# Development of a Quantitative Analysis System for Greener and Economically Sustainable Wind Farms

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**Abstract**

This paper reports the development of a quantitative analysis system for selecting a greener and economically sustainable wind farm at the early design stage. A single wind turbine produces a limited amount of carbon emissions throughout its lifecycle. By taking a broader view, such as wind farms, collectively such an application would have a greater impact upon the environment and cost. Recent research on wind farms tends to focus on wind flow modelling to enable accurate prediction of power generation. Therefore, this paper presents a quantitative approach to predict a wind farm's lifetime (i) carbon emissions and intensity; (ii) potential energy production; (iii) return on investment and (iv) payback time from an early design perspective. The overall contribution of this work is to develop a quantitative approach to enable the selection of 'greener' designs for reducing the environmental impacts of a wind farm with hub heights between 44 m and 135 m while still considering its economic feasibility assessment. This newly developed system could potentially be used by top-management and engineers of wind turbine manufacturers and wind energy service providers for cleaner energy provision.

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**Highlights:**

- Sustainable wind farm evaluations method for the early design stage is presented.
- A software system is developed to support early design decision in wind farms.
- Wind farm design based on carbon emissions and investment reduction is improved.
- Policy recommendations and implications are proposed for wind farm designers.

**Word count**: 8483

**Keywords:** the early wind farm design stage; cleaner energy; environmental impact reduction; return on investment

**Nomenclature**

| | |
|---|---|
| %C | Percentage of grid electricity produced from coal |
| %NG | Percentage of grid electricity produced from natural gas |
| %P | Percentage of grid electricity produced from petroleum |
| A | Swept area ($m^2$) |
| ag | Age of wind farm (a) |
| C | Rated capacity of wind farm (kW) |
| $Carbon_{payback\ time}$ | Length of time in years to offset the carbon emissions (a) |
| $C_p$ | Coefficient of performance |
| CES | Carbon emission signature ($kgCO_2$/GJ) |
| $CO_{2emissions}$ | Overall $CO_2$ emissions of a wind farm ($kgCO_2$) |
| cA | Assembly and installation costs (GBP) |
| cLL | Land leasing costs (GBP) |
| cOM | Operations and maintenance costs (GBP) |
| cR | Cost of component replacement (GBP) |
| cRC | Cost of roads and civil work (GBP) |
| cT | Cost of transport and installation (GBP) |
| cMT | Cost of manufacturing a wind turbine (GBP) |
| $Cost_{total}$ | Total cost of building and maintaining a wind farm (GBP) |
| D | Rotor diameter (m) |
| $Energy_{transmitted}$ | Energy transmitted to an electrical grid (Wh) |
| $Energy_{windfarm}$ | Energy produced by a wind farm in its life time (Wh) |

| | |
|---|---|
| $Energy_{wind\ turbine}$ | Energy produced by a wind turbine with depreciation factor in its life time (Wh) |
| f | Array efficiency |
| h | Hub height (m) |
| $Income_{total}$ | Total income of a wind farm by the amount of electricity generated over its life time (GBP) |
| k | Shape factor of the Weibull function |
| l | Wind farm length (m) |
| Lifespan | Lifetime of a wind farm in years (a) |
| n | Number of wind turbines in a wind farm |
| $n_l$ | Number of wind turbines in a column |
| $n_w$ | Number of wind turbines in a row |
| P | Power (W) |
| R | Rated power (MW) |
| ROI | Net income of a wind farm over its life time (GBP) |
| Sp | Inter-turbine spacing in a windfarm (m) |
| $Transmission_{eff}$ | Energy transmission efficiency to an electrical grid |
| Total $CO_{2\ emissions\ offset}$ | Carbon emissions offset by the energy transmitted from a wind farm over its life time ($kgCO_2$) |
| $V_r$ | Rated wind speed (m/s) |
| w | Wind farm width (m) |
| $\eta$ | Energy conversion efficiency |
| $\lambda$ | Scale factor of the Weibull function |
| $\rho_a$ | Density of air ($kg/m^3$) |

**Abbreviations**

| | |
|---|---|
| CCL | Climate Change Levy |
| CFD | Computational Fluid Dynamics |
| $CO_2$ | Carbon emissions |
| GBP | British Pound Sterling |
| GHG | Greenhouse gas |
| GUI | Graphical user interface |
| HAWT | Horizontal axis wind turbine |
| LCA | Life cycle assessment |

| | |
|---|---|
| LECs | Levy Exemption Certificates |
| ROI | Return on investment |
| VAWT | Vertical axis wind turbine |
| VBA | Microsoft Visual Basic for Applications |
| VWiS | Virtual Wind Simulator |
| WAsP | Wind Atlas Analysis and Application Program |

## 1. Introduction

In accordance with Lund (2010) and Dovi et al.'s (2009) findings, cleaner environmental technologies offer various benefits such as reduced carbon emissions and cost savings from minimum energy and resource requirements during production and operation. Wind turbines that operate in a wind farm are technologies which are capable of achieving these advantages (Alvarez et al., 2015). As a result, the installation of wind farms across the world has increased to 30% in the past decade (Daim et al., 2012). While wind turbines do not produce many harmful emissions during their normal operation (Guezuraga and Zauner., 2012), nevertheless they can dispense with greenhouse gases (GHGs) at a rate of between 72% and 90% in their lifetime (Weisser., 2007) and especially in the manufacturing stage (Haapala and Prempreeda., 2014; Garrett and Rønde., 2013). For example, Marimuthu and Kirubakaran's (2013) finding concluded that a 1.65 MW wind turbine can emit as much as 394 t of $CO_2$ during its lifetime, therefore, by taking a broader view such as the number of wind turbines in a windfarm, collectively they do contribute to the release of a large amount of GHGs (Arent et al., 2011). For this reason, a system to facilitate wind farm design to reduce these negative environmental impacts while maintaining its potential to become economically sustainable, is necessary. However, benefits such as cost savings, improving the energy and environmental performance can only be achieved with optimum design and development solutions (Yuan et al., 2015). By nature, product development is a complex and influential activity (Cheung et al., 2015b), where decision-making at the design and specification stages of product development are responsible for up to 80% of all environmental (Maxwell and Van der Vorst, 2003) and financial impacts (Cheung et al., 2015a). As stated by Cheung et al. (2015b), although the design stage only constitutes 5% of the total product cost, its influence in design and development stages could contribute up to 75% to 90% of the total lifecycle cost. Therefore, the early design phase is identified as the best opportunity to envisage the performance of a new product or process (Vichare et al., 2014). Another challenge for wind energy development is reduction of cost and this is usually obtained through minimum capital investment. Therefore, a system that can estimate return on investment (ROI) and carbon emissions ($CO_2$) at the early design and development stage will be very useful to both wind turbine manufacturers and wind energy service providers.

Recent research on wind farms tends to focus on wind flow modelling to enable accurate predictions of power generation and fatigue loads. When Crespo et al. (1999) reviewed modelling methods for wind farm wakes, modelling turbines as roughness elements was replaced by more complex Computation Fluid Dynamics (CFD) based models such as UPMPARK and EVFARM. While these provided reasonable estimates of wake effects, the need to model turbulence was highlighted. Barthelmie et al. (2009) stated that existing wind farm models tend to underestimate the power deficit in a wind farm due to wakes whereas CFD models overestimate power deficit. More accurate CFD models exist but require excessive computation, limiting their usefulness with larger wind farms. Frandsen et al. (2009) echo these conclusions, and found that “Wind Atlas Analysis and Application Program” (WAsP) is the preferred program in the industry which can produce accurate results. Barthelmie and Jensen (2010) investigated wake at Nysted wind farm. They found that wakes depend most strongly on wind speed but not wind direction or atmospheric stability and turbulence. WAsP underestimates deep wake effects but produces realistic results for the whole wind farm. Politis et al. (2012) applied flow models to wind farms in complex terrain. The investigated CFD models “CRES-flowNS” and “CFDWake” could accurately predict free wind flow through the terrain but had significantly different results when a wind farm was modelled. Wind farms can be accurately modelled using CFDWake and a blade element momentum solver, but this requires data about the wind turbine, which is not usually known and has a high computational cost. Yang et al. (2015) developed the “Virtual Wind Simulator” (VWiS) to model turbulent flow over a wind farm and verified the results with wind tunnel testing. They found that overall VWiS is an accurate tool for investigating the effect of complex terrain on a wind flow. The estimates have improved by adding artificial simulated turbulence to the inlet flow. VWiS has the same drawbacks as other accurate models, being computationally intensive.

Kusiak et al. (2009) used two data mining algorithms to predict the power for a wind farm based on weather forecasting data. A recent article published by Astolifi et al. (2015) also adopted data mining techniques to analyse the performance of onshore wind farms. The aim of this work is to analyse a wind farm's operational behaviour during its productive cycles and a wind farm's efficiency based on wind directions. They found that the power output of wind farms depends on the mechanical behaviour of wind turbines. Girard et al. (2013) developed an approach to predict the wind power of a wind farm. The method utilised historical data from existing wind farms and the aim of the study was to predict power as a decision factor for future investment of a wind farm. A review of the scale and siting of wind farms in China was undertaken by Deng et al. (2011). They found that the average capacity of wind farms is increasing and complex terrain can limit the size of wind farms due to increased costs. The siting of a wind farm is a complicated process with considerations including planning permission, economic feasibility and wind resource assessment. Liu et al. (2013) focused on offshore wind farms in China. They identified six considerations for wind farm siting: economics, location, grid connection, technological development, environmental suitability and national policy. They concluded that government policy is very important in supporting the wind industry.

TOPFARM is a system which optimises wind farm layout based on cost, power production and fatigue loads, developed by Réthoré et al. (2014). This includes a sophisticated electrical grid connection cost model and the depreciation and replacement costs of components caused by wake-induced fatigue loads. They deployed a multi-fidelity approach to model wind flow which reduces computing costs while maintaining its accuracy. Gao et al. (2014) investigated the potential and feasibility of offshore wind energy in Hong Kong. This research utilised the Multi Population Genetic Algorithm to obtain an optimum wind farm layout. To integrate into this work, they also developed a Wind Farm Power Generation Calculation Tool for estimating a wind farm's power generation after the layout of wind turbines was established. Their approach also took into account the wake effects of all the wind directions and the probability of wind speed. They concluded that the approach could provide an accurate power generation of any given offshore wind farm. Another approach that utilised wind farm layout optimisation was developed by Park and Law (2015). In this method, they deployed a mathematical optimisation scheme to optimise a large number of wind turbines to maximise wind farm power production.

In summary, the trend of wind farm development is towards larger wind farms with more powerful wind turbines. Wind flow is affected by turbine wakes, affecting the power produced by a wind farm. There are a variety of programs available to model wind flow and power, the more sophisticated of these produce very accurate results but require excessive computations. Simpler wind resource assessment tools such as WAsP continue to be favoured by wind farm designers.

There are a variety of wind turbine designs commercially available. These can be divided into two main types: vertical axis wind turbines (VAWTs) and horizontal axis wind turbines (HAWTs). VAWT technology is not as well established and they are not commercially viable when compared to HAWTs (Burton et al., 2011) due to their relatively low power rating (Uddin and Kumar, 2014), therefore, this proposed work only considers large HAWTs as used in commercial wind farms. A distinction must be made between onshore and offshore wind farms since they require a different approach for cost, energy and subsequently GHG emission analysis. The proposed work described in this article is focused on onshore wind farms.

As this work is a continuation of the corresponding authors' previous work (Aso and Cheung, 2015), a number of assumptions are inherited. For example, the structure of the wind turbine is assumed to be a tubular steel tower with a hollow drilled pier foundation. The size of hub heights considered in the study is between 44 m and 135 m so it is recommended that the system is only used within this range. While the previous work by Aso and Cheung (2015) focused on individual wind turbines, a large scale wind farm may consist of several hundred individual wind turbines and cover an extended area of 10 km to 30 km or greater (Brower, 2012). A single wind turbine produces a limited amount of carbon emissions throughout its lifecycle. By taking a broader view, such as wind farms, collectively such an application would have a greater impact upon the environment and cost. The construction of a wind farm requires extensive investment of hundreds of millions of GBP (British Pound Sterling); therefore, a tool and method to aid the concept design and capable of estimating

ROI at this early stage is essential. The proposed analysis system could be extended to provide accurate evaluations of such large scale projects by predicting a wind farm's life-time (i) carbon emissions and intensity; (ii) potential energy production; and (iii) ROI and payback time from an early design perspective. Therefore, the overall contribution of this work is to develop a quantitative approach to enable the selection of 'greener' designs for reducing the environmental impact of a wind farm while still considering its economic feasibility assessment. The remainder of this paper is organised as follows: Section 2 describes the background theory on wind farms; Section 3 discusses the proposed methodology and implementation; Section 4 presents relevant case studies and finally the discussions, policy recommendations and implications, conclusion and future work.

## 2. Relevant Theory on Wind Farms

This section discusses the theoretical background of wind turbines layout; potential energy output; carbon emissions; cost modelling and return on investment of a wind farm.

### *2.1 Arrangement of wind turbines on a wind farm*

The arrangement of wind turbines in a wind farm depends on many situations and typically involves complex calculations with specialist software following at least a year of gathering wind data from a site. This proposed analysis system is intended to provide comparisons independent from site specific conditions, such as wind turbulence intensity, so a simple rule for spacing wind turbines is required. Brower (2012) suggests wind turbines should be 3 to 4 rotor diameters apart in the crosswind direction and 6 to 10 rotor diameters apart in the prevailing wind direction to reduce wake effects. Crespo et al. (1999) found that significant wake effects disappeared between 7 to 9.5 rotor diameters downstream. Barthelmie and Jensen's (2010) research findings proposed that there is a 1.3% loss in efficiency with every rotor diameter closer together that HAWTs are placed. Builtjes and Smith (1978) and Milborrow and Surman (1987) agreed that 3 rotor diameters is the minimum distance regardless of wind direction. Taking the average of Brower's (2012) figures, the distance between wind turbines is calculated as 3.5 rotor diameters in the crosswind direction and 8 rotor diameters apart in the prevailing wind direction.

*2.2 Calculation of power generated by wind turbines in a wind farm*

The power generated by a wind turbine is given by Burton (2011).

$$P = \frac{1}{2} \times C_p \times \rho_a \times A \times V_r^3 \tag{1}$$

Where:

$P$ = Maximum power output (W)
$C_p$ = Coefficient of performance
$\rho_a$ = Air density (kg/m$^3$)
$A$ = Swept area (m$^2$)
$V_r$ = Rated wind speed (m/s)

It is widely accepted that the useful energy which can be extracted from the wind has a maximum efficiency of 59.3% (Betz, 1966) and the actual coefficient of performance “$C_p$” is lower, typically around 70% of the Betz limit. The British Standard for wind turbine design requirements (BS EN 61400-1:2005+A1:2010) states that the air density “$\rho_a$” should be taken as 1.225 kg/m$^3$.

A wind turbine’s power rating is calculated using equation (1) at a rated wind speed $V_r$. Rated wind speed values are specific to wind turbine manufacturers and considered confidential, so an empirical method is used to determine the default value and the user has the option to input their own $V_r$. Currently, HAWTs are generally assumed to have a lifespan of 20 years (Gonçalves da Silva, 2010; Chen et al., 2015). This value is required to calculate a wind farm’s lifetime energy generation and ROI. Hughes (2012) suggests that 10 to 15 years would be more realistic because after this time, replacing or repowering wind turbines becomes more economical than to perform continued maintenance. Although most wind turbine manufacturers quoted longer lifespans, maintenance packages tend to last for 15 years at the most (Renewables First, 2014; Enercon, 2010). In contrast, the Department of Energy and Climate Change assume a wind turbine has a lifespan of 25 years (Hughes, 2012). The default lifespan used in this proposed analysis system is assumed to be 20 years as suggested by Gonçalves da Silva (2010) and Chen et al. (2015).

The air flowing through the swept area of a wind turbine loses energy and wake effects are observed which affect wind turbines downstream. The British Standard for wind turbine design requirements states that these wake effects must be considered when designing a wind farm (BS EN 61400-1:2005+A1:2010, 2006). The energy loss can be quantified by the array efficiency as shown in equation (2) (World Wind Energy Platform, 2014). The array efficiency f can be calculated using equation (3) (Milborrow and Surman, 1987; Barthelmie and Jensen, 2006).

$$\text{Array efficiency} = \frac{\text{Energy produced by a wind farm}}{\text{Energy produced by the same number of isolated HAWTs}} \tag{2}$$

$$f = (1/n)^{0.03} \tag{3}$$

Where:

f = Array efficiency
n = Number of wind turbines in a wind farm
0.03 = The value of decay coefficient

Tremeac and Meunier (2009) indicated that transmission losses are normally 1%. This is supported by Guezuraga et al. (2012) who also used 1% for calculating energy output to cover operational consumption. As a result of this argument, this work assumed that the energy produced by a wind farm could be transmitted into an electrical grid with 99% efficiency. Wind turbines are not available for normal operation all the time due to breakdowns and scheduled maintenance. The availability can be expressed as a percentage of the time that a wind turbine is available to produce power, given the correct wind conditions. Enercon (2010) guarantee to their customers a service availability of 97% through their service package so this value is taken as a reasonable assumption for availability.

Grid curtailment occurs when a restriction is imposed on the number of wind turbines operating in a wind farm or on their output. Curtailment is difficult to predict and can be a source of error in energy calculations. Burke and O'Malley (2011) investigated the curtailment of wind energy in the Irish grid and found highly variable curtailment values between 1.86% to 18.27%. Brower (2012) summarised energy production losses according to the type of wind turbines and gave a typical curtailment loss of 0% which means curtailments can be disregarded from energy calculations.

Hughes (2012) reported on the depreciation of wind turbine performance with age and concluded that the load factor reduces significantly as the wind farm ages. This depreciation could be factored into the energy calculations of the proposed analysis system. The approach is not commonly used for calculating the energy produced in a wind farm so the user may omit the effect of the load factor.

*2.3 Carbon emissions and carbon intensity*

The percentage of electricity supplied from different sources in the UK is summarised in Table 1 (DECC, 2014). This can be used to calculate the $CO_2$ emissions associated with every unit of supplied energy with the carbon emission signature (CES) by using the following equation (Jeswiet and Kara, 2008):

$$\text{CES} = \frac{\eta \times [112 \times \%C + 49 \times \%NG + 66 \times \%P]}{100} \tag{4}$$

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

Table 1. UK Energy Supply (DECC., 2014)

| Energy type | Production (TWh) | % |
|---|---|---|
| Coal | 124.06 | 35.27 |
| Oil | 1.94 | 0.55 |
| Natural Gas | 93.80 | 26.67 |
| Other sources | 131.96 | 37.51 |
| Total | 351.76 | 100 |

The carbon emitted in kg is equal to the energy in GJ multiplied by the CES. The climate change mitigation effect of a wind farm can be quantified by the mass of $CO_2$ which would have been emitted had the power produced over the lifetime of the wind farm have been produced using the current UK grid energy mix. This approach is used by Marimuthu and Kirubakaran (2013) in their life cycle assessment (LCA) and is supported by Weisser (2007) in lifecycle emissions of power technologies. The efficiency is commonly quoted as 0.34 (Jeswiet and Kara, 2008). By using equation (4) the CES of National Grid is equal to18 $kgCO_2/GJ$. This shows that 18 kg of $CO_2$ is emitted per GJ of energy consumed.

Carbon intensity is widely used as a measure of the environmental impact of a wind turbine. It is the $CO_2$ emitted by the manufacturing and decommissioning of the wind turbine per unit of energy generated and this is commonly given as g/kWh (Marimuthu and Kirubakaran, 2013; Weisser, 2007):

$$\text{Carbon intensity} = \frac{CO_2\text{emissions over life}}{\text{Energy produced over life}} \tag{5}$$

Where:

Carbon intensity = Environmental impact of a wind turbine ($gCO_2/kWh$)
$CO_2$emissions over life = Carbon emissions emitted by manufacturing and decommissioning processes of a wind turbine in its lifetime ($gCO_2$)
Energy produced over life = Energy generated by a wind turbine in its lifetime (kWh)

*2.4 Cost modelling of return on investment of a wind farm*

The costs of a wind farm can be broken down into initial capital costs and annual operating expenses. The initial capital costs are:

i. the cost of wind turbine manufacture (as calculated by Aso and Cheung (2015) using a combination of cost estimation relationships);
ii. material cost scaling;
iii. the cost of roads and civil works;
iv. the cost to transport the wind turbine to the site, and
v. the cost of assembly and installation.

Annual operating expenses include the cost of component replacements, operation and maintenance costs and land lease costs. Fingersh et al. (2006), developed a cost model for each of these cost components as summarised in equations (6-11). Since the cost model is measured in US$, therefore an exchange rate mechanism has been implemented to convert US$ into GBP.

$$cRC = (2.17\times10^{-6}\times R^3) - (0.0145\times R^2) + (69.54\times R) \tag{6}$$

$$cT = (1.581\times10^{-5}R^3) - (0.0375\times R^2) + (54.7\times R) \tag{7}$$

$$cA = 1.965 \times (h \times D)^{1.1736} \quad (8)$$

$$cR = 10.7 \times R \times Lifespan \quad (9)$$

$$cOM = 0.007 \times Energy_{transmitted} \quad (10)$$

$$cLL = 0.00108 \times Energy_{transmitted} \quad (11)$$

Where:

cRC = Cost of roads and civil work (GBP)
cT =Cost of transport (GBP)
cA = Cost of assembly and installation (GBP)
cR = Cost of component replacement (GBP)
cOM = Cost of operation and maintenance (GBP)
cLL = Cost of land leasing (GBP)
R = the rated power of a wind turbine (MW)
h = the hub height (m)
D = the rotor diameter (m)
Lifespan = Lifetime of a wind farm in years (a)
$Energy_{transmitted}$ = Energy transmitted to an electrical grid (Wh)

The income that can be generated by a wind farm comes from three components: the "Feed-in Tariff"; export value and renewable Levy Exemption Certificates (LECs) (Renewables First, 2014a). The largest is the "Feed-in Tariff" which is paid on electricity produced. The "Feed-in Tariff" is more generous for smaller wind farms to enable smaller projects and investments to be economically viable. The current rate is shown in Table 2.

Table 2. Feed-in Tariff for Wind Energy (Renewables First, 2014a)

| Capacity of wind farm | Feed-in Tariff (p/kWh) |
|---|---|
| 15 kW to 100 kW | 17.32 |
| 100 kW to 500 kW | 14.43 |
| 500 kW to 1.5 MW | 7.83 |
| 1.5 MW to 5 MW | 3.32 |

The export value is the price of the electricity sold to the electrical grid. This is negotiable so tends to favour larger wind farms. There is a guaranteed minimum export value of 4.5 p/kWh under the "Feed-in Tariff" which is used by this proposed analysis system (Renewables First, 2014a). The final component of the income is renewables LECs. These are issued by Ofgem to generators of renewable energy such as wind farms and are then sold on with the electricity to claim exemption from the Climate Change Levy (CCL) (Excise Notice CCL1/4, 2014). These LECs are worth 0.507 p/kWh but are subject to a 90% administration fee when sold, so the net income they produce is equivalent to 0.456 p/kWh (Renewables First, 2014a).

The ROI of a wind farm is the net income from the wind farm and this can be calculated as the gross income minus the total costs of a wind farm project. The payback time is the time required for the amount invested in an asset to be repaid by the net cash outflow generated by the asset, typically given in years (Renewables First, 2014b). By adopting Taillard's (2012) payback method, the payback time of a wind farm per year can be expressed in equation (12), and, in general, large scale wind farms have payback times of up to three years (Renewables First, 2014b).

$$\text{Payback time} = \frac{\text{Total cost of the wind farm}}{\text{Income from the wind farm per year}} \tag{12}$$

Where:

Payback time = Time to produce the amount of energy required to offset the cost of making and maintaining a wind farm over its life time (a)
Total cost of the wind farm = Total cost of building and maintaining a wind farm over its lifetime (GBP)
Income from the wind farm per year = Total income of a wind farm per year by the amount of electricity generated (GBP)

## 3. The proposed methodology and implementation

The method of evaluation of wind turbine and wind farm early design concepts is shown in Fig. 1. The analyses are based on four basic input parameters: hub height, blade length, wind farm length and wind farm width. Subsections 3.1 to 3.8 (as indicated in Fig. 1) discuss the detailed implementation of each of the attributes. The software system was implemented in Microsoft Excel's Visual Basic for Applications (VBA) which is highlighted in Section 3.9 and the supplementary material.

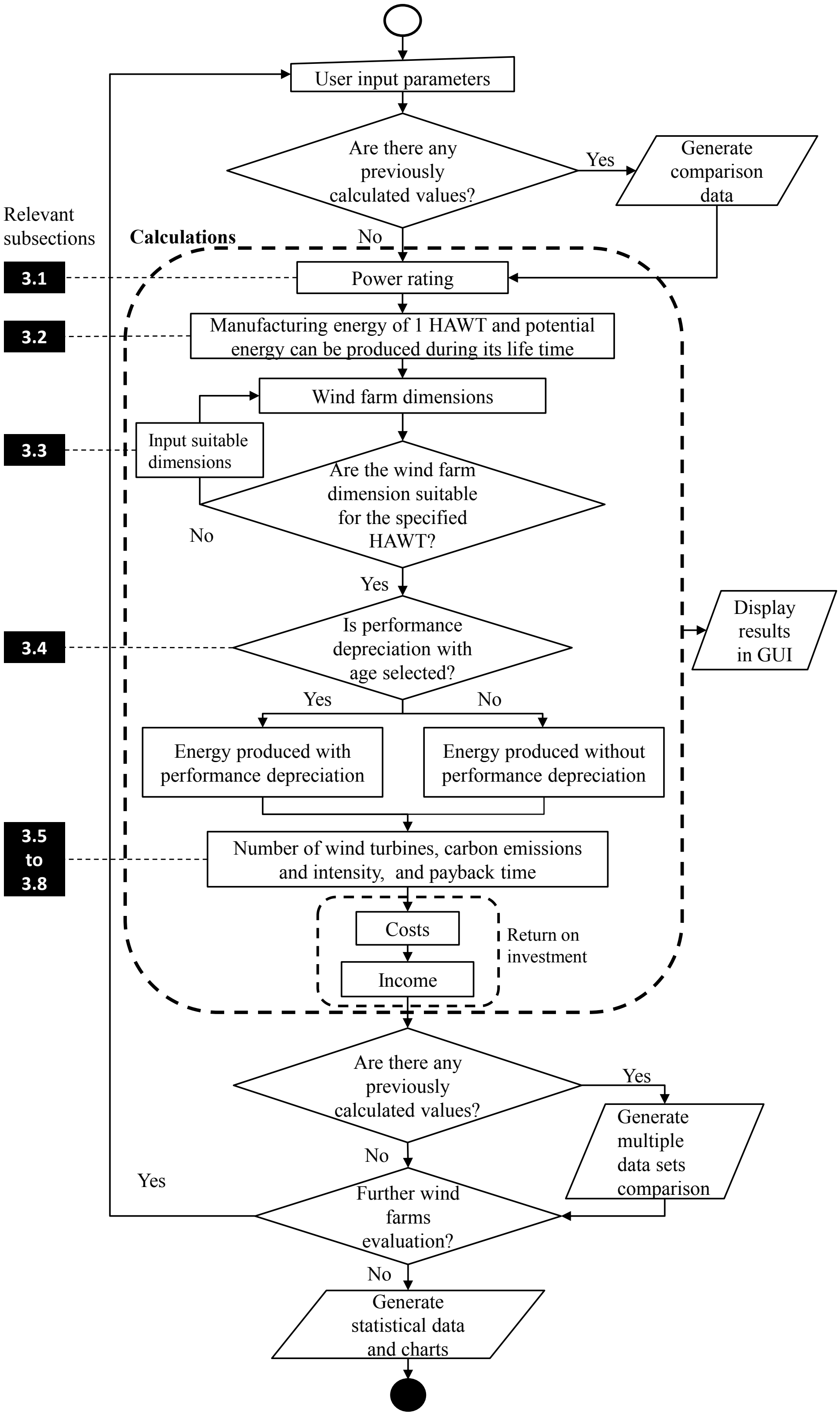


Fig. 1. Algorithm of the Quantitative Analysis System

### 3.1 Power rating

The original system developed by Aso and Cheung (2015) evaluates power rating using the average wind speed in equation (1); this is improved in this proposed work by introducing the reference wind speed "$V_r$". An iterative method was used to find the default "$V_r$". For example, the power rating for each of the rotor diameters as shown in Table 3 was calculated using equation (1) with a variable wind speed. This wind speed was changed until the average difference between quoted power ratings and calculated power ratings was at its minimum which is 10.4 m/s.

Table 3. Example rotor diameter VS power rating (Renewables First, 2014b)

| Manufacturer | Rotor Diameter (m) | Rating (MW) | Wind Speed (m/s) |
|---|---|---|---|
| Vestas | 100 | 1.80 | 6.0 – 7.5 |
| Vestas | 90 | 1.80 | 6.0 – 12.0 |
| Vestas | 90 | 1.82 | 6.0 – 12.0 |
| Vestas | 110 | 2.0 | 6.0 – 8.5 |
| Vestas | 100 | 2.0 | 7.5 – 12.0 |
| Vestas | 90 | 2.0 | 6.0 – 12.0 |

### 3.2 Energy

This work has adapted the method developed by Aso and Cheung (2015) of calculating the energy required for producing a single wind turbine. Therefore, the overall energy used by a wind farm is simply the energy used to manufacture one wind turbine multiplied by the number of wind turbines.

The energy that can be produced by a wind turbine during its lifetime is described as follows. The wind speed is split into bins of 1 m/s, each with a probability of occurrence given by the Weibull function. Using VBA through Microsoft Excel enables the use of the worksheet function WEIBULL.DIST with the inputs k= 2 and λ= annual average wind speed in m/s. The power is calculated for each wind speed bin using equation (1). This is converted into a partial power by multiplying by the probability of occurrence of that bin. The total power of the wind turbine is the sum of the partial powers.

The energy produced by the wind turbine is simply "power multiplied by time" as shown in equation (13). The energy produced is given in Wh so the lifetime is multiplied by 8766 (the average number of hours in a year (Year, 2016) and the availability of 0.97 (Enercon, 2010).

$$Energy_{wind\ turbine} = P \times Lifespan \times 8766 \times 0.97 \qquad (13)$$

Where:

$Energy_{wind\ turbine}$ = Energy produced by a wind turbine in its lifetime (Wh)
P = Potential power of a wind turbine (W)
Lifespan = Lifetime of a wind turbine in years (a)
The average number of hours in a year = 8766 (h)
Availability of a wind turbine = 0.97

*3.3 Wind farm dimensions*

The maximum number of wind turbines in a wind farm is calculated by equation (14) (Brower, 2012).

$$n = n_w \times n_l \qquad (14)$$

Where:

n = Number of wind turbines in the wind farm
$n_w$ = Number of wind turbines in a row
$n_l$ = Number of wind turbines in a column

The number of wind turbines in a given area is a function of the rotor diameter (D) which is calculated as twice the blade length. The number of wind turbines in a row (equation 15) and in a column (equation 16) of a wind farm are suggested by Crespo et al., (1999) and Brower (2012), where "Sp" is the spacing, 8 rotor diameters in the prevailing wind direction and 3.5 rotor diameters across the main wind direction.

$$n_w = 1 + \frac{(w - 20 \times D)}{(Sp \times D)} \qquad (15)$$

Where:

w = Wind farm width (m)
D = Rotor diameter (m)
$n_w$ = Number of wind turbines in a row

Sp = Inter-turbine spacing of 8 rotor diameters (m)

$$n_l = 1 + \frac{(l - 20 \times D)}{(Sp \times D)} \tag{16}$$

Where:

l = Wind farm length (m)
D = Rotor diameter (m)
$n_l$ = Number of wind turbines in a column
Sp = Inter-turbine spacing of 3.5 rotor diameters (m)

*3.4 Wind farm performance depreciation*

This proposed work has to take into consideration the potential depreciation of a wind farm. The relationship between the age of a wind farm and the load factor can be defined using data from Hughes' report as shown in Fig. 2 (Hughes, 2012).

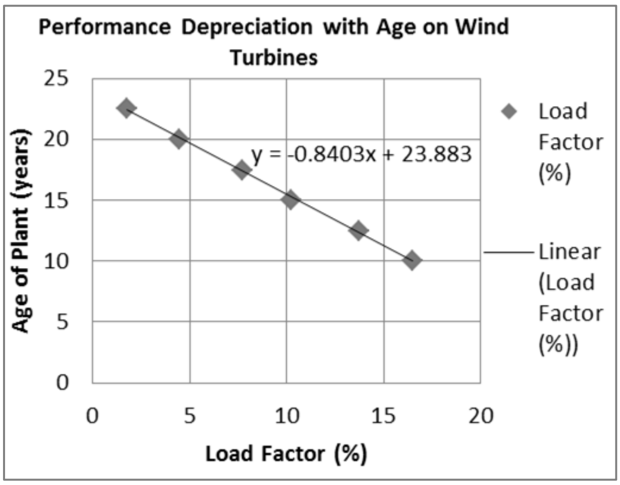


Fig. 2. Age of Plant vs Load Factor

The gradient shown in Fig. 2 represents the decline of a wind turbine in energy production for each year. The depreciation factor for each year of a wind farm's life is calculated using equation (17); where "ag" is the age of a wind farm. The final depreciation factor is the value when "ag" is equal to the lifespan of a wind farm.

$$\text{Depreciation Factor}_{ag} = \text{Depreciation Factor}_{ag-1} \left(1 - ag \times 0.008403\right) \times (1 - \text{Lifespan}) \tag{17}$$

Therefore, the total energy produced by a wind turbine is simply multiplying the energy from equation (13) by the depreciation factor. The energy produced by a wind farm is determined using equation (18) where "f" (array efficiency) is estimated using equation (3).

$$\text{Energy}_{\text{wind farm}} = (\text{Energy}_{\text{wind turbine}} \times \text{Depreciation Factor}_{ag}) \times n \times f \tag{18}$$

Where:

$\text{Energy}_{\text{windfarm}}$ = Energy produced by a wind farm in its life time (Wh)
$\text{Energy}_{\text{wind turbine}}$ = Energy produced by a wind turbine in its lifetime multiply by the depreciation factor (Wh)
n = Number of wind turbines in a wind farm
f = Array efficiency

A careful distinction must be made between the energy produced and the energy transmitted from the site. The energy transmitted to an electrical grid is the energy produced multiplied by the transmission efficiency of 0.99 (see equation 19). The energy produced per year and per wind turbine is calculated from the total transmitted energy (as explained in section 2.2).

$$\text{Energy}_{\text{transmitted}} = \text{Energy}_{\text{windfarm}} \times \text{Transmission}_{\text{eff}} \tag{19}$$

Where:

$\text{Energy}_{\text{transmitted}}$ = Energy transmitted to an electrical grid (Wh)
$\text{Energy}_{\text{windfarm}}$ = Energy produced by a wind farm in its life time (Wh)
$\text{Transmission}_{\text{eff}}$ = Energy transmission efficiency with a rate of 0.99

*3.5 Costs*

The total cost of the wind farm is determined using equation (20). "cMT" is the cost of manufacturing a single wind turbine (Aso and Cheung, 2015). "cT" is the cost of transportation. "cRC" is the cost of roads and civil work. "cR" is the cost of replacing components. "cA" is the cost assembly and installation of the wind turbines. "cOM" is the operations and maintenance cost and "cLL" is the land leasing cost (See Section 2.4, equations (6) to (11)). An exchange rate mechanism is used to convert US$ into GBP.

$$Cost_{total} = n\,(cT + cR + cMT + cA) + cOM + cRC + cLL \qquad (20)$$

Where:

$Cost_{total}$ = Total cost of building and maintaining a wind farm (GBP)
n = Number of wind turbines in a wind farm

*3.6 Total Income of a wind farm*

The total income from a wind farm is made up of the “Feed-in Tariff” (see Table 2, Section 2.4). The maximum capacity “C” is the sum of the rated powers of each wind turbine in a wind farm. Therefore, the income generated by a wind farm from each kWh of $Energy_{transmitted}$ (equation 17) is shown in Table 4.

Table 4: Income per kWh of Transmitted Energy (Renewable First, 2014a)

| Maximum Capacity (kW) | Income (p/kWh) |
|---|---|
| $15 \leq C < 100$ | 22.276 |
| $100 \leq C < 500$ | 19.386 |
| $500 \leq C < 1500$ | 12.786 |
| $1500 \leq C < 5000$ | 8.276 |

*3.7 Return on investment and payback time*

ROI is the net income from a wind farm over its lifetime and is simply given as:

$$ROI = Income_{total} - Cost_{total} \qquad (21)$$

Where:

ROI = Return on investment of a wind farm over its life time (GBP)
$Income_{total}$ = Total income of a wind farm by the amount of electricity generated over its life time (GBP)
$Cost_{total}$ = Total cost of building and maintaining a wind farm (GBP)

As defined in equation (12) (Taillard, 2012), the investment payback time of a typical wind farm during its lifespan in years can be determined as:

$$\text{Payback}_{time} = \frac{(\text{Cost}_{total} \times \text{Lifespan})}{\text{Income}_{total}} \qquad (22)$$

Where:

$\text{Payback}_{time}$ = Time to produce the amount of energy required to offset the cost of making and maintaining a wind farm over its life time (a)
$\text{Cost}_{total}$ = Total cost of building and maintaining a wind farm (GBP)
Lifespan = Lifetime of a wind farm in years (a)
$\text{Income}_{total}$ = Total income of a wind farm over its life time as a result of the amount of electricity generated (GBP)

*3.8 Carbon footprints*

The previous work by Aso and Cheung (2015) is capable of evaluating the carbon footprint of one wind turbine only. For the overall $CO_2$ emissions of a wind farm, this value is simply multiplied by the number of wind turbines in a wind farm "n" (i.e. $CO_2$ emissions = CES x n). The carbon intensity is determined using equation (5) (Section 2.3). The $CO_2$ emissions offset by the energy transmitted from a wind farm are calculated using the CES of the UK power grid: 18 $kgCO_2/GJ$ (equation (4). The energy transmitted by the wind farm is calculated in Wh and must be "converted to GJ" by multiplying with $3.6 \times 10^{-6}$. The total $CO_2$ emissions offset of a wind farm is therefore given as:

$$\text{Total } CO_{2\,\text{emissions offset}} = (\text{Energy}_{\text{transmitted}} \times 3.6 \times 10^{-6}) \times \text{CES} \qquad (23)$$

Where:

Total $CO_{2\,\text{emissions offset}}$ = Carbon emissions offset by the energy transmitted from a wind farm over its life time ($kgCO_2$)
$\text{Energy}_{\text{transmitted}}$ = Energy transmitted to an electrical grid (Wh)
CES = 18 $kgCO_2/GJ$

The carbon payback time is the length of time in years to offset the carbon emissions released over the lifetime of the wind farm. It is given as (Marimuthu and Kirubakaran, 2013):

$$\text{Carbon}_{\text{payback time}} = \frac{(CO_{2\,\text{emissions}} \times \text{Lifespan})}{\text{Total } CO_{2\,\text{emissions offset}}} \qquad (24)$$

Where:

$\text{Carbon}_{\text{payback time}}$ = Length of time in years to offset the carbon emissions (a)

Lifespan = Lifetime of a wind farm in years (a)
$CO_{2emissions}$ = Overall $CO_2$ emissions of a wind farm ($kgCO_2$)
Total $CO_{2emissions\ offset}$ = carbon emissions offset by the energy transmitted from a wind farm over its life time ($kgCO_2$)

*3.9 The software system developed*

The software system implemented is shown in Fig. 3. The basic required inputs are material, hub height and blade length. The user may choose to input the length and width of a wind farm or just to evaluate a single wind turbine. The average annual wind speed has a default value of 12 m/s.

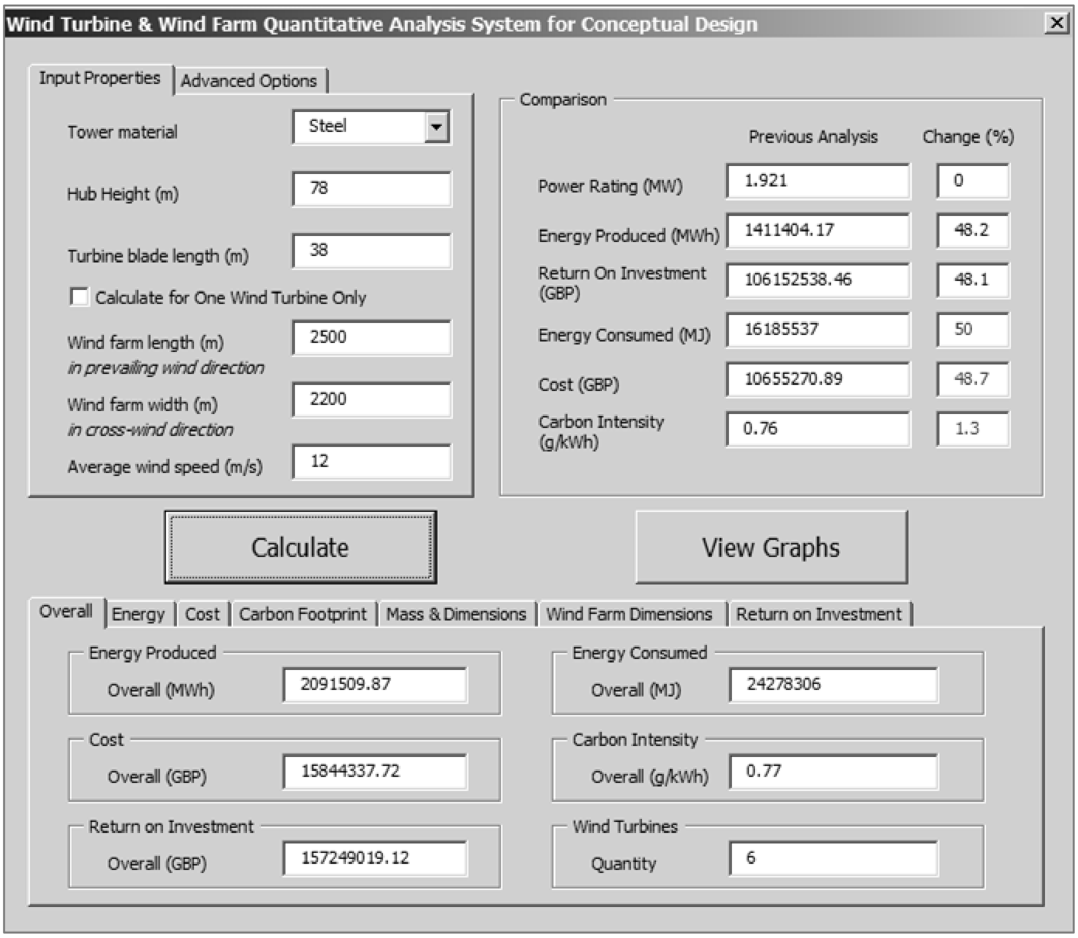


Fig. 3. The Graphical User Interface of the quantitative analysis system

The advanced options input tab is shown in Fig. 4 where the user can change the reference wind speed, lifespan, exchange rate and performance depreciation.

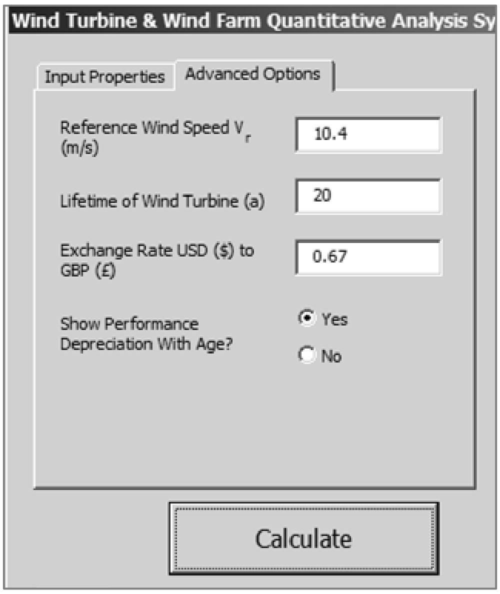


Fig. 4. Advanced options

When the “Calculate” button is selected, the system performs an evaluation and the results will be displayed in the Graphical User Interface (GUI). The first tab provides a summary of the most important measures of wind farm performance, economics and carbon emissions. The other tabs provide more detailed results about each section and these are shown in the attached supplementary material. When the inputs are changed and the “Calculate” button is selected again, the previous values will be stored into the comparison box. The new results and their differences in percentage will be determined. This allows the user to easily identify positive or negative changes. When the “View Graphs” button is selected a summary of the current and previous results will be displayed into a spreadsheet as shown in Fig. 5. Further evaluation can be added into the same statistical chart and hence multiple evaluations can be performed and compared.

| | Parameter set 1 | Parameter set 2 |
|---|---|---|
| Power Rating (kW) | 1455 | 1753 |
| Energy Produced (GWh) | 1242.97199 | 1497.334 |
| Return on Investment (GBP x10^5 | 940.2507085 | 1132.636 |
| Energy Consumed (MWh) | 3371.986944 | 3542.138 |
| Cost (GBP x10^4) | 884.329122 | 1065.58 |
| Carbon Intensity (g/Wh) | 650 | 570 |
| | | |
| | | |
| Hub height (m) | 78 | 80 |
| Turbine blade length (m) | 41 | 45 |
| Wind farm length (m) | 2000 | 2000 |
| Wind farm width (m) | 2500 | 2500 |
| Average wind speed (m/s) | 12 | 12 |

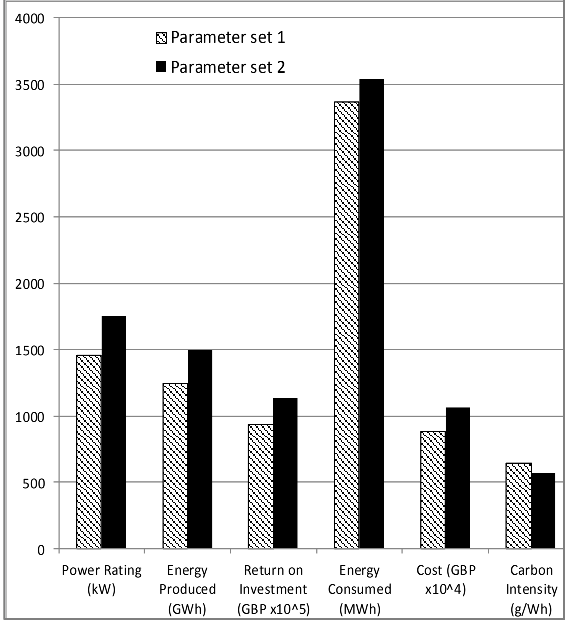


Fig. 5. Statistical comparison

## 4. Case studies demonstration

Three hypothetical wind farms were analysed using the quantitative analysis system developed. The available size of the wind farm was assumed to be constant for all three cases at 2.5 km by 2.5 km. The evaluation assumes that all wind turbines within the three hypothetical wind farms were operated twenty four hours per day. This is a reasonable assumption because breakdowns and maintenance of wind turbines are covered by the 97% availability, and the probability of low wind conditions affecting power output is included in the energy calculations. Sizes of different wind turbines and average wind speed were adapted from Aso and Cheung's (2015) case studies and the input data are summarised in Table 5.

Table 5. Demonstration case studies

| | Hub Height (m) | Blade Length (m) | Average Wind Speed (m/s) | Wind Farm Length (m) | Wind Farm Width (m) |
|---|---|---|---|---|---|
| Case Study 1 | 70 | 40 | 12 | 2,500 | 2,500 |
| Case Study 2 | 65 | 35 | 12 | 2,500 | 2,500 |
| Case Study 3 | 80 | 45 | 12 | 2,500 | 2,500 |

A screen shot of the demonstration is shown in Fig. 6 which presents the estimation of payback, energy and environmental impact of three hypothetical wind farms over their service life. The case studies were evaluated by taking into consideration the load factor depreciations with a 20 year service life. "$V_r$" was 12 m/s to maintain consistency with Aso and Cheung's (2015) case studies and the results are shown in Table 6.

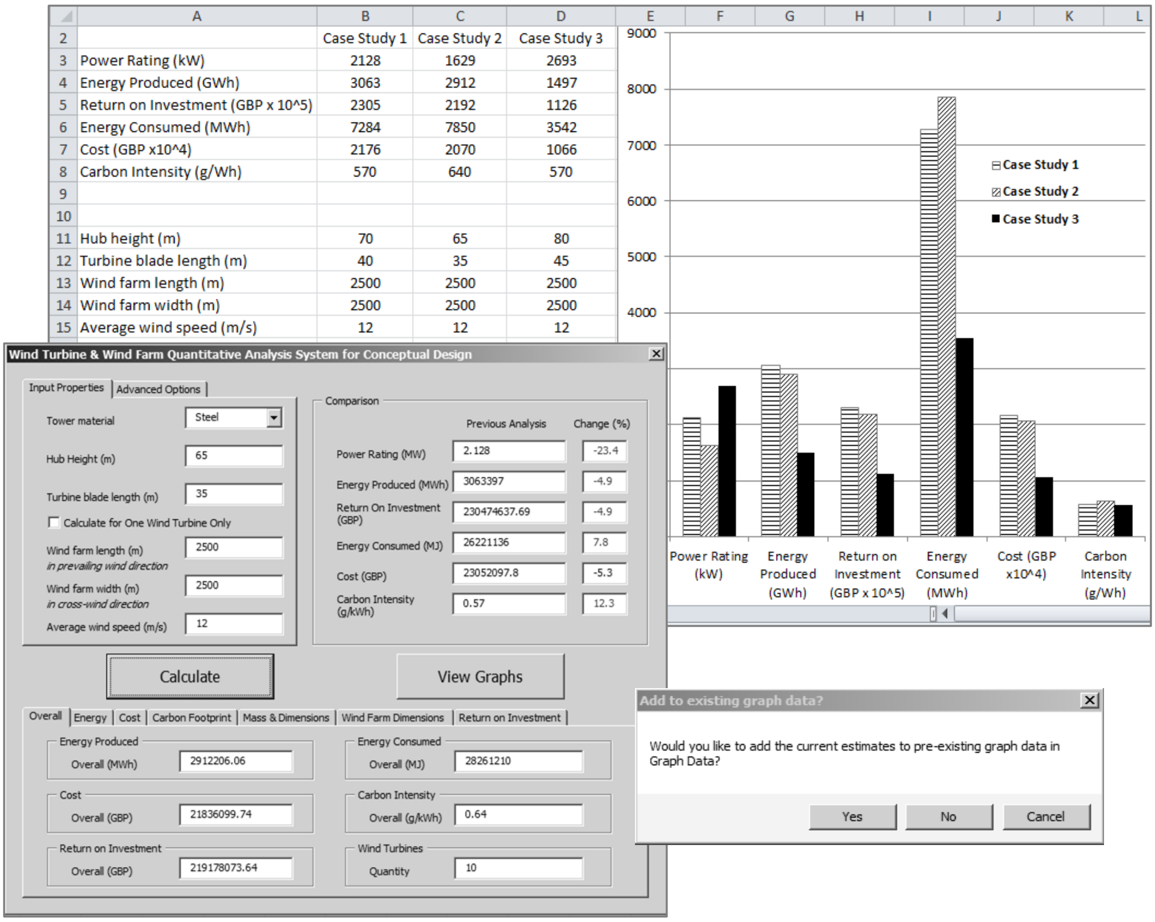


Fig.6. Case studies demonstration

Table 6. Demonstration case studies result

| | Case Study 1 | Case Study 2 | Case Study 3 |
|---|---|---|---|
| Power Rating (MW) | 2.13 | 1.63 | 2.69 |
| Number of Wind Turbines | 8 | 10 | 3 |
| Potential Lifetime Energy produced (GWh) | 3063 | 2912 | 1497 |
| Potential Lifetime Return-on-Investment (GBP x $10^6$) | 230 | 219 | 113 |
| Potential Lifetime Carbon Emission (t) | 1733 | 1865 | 846 |
| Potential Lifetime cost (GBP x $10^6$) | 23.1 | 21.8 | 11.4 |
| Potential Payback Time (a) | 2 | 2 | 2 |
| Wind Farm Life time (a) | 20 | 20 | 20 |
| Carbon Intensity (g/kWh) | 0.57 | 0.64 | 0.57 |

The main influence on energy produced, carbon emissions, cost and ROI is the number of wind turbines in a wind farm. The results from case studies 1 and 2 are alike because they have a similar number of wind turbines. Even though the wind turbine in case study 1 has a smaller swept area than case study 3, power production is more than doubled due to the greater number of wind turbines in the wind farm. This directly influences the ROI, meaning that the biggest wind turbine is not always the best. Installing eight 2 MW wind turbines, as in case study 1, is the most cost effective option because it has generated the highest ROI. The project budget may constrain the design because case study 1 does require higher capital and operational costs.

From an environmental point of view, case study 3 has the lowest carbon emissions. When deciding which design is 'greener' the electricity produced must also be considered. Looking at the carbon intensities of energy, case study 2 does not produce enough electricity to offset its higher carbon emissions. Case studies 1 and 3 have similar carbon intensities so they would have the same environmental impact. Carbon intensity and ROI must be balanced in order to select an optimum design. Of the three scenarios considered, case study 1 is the best, having the lowest carbon intensity and highest ROI.

## 5. Discussion, policy recommendations and implications

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, ROI and carbon emissions of a wind turbine or a wind farm. Selecting the right design concept may lead to minimising carbon footprints whilst also reducing capital investment and energy used in manufacturing, and maximising the energy output of a wind turbine or a wind farm. The approach allows wind energy service providers and wind turbine manufacturers to make design decisions at the early design stage without spending too much time and effort prior to the next phase of a fully-detailed wind turbine and wind farm design. The cost and carbon emission models are based on three-bladed HAWTs so it is uncertain how accurate the results would be for HAWTs with less or more than three blades.

The result of this study illustrates the importance of evaluating wind farm designs at the early development stages and therefore a number of policy recommendations and implications can be made based on this study:

- This proposed method is only used at the early design stage of comparing multiple standalone wind turbines or wind farm designs. The system developed is used on large scale HAWTs with hub heights between 44 m and 135 m. Therefore, the assessment aspects should be based on this recommended boundary for the core of the design decision-making process.
- The recommended noise exclusion zone lengths are measured from the wind turbine to the nearest noise sensitive neighbour such as a house. The size of the noise exclusion zone is as accurate as can be obtained without knowing the noise intensity of the specified wind turbine at ground level. This noise exclusion zone is used to set apart wind turbines within a wind farm and this allocation is measured from the edge of the site. In reality, this zone may cover less of the site area if there is no noise sensitive neighbour at the site's edge, allowing more wind turbines to be installed. If there is a noise sensitive building within the wind farm such as an office, this will have its own noise exclusion zone and hence this will reduce the area of the site with less wind turbines being installed.
- This proposed approach could support wind farm designers to curb $CO_2$ emissions as set out by regional or national renewable energy policy makers, for example, the UK government (Module 3, 2016). By using this method, wind farm

designers could synchronously assess multiple wind farms at the early design stage by comparing their potential energy outputs, $CO_2$ emissions and ROIs.

- Planning policy is an important part of wind farms development and hence, this approach could help to obtain onshore wind farm planning permission decisions more quickly due to the rapid evaluation capability of the system developed.
- Wind farm development requires a large initial investment and the proposed method could potentially support wind farm designers to estimate an appropriate up-front cost for the lifetime of a wind farm and therefore allow wind farm designers to avoid costs incurred as a result of wind farm planning delays.

## 6. Conclusions and future work

The system developed provides rapid estimation of the income, ROI and payback time, energy produced and carbon emissions, carbon intensity of energy and carbon payback time. This system presents not only the carbon emitted during the life cycle of a wind farm, but also quantifies the carbon saved through operation of a wind farm. Furthermore, the system can be used to choose a wind turbine at the early stage of designing a wind farm using various site dimensions, wind speeds and wind turbine dimensions. This allows the evaluation of different wind turbine and wind farm concepts with the (i) greatest ROI; (ii) energy produced; (iii) lowest carbon and (iv) payback time.

A direct comparison with other wind farm research to evaluate the four attributes as proposed by this study is difficult due to fact that this study employs the development of a quantitative software approach. The closet studies available in the literature for comparison are Kabir et al. (2012) and Ardente et al. (2008), however, both studies used the LCA technique to measure existing wind farms with small scale wind turbines (100 kW and 660 kW) and are focused on energy requirement and environmental impact analyses. Furthermore, LCA requires detailed and historical data to measure existing wind farms' performances which is difficult at the early design stage when there is very little concrete information and data available (Cheung et al., 2011). Nevertheless, the advantages of the LCA approach do come with uncertainty analysis and ecological footprint evaluation (Tait and Cheung, 2016).

The authors accept that there are limitations in this study. Within this work the authors have proposed the following for further investigations: (i) the system developed assumes that all wind turbines within a hypothetical wind farm operate (or the wind blows) twenty four hours per day. Future work should include an additional option in the software system to allow users to define the average hours a wind farm could operate per day. (ii) Consideration of wake effects of a wind farm so that a more realistic result could be obtained. (iii) The impacts of carbon footprints and costs of both the civil works of substation, and medium-voltage and transport lines could be included in the software system to make the analysis more comprehensive. (iv) Uncertainty is one of the characteristics of the real world. Uncertainty is a topic that could be applied to the parameters (Matthews, 2011) and, thus, this could enhance the result in the design decision.

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## CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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**Appendix - Further Graphical User Interfaces are shown in Fig. A1 – A7**

**Fig. A1 – Overall Tab**

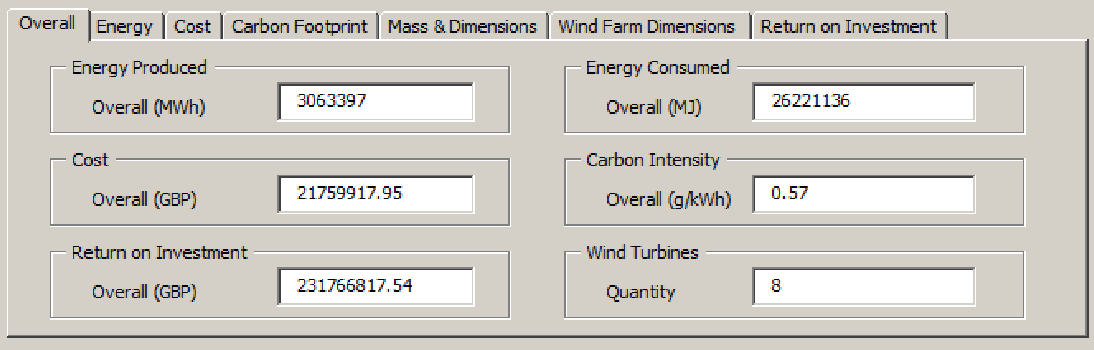


**Fig. A2 – Energy Tab**

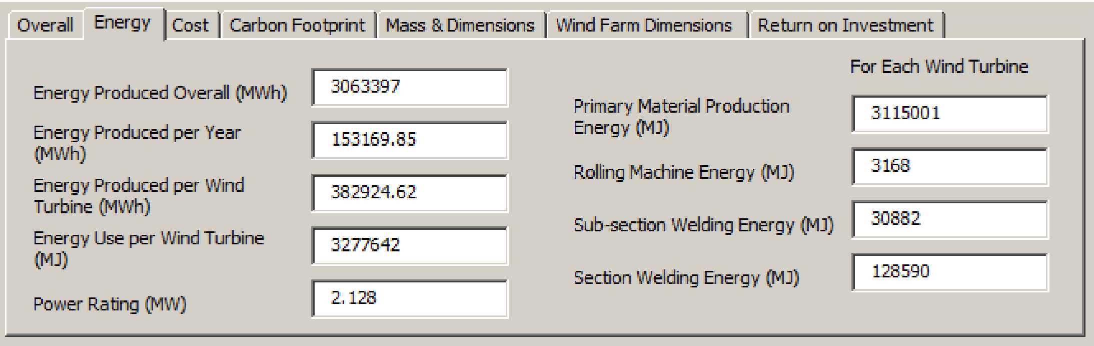


**Fig. A3 - Cost Tab**

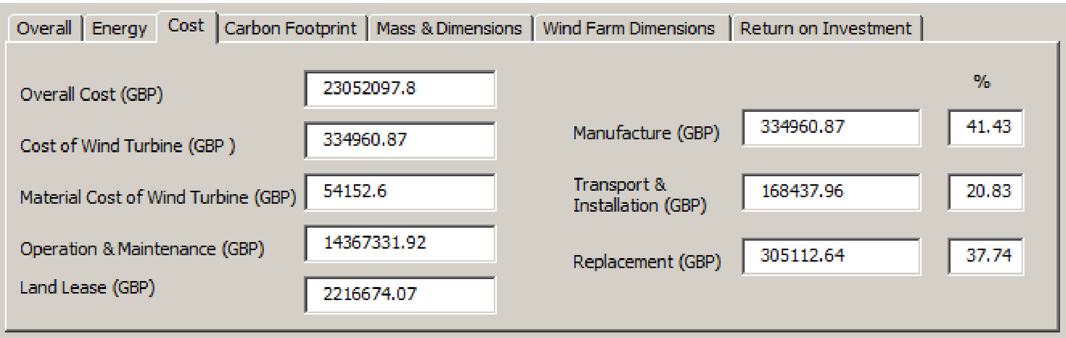


**Fig. A4– Carbon Footprint Tab**

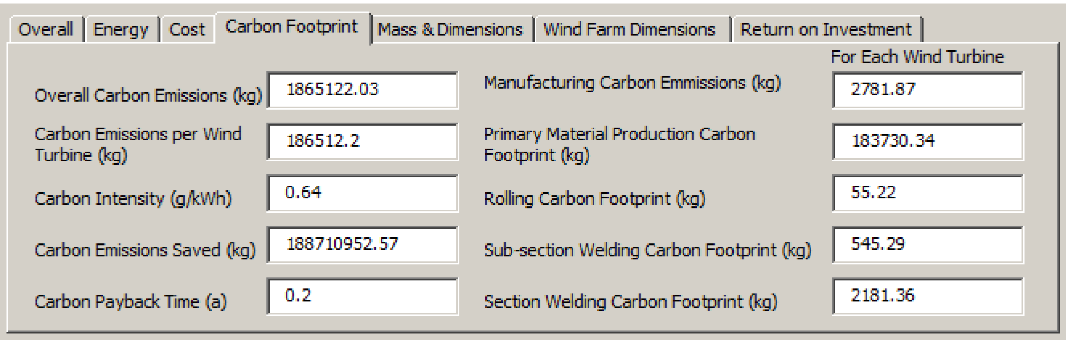


**Fig. A5 – Mass & Dimensions Tab**

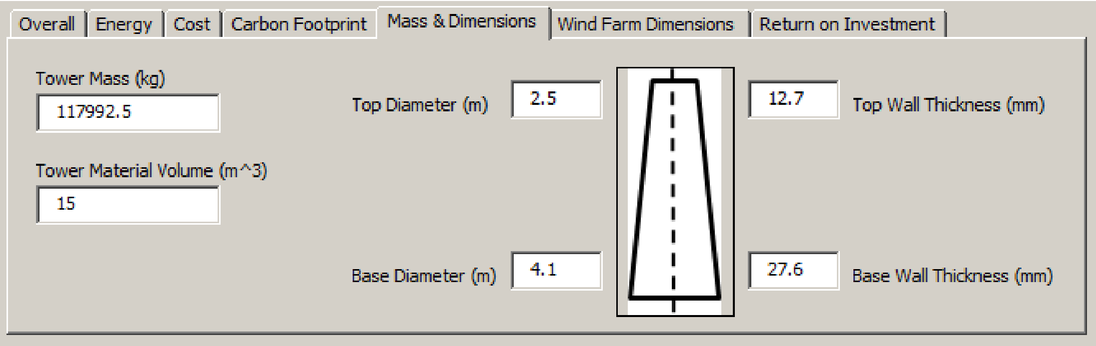


**Fig. A6 – Wind Farm Dimensions Tab**

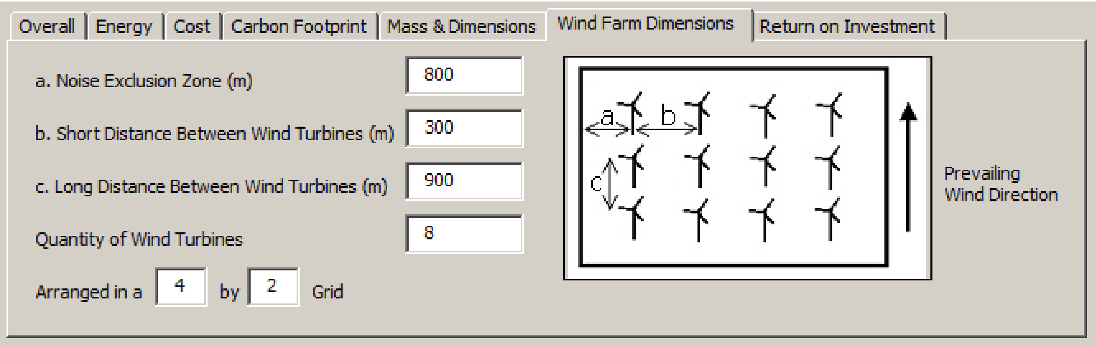


**Fig. A7 – Return on Investment Tab**