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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.

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 et al., 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%–90% of the total lifecycle cost. Therefore, the

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.

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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)
η	Energy conversion efficiency
λ	Scale factor of the Weibull function
ρ_a	Density of air (kg/m^3)

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 Astolfi 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