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Article

Performance and Cost Analysis of Energy Production from Offshore Wind Turbines

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Abstract: Offshore wind turbine is analyzed theoretically and experimentally for improving wind energy harvesting. The energy produced is calculated at different wind speeds. The wind speed curve is generated by measuring the wind speed on daily base for one year. Curves that show the power extraction for experimental study and from the theoretical calculations are generated. The energy production investigation is expanded over a period of 15 years after comparing the annual energy production in theory and practice. The study shows the cost of electricity over the same time period assuming different interest rates. Three time intervals are shown that are 5, 10, and 15 years. Results show a comparable power harvesting between calculated and extracted power which is around 130 MW per year. The cost analysis shows a reduction in the cost of electricity (pence/kWh) as the operating time of the turbine increases. Tables of results show that the cost of electricity produced using the offshore wind turbine for 15 years' operating time is 8.36 pence/kWh compared to 16.92 pence/kWh for 5 years' operating time. These values are decreased when the interest rate is decreased, where the results as expected show an increase in the values when the interest rate is increased regardless of the operating time.

Keywords: Wind energy; renewable energy; offshore; electricity cost

1 Introduction

Using of wind energy to generate power is a way to promote the usage of renewable energy and provide efficient results with acceptable costs. Thus, reducing energy consumption and the reliance on fossil fuels especially for countries where solar radiations and/or wind energies exist is great. Cost of renewable energy witnesses a reduction in production costs [1,2]. The reduction in costs helped to fulfil the world demand on electricity that reached more than 23,000 TWh in 2018 [3].

Despite many ways to utilize the renewable energy in electricity generation such as wastes, geothermal, solar, tidal energy, etc. [4-7], the wind energy is promising mainly in countries located close to the coastal regions where it is possible to harvest more energy by utilizing the offshore wind [8,9].

The cost of energy production from the offshore wind turbines showed to be reduced by applying mechanisms to reduce the support load effects into the initial design [10]. Many researchers [11-13] performed modeling and simulation of the offshore wind turbines to maximize the power output and reduce the cost. They started from initial structural design and ended by optimization studies to maximize power and reduce cost. Literature shows [14] that at 10 m/s wind speed, at the installed cost of $6,000/kW, generation cost is about $194/MWh. At the another lower installed costs of $4,000/kW, the cost of electricity is ranging from $200/MWh at 7.5 m/s to $150/MWh at 9 m/s.

As it can be clearly seen from the importance of wind energy as a renewable energy source, scientists are trying to develop new technologies to enhance the energy harvesting from wind turbine and minimize the cost. Current developments in wind turbine design for energy harvesting from the wind include adding a second rotor [15-17]. The addition of second rotor helps in capturing the residual energy in the wind stream passing through the swept area of the first rotor. This enables the turbine to extract more power from the main source which means higher efficiency.

This is attributed to practical applications of such devices for power generation [7]. Double rotor wind turbines can improve the power generation, thus, it needs more theoretical and experimental investigations. Several computer programs were developed to investigate performance of a counter rotating wind turbine with two 500 kW rotors [18].

This research paper is going to examine an offshore wind turbine according to energy generation performance, financial concerns including capital cost and energy price. Finally, this work will discuss the environmental impact that offshore wind turbine is facing and how it can affect its future potential.

The work started by performing the energy performance analysis by calculating its annual energy output at a proposed site by finding the following: the velocity expedience curve, power calculations, obtaining of the interference factor, extracted power calculation with relevant curves, and finally the cost analysis.

2 Methodology

The daily velocity for a year can be estimated using Eq. (1):

$$v_\infty T^{0.5} = 60.0 \tag{1}$$

where v_∞ is the free air velocity, m/s. T is the number of days when the mean wind speed exceeds v. After obtaining the velocity, the expedience curve can be derived as shown in the Fig. 1.

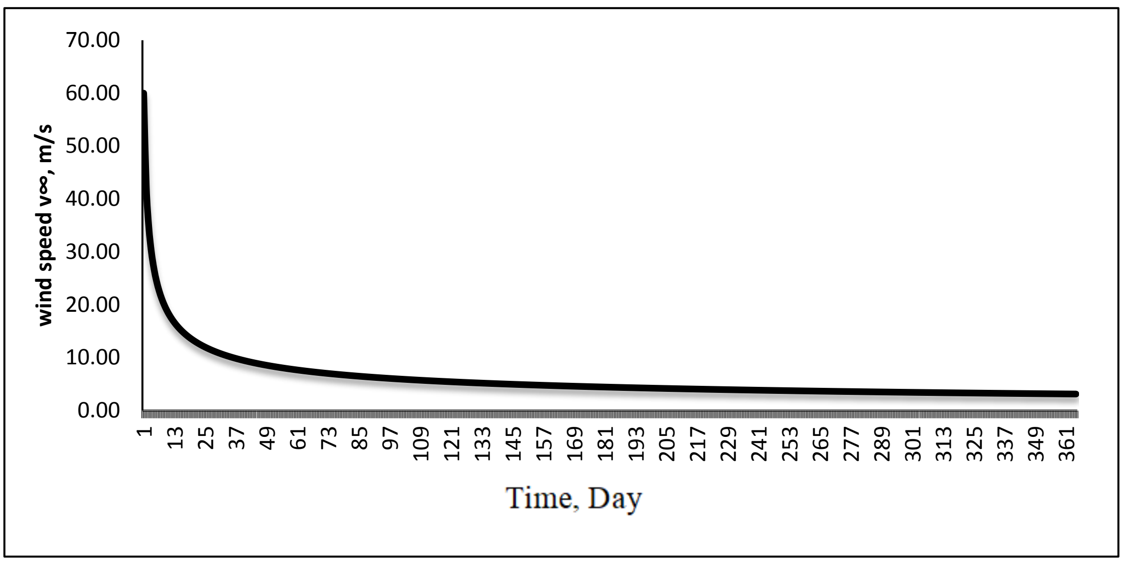

Figure 1: Daily wind speed calculated over the year

The extracted power can be derived by applying Bernoulli equation on a control volume Fig. 2 at the rotor which will provide the equation to calculate the extracted power Eq. (2):

$$P = 2\rho A v_\infty^3 \left(a - 2a^2 + a^3\right) \tag{2}$$

Eq. (2) presents the extracted power $P, Watt$, as a function of, air density (ρ = 1.2 kg/m^3), the cross sectional area of the rotor ($A = \pi$ d^2), Rotor diameter (d = 94 m), the air velocity $v\infty 3$ m/s, and the interference factor a. Since the power coefficient C_p is a function of the interference factor Eq. (3), the value of interference factor can be obtained when $C_p = 0.42$ that is a value between rated speeds and cut out speed.

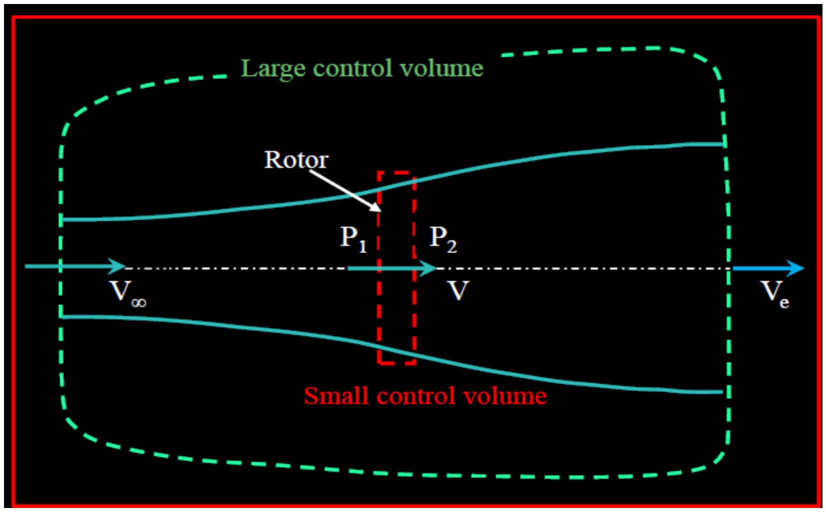

Figure 2: Control volume at the rotor, for derivation of the power equation by applying Bernoulli equation

$$Cp = 4a(1-a)^2 \qquad (3)$$

Thus a value of 0.15 for (a) is obtained.

3 Results and Discussions

The extracted power from the turbine depends on the power coefficient, tip-speed ratio, rated power, cut-in and cut-out speeds. The Fig. 3 shows the power curve obtained from Eq. (2). However, the turbine should be operating between cut-in and cut-out speed only as well as the power will be at constant coefficient between the rated speed and the cut-out speed.

Therefore, in this analysis the turbine operates at Cp = 0.42 between cut-in and cut-out speeds, and that above rated speed the power remains constant until cut-out, Cut-in = 4 m/s, Cut-out = 24 m/s and the Rated speed = 10 + 0.2 m/s = 10.2 m/s as it can be shown in Fig. 4. Therefore the power extracted curve will be as shown in Fig. 5.

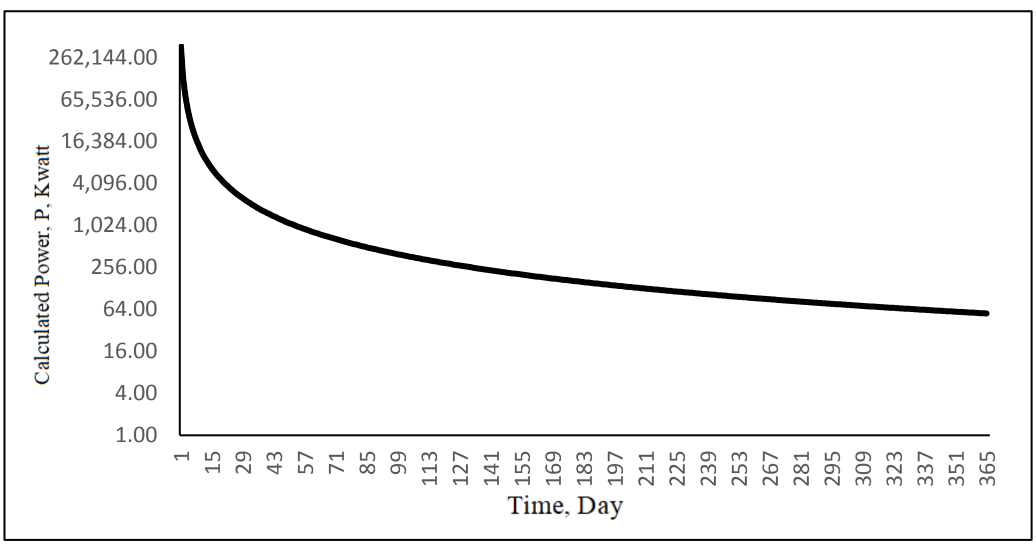

Figure 3: Calculated power on daily base of the turbine along one year

By calculating the total area under the extracted power in Fig. 6, the total power extracted can be obtained. Which is equal to 131,223 kW/year, where the total annual energy is 472,404,760 kWh.

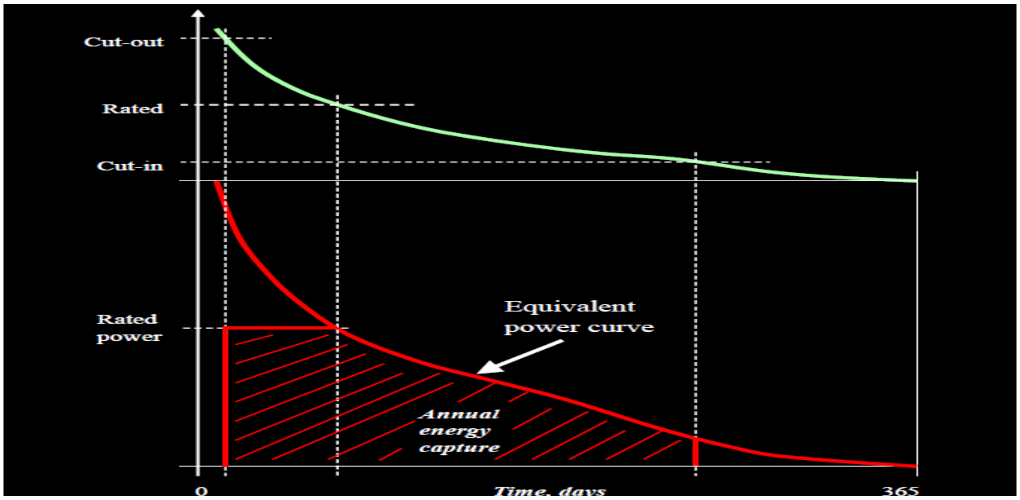

Figure 4: Power and speed curves of the turbine on daily basis

Energy cost is very crucial in any renewable energy system. The calculation of the cost of electricity during the first 15 years of operation of the turbine is shown in this section. The cost study includes both the maintenance costs and interest rate.

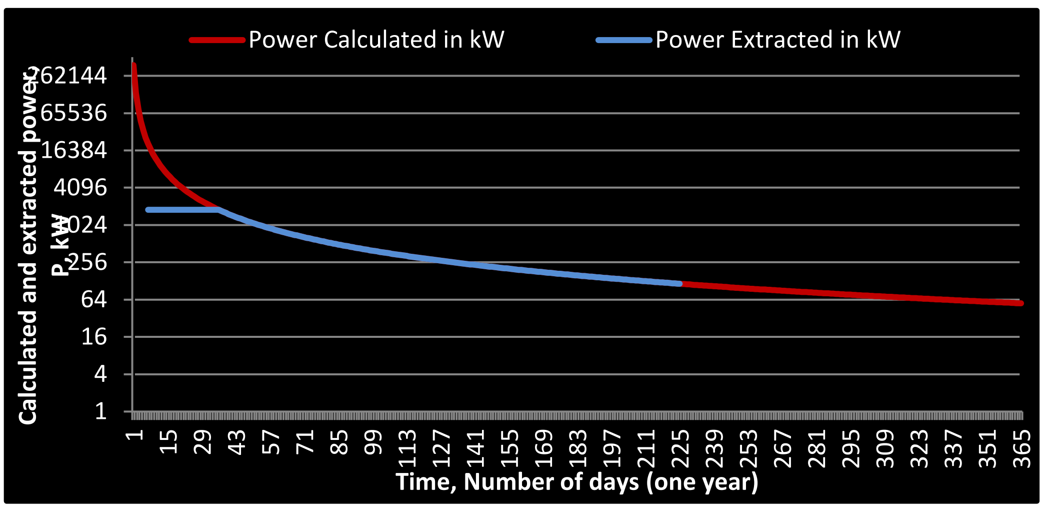

Figure 5: A comparison between the calculated power and the extracted one

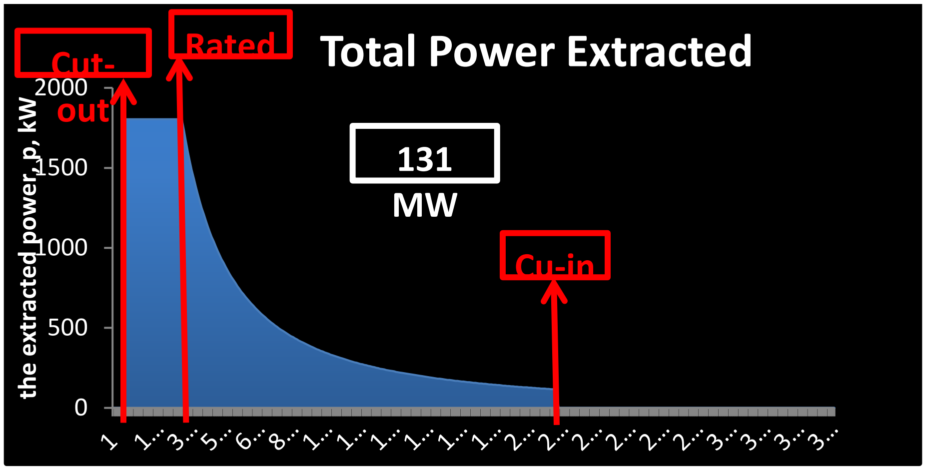

Figure 6: Annual total extracted power

According to the National Renewable Energy Laboratory in the Wind Turbine Design Cost and Scaling Model Report, the cost of energy (COE) can be calculated from Eq. (4):

$$COE = \frac{FCR.ICC}{AEP_{net}} + AOE \quad (4)$$

where:

COE is the levelized cost of energy (\$/kWh) (constant \$)

FCR is the fixed charge rate or annual repayment (constant \$) (1/yr)

ICC is the initial capital cost (\$)

AEP_{net} is the net annual energy production (kWh/yr)

AOE is the annual operating expenses which is defined in Eq. (5):

$$AOE = LLC + OM + LRC \quad (5)$$

where:

LLC is the land lease cost

OM is the levelized operation and maintenance costs

LRC is the levelized replacement/over whole cost

For this case the land lease cost and the replacement cost are ignored, and the cost based on its first 15 years of operation, then the equation will be shown in Eq. (6):

$$COE = \frac{(Annual\ bank\ return/year + annual\ maintenenace\ cost/year).15\ years}{AEP_{net/year}} \quad (6)$$

Thus, the total cost including foundation and electrical connection can be described as:

Cost of the turbine = £ (2 + 0.025 N) * 10^6 = £ 2,025,000

The maintenance cost is calculated in the Tab. 1, for 3% the annual maintenance cost is £ 4,050.00.

Table 1: Maintenance cost

Annual Maintenance Cost	3%	6%	9%
	£4,050.00	£8,100.00	£12,150.00
Total 15 years	£60,750.00	£121,500.00	£182,250.00

The Annual repayment required is calculated based on Eq. (7), and the results of the calculations are shown in Tab. 2. The energy costs are summarized in Tab. 3 at different values of interest rates and different operating times.

$$Annual\ payment\ required = \frac{Cr(1+r)n}{(1+r)n-1} \quad (7)$$

where:

C is the capital loan,

r is the rate of interest

n is the number of years to complete the repayment

Table 2: Annual repayment at different rates of interest

	Annual Repayment		
Interest Rate	**5 years**	**10 years**	**15 years**
3%	£442,168.01	£237,391.78	£169,627.33
6%	£480,727.71	£275,132.62	£208,499.6
9%	£520,612.23	£315,535.68	£251,219.24

Then the electricity cost is equal to: (£4,050.00 + £208,499.60) * 100/3,149,365.07 = 6.75 Pence per year.

Table 3: Cost of electricity

	Cost of electricity pence/kWh		
Interest Rate	**5 years**	**10 years**	**15 years**
	3% Maintenance		
3%	14.17	7.67	5.51
6%	15.39	8.86	6.75
9%	16.66	10.15	8.11
	6% Maintenance		
3%	14.30	7.79	5.64
6%	15.52	8.99	6.88
9%	16.79	10.28	8.23
	9% Maintenance		
3%	14.43	7.92	5.77
6%	15.65	9.12	7.01
9%	16.92	10.40	8.36

4 Conclusions

Results show that an offshore wind turbine can produce 131,223 kW/year which is equal to a total annual energy of 472,404,760 kWh. The same result is obtained from theoretical analysis and from experimental investigation around one year referred to as extracted power where the power output is recorded daily. This allows an expansion of the theoretical analysis for three time intervals that is 5, 10, and 15 years.

The cost analysis shows an increase in the electricity cost which is 6.75 Pence per year when the interest rate increases. The increase in the cost is proportional to the increase of the interest rate in any of the time intervals. Increasing the operating time to 15 years reduces the cost of electricity in comparison to 5 and 10 years. Maintenance costs and interest rates have a direct effect in the prices of electricity produced from wind turbines. How beneficial the cost analysis is depends on the real costs and interest rates in each country. Considering the environmental impact of offshore wind turbines and energy savings make the offshore wind turbine an excellent choice as wind energy can be hybrid with other renewable energy sources referred to in the introduction such as tidal energy, solar energy, etc.

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