensional approximation process was implemented to provide an accurate estimation of the mass of a wind turbine tower. This process was based on commercial wind turbines dimensional data obtained from the following publications and websites:

- data for case 1 (The Lincoln Electric Company, 2011);
- data for cases 2 and 3 (Chantharasenawong et al. 2011);
- data for case 4 (Lavassas et al. 2003);
- data for case 5 (Nicholson, 2011);
- data for case 6 (Vestas, 2005);
- data for case 7 (Yoshida, 2006).

Based on those data, the relationships between the hub height and other dimensions of a wind turbine were identified. The hub height, base and top wall thicknesses (WT) and base and top diameters were recorded from these studies. The findings are shown in Table 2.

Table 2 - Wind turbine dimensions

The taper ratio was obtained from the characteristics as shown in Table 2. The data from Table 2 was applied statistically to establish the relationships between: (i) the hub height and the taper ratio; (ii) the base diameter (Base D) to hub height ratio; (iii) the base wall thickness (Base WT) to hub height ratio; and (iv) the top wall thickness (Top WT) to base wall thickness ratio. The statistical charts are represented in Fig. 4(a) and (b); and Fig. 5(a) and (b).

Fig. 4. (a) Relationship between taper ratio and hub height; (b) relationship between the base diameter to hub height ratio and hub height

Fig. 4 (a) shows that apart from case 2, there is a good correlation between the taper ratio and hub height of the wind turbine. By plotting the data sets into the Microsoft Excel spreadsheet,

an equation has been derived using the spreadsheet's "chart tools" and followed by selecting the trend line options such as exponential, linear or polynomial for best fit. The equation to derive the taper ratio for a given hub height is given as:

$$T_r = -0.015 \times \ln(h) + 0.0873 \tag{11}$$

Where: T_r = Taper ratio
h = Wind turbine hub height (m)

Fig. 4(b) indicates that there is a good correlation between the base diameter to hub height ratio and the hub height. In this graph, case 2 again lies much further away from the trend line than the other cases. Using the same approach of obtaining equation (11), a mathematical expression to derive the base diameter to hub height ratio for a given hub height is:

$$\frac{D_b}{h} = -0.041 \times \ln(h) + 0.2332 \tag{12}$$

Where: D_b = Base diameter (m)
h = Hub height (m)

This equation can be rearranged to give the base diameter directly as:

$$D_b = h[-0.041 \times \ln(h) + 0.2332] \tag{123}$$

Fig. 5. (a) Relationship between the Base Wall Thickness to Hub Height Ratio and Hub Height (b) Top Wall Thickness to Base Wall Thickness Ratio and Hub Height

Case 2 can be seen to be an outlier in Fig. 5(a). Excluding case 2, a positive linear correlation can be established between the base wall thickness to hub height ratio and the hub height. Using the same approach of obtaining equation (11), a mathematical expression of the base wall thickness to hub height ratio for a given hub height can be defined as:

$$\frac{t_b}{h} = 0.3443 \times h + 3.535 \tag{14}$$

Where: t_b = Base wall thickness (mm)
h = Hub height (m)

This equation can be rearranged to give the base wall thickness directly as:

$$t_b = 0.3443 \times h^2 + 3.535 \times h \tag{15}$$

Again case 2 can be seen as an outlier in Fig. 5(b). The top wall thickness to base wall thickness ratio can be seen as decreasing while the height of a hub increases. Using the same approach of obtaining equation (11), a mathematical expression of the top wall thickness to base wall thickness ratio for a given hub height can be derived as:

$$\frac{t_t}{t_b} = -0.24 \times \ln(h) + 1.4804 \tag{16}$$

Where: t_t = Top wall thickness (mm)
t_b = Base wall thickness (mm)
h = Hub height (m)

This equation can be rearranged to obtain the top wall thickness directly as:

$$t_t = t_b[-0.24 \times \ln(h) + 1.4804] \tag{17}$$

Finally, the top diameter of the tower was found using the taper ratio and the base diameter as shown in equation 18.

$$D_t = D_b - hT_r \tag{18}$$

Where: D_t = Top diameter (m)
D_b = Base diameter (m)
h = Hub height (m)
T_r = Taper ratio

Equations (11) to (18) were used to estimate the dimensions of a commercial wind turbine tower based on a given hub height. With these dimensions, the total mass of the wind turbine tower could be calculated. This was performed by first obtaining the volume of the tower. The volume of the tower was calculated by subtracting the conical section of the inner top and base diameters from the conical section of the outer top and base diameters.

$$V_T = V_o - V_i \tag{19}$$

Where:

V_T = Total volume of a wind turbine tower (m^3)
V_o = Outer conical volume (m^3)
V_i = Inner conical volume (m^3)

The inner and outer conical volumes are given by equations (20) and (21).

$$V_o = \pi \times h \times \left[\frac{\left(\frac{D_b}{2}\right)^2 + \left(\frac{D_t}{2}\right)^2 + \frac{D_b \times D_t}{4}}{3} \right] \tag{20}$$

$$V_i = \pi \times h \times \left[\frac{\left(\left(\frac{D_b}{2}\right) - t_b\right)^2 + \left(\left(\frac{D_t}{2}\right) - t_t\right)^2 + \frac{(D_b - t_b) \times (D_t - t_t)}{4}}{3} \right] \tag{21}$$

After calculating the total volume of steel in the wind turbine from the dimensions, the mass of the steel used could be calculated by multiplying the total volume of steel by the density of steel.

$$m = V_T \times \rho_s \tag{22}$$

Where:

m = Mass of steel used (kg)
V_T = Total volume of a wind turbine tower (m^3)
ρ_s = Density of steel (kg/m^3)

The density of steel is taken as 7,850 kg/m^3 (CES EduPack, 2013).

4.2 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 total energy requirements to manufacture a wind turbine tower were calculated using data from machine manufacturers' websites and technical manuals (AMI, 2013; HB Machinery, 2013)

The rolling of metal plate into a cylinder typically measures in width of 3 m (Hau and Renouard, 2013). Therefore the hub height was divided by 3 and rounded up to the nearest integer. This will give the number of plate sections used to form the turbine tower. When rolling a plate into a conical section in a steel tubular wind turbine, extra consideration is needed to ensure the plate fits within the rolling machine. 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:

$$E = P \times t \tag{23}$$

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. The energy required to weld those plates into cylinders was calculated by using equation (23). However in this process, the time taken was obtained by dividing the height of the tower by the travel speed of the arc welder, as the path of the arc welder travelled was equal to the height of the wind turbine tower. Multiplying this time by the power of the arc welder equated to the total energy used of a single sheet welding process.

The overall energy required to weld the subsequent tubes together was calculated using equation (23). Consideration of the size of each cylinder has also been taken account of, this is due to the fact that the succeeding circumference of a cylinder is always slightly smaller than the preceding cylinder from the base to top of the tower. To calculate the total distance travelled, the diameters at each intersection between cylinders were calculated by assuming that a linear change in diameter between each of the cylinders from the base and to top of the tower. Based on the value of each of the cylinder's diameters, the overall energy required to weld the tower was determined by the total time taken and the welder's travel speed and the power of the welder. The energy used in the primary material production of the steel was also calculated by the developed software. This was perform by multiplying the embodied energy per kg of steel; 26.4 MJ/kg (CES EduPack, 2013), by the total mass of steel in the wind turbine tower.

4.3 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 (Energy trends section 5, 2013).

Table 3. UK electricity fuel source contributions

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 (Jeswiet and Kara, 2008). 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, (2013) 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.

4.4 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, 2013. The exact material was structural steel S275N

(Chantharasenawong et al. 2011). 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.

4.5 To display results statistically from the developed software system

After all the calculations concerning the energy consumed, carbon footprint and cost of the tower have been completed, the information will be displayed on the Graphical User Interface (GUI) as shown in Fig. 6.

Fig. 6. Output data from the wind turbine quantitative analysis system

If the input properties were changed and re-calculated, the previous values would be stored into the comparison section and were compared to the current set of calculated values. The percentage differences between the two are displayed in the 'Change %' column. The user can also chose a statistical display of the overall result as shown in the example of Fig. 7. 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$.

Fig. 7. Output graph data of a single dataset

5. Case Studies and Data Analysis

Input parameters of various wind turbine concepts are shown in Table 4. The historical data was obtained from Chantharosenwong et al. (2011) and Martinze et al. (2009). The number of

turbine blades and average wind speed were assumed to be constant throughout the case studies to ensure differences were not caused by these factors. The input parameters were entered into the software for further analysis. The output data was recorded as shown in Table 5. Table 6 shows the comparison of the final result of the 3 case studies.

Table 4. Input parameters to the software system

Table 5. Summary of output data

Table 6. Comparison of energy, cost and carbon footprint of the manufacturing process

It can be seen from Table 6 that by comparing Case Study 1 with Case Study 2, there was a 7.1% reduction of the hub height (from 70 to 65 m) and a 12.5% reduction in blade length (from 40 to 35 m) and this could result a maximum power loss of 23.4% if Case Study 2 was selected. However, the benefits of selecting Case Study 2 was that the tower's production cost could be reduced by 29.2% and the overall manufacturing energy consumed and carbon footprints could reduce by 10% respectively. While there was a reduction in the overall cost, manufacturing energy requirement and carbon footprints and a significant reduction in the power output, these were one-off factors whereas the maximum power affects the whole lifetime of a wind turbine. Hence, decreased the maximum power would significantly lower the total power generated by the wind turbine over its lifetime and would increase the time taken for the wind turbine to generate the same amount of energy used in manufacturing.

By comparison with Case Study 1 and Case Study 3, there was 14.3% increased of the hub height (from 70 to 80 m) and a 12.5% increase in blade length (from 40 to 45 m) and this could result a maximum power gained of 26.6%. As a result, the tower cost could be increased by 45.1% and a reduction of the manufacturing energy consumed and manufacturing carbon footprints could increase by approximately 17%. As discussed before, a greater power output factor affects the entire lifetime of wind turbine whereas the cost, energy and carbon footprints of the manufacturing processes are one-off factors. As the wind turbine

could produce more power, this meant that the wind turbine could contribute more power to the electrical grid in place of other electricity generation methods such as natural gas, petroleum and coal powered power plants. This could directly reduce the CES of the electrical grid as the contributions of natural gas, petroleum and coal powered power plants to the electrical grid were lowered, and thus reducing the overall carbon footprints of electricity generation. The calculations in this investigation was focused on commercial wind turbine towers between 44 to 135 m in height, therefore only hub heights between these values should be used in the dimensional approximation model as there is lack of data about wind turbine towers outside this range.

Energy to manufacture the tower is the sum of the rolling, sub-section welding and section welding processes. As shown in Table 6, Case Study 1 required a total manufacturing energy of 162,000 MJ and Case Study 2 required a total manufacturing energy of 146,000 MJ. These are comparable to the 170,000 MJ given by Martinez et al. (2009). As seen in Figure 8, the overall results show that taller wind turbine towers will increase the amount of energy consumed in the manufacturing stage. This directly leads to a greater carbon footprint and cost of the tower. However, taller wind turbines allow for larger turbine blade length and this will create a larger swept area which will produce a greater power output.

Fig. 8. Case studies comparison

6. Conclusion and future work

In conclusion, this developed approach enables concept design of commercial wind turbine towers of hub heights between 44 and 135 m in the early stages of the product design process. The proposed method supports an accurate estimation in regards to the dimension, energy consumed, maximum power output, cost and carbon emission which may aid in the early design phases of wind turbines. The novel approach allows for rapid initial assessment of multiple design concepts of wind turbines, enabling the “greener” concept to be selected quickly and proceed 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 (i) by taking account of other components of a wind turbine such as the nacelle, blades and foundation and; (ii) evaluation of energy payback time, energy intensity and CO_2 intensity.

Acknowledgements

The authors would like to express their gratitude to the anonymous reviewers for their constructive comments and suggestions. The authors would also like to thank Dr KP Lim for his guidance of obtaining relevant industrial data for validation purposes. This research received no specific grant from any funding agency in the public, commercial, or not for-profit sectors.

References

AMI, 2013. Model 15 Large Diameter Pipe Weld Head <www.arcmachines.com/products/pipe-welding/model-15> [accessed 16/12/2013]

Cellura, M., La Rocca, V., Longo, S., Mistretta, M., 2013. Energy and environmental impacts of energy related products (ErP): a case study of biomass-fuelled systems. J. Clean. Prod. http://dx.doi.org/10.1016/j.jclepro.2013.12.059

CES EduPack., 2013. Granta Design Limited. <www.grantadesign.com/education/edupack/index.htm> [accessed 16/12/2013]

Chantharasenawong, C., Jongpradist, P., Laoharatchapruek, S., 2011. Preliminary design of 1.5-MW modular wind turbine tower, in the 2nd TSME International Conference on Mechanical Engineering. October 19-21, Krabi, Thailand, Paper No. AEC17.

Chen, G.Q., Yang, Q., Zhao, Y.H., 2011. Renewability of wind power in China: A case study of non-renewable energy cost and greenhouse gas emission by a plant in Guangxi. Renew. Sustain. Energy. Rev. 15(5), 2322-2329.

Cheung, W. M., Mileham, A. R., Newnes, L. B., Marsh, R., Lanham, J. D. 2011. Data-driven through-life costing to support product lifecycle management solutions in innovative product development. Int. J. Prod. Lifecycle Manag. 5(2), 122-142.

Čuček, L., Klemeš, J.J., Kravanja, Z. 2012. A review of footprint analysis tools for monitoring impacts on sustainability. J. Clean. Prod. 34, 9-20.

Davidsson, S., Höök, M., Wall, G. 2012. A review of life cycle assessments on wind energy systems. The Int. J. Life Cycle Assess. 17(6), 729-742.

Demir, N. and Taşkın, A. 2013. Life cycle assessment of wind turbines in Pınarbaşı-Kayseri. J. Clean. Prod. 54, 253-263.

Dormer, A., Finn, D. P., Ward, P., Cullen, J. 2013. Carbon footprint analysis in plastics manufacturing. J. Clean. Prod. 51, 133-141.

Ecodesign Directive 2009/125/EC., 2009. Establishing a framework for the setting of ecodesign requirements for energy-related products. Off. J. of the Eur. Union.

Energy trends section 5. 2013. Electricity; <www.gov.uk/government/uploads/system/uploads/attachment_data/file/295355/5_Electricity.pdf> [accessed 16/12/2013]

Fingersh, L.J., Hand, M.M., Laxson, A.S., 2006. Wind turbine design cost and scaling model. Publisher: National Renewable Energy Laboratory, Golden, CO, USA, Report No. NREL/TP-500-40566.

Fleck, B., Huot, M. 2009. Comparative life-cycle assessment of a small wind turbine for residential off-grid use. Renew. Energy, 34(12), 2688-2696.

Garrett, P., Rønde, K. 2013. Life cycle assessment of wind power: comprehensive results from a state-of-the-art approach. The Int. J. Life Cycle Assess. 18(1), 37-48.

Guezuraga, B., Zauner, R. and Pölz, W., 2012. Life cycle assessment of two different 2 MW class wind turbines. Renew. Energy, 37(1): p. 37-44.

Haapala, K.R., Prempreeda, P. 2014. Comparative life cycle assessment of 2.0 MW wind turbines. Int. J. Sustain. Manuf. 3(2), 170-185.

Hau, E., and Von Renouard, H., 2013. Wind turbines: fundamentals, technologies, application, economics. 3rd ed. Publisher: Springer, UK.

HB Machinery. 2013., Hydraulic Four Roller Plate Rolling Machine. <www.platerollingmachines.com/roller-plate-rolling-machine-1.html.> [accessed 16/12/2013]

Jeswiet, J. and Kara, S., 2008. Carbon emissions and CES™ in manufacturing. CIRP Ann. – Manuf. Technol., 57(1), 17-20.

Jungbluth, N., Bauer, C., Dones, R., Frischknecht, R. 2005. Life cycle assessment for emerging technologies: case studies for photovoltaic and wind power. The Int. J. Life Cycle Assess. 10(1), 24-34.

Lavassas, I., Nikolaidis, G., Zervas, P., Efthimiou, E., Doudoumis, I. N., and Baniotopoulos, C. C., 2003. Analysis and design of the prototype of a steel 1-MW wind turbine tower. Eng. Struct., 25(8), 1097-1106.

Lee, M.Y., Hashim, H., 2014. Modelling and Optimization of CO_2 Abatement Strategies. J. Clean. Prod. http://dx.doi.org/10.1016/j.jclepro.2014.01.005

Lenzen, M. and Munksgaard, J. 2002. Energy and CO_2 life-cycle analyses of wind turbines—review and applications. Renew. Energy, 26(3), 339-362.

Maki, K., Sbragio, R. and Vlahopoulos, N., 2012. System design of a wind turbine using a multi-level optimization approach. Renew. Energy, 43(0), 101-110.

Malcolm, D.J., Hansen, A.C., 2006. WindPACT Turbine Rotor Design Study, Work performed by Global Energy Concepts, LLC, Kirkland, WA and Windward Engineering, Salt Lake City, UT. Golden, CO, USA, Publisher: National Renewable Energy Laboratory, Report No. NREL/SR-500-32495.

Manwell, J.F., McGowan, J.G. and Rogers, A.L., 2009. Wind Energy Explained: Theory, Design and Application, first ed., John Wiley and Sons.

Martinez, E., Sanz, F., Pellegrini, S., Jimenez, E., Blanco, J., 2009. Life cycle assessment of a multi-megawatt wind turbine. Renew. Energy, 34(3), 667-673.

Nalukowe B.B., Liu, J., Damien, W., and Lukawski, T., 2006, Life Cycle Assessment of a Wind Turbine, Report 1N1800 <ebookbrowsee.net/gdoc.php?id=227870545&url=2d7d21b38c899d211697032d4fbdbc25> [accessed 16/12/2013]

Newnes, L. B., Mileham, A. R., Cheung, W. M., Marsh, R., Lanham, J. D., Saravi, M. E., Bradbery, R. W., 2008. Predicting the whole-life cost of a product at the conceptual design stage, J. Eng. Des., 19(2), 99-112.

Nicholson, J.C., 2011. Design of wind turbine tower and foundation systems: optimization approach. Master Thesis, the University of Iowa, USA.

Ortegon, K., L.F. Nies, and J.W. Sutherland., 2013. Preparing for end of service life of wind turbines. J. Clean. Prod. 39, 191-199.

Patel, M.R., 2012. Wind and solar power systems: design, analysis, and operation. 2nd ed., Publisher: CRC press, USA.

Qi, C., Chang, N.B., 2012. Integrated carbon footprint and cost evaluation of a drinking water infrastructure system for screening expansion alternatives. J. Clean. Prod. 27, 51-63.

Rogers, G.F.C., Mayhew, Y.R., 1995. Thermodynamic and Transport Properties of Fluids. 5th ed., Publisher: Blackwell, Oxford, UK.

Scipioni, A., Manzardo, A., Mazzi, A., Mastrobuono, M. 2012. Monitoring the carbon footprint of products: a methodological proposal. J. Clean. Prod. 36, 94-101.

Smith, K., 2001. WindPACT turbine design scaling studies technical area 2: turbine, rotor and blade logistics, Publisher: National Renewable Energy Laboratory., Golden, CO, USA, Report No. NREL/SR-500-29439.

The Carbon Brief., 2013. Five facts about Europe's carbon emissions, <www.carbonbrief.org/blog/2013/11/5-facts-about-europes-carbon-emissions/> [accessed 28/8/2014]

The Lincoln Electric Company., 2011. Lincoln Electric Raises Wind Tower at Global Headquarters. <www.lincolnelectric.com/en-us/industries/wind-power/Pages/wind-tower.aspx.> [accessed 16/12/2013]

Tremeac, B., Meunier, F. 2009. Life cycle analysis of 4.5 MW and 250W wind turbines. Renew. Sustain. Energy Rev. 13(8), 2104-2110.

Uddin, M.S., Kumar, S., 2014. Energy, emissions and environmental impact analysis of wind turbine using life cycle assessment technique. J. Clean. Prod., 69, 153-164.

Ulrich, K.T., Eppinger, S.D., Goyal, A., 2011. Product design and development. Vol. 2, Publisher: McGraw-Hill/Irwin, New York, USA.

Valori, L., Bravi, M., Basosi, R. Life cycle assessment of micro-wind generators. Int. J. Energy Technol. 5(5), 1-6, 2013.

Vestas., 2005. General Specification V90 – 1.8/2.0 MW OptispeedTM – Wind Turbine. Vestas Wind Systems A/S, <www.edprwindfarms.com/northeast-region/documents/under-dev/arkwright/Exhibit7_General%20Specifications.pdf> [accessed 8/04/2014]

Vestas., 2006. Life cycle assessment of offshore and onshore sited wind power plants based on Vestas V90-3.0 MW turbines. Vestas Wind Systems A/S 2006, <vestas.com/~/media/vestas/about/sustainability/pdfs/lca_v90_june_2006.pdf.> [accessed 8/04/2014]

Wiedmann, T., Minx, J., 2007. A Definition of Carbon Footprint. In: C.C. Pertsova, Ecological Economics Research Trends: Chapter 1, pp. 1-11, Publisher: Nova Science, Hauppauge NY, USA.

Wu, B., Lang, Y., Zargari, N. and Kouro, S., 2011. Power conversion and control of wind energy systems. Publisher: John Wiley and Sons, NY, USA.

Yoshida, S., 2006. Wind turbine tower optimization method using a genetic algorithm. Wind Eng., 30(6), 453-469.

Figure Captions:

Fig. 1. The overall proposed method

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

Fig 3. The developed software system

Fig. 4. (a) Relationship between taper ratio and hub height; (b) relationship between the base diameter to hub height ratio and hub height

Fig. 5. (a) Relationship between the base wall thickness to hub height ratio and hub height; (b) Top wall thickness to base wall thickness ratio and hub height

Fig. 6. Output data from the wind turbine quantitative analysis system

Fig. 7. Output graph data of a single dataset

Fig. 8. Case studies comparison

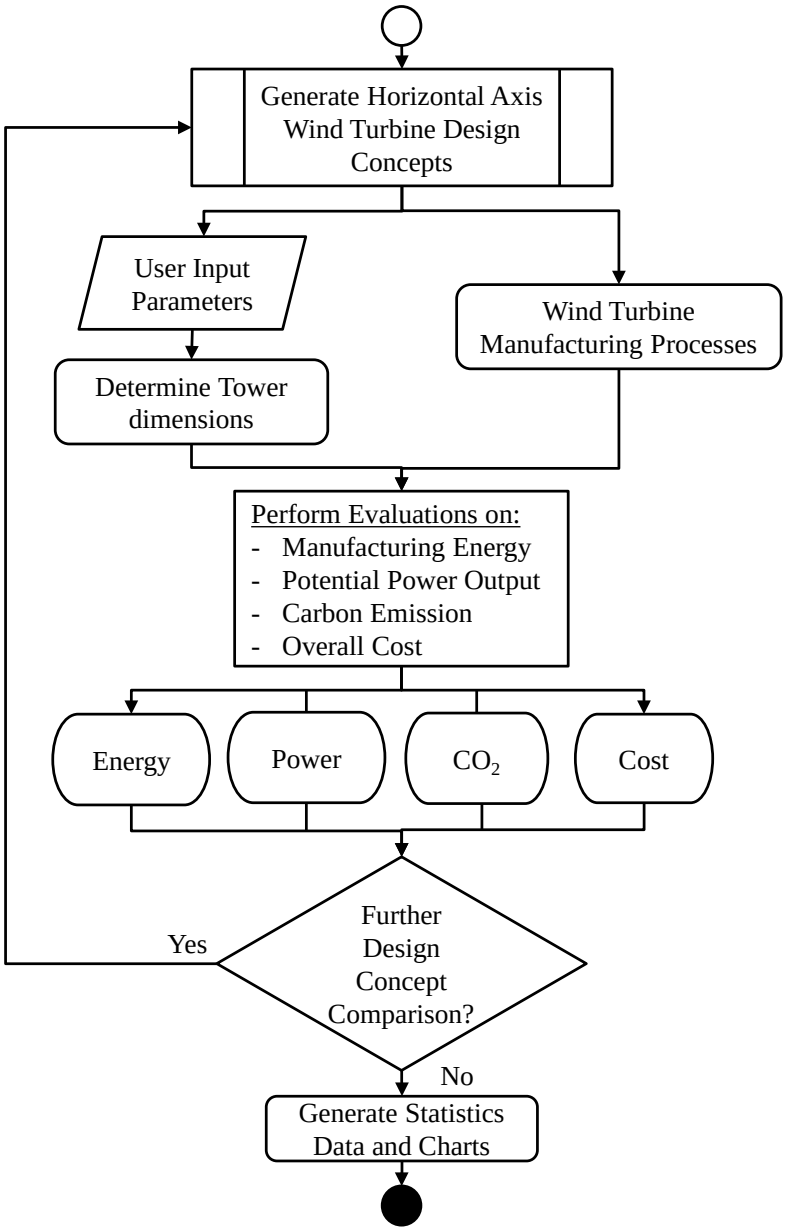

Fig. 1. The overall proposed method

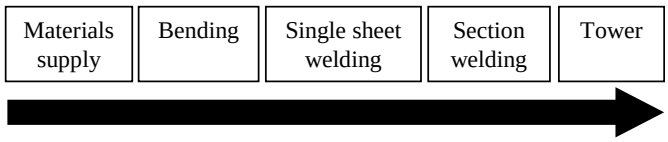

Fig 2. Flow chart of the manufacturing process of a wind turbine tower

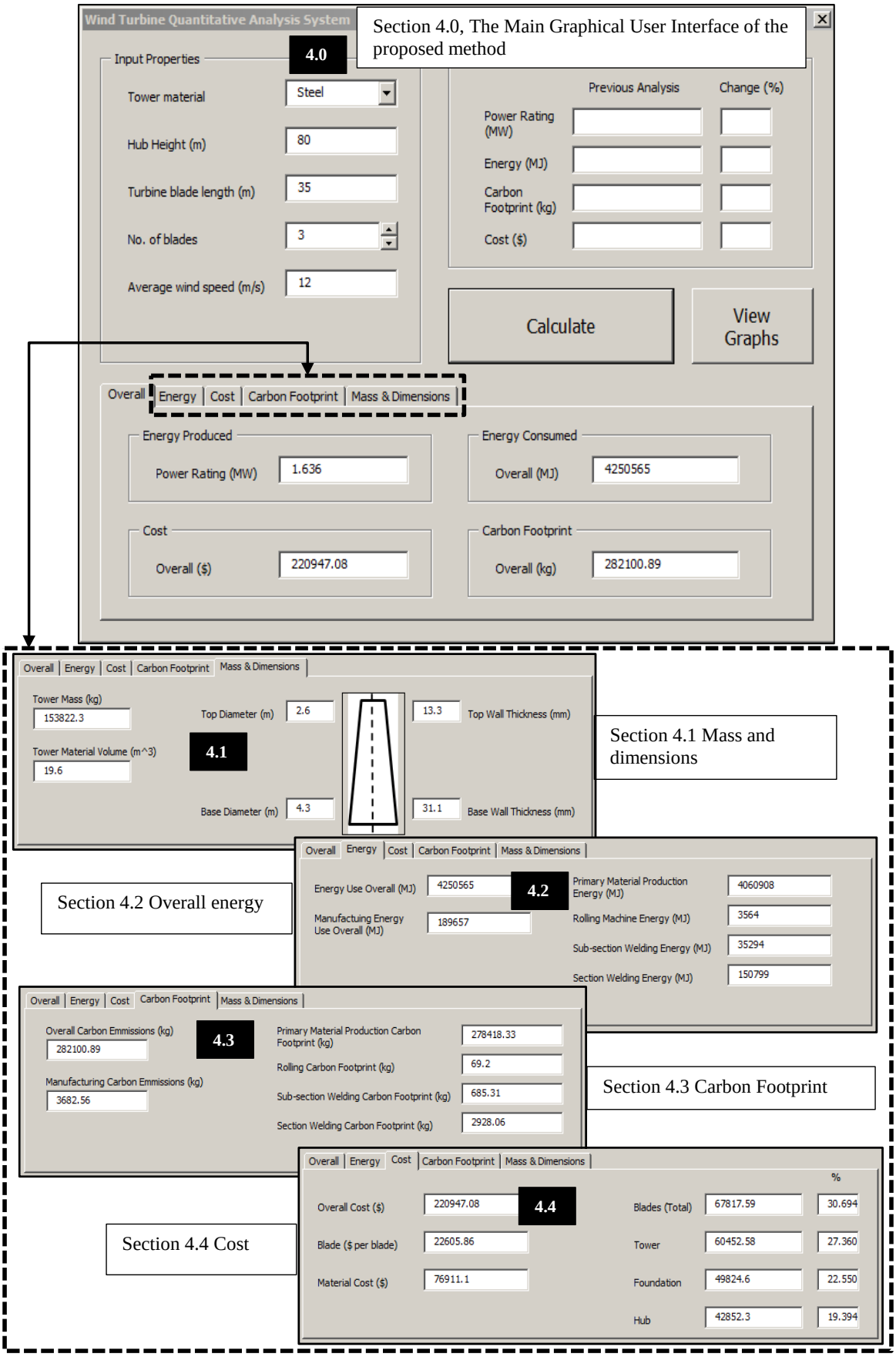

Fig 3. The developed software system

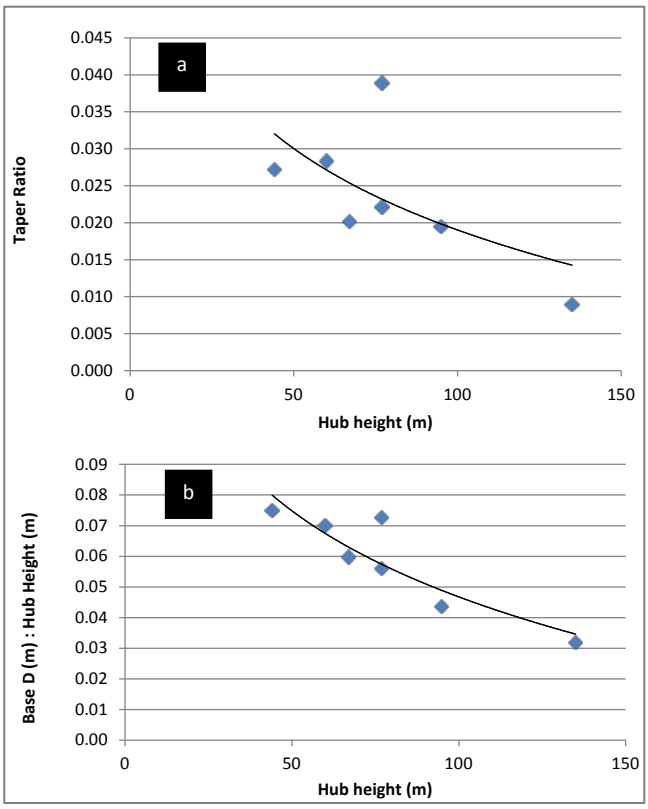

Fig. 4. (a) Relationship between taper ratio and hub height; (b) relationship between the base diameter to hub height ratio and hub height

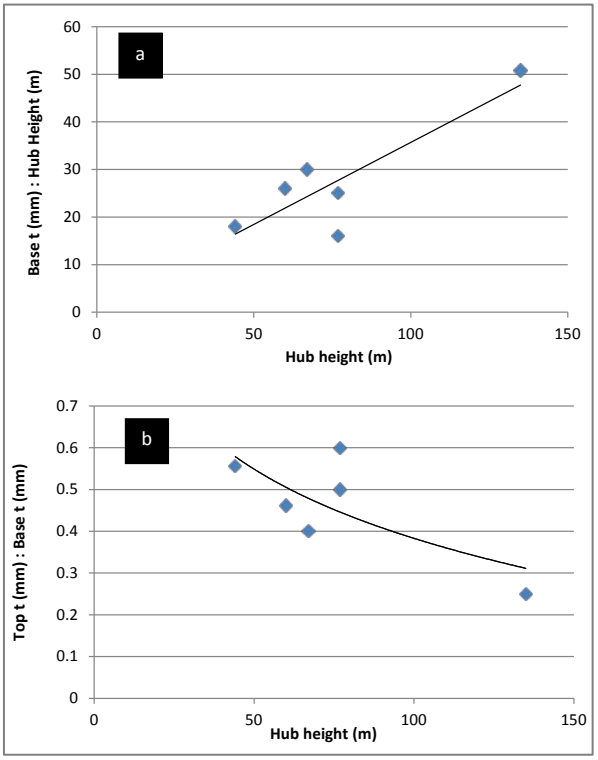

Fig. 5. (a) Relationship between the base wall thickness to hub height ratio and hub height; (b) Top wall thickness to base wall thickness ratio and hub height

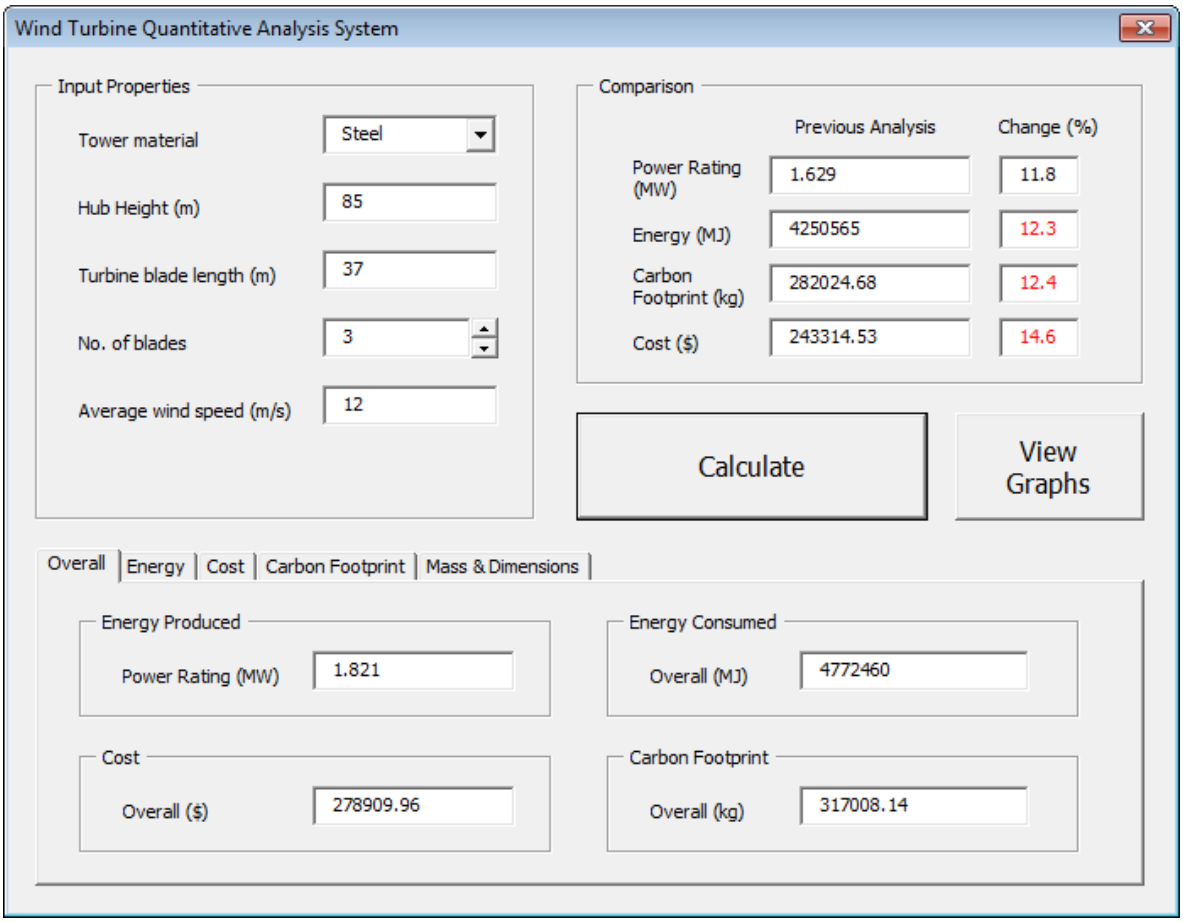

Fig. 6. Output data from the wind turbine quantitative analysis system

Fig. 7. Output graph data of a single dataset

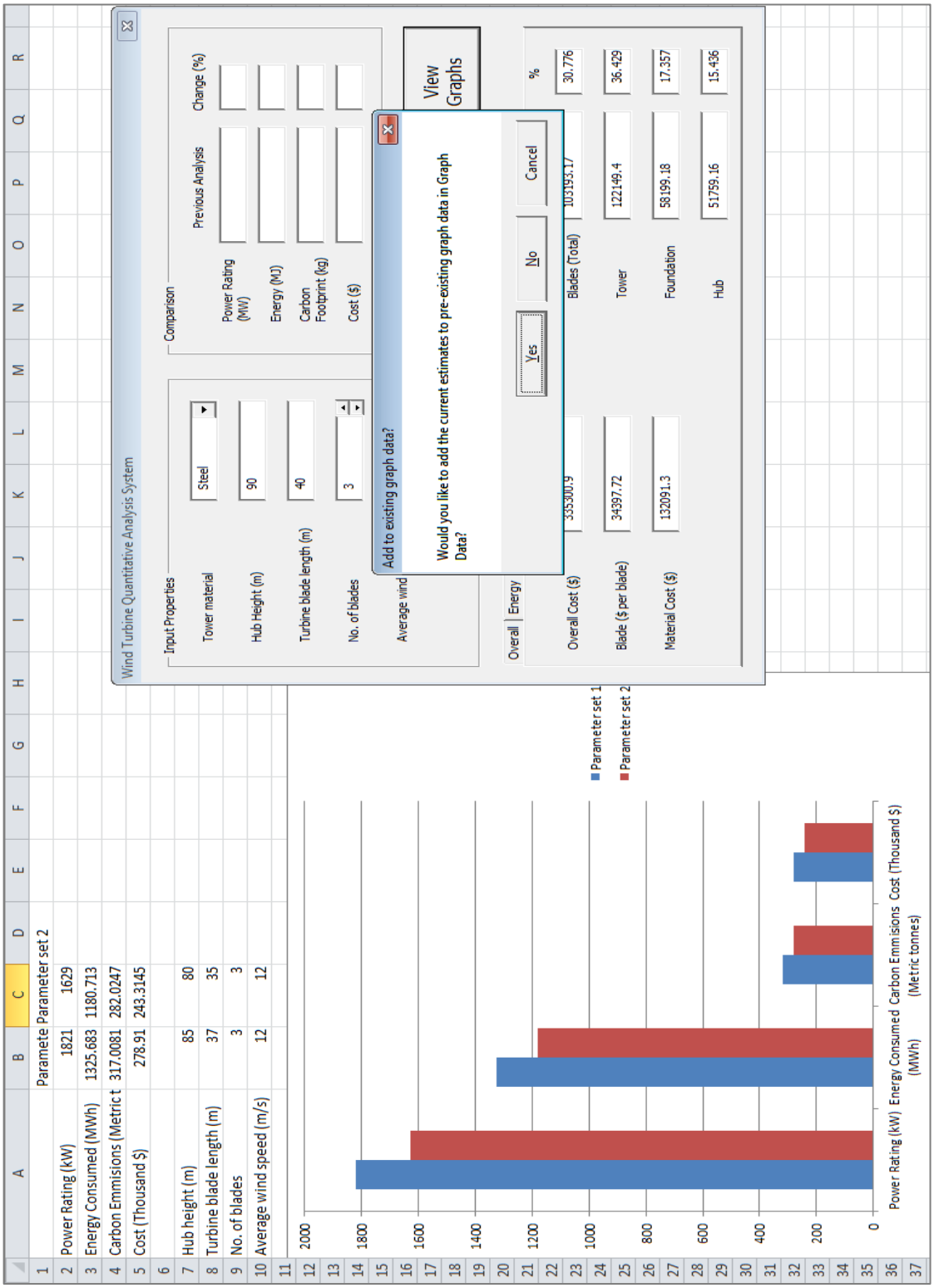

Fig. 7. Output graph data of a single dataset

	Case Study 1	Case Study 2	Case Study 3		
Power Rating (kW)	2100	1600	2700		
Energy Consumed (MWh)	910	785	1180		
Carbon Emmisions (t)	217	186	282		
Cost (US$ × 10^3)	302	223	410		
Hub height (m)	70	65	80		
Turbine blade length (m)	40	35	45		
No. of blades	3	3	3		
Average wind speed (m/s)	12	12	12		

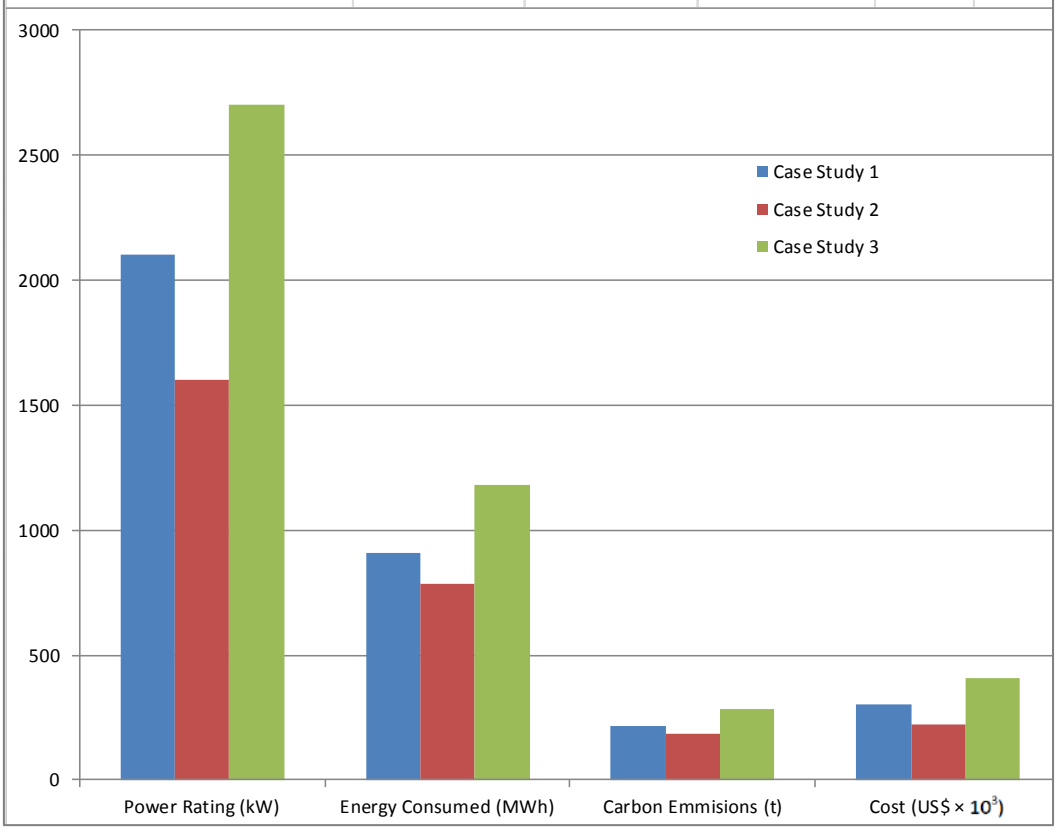

Fig. 8. Case studies comparison

Table Captions:

Table 1. Heat and CO_2 released by energy production fuels (Jeswiet and Kara, 2008)

Table 2. Wind turbine dimensions

Table 3. UK electricity fuel source contributions

Table 4. Input parameters to the software system

Table 5. Summary of output data

Table 6. Comparison of energy, cost and carbon footprint of the manufacturing process

Table 1. Heat and CO_2 released by energy production fuels, where ΔH = Enthalpy (Jeswiet and Kara, 2008)

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	$C_{20}H_{42} + 30O_2 \rightarrow 20CO_2 + 21H_2O$	-13,300	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

Table 2. Wind turbine dimensions

		WT (mm)		Diameter (m)					
	Height (m)	**Base**	**Top**	**Base**	**Top**	**Taper Ratio**	**Base D: height**	**Base WT: height**	**Top WT: Base WT**
Case 1	135	50.8	12.7	4.3	3.1	0.0089	0.0319	0.3763	0.25
Case 2	76.9	16	8	5.59	2.6	0.0389	0.0727	0.2081	0.5
Case 3	76.9	25	15	4.3	2.6	0.0221	0.0559	0.3251	0.6
Case 4	44.1	18	10	3.3	2.1	0.0272	0.0749	0.4084	0.56
Case 5	67	30	12	4	2.65	0.0201	0.0597	0.4478	0.4
Case 6	95	-	-	4.15	2.3	0.0195	0.0437	-	-
Case 7	60	26	12	4.2	2.7	0.0250	0.0700	0.4333	0.46

Table 3. UK electricity fuel source contributions

Fuel Source	Electricity Supplied (TWh)	Percentage contribution (%)
Coal	135.89	37.60
Oil	2.74	0.76
Gas	98.17	27.17
Nuclear	63.95	17.70
Hydro (natural flow)	5.25	1.45
Wind and Solar	20.78	5.75
Offshore	7.46	2.07
Bioenergy	13.40	3.71
Pumped storage (net supply)	-1.02	-0.28
Other fuels	2.71	0.75
Net imports	12.04	3.33
Total all generating companies	361.36	100

Table 4. Input parameters to the software system

	Hub Height	Blade Length	No. of Blades	Average Wind Speed
	(m)	**(m)**		**(m/s)**
Case Study 1	70	40	3	12
Case Study 2	65	35	3	12
Case Study 3	80	45	3	12

Table 5. Summary of output data

		Case Study 1	Case Study 2	Case Study 3
Overall	**Power Rating (MW)**	2.1	1.6	2.7
	Overall Energy Consumed (GJ)	3,280	2,830	4,250
	Overall Cost (US$ × 10^3)	302	223	410
	Overall Carbon Footprint (t)	217	186	282
Energy Consumed	**Primary Material Production (GJ)**	3,120	2,680	4,060
	Rolling Machine (GJ)	3.2	2.9	3.6
	Sub-section Welding (GJ)	31	29	35
	Section Welding (GJ)	128	115	151
Cost	**Blades (US$ × 10^3)**	103	68	149
	Tower (US$ × 10^3)	95	67	138
	Foundation (US$ × 10^3)	53	46	61
	Hub (US$ × 10^3)	51	43	63
Carbon Footprint	**Primary Material Production (kg)**	213,566	183,730	278,418
	Rolling Machine (kg)	60	55	68
	Sub-section Welding (kg)	587	545	671
	Section Welding (kg)	2,445	2,181	2,867
Mass & Dimensions	**Tower Mass (kg)**	117,993	101,509	153,822
	Top Diameter (m)	2.5	2.4	2.6
	Base Diameter (m)	4.1	4	4.3
	Top Wall Thickness (mm)	12.7	12.4	13.3
	Base Wall Thickness (mm)	27.6	25.9	31.1

Table 6. Comparison of energy, cost and carbon footprint of the manufacturing process

	Case Study			Change	
	1	**2**	**3**	**From Case Study 1 to Case Study 2**	**From Case Study 1 to Case Study 3**
Hub Height (m)	70	65	80	-7.1%	14.3%
Blade Length (m)	40	35	45	-12.5%	12.5%
Power Rating (MW)	2.1	1.6	2.7	-23.4%	26.6%
Manufacturing Energy (GJ)	162	146	190	-10.0%	16.6%
Tower Cost (US$ × 10^3)	95	67	138	-29.2%	45.1%
Manufacturing Carbon Footprint (t)	3.1	2.8	3.6	-10.0%	16.6%