Optimization of rotating equipment in offshore wind farm

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Abstract. The paper considered the improvement of rotating equipment in a wind farm, and how these could maximise the farm power capacity. It aimed to increase capacity of electricity generation through a renewable source in UK and contribute to 15 per cent energy-consumption target, set by EU on electricity through renewable sources by 2020. With reference to a case study in UK offshore wind farm, the paper analysed the critique of the farm, as a design basis for its optimization. It considered power production as design situation, load cases and constraints, in order to reflect characteristics and behaviour of a standard design. The scope, which considered parts that were directly involved in power generation, covered rotor blades and the impacts of gearbox and generator to power generation. The scope did not however cover support structures like tower design. The approaches of detail data analysis of the blade at typical wind load conditions, were supported by data from acceptable design standards, relevant authorities and professional bodies. The findings in proposed model design showed at least over 3 per cent improvement on the existing electricity generation. It also indicated overall effects on climate change.

Keywords: wind farm power capacity, load cases, load conditions, wind turbine.

1. Introduction
According to conservation law of energy (first law of thermodynamics), energy cannot be created nor destroyed, but can be transferred from one form to another. While the energy in a system may take various forms (like heat, kinetic etc), depending on its source, the energy can get diminished. Thus, the source of energy generation can be said to be either renewable or non-renewable. Unlike non-renewable (fossil fuels), renewable energy source (solar, wind, geothermal etc) is not exhaustible and emits lower levels of carbon dioxide emissions.

In order to reduce the effects of emissions being caused by non-renewable source and avoid bad global warming, then there is a need to integrate the use of renewable source of energy in the national consumption. This need was echoed by European Union (EU) by setting 15 per cent (15 %) target of all energy consumption in UK to come from renewable source by 2020 (Carbon Trust, 2008). This target could cut across the energy consumption categories of transport, heat and electricity. The percentage is three-quarter of the 20 per cent (20 %) target that was set for the entire Europe by the Union in March 2007, according to the Carbon Trust. This target set for UK means that at least 29 GW (91 TWh) of offshore wind power could be needed to meet the 15 % EU renewable energy, even as the global leader for offshore wind energy (DECC, 2011), and wind power, as the primary renewable energy source (IMechE, 2013).

An offshore wind farm is a group of wind turbines located in the seabed or base of the ocean, to produce electric power. A wind turbine is device that converts the kinetic energy in fast-moving flow
of wind to produce mechanical power, via wind medium to rotate a bladed rotor. The device consists of a foundation, tower, nacelle and a rotor. The tower holds up the rotor and a nacelle (box). While the nacelle contains components like main axle, gearbox, generator, transformer and the control system, the rotor is made of blades and hubs. The rotary equipment converts the kinetic energy into mechanical power, and therefore, the rotary equipment can be said to influence the mechanical power output, among other factors.

DECC indicated that between 33-58 TWh offshore wind technology would make up for 234 TWh, which is equivalent to the estimated 15% target for year 2020. By projection, offshore wind power could cost-effectively deliver 20-50% of total electricity generation by 2050 (LCICG, 2012).

2. Methodology

As the largest and operational offshore wind farm in UK (as at the time of conceiving this as case study), it was believed that Greater Gabbard, being commissioned in August 2012, was among the latest commissioned wind farm that could still be improved. The improvements could be instrumental to meeting the 15 per cent renewable target by the year 2020. Its latest commissioning and being the largest in term of its capacity therefore, provided motivation for choosing it as case study.

Using turbines within the designed conditions is vital for design layout. The minimum acceptable turbine spacing is dependent on the nature of the terrain and the wind rose on a particular site. While a tight spacing turbines are affected by turbulence, positioning turbines spaced closer than five rotor diameters (5D) is likely to result in high wake losses, according to Renewable Energy World Magazine (REWM). Hence, minimum space required in positioning two turbines apart can be said to be sum of blade radius for turbine 1, minimum acceptable turbine spacing, and blade radius for turbine 2, assuming uniform blade diameter in a farm location. This is spacing efficiency.

\[ r_1 + 5D + r_2 \Rightarrow \text{where } r_1 = r_2 = r \text{ for uniform blade diameter } = D + 5D \]

![Europe share of 2011 offshore wind farm installations in MW. (Source: EWEA, 2012)](image)

Table 1.1: Technology breakdown (TWh) for central view of deployment in 2020. (Source: DECC, 2011).

| TECHNOLOGIES          | CENTRAL RANGE FOR 2020 (TWH) |
|-----------------------|-------------------------------|
| Offshore wind         | 24 - 33                       |
| Offshore wind         | 33 - 58                       |
| Bioenergy electricity | 22 - 59                       |
| Marine                | 1                             |
| Bioenergy heat (Non-  | 36 - 59                       |
| domestic)             |                               |
| Air- and ground-source heatpumps | 16 - 22                  |
| Renewable transport   | Up to 48                      |
| Other (Hydro, geothermal, solar) | 14                  |
| ESTIMATED 15% TARGET  | 234                           |

![Table 2.1: Classes of Wind Turbine (Source: IEC 61400-1, 2005).](image)

| Wind Turbine Class | Class I | Class II | Class III |
|--------------------|---------|----------|-----------|
| V_{ref} (ms)       | 50      | 42.5     | 37.5      |
| A \( I_{ref} (-) \) | 0.16    |          |           |
| B \( I_{ref} (-) \) | 0.14    |          |           |
| C \( I_{ref} (-) \) | 0.12    |          |           |

A = Higher Turbulence characteristics of the site
B = Medium Turbulence
C = Lower Turbulence
I_{ref} = Expected Mean Value of Hub-height Turbulence at 10 mins average wind speed of 15 m/s
S = Special Class Design (when special wind or external conditions are required by designers or customers).
With respect to operation, loading and durability of the wind turbine, regulation standard (IEC 61400-1, 2005) indicated that turbines can be subjected to external condition. For the purpose of design analysis, this external condition can be categorised into normal and extreme conditions, based on parameters wind speed and turbulence intensities.

**Normal Wind Profile Model (NWP)**: A normal external condition occurs when there is a continual structural loading, i.e. when the loading (wind) occurs frequently during the normal operation of a wind turbine. Models under this condition are called normal wind profile models (NWP). From standard, in order to model for this profile model (NWP) with ultimate strength, then

\[ v_z = \frac{v_{hub}}{z_{hub}} \alpha \]  

where \( v_z \) = average wind speed as a function of height \( z \) above the sea from standard

\( v_{hub} = \) standard 15m/s at standard 10m/s \( z_{hub} \);

\( \alpha = \) Power law exponent = 0.2

**Extreme Wind Speed Model (EWP)**: An extreme condition arise when there is an unusual or rare external design conditions, i.e. when having a 1-year or 50-year recurrence period. Models under this conditions are called extreme wind speed models (EWP). The design of load cases therefore consists of external conditions and other designs situations. From standard,(IEC 61400-1, 2005), in order to model for this profile model (EWP) with ultimate strength, then

\[ v_{e50}(z) = 1.4 v_{ref}(z) \alpha^{0.11} \]  

\[ v_{e1}(z) = 0.8 v_{e50}(z) \]  

where \( v_{e50} = \) Turbulent extreme wind speed with recurrence period of 50 years.  

\( v_{e1} = \) Steady extreme wind model with a recurrence period of 1 year.

### 2.1 Mathematical Model

The usable produced power is only some fraction of the available power in the wind, according to BETZ LIMIT. Hence, the need to calculate the power available in the wind. The algorithms to model output power are by calculating the power in the wind, extract it and then average output over a year.

#### 2.1.1 Power in the wind.

This is the amount of power present in the wind at a particular wind speed to rotate the rotor blade. The kinetic energy (KE) of an object with a mass (m) at a velocity (v) equals the work done in displacing the object, i.e. KE = Work done. From the Newton law of motion, \( F = ma \) (where \( m = \) mass, and \( a = \) acceleration), and by combining with third equation of motion (\( v^2 = u^2 + 2as \)), then power is produced.

The power available in the wind (\( P \)) is proportional to the square of the blade length, cube of the wind speed and the air density. This is given by

\[ P = \frac{1}{2} \rho A V^3 \]  

where, Power is in watts (W);  
\( \rho = \) (kg/m\(^3\))  
\( A = \) (m\(^2\))  
\( V = \) (m/s)

However, not all these power available in the wind are usable to generate electricity.

#### 2.1.2 Extract Actual Power.

This is amount of usable power that generates electricity. According to Betz Limit, in theory, wind mill can possibly extract a maximum of 59.3% of power from the wind only, while in reality, it is 45% maximum. This proportion of power extraction is termed coefficient of performance or efficiency (\( C_p \)). Primarily, this energy are extracted through the physical principle of lift and drag forces.

So, power extracted (\( P_e \)) from the wind is modified to:

\[ P_e = P \times C_p = \frac{1}{2} \rho A V^3 \times C_p \]  

where \( C_p = \) Coefficient of performance of the wind turbine.

\( C_p \) is the average power coefficient defined by Betz Law with a limit of 0.59 for marine turbine. Amount of power produced \( P_p = P_e \times \eta_g \times \eta_b \)

where \( \eta_g \) & \( \eta_b \) are efficiencies for generator and gearbox.  
\( \eta_g = 80\%; \)  
\( \eta_b = 90 \) to 95%.
2.1.3 Energy in a year. From BSI, average percentage of running turbine in a year is 23%. This is
given as load factor of 40% from the Case Study data. The load factor, which varies depending on
resource, technology and purpose, is determined by evaluating amount of load and amount of time the
system operates at that load. For analysis purpose, given data from case study was used.
1 MW of electric power = 1GWh in a year (GigaWatts hour)
where 1 year of turbine = 8760 hours;
1 MW of load = 0.4 * 8760 hrs
Therefore, energy produced in a year 1 MW = 3.5 GWh

2.2 Case Study Data Analysis
From table 2.2, Turbine Unit Power = 3.6MW, Total Power = 504MW, Rotor Diameter = 130m;
Assumed density $\rho = 1.225 \text{ kg/m}^3$; where $A = \pi r^2$.

2.2.1 Calculating for wind speed that produced this unit power. It is assumed that this unit power 3.6
MW is the actual power produced. From equations 5 and 6, and section 2.1.2, then
$3.6 = P \times 0.59 \times 0.8 \times 0.925$ => Power available in the wind is 8.246 MW
Substituting this in eq. (4) to calculate for wind speed that produced available power in the wind
$8.246 \times 10^6 = 0.5 \times 1.225 \times (3.142*65^2) \times v^3$
$v = 10.05 \text{ m/s}$
This is equivalent to average speed of 10 m/s of generic
class 1 offshore for environmental condition (Camp,
2003).

2.2.2 Calculating for energy produced in a year. From eq. (7), 3.6 MW load of unit turbine runs in a year is 3.5 *
3.6 = 12.6 GWh. Hence, 140 units will produce 1764 GWh.

2.2.3 Calculating for spacing efficiency. For Case Study
with 130 m rotor diameter, the spacing efficiency (section 2.) equals 130 m + 5(130 m) = 780 m i.e. 780 m is the
required spacing in positioning the two turbines apart.
But given that total turbine units in the farm are 140,
therefore, the amount of space consumption for whole farm = 780 * 140 = 109200 m² = 109.2 km².
Hence 109.2 km² does not justify effective use of the available location area, as there still exists 37.8
km² of unproductive space.

2.3 Proposed Optimized Analysis
In order to model for the maximum energy output in a year, this is analyzed using three approaches.
Each approach followed the algorithms of each of mathematical model (section 2.1). The approaches
were achieved by calculating energy produced with proposed 100 m rotor diameter using existing case
study wind speed; and according to standard IEC 61400-1, normal wind profile model (NWP) and
extreme wind speed model (EWP).

From section 2, spacing efficiency with proposed 100 m rotor diameter, will be 600 m in
positioning two turbines apart. Assuming for same numbers of unit of 140 turbines as case study, these
require 84000 m² = 84 km². However, since available case study site area is 147 km², then there
remains a large space that can still be maximized. In order to achieve this, the number of turbine units
were therefore increased.
100 per cent use of the site area will require 245 units of turbines.
i.e. 245 units turbine * 600 m = 147000 m² = 147 km² (same as case study site area).
2.3.1 Using Calculated Case Study Wind Speed. This is 10.05 m/s from section 2.2.1. Applying this with proposed 100 m diameter, mathematical model evaluation was as follows.

i). Calculate for Power Available in the wind.
From eq. (4), \( P = 0.5 \times 1.225 \times (3.142 \times 50^2) \times 10.05^3 \), 
\( P = 4.88 \text{ MW} \).

ii). From eqs. 5 & 6, Power produced \( P_p = (4.88 \times 10^6) \times 0.59 \times 0.8 \times 0.925 \), 
\( P_p = 2.13 \text{ MW} \).

Therefore total power produced by maximum units of 245 turbines, at 100% efficient use of location area = 2.13 MW * 245 = 521.85 MW.

iii). From eq. (7), one unit turbine of 2.13 MW will run in a year for 3.5 * 2.13 = 7.46 GWh.

Hence 1827.7 GWh of energy will be produced by 245 units.

2.3.2 Normal Wind Profile Model (NWP). This was modelled according to standard in section 2.0.

i) From eq. (1) average wind speed at given height of case study (170 m)
\( v_z = 15 \times (170/10)^{0.2} \), 
\( v_z = 26.4 \text{ m/s} \).

ii) From eqs. (5 & 6), Power produced \( P_p = (0.5 \times 1.225 \times 3.142 \times 50^2 \times 26.4^3) \times 0.59 \times 0.8 \times 0.925 \), 
\( P_p = 38.65 \text{ MW} \).

Hence, a normal wind profile model, at 100 m rotor diameter produces 38.65 MW for a unit.

Actual power produced for 245 units equals 9469.25 MW.

iii) Energy produced in a year by a unit turbine with actual power of 38.65 MW would run for 3.5 * 38.65 = 135.28 GWh (eq. 7). Equivalent of 33143.6 GWh energy produced by 245 units.

2.3.3 Extreme Wind Speed Model (EWP). According to standard 61400-1 (section 2.0), this was considered in two cases: as turbulent and steady EWP with recurrence periods of 50 years and 1 year respectively. From table 2.1, assume \( v_{ref} \) for turbulent EWP is 50 m/s, then from eq. 2,

i). average wind speed at height of case study, 170 m
\( v_{e50} = 1.4 \times 50 \times (170/10)^{0.11} \), 
\( v_{e50} = 95.59 \text{ m/s} \).

Hence, for extreme wind speed model with recurrence in 50 years period, the wind speed shall be 95.59 m/s. This means that with this speed, the turbine must be able to withstand the extreme events possible with a return period of 50 years.

For steady EWP, then eq. 3 becomes \( v_{e1} = 0.8 \times 95.59 \text{ m/s} = 76.5 \text{ m/s} \).

Now was considered model for analysis of 1 year reoccurrence.

ii). From eq. 5 & 6, actual power produced \( P_p = (\frac{1}{2} \times \rho \times A \times v_{e1}^3) \times \eta_g \times \eta_b \), 
\( P_p = (0.5 \times 1.225 \times 3.142 \times 50^2 \times 76.5^3) \times 0.59 \times 0.8 \times 0.925 \), 
\( P_p = 940.42 \text{ MW} \).

Therefore, a steady EWP with 1 year reoccurrence produces 940.42 MW for a unit.

Total Output for 245 units equals 230402.9 MW.

iii). Energy produced in a year - If actual power produced by a turbine due to steady EWP was 940.42 MW, then according to eq. 7, then 3291.47 GWh amount of energy would be produced in a year.

Hence, 806410.15 GWh of energy will be produced by 245 units.

3. Results
The tabulated results show effects of analytical model and redesign of blade to the proposed diameter, and efficient location areas, while maximising the energy productivity.
4. Discussions

While the wind farm capacity in first approach showed an increase in total units capacity of actual power produced and energy in a year, occurrence of frequent wind loading in the second approach resulted in the wind speed almost triple the initial case capacity. Consequently, the unit power capacity an energy produced in a year also got increased. In the third approach, the unusual event of design with recurrence 1 year period resulted in unusual increase of wind speed, and consequently the unit power and energy produced in a year. The variations in these wind speeds according to different approaches limits the capacity of power generation, and also are adequate position of the rotor blade in the wind speed direction, altitude of the tower among others. With estimated 91 TWh of offshore wind power predicted to be needed to meet the 15% target (DECC, 2011), this would mean an approximate numbers of 50 wind farms will be needed, should each farm consists of 245 numbers of turbines, and each generating 1827.7 GWh like that in the first approach.

5. Conclusions

The first approach showed 3.5 per cent increase of actual power produced by total units of turbines, and 3.6 percent of energy produced in a year. The unit power and energy produced were almost 10 per cent increase each as against the given case study data in the second approach, while there was a rare very high percentage increase resulted in the third approach. With this least percent increase of 3.5 on a wind farm, this would mean a greater addition of percentage increase on all operational wind farms in the country. The percentage increments on all operational wind farm would mean serving greater number of homes and hence beneficial to everyone, as it makes environments more friendly, due to its source. As the most significant gases in the atmosphere, the effects of carbon dioxide concentration are eliminated, hence, there is less severity of changes, both physical and ecological, which could affect national population, productivities etc. Also, as predicted by the Department of Energy and Climate Change that offshore wind technology would produce most amount of energy (table 1.1), and couple with the percentage increase obtained via the analysis, it could be said that government supports would be of great importance at realizing this prediction. This could contribute immensely to meeting set target of the need for energy consumption in the country to come from renewable source, and increase chances of meeting it earlier than predicted. The redesign optimization of existing farms could save money, time and other resources instead of construction new ones. Hence, the economy thrives, while maximizing the operational qualities and productions of the existing farms.

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