IMPACT OF THE GROUND CLEARANCE ON THE ANNUAL ENERGY PRODUCTION AND TOWER COST OF AN OFFSHORE WIND TURBINE

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Abstract - This article analyzes the impact of the ground clearance on the Annual Energy Production (AEP) and tower cost of a 20 MW offshore wind turbine. In addition, the influence of the rated wind speed on the analysis result will be considered. The AEP is computed by considering wind speed variation over the swept area of the rotor blades. The tapered tubular steel tower is considered for mass and cost calculation. The tower is considered as a fixed-free cantilever beam with concentrated mass at the free end. The analysis shows that the ground clearance only has a minor impact on the AEP but it has a remarkable impact on the tower mass. Specifically, when the ground clearance reaches 50 meters, the AEP only increases by roughly 3% while tower mass is nearly doubled compared to the case with no ground clearance. The results also reveal the significant impact of the rated speed on both the AEP and tower mass.

Key words - Offshore wind; ground clearance; Annual Energy Production (AEP); tower cost

1. Introduction

In order to make wind energy more competitive with traditional fossil fuel types as well as other renewable energy resources, technology advancement has been continuously applied to lower the Levelized Cost of Energy (LCOE). The typical trend to lower the LCOE is the introduction of larger and higher rating wind turbines with turbine's components of the wind turbine are designed to increase the mechanical strength and at reduced masses Accessing winds at higher altitude improves the overall energy production and capacity factor of wind turbines. For a single wind turbine, the increase in energy production and capacity factor, by having larger blades and hub height, will be partially compensated by the increase in the cost of materials for blades, tower and foundation. For wind farms in specific site conditions, the change from 6 MW to 12 MW turbines could give an overall 17% reduction of LCOE as it saves a significant amount of costs for foundations, construction, and operation, maintenance by virtue of having fewer turbines for a given wind farm rated power [1].

The ground clearance (also called tip clearance) of a wind turbine is defined as the vertical distance from ground level (for onshore turbine) or sea level (for offshore turbine) to the tip of a wind turbine blade when the blade is at its lowest point [2, 3, 4]. The ground clearance and hub height are illustrated in Figure 1. For a given rotor diameter, the change in ground clearance directly implies the change in hub height of a wind turbine. There seems to be a limited number of works targeting the analyses of ground clearance. M. Shields *et al*. [5] provided an insightful analysis on the effect of upsizing offshore wind turbine and wind farm capacities on the LCOE. However, the authors considered a fixed cost of wind turbine ($1300/kW), thus, focused on the cost reduction induced by having a smaller number of required wind turbines. Study in [6] only analyzed the energy production and energy efficiency of wind turbines with various hub heights. The economic aspect was neglected in this study. Authors of [7] and [8] attempted to find the optimum hub height for cost minimization or optimal economic gain. However, the tower cost changed as the variation of the hub height was considered by simple empirical equations. Authors in [9] and [10] investigated the impact of ground clearance and hub height on the wind farm performance. The work only focused on the impact on the wake losses or the power coefficient and did not consider the overall performance such as wind energy production and LCOE, which are key indicators of a wind farm.

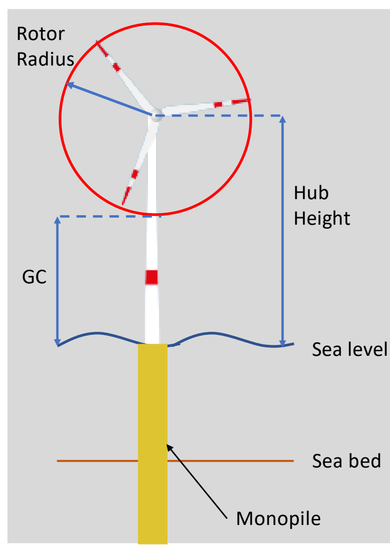

Figure 1. *Ground clearance concept for offshore turbine*

This work will take a different approach as the impact of ground clearance on the AEP and tower cost of an offshore wind turbine will be analyzed. The tower structure is optimized with stress calculation. By this, the changes in the ground clearance and hub height are better understood. In this article, analyses are performed based on a 20 MW offshore wind turbine. The AEP is computed by considering wind speed variation over the swept area of the rotor blades. The tapered tubular steel tower is considered for mass and cost calculation. Tower is considered as a fixed-free cantilever beam with concentrated mass at free end.

2. Methodology

2.1. AEP calculation

A wind turbine turns wind power into electric power using the aerodynamic force from the rotor blades, which work like an airplane wing or helicopter rotor blade. The blades are designed so that they will spin when the wind flows through. The rotor connects to the generator, either directly (direct drive generator) or through gears to increase the speed of the generator's shaft and allow a smaller generator.

The power of flowing air with velocity V, through a surface with area A can be calculated by Equation (1), where ρ is the air density. For standard conditions (sea-level, 15ºC), the density of air is 1.225 kg/m^3.

$$P_w = \frac{1}{2}\rho V^3 A \tag{1}$$

For horizontal axis wind turbine, the area A can be substituted by πR^2, which is the swept area of the rotor with radius R. However, this can only be done when the wind flows with constant speed across the whole swept area. In practice, due to the wind shear effect, the wind speed increases at higher latitudes. For small wind turbines, the wind shear effect can be neglected, however, for offshore wind turbines with larger blades, the wind shear should be taken into the calculation of wind power. In this work, a detailed methodology to estimate the wind power flowing through the swept area will be presented. Similar to the rotor equivalent wind speed (REWS) method [7, 11], the presented method provides a better estimation of wind power and hence, of AEP, compared to the conventional method of using hub height wind speed.

Firstly, the swept area is divided into n segments, with equal height. These segments will be numbered from lowest to highest by $1, 2, \dots, i, \dots, N$. The elevation of the lower boundary of segment i will be denoted as z_{i-1}, and z_i for the upper one. The representative wind speed for segment i will be approximated at the center of the segment, i.e. at the elevation $(z_{i-1} + z_i)/2$. The area of segment i is calculated by:

$$A_i = 2\int_{z_{i-1}}^{z_i} \sqrt{R^2 - (z_{hub} - x)^2}dx \tag{2}$$

Then, applying the wind shear power-law (with the hub height z_{hub} as reference height and the rated wind speed V is the wind speed at hub height), the representative wind speed of each segment can be approximated by Equation (3), in which α is the power law exponent or wind shear exponent.

$$V_i = V\left(\frac{z_{i-1} + z_i}{2z_{hub}}\right)^{\alpha} \tag{3}$$

Finally, the wind power flowing through the rotor swept area can be derived as:

$$P_w(V) = \rho V^3 \sum_{i=1}^{N}\left(\frac{z_{i-1} + z_i}{2z_{hub}}\right)^{3\alpha}\int_{z_{i-1}}^{z_i}\sqrt{R^2 - (z_{hub} - x)^2}dx \tag{4}$$

It should be noted that when $N = 1$, this is equivalent to the assumption that the wind speed through the whole swept area is constant. Afterward, the rotor power P_{wt} can be easily calculated by multiplying the right-hand side of Equation (4) with the power coefficient C_p. However, in the design phase, an objective is to determine the required rotor radius at a given rated power, it will be sufficiently difficult to determine the rotor radius directly from Equation (4) when $N > 1$. Hence, in this work, an algorithm to determine the required rotor radius with a given rated power is presented as follows.

Table 1. *Algorithm for calculating the required rotor radius R for a given rated power* P_n

Step No.	Description
1	Choose a value of C_p (e.g. $C_p = 0.5$) and ground clearance GC (e.g. GC = 15m)
2	(i) Initialize $R_0 = \sqrt{2P_n / \rho\pi C_p V_n^3}$, which is the rotor radius when the wind speed is assumed to be constant over the rotor swept area. (ii) Calculate $P_{wt,0}$ using Equation (4), in which the hub height z_{hub} is determined by: $z_{hub} = GC + R$ (5) (iii) Loop until the error $e = \left\lvert P_n / P_{wt,i} - 1\right\rvert$ is lower than or equal to a specific threshold: • Calculate new radius $R_i = R_{i-1}\sqrt{P_n / P_{wt,i-1}}$ • Calculate new turbine power $P_{wt,i}$ with new radius, using Equation (4) and Equation (5). • Calculate the error and check if it is lower than the predefined threshold.

For a given wind speed probability density function, $p(V)$, and a known turbine power curve, $P_{wt}(V)$, the AEP is given by Equation (6) in which $T = 8760$ is the number of hours in a year.

$$AEP = \eta T \bar{P}_{wt} = \eta T \int_{V_{in}}^{V_{out}} P_{wt}(V)p(V)\,dV \tag{6}$$

The power curve of a wind turbine relates its power production to the wind speed it experiences. The power curve illustrates three important characteristic speeds: (1) Cut-in speed; (2) Rated speed; And (3) cut-out speed. Figure 2 shows an example of power curve of wind turbine, in which P_n and V_n are the rated power and rated speed of the wind turbine.

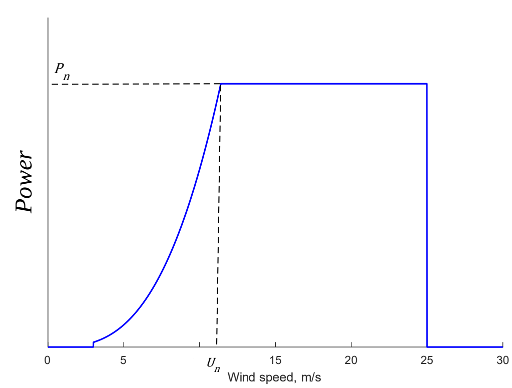

Figure 2. *Power curve of wind turbine*

The commonly used distribution of wind speed is the Weibull distribution with the probability density function given by Equation (7) [12]. The Weibull distribution is characterized by two parameters: k – shape factor, and c – scale factor. Both parameters are functions of mean wind speed $\bar{V}$, and standard deviation of wind speed σ_V.

$$p(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{7}$$

If wind speed measurements are available for a relatively long period of time, these parameters can be determined by probability distribution fitting. It is also possible to approximate the shape factor k by using the empirical Equation (8), then using Equation (9) to determine the scale factor c [13]. In Equation (9), $\Gamma(x) = \int_0^\infty e^{-t} t^{x-1}\,dt$ is the gamma function. It has been concluded from experience that $k = 2$ represents well enough wind speed distribution [14].

$$k = \left(\frac{\sigma_V}{\bar{V}}\right)^{-1.086} \tag{8}$$

$$\bar{V} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{9}$$

2.2. Tower mass calculation

The tower is typically a tubular steel structure, hence, the tower cost is significantly affected by the cost of material. For example, the tower cost of a 10 MW offshore wind turbine is about $970,000 in which the cost for steel is $8300,000 [15]. Thus, in this work, the tower mass will be the main concern as any change to the tower mass directly implies a change in its cost.

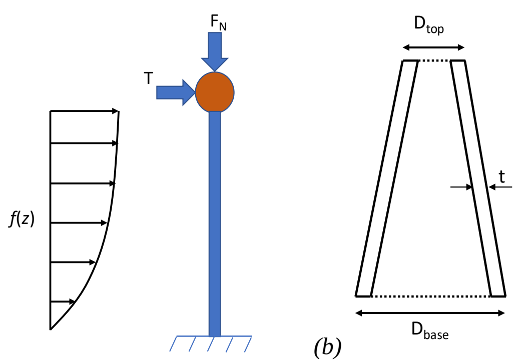

Figure 3. *(a) Tower loads model, (b) Tower vertical cross section*

To estimate the tower mass, this study follows the two standards IEC 61400-1 and IEC 61400-3-1 regarding the design of wind turbines and the two standards EN 1993-1-1:2005 and BS 5950-1:2000 regarding the design of steel structures. For simplicity, a mathematical approach will be used to calculate the dimension, hence, the mass and cost of a wind turbine tower. A tapered tubular steel tower will be considered in this analysis, and the thickness of the tower is assumed to be constant across its length. Then, the approach in [16] and [17] will be adopted, i.e. the tower is considered as a fixed-free cantilever beam with concentrated mass at free end. The beam will be considered massless as the mass of the tower will also be lumped to the concentrated mass at the top of the tower. As this study only concerns the tower, the monopile (or other substructures) will be considered as a fixed foundation. The model is illustrated in Figure 3.a, in which T is the thrust force, $f(z)$ is the distributed force acting on the tower, and F_N is the gravitational force of the concentrated mass.

The dimension of the tower will be estimated such that the maximum stress in the tower will not exceed the yield strength of material. In the analysis, three variables will be considered, namely: The top diameter D_{top}, the base diameter D_{base} and the thickness t of the tower.

In the analysis, the maximum stress in the tower should not exceed the strength of steel. The stress in the tower consists of two components, the bending stress caused by bending moment from thrust force T and the distributed force $f(z)$ and the compressive stress caused by the concentrated mass at the top of the tower. The maximum stress will occur at the point of maximum bending moment as the compression stress caused by the concentrated mass will be constant at any given height of the tower. Therefore, only the bending moment at the base of tower will be calculated as it is the maximum bending moment.

The total bending moment is calculated by Equation (10) in which C_T is the thrust coefficient, D_w is the dynamic force caused by the air flowing through the swept area, C_D is the drag coefficient of the tower, $V(z)$ and $D(z)$ are the wind speed and diameter profiles along the tower height.

$$M_{total} = C_T D_w z_{hub} + \frac{1}{2}\rho C_D \int_0^{z_{hub}} V(z)^2 D(z) z dz \tag{10}$$

The drag coefficient will be assumed to be constant and equal to 0.5 [16]. It should be noted that in the normal operation of the turbine, i.e. the wind speed lies between the cut-in and cut-out speeds, the moment caused by the thrust force is the dominant component in the total bending moment as illustrated in Figure 4. Also, from this figure, it could be concluded that the maximum bending moment will occur when the wind speed equals the nominal one of the turbines. Hence, all subsequence stress analyses will be performed at the nominal wind speed.

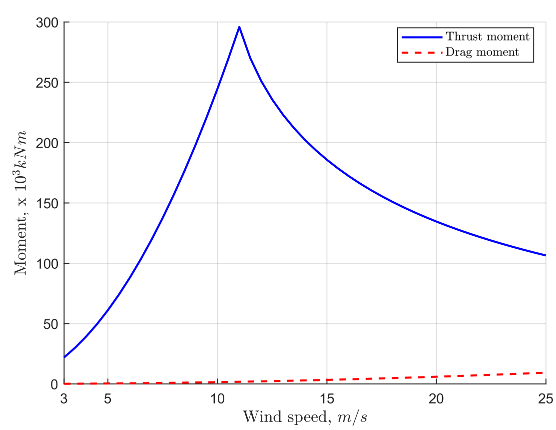

Figure 4. *Bending moment diagram*

Afterward, the maximum bending stress σ_b is calculated by multiplying the base bending moment with the base section modulus. The section modulus depends on the width-to-thickness ratio of the hollow circular section and is calculated following the instruction from EN 1993-1-1:2005 and BS 5950-1:2000. The compression stress

σ_c in the tower can be simply calculated by the ratio of the gravitational force of the lumped mass and the area of the top cross section.

The lumped mass consists of masses of the three blades, hub, nacelle and tower. In general, these masses could be approximated from empirical equations which are obtained by fitting historical data to a power function ($y = \alpha x^{\beta}$). The blade mass and hub mass can be estimated by Equation (11) and Equation (12) [18], in which the rotor radius and rated power are expressed in meters and MW, while blade and hub masses are in kilograms.

$$m_{blade} = 3.549R^{2.063} \tag{11}$$

$$m_{hub} = 8513P_n^{0.975} \tag{12}$$

The nacelle mass estimation is performed using the same approach in which the data is collected from various sources. The fitted result is shown in Figure 5.

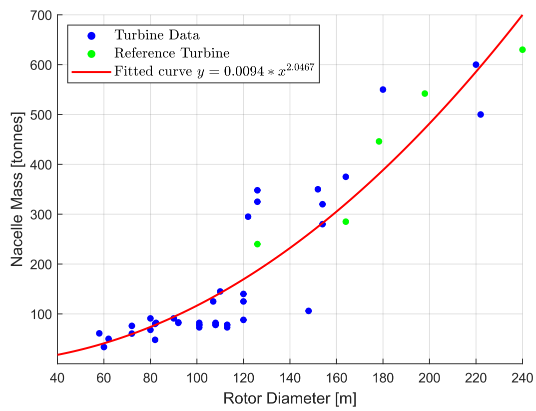

Figure 5. *Nacelle mass fitting*

Then the design stress σ_d is determined by Equation (13) as instructed in IEC 61400-3-1 and IEC 61400-1:

$$\sigma_d = \gamma_f \gamma_m \gamma_n (\sigma_b + \sigma_c) \tag{13}$$

where:

$\gamma_f = 1.25$ is the partial safety factor for load;

$\gamma_m = 1.1$ is the partial safety factor for material;

$\gamma_n = 1$ is the partial safety factor for consequences of failure.

As discussed above, there are three dimensional variables of the tower to be determined, namely, the top diameter, base diameter and thickness. To determine the optimal values of these parameters, an optimization is carried out. The objective is to minimize the tower mass, with the constraint is keep the design stress σ_d smaller than the yield strength f_y of steel.

2.3. Analyze the impact of ground clearance

Assumptions used in this analysis are summarized in Table 2. To analyze the impact of ground clearance on the AEP and tower mass, the rotor radius will be determined following the procedure described in Table 1 with GC varies from 0 to 50 meters.

After the required rotor radius is determined, the hub height will be calculated by using Equation (5). Afterward, the power curve and AEP are formulated and calculated. As GC increases, the blades get access to higher wind speed, which leads to the lower rotor radius.

Table 2. *Assumptions used in the analysis*

Category	Parameter	Unit	Value
Wind turbine	Nominal Power, P_n	MW	20
	Nominal Speed, V_n	m/s	11
	Cut-in speed, V_{in}	m/s	3
	Cut-out speed, V_{out}	m/s	25
	Ground clearance, GC	m	0 - 50
	Power Coefficient, C_p	-	0.5
	Overall Efficiency, η	-	0.85
Wind speed profile	Mean Wind speed at 80m	m/s	10
	Weibull's Shape factor, k	-	2
	Wind shear exponent, α	-	0.14
Wind turbine tower	Top diameter, D_{top}	m	1 – 10
	Base diameter, D_{base}	m	1 – 100
	Thickness, t	mm	10 – 40
	Drag coefficient, C_D	-	0.5
Steel	Density	kg/m^3	7850
	Yield strength, f_y	MPa	420

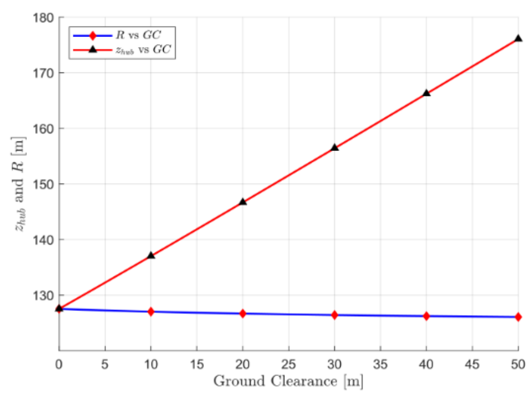

Figure 6. *Effect of increasing ground clearance to rotor radius and hub height*

Figure 6 shows that when GC increases, the rotor radius just slightly decreases from 127.53 m to 126.07 m, thus the hub height increases at roughly the same rate with GC. This effect can be explained by the fact that the wind speed at higher altitude increases slower compared to at low altitude so it required nearly the same blade length to achieve the rated power of 20 MW.

It should be noted that the minimum GC is often regulated by the regulatory agency of each state/country. For example, in Denmark, the Danish Maritime Authority required that the lowest blade tip shall be at least 20 meters above the highest astronomical tide [2]; While in United Kingdom, the Maritime and Coastguard Agency required a minimum of 22 meters between the lowest point of rotor sweep and mean high water springs [3].

3. Results and discussion

First, the effect of segment model, i.e. the number of segments N, in the wind power calculation to the rotor radius and AEP calculation is analyzed. Figure 7 shows the results of rotor radius R and AEP when increasing N from

1 to 50, using the assumptions in Table 2 and $GC = 15m$. It can be seen that when N increases from 1 to 5, both the rotor radius and AEP quickly increase, and then remain almost unchanged when the number of segments further increases. From this analysis, a value between 15 and 20 for the number of segments is sufficient to provide good results for the approximation of the AEP. In all following analyses, $N = 20$ will be used.

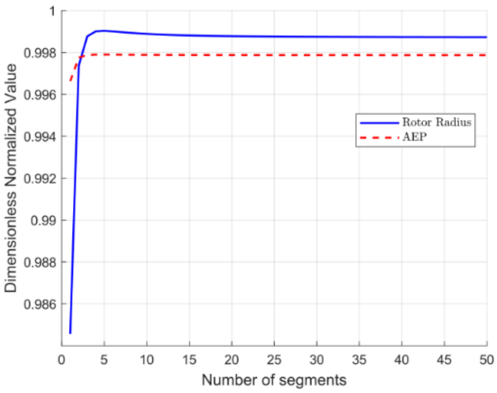

Figure 7. *AEP and R vs. Number of segments (Normalized to base values: 127 meters for R and 91,600 MWh for AEP)*

Next, the impact of GC on the AEP and tower mass is analyzed, the result is shown in Figure 8. It can be seen that AEP increases almost linearly when GC increases from 0 to 50 meters. Specifically, the AEP grows by approximately 3.10%, from 90.44 GWh to 93.24 GWh. The AEP increases when GC increases because the wind turbine has access to higher wind speed as discussed previously.

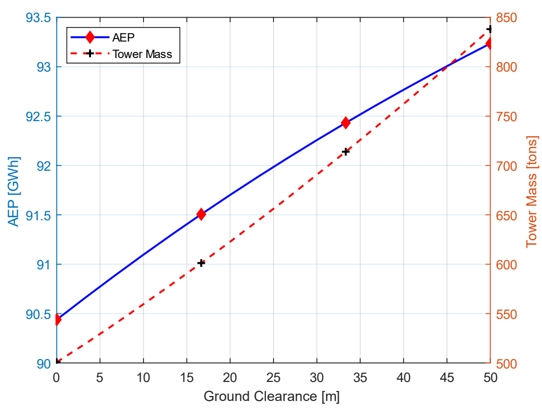

Figure 8. *Impact of GC on AEP and tower mass*

Similar to the AEP's results, the tower mass also undergoes a close-to-linear trend when GC increases from 0 to 50 meters as illustrated in Figure 8. However, the rate of the increase is much higher than the tower mass when GC is 50 m is about 1.7 times this value when there is no ground clearance. The tower height is directly impacted by the ground clearance; hence, this result is reasonable.

Afterward, the impact of the rated speed V_n is studied. The result in Figure 9 shows that both the AEP and tower mass reach their lowest values at small ground clearance and high rated speed. The rated speed of the turbine determines not only its rotor radius but also its power curve (see Figure 2). As a simplification, the energy production by a wind turbine can be interpreted as the area under the power curve. Thus, when V_n decreases, this area expands and the energy production increases accordingly.

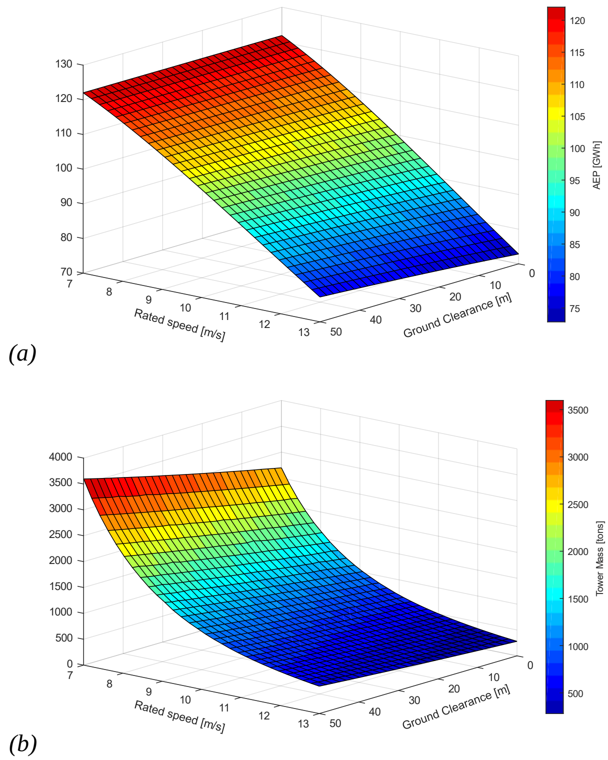

Figure 9. *Impact of rated speed and ground clearance on (a) AEP and (b) tower mass*

The impact of the ground clearance on the AEP is negligible compared to the effect of the rated speed, especially at low rated wind speed, the AEP is almost constant when GC varies. At high rated speed, the ground clearance affects AEP slightly more than at low rated speed. For example, when the rated speed is 8 m/s, the AEP only increases by 0.6% when GC increases from 0 to 50 meters. While this number is 3.1% when the rated speed is 11 m/s as shown previously, and further increases to 5.94% when the rated speed is 13 m/s. The same trend can also be observed while analyzing the impact of the rated speed and ground clearance on the tower mass. However, the ground clearance seems to have more impact on the tower mass at all rated speeds.

These effects can be explained as follows. When the rated speed is low, the rotor radius is significantly larger compared to the cases with high rated speeds. For example, when $V_n = 7m/s$, the rotor radius is about 250 meters while it is only about 98 meters in case $V_n = 13m/s$. Hence, the proportion of the ground clearance ($GC = 50m$) in the hub height is substantially increased from 16.71% to 33.79% when the rated speed increases from 7 to 13 m/s. This is the reason why the influence of the ground clearance is remarkably reduced at lower rated speed since the hub height is the determinant factor in both AEP and tower mass.

4. Conclusion

In this work, a method to estimate the wind power flowing through a circular plate as well as a simplified model for determining the dimension and mass of a tubular steel tower were developed. Then, the effect of ground clearance on the annual energy production and tower mass of a 20 MW wind turbine is analyzed. The analysis shows that the ground clearance has a large impact on the tower mass, though it only has a negligible effect on the AEP. Notably, the tower mass is nearly doubled when the ground clearance is increased from 0 to 50 meters. As the cost for material takes the most part in the cost of the turbine's tower, this implies that the tower cost could be nearly doubled as well. Furthermore, the impact of the turbine's rated speed is also analyzed and it is indicated that the rated speed has a much more significant impact on both the AEP and tower mass. This is mainly due to the major influence of rated speed on rotor radius.

Nevertheless, the model used for determining tower dimension in this study is simplistic and cannot cover necessary design load cases and structural stability analysis. Furthermore, this study ignored the logistic constraints (transportation and installation) regarding the tubular steel tower. If these constraints are to be considered, the diameter and even the height of tower will be limited. Or else, the cost structure of tower must be modified to represent the incurred cost to overcome these constraints.

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