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INFLUENCE OF THE HUB HEIGHT ON THE ON-GRID SMALL SCALE WIND TURBINE-BASED POWER SUPPLY SYSTEM

BY

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Abstract. In this paper the influence of hub height on the on-grid small scale wind turbine-based power supply system for a community consumer is presented. Based on the wind and temperature site resources, on the technical and financial characteristics of two wind turbines (BE6 and BE10), assuming different CO_2 penalties (0÷50 \$/tCO_2), different hub heights (18÷49 m), and using HOMER software, the following parameters are obtained: annual energy production AEP, [kWh/year]; annual energy purchased, [kWh/year]; annual energy sold, [kWh/year]; renewable fraction, [%]; annual CO_2 emissions, [kg/year]; operating cost, OPC [\$]; cost of energy, COE [\$/kWh]; net present cost, NPC [\$]. The optimal hub heights, in terms of COE and NPC, are: 24-30 m for BE10 wind turbine, depending on carbon dioxide penalties, and 24 m for BE6 wind turbine.

Keywords: wind turbine hub height; logarithmic profile; HOMER.

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1. Introduction

The wind turbines manufacturers recommend different installation hub heights and provide different types of towers with different heights. While for small scale wind turbines different types of towers can be used (the guyed-lattice towers, the tilt-up guyed towers, the self-supporting lattice towers, and the monopole towers), for large-scale wind turbines the free-standing steel tube towers are almost always recommended (Hau, 2006).

Selecting a tall tower will have the principal benefit in increasing the annual energy production (AEP) due to stronger and steadier winds at higher heights. Another advantage of tall towers is avoiding the large wind shear and turbulence level generated by some obstacles in the vicinity of wind turbine site. However, increasing the tower height will also increase the cost, and not only for the tower, but also for the tower transportation, for tower lifting and tower foundation, increasing thus the total cost of installed wind turbine. Different types of tall towers (80÷150 m) for wind turbines in range of 3÷5 MW have been analysed in terms of technical and financial aspects for tower, lifting and foundation in (Engström *et al*., 2010).

The optimum hub height has been analysed in terms of minimizing the AEP for a single wind turbine working at different wind speeds and different locations, thus for different roughness lengths in (Lee *et al*., 2014).

The influence of wind turbine hub heights on the AEP for a wind farm has been analysed in (Vasel-Be-Hagh and Archer, 2017). It has been found that the AEP of the multiple hub heights wind farm was approximately 2% higher than that of the single hub height wind farm.

A comparative efficiency analysis of 4 different wind turbines with different heights in terms of AEP for a certain wind resources is presented in (Bezrukovs *et al*., 2014). The wind speed distribution curves depending of the height have been comparatively obtained with power and logarithmic law.

In this paper the influence of hub height on the on-grid small scale wind turbine-based power supply system for a community consumer will be presented. Two wind turbines with rated power of 5.5 kW (BE6) and 8.9 kW (BE10) will be comparatively analysed for a specific site and a specific consumer. According to the wind turbines manufacturer recommendations, different tower heights can be used, defining thus the first sensitive parameter of this analysis, the wind turbine hub height H={18, 24, 30, 37, 43, 49} m.

The wind speed data obtained at the anemometer height will be extrapolated at the wind turbine hub height using the logarithmic law.

Considering the existing carbon dioxide penalties that vary from ≅US\$1/tCO_2÷US\$140/tCO_2, (World Bank Group, 2017), the second sensitive parameter for this study will be the carbon dioxide penalties {0, 10, 20, 30, 40, 50} \$/tCO_2.

The numerical simulation will be performed using the HOMER software, (Homer Energy, 2017), and some important technical and financial parameters will be thus obtained: annual energy production AEP, [kWh/year]; annual energy purchased, [kWh/year]; annual energy sold, [kWh/year]; renewable fraction, [%]; annual CO_2 emissions, [kg/year]; operating cost, OPC [$]; cost of energy, COE [$/kWh], and net present cost, NPC [$]. Analysing all these parameters, it has been found that optimum hub heights can be obtained for both wind turbines only in terms of COE and NPC, which are 24-30 m for BE10 wind turbine, depending on carbon dioxide penalties, and 24 m for BE6 wind turbine.

2. Wind Resources

The proposed wind turbine site for this analysis is located in Romania, in Constanța County, at the coordinates 44°29.0' N 28°37.7' E, having as neighbour at east, the village of Săcele. The temperature data will be obtained from NASA Surface meteorology and Solar Energy database (NASA Langley Research Centre Atmospheric Science Data Centre Surface meteorological and Solar Energy -SSE -web portal supported by the NASA LaRC POWER Project), (NASA Atmospheric Science Data Centre, 2017). The monthly average temperature data for the selected site are presented in Fig. 1. The maximum temperature is 23.86°C in July, while the minimum temperature is 1.98°C in January, the temperature range is 21.88°C, and the annual average temperature is 12.69°C.

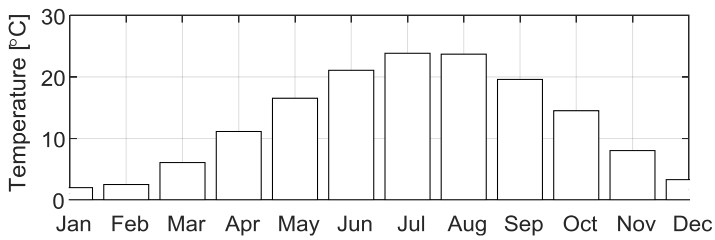


Fig. 1 – The monthly average temperature.

As for the wind speed, let us assume that by on-site measurement at anemometer height of 50 m, the following annual wind speed distribution has been obtained, Fig. 2. The measurement process has been defined with 30-seconds measurement time span, and 1-hour average time span, so there are 8760 data points. Analysing the wind speed data, the annual average wind speed is obtained V_m = 6.8 m/s. As for the wind speed variation with height, the logarithmic law with surface roughness length 0.05 m has been considered.

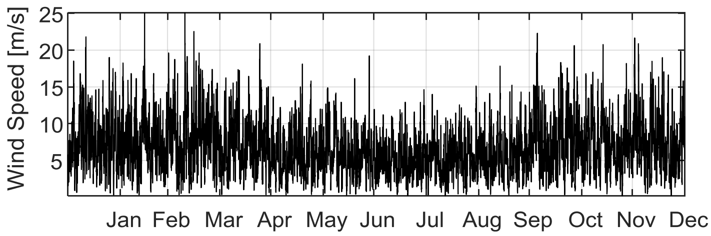


Fig. 2 – The annual wind speed at 50 m.

3. Electric Load

Let us suppose that there is a single consumer, a community consumer, for which the consumption parameters are: the annual energy consumption 27375 kWh/year; the daily average energy consumption 75 kWh/day; the daily average power 3.13 kW; the peak load 9.41 kW. The daily average load profile for this particular type of consumer is presented in Fig. 3.

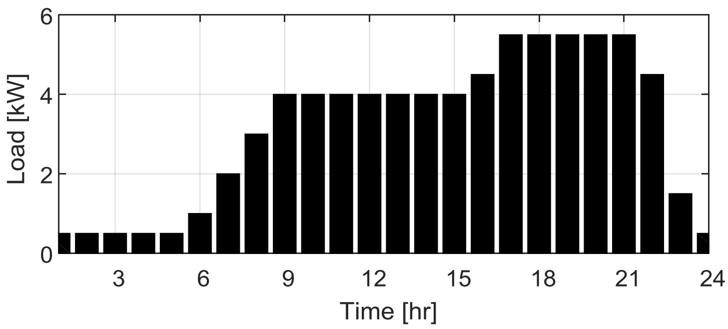


Fig. 3 – Daily average load profile.

4. Power Supply System

The power supply system is composed by the consumer, the grid and a wind turbine, and has the following principal characteristics: lifetime - 20 years; nominal discount rate - 8%; expected inflation rate - 2%; currency - $; grid power price - 0.113 $/kWh; grid sellback price - 0.09 $/kWh; carbon dioxide penalty {0,10, 20, 30, 40, 50} $/t$CO_2$. Two horizontal axis wind turbines will be comparatively analysed Bergey Excel 6 (BE6) and Bergey Excel 10 (BE10). The principal characteristics of these two wind turbines are presented in Table 1 (Bergey WindPower, 2017). The wind turbine can be installed on a guyed-lattice tower with 6 different heights, the hub height having the values H={18, 24, 30, 37, 43, 49} m. The price of these 6 different height towers is presented in Table 2 (Bergey WindPower, 2017).

Table 1
Wind Turbine Characteristics

Characteristic	Unit	BE6	BE10
Rated power	[kW]	5.5	8.9
Rated wind speed	[m/s]	11	
Cut in wind speed	[m/s]	2.5	
Rotor diameter	[m]	6.2	7
Weight	[kg]	350	545
Price	[$]	21995	31770

Table 2
Wind Turbine Tower Price

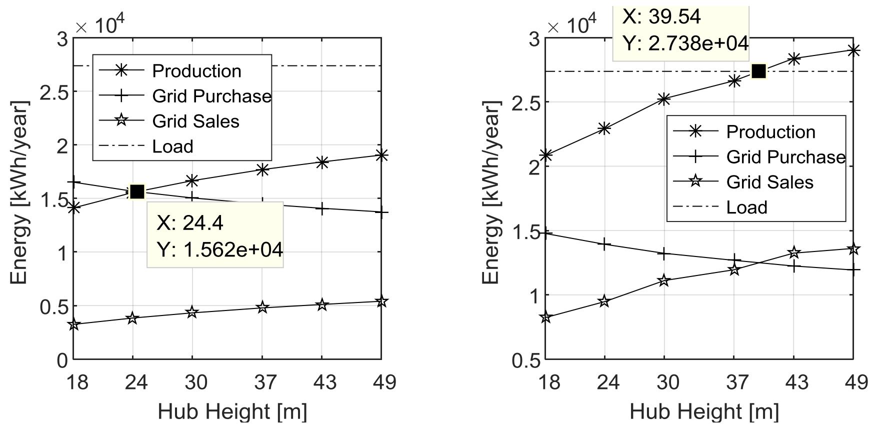
Height, [m]	18	24	30	37	43	49
Price, [$]	10350	11525	14145	17965	20385	23995

5. Methodology

Considering 2 wind turbines working at 6 hub heights with 6 carbon dioxide penalties, this will define 72 different problems which will be simulated and solved using the HOMER software. For every case, the solution will provide numerical values for the most important technical and financial parameters of the power supply system: net present cost - NPC, [$]; levelized cost of energy - COE, [$/kWh]; operating cost - OPC, [$]; renewable fraction, [%]; CO_2 emissions, [kg/year]; initial capital, [$]; annual energy production, [kWh/year]; annual energy purchased from the grid, [kWh/year]; annual energy sold to the grid, [kWh/year]. The numerical results will be analysed with respect to the hub height, and the carbon dioxide penalties, comparatively for both wind turbines.

6. Results and Discussion

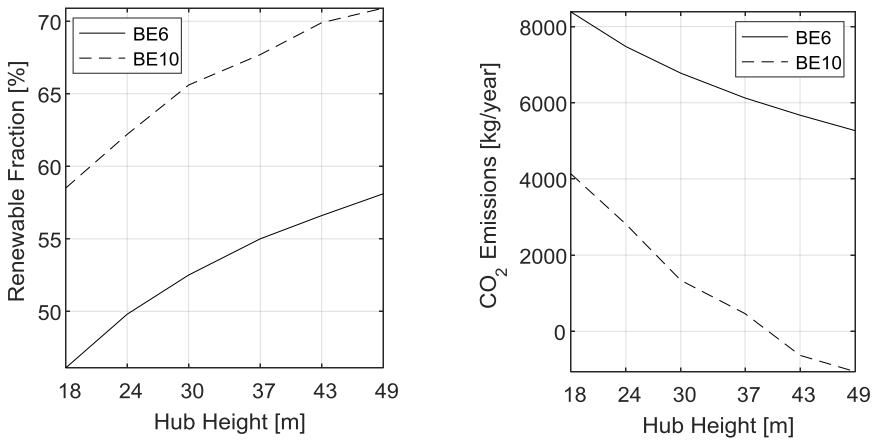
The first and the most important parameter that will be analysed is the wind turbine annual energy production (AEP), which is presented together with energy purchased from the grid, energy sold to the grid, and the load in Fig. 4*a* for wind turbine BE6 and Fig. 4*b* for wind turbine BE10.



a) BE6 *b*) BE10

Fig. 4 – Energy parameters.

For both wind turbines, the annual energy production increases with the hub height, which is an expected result. For BE6 wind turbine, no matter the hub height, the annual energy production is lower than the power load. Moreover, until 24.4 m, the annual energy production is lower than the energy purchased from the grid too. On the contrary, for the BE10 wind turbine, after 39.54 m the annual energy production is greater that the power load, thus the energy purchased form the grid will become smaller that the energy sold to the grid. For every hub height, the annual energy production is greater than the energy purchased from the grid.



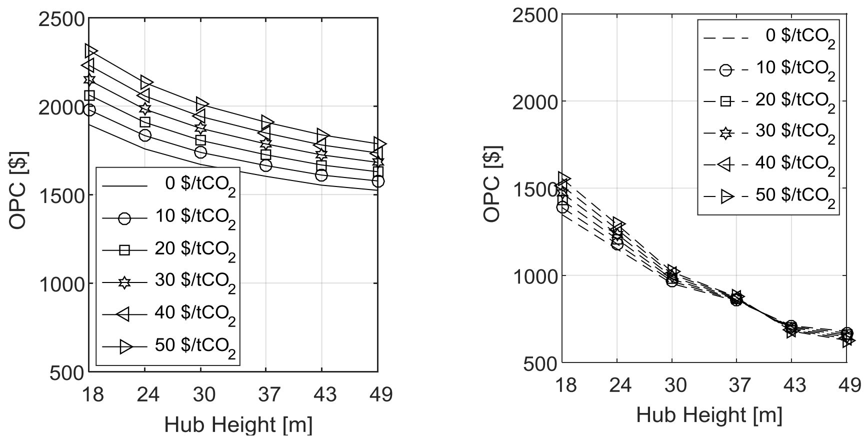
a) renewable fraction *b*) CO_2 emissions

Fig. 5 – Energy related parameters.

The renewable fraction and the CO_2 emissions are presented in Fig. 5*a* and Fig. 5*b*, comparatively for both wind turbines. Increasing the hub height, these parameters are better, higher renewable fraction, and lower emissions. Interesting to note that for BE10 wind turbine, after the hub height 39.54 m, the CO_2emissions becomes negative due to higher energy sales to the grid than energy purchased from the grid.

The parameters discussed above (wind turbine annual energy production, energy purchased from the grid, energy sold to the grid, renewable fraction, and carbon dioxide emissions) are independent of the carbon dioxide penalties. On the other side, the parameters that will be further discussed OPC, COE and NPC, are dependent on the carbon dioxide penalty.

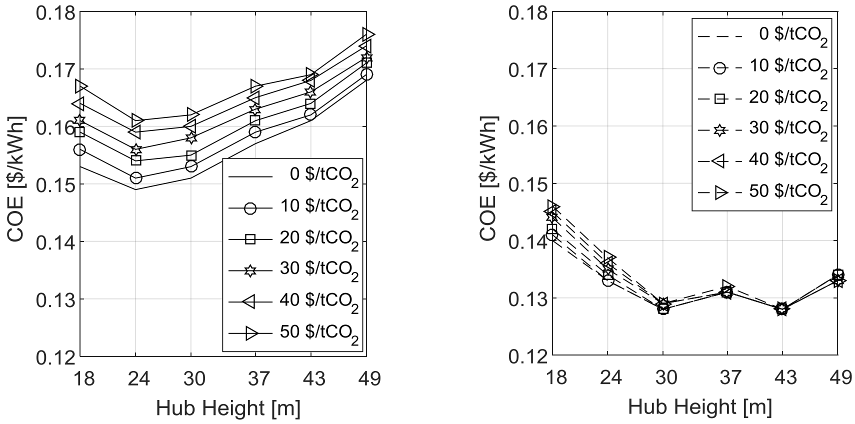
The annualized value of all costs and revenues other than initial capital costs (OPC) is presented in Fig. 6*a* for BE6 and Fig. 6*b* for BE10.The operating cost decreases with the hub height and increases with the CO_2 penalty. For BE10 wind turbine and for hub heights greater than 39.54 m, there is a different behaviour, where the operating cost decreases with CO_2 penalty due to negative CO_2 emissions. Due to higher energy production, for power supply system with the BE10 wind turbine, for any hub heights, and for any carbon dioxide penalties, the operating costs are lower than for the power supply system with BE6 wind turbine.



a) BE6 *b*) BE10

Fig. 6 – Operating cost.

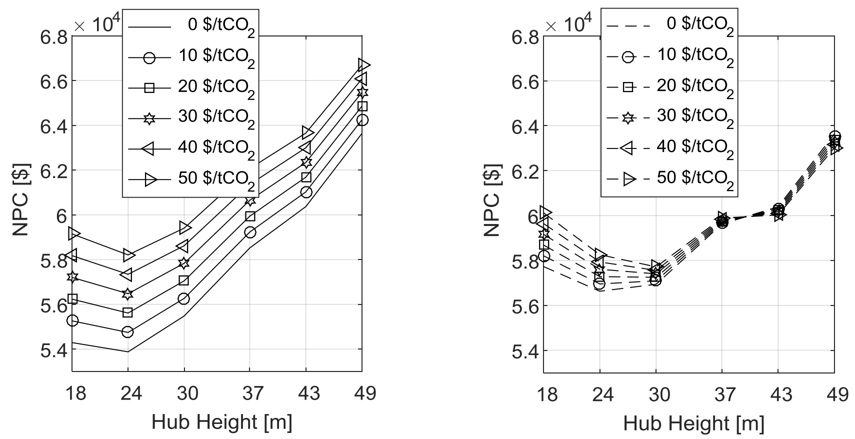
The average cost per kWh produced by the power supply system (COE) is presented in Fig. 7*a* for BE6 and Fig. 7*b* for BE10. This is the first parameter that can define the optimal hub height for both wind turbines, more clearly for BE6, for which 24 m is, without doubt, the optimal hub height, but also for BE10 as well, for which 30 m will represent the optimal hub height. These heights, 24 m for BE6, and 30 m for BE10, are the hub heights for which the minimum values of the levelized cost of energy can be reached. The second minim point that can be observed for BE10, at 43 m, could be a consequence of the phenomena at the hub height of 39.54 m, and probably will not exist if the energy purchased from the grid will be greater than the energy sold to the grid, which is not the case for this study.



a) BE6 *b*) BE10

Fig. 7 – Levelized cost of energy.

The present value of all the costs of installing and operating the power supply system, minus the present value of all the revenues that it earns over the lifetime (NPC) is presented in Fig. 8*a* for BE6 and Fig. 8*b* for BE10.



a) BE6 *b*) BE10

Fig. 8 – Net present cost.

This is the second parameter that will define the optimal hub height, in fact will validate or not the optimal hub height obtained in terms of levelized cost of energy.For BE6 wind turbine, the optimal hub height is also 24 m, as it has been obtained in terms of COE; for all values of carbon dioxide penalty, the NPC curves having a minimum point at 24 m hub height.

For BE10 wind turbine, the optimal hub height is 30 m, as it has been obtained in terms of COE, but only for the last four values of carbon dioxide penalties. For the first two carbon dioxide penalties, 0\$/tCO_2 and 10 \$/tCO_2, it appears that the optimal hub height is 24 m.

The initial investment for installing both wind turbines at different heights is presented in Fig. 9.

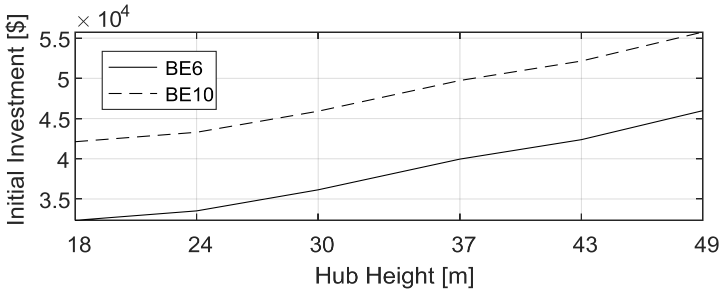


Fig. 9 – Initial investment.

7. Conclusions

Increasing the wind turbine hub height, a significant improvement of the power supply system can be observed related with the following parameters: annual energy production, annual energy purchased from the grid, and annual energy sales to the grid, Fig. 4; renewable fraction and carbon dioxide emissions, Fig. 5. On the other hand, increasing the hub height, the total initial investment increases as well, Fig. 9.

For BE6 wind turbine, an improvement can be observed on the operating cost too, which will decrease with respect to the hub height, Fig. 6*a*. A much better improvement is related with the operating cost for the second wind turbine, BE10, for which this parameter will decrease with increasing hub height, but after a certain critical height (39.54 m), will decrease, and with the rise of the carbon dioxide penalties, Fig. 6*b*. This critical hub height, 39.54 m, represents for the BE10 wind turbine, the height for which the annual energy production becomes equal with the power load, the annual energy purchased from the grid becomes equal with the annual energy sales to the grid, Fig. 4*b*; and, finally, the carbon dioxide emissions becomes zero, Fig. 5*b*. Based on these observation, it can be concluded that for a certain site and a certain consumer, the selected wind turbine will have a better impact on the carbon dioxide emissions if two more aspects will be satisfied: the existence of this critical hub height (for example, for BE6 wind turbine this critical point cannot be observed, Fig. 6*a*, and the installation hub height should be greater than this critical height.

The levelized cost of energy is the first parameter which clearly indicate the optimum hub height for both wind turbines: 24 m for BE6 wind turbine, Fig. 7*a*, and 30 m for BE10 wind turbine, no matter the carbon dioxide penalties.

For BE6 wind turbine, and for all carbon dioxide penalties, the net present cost will indicate the same optimum hub height, 24 m, Fig. 8*a*. For BE10 wind turbine, the carbon dioxide penalties will indicate two different optimum hub heights: 30 m for carbon dioxide penalties in range of 20÷50 $/tCO_2$, and 24 m for carbon dioxide penalties in range of 0÷10 $/tCO_2$.

The results presented in this paper are strongly dependent on the site wind resource, and the wind turbine technical and financial parameters, having thus, the significance of a case study.

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INFLUENȚA ÎNĂLȚIMII DE AMPLASARE A ROTORULUI UNEI TURBINE EOLIENE DE MICĂ PUTERE DINTR-UN SISTEM ON-GRID DE ALIMENTARE CU ENERGIE ELECTRICĂ

(Rezumat)

În lucrare se prezintă un studiu privind influența înălțimii de amplasare a rotorului unei turbine eoliene de mică putere dintr-un sistem on-grid de alimentare cu energie electrică a unui consumator de tip comunal. Pornind de la parametrii energetici eolieni ai locației propuse, de la caracteristicile tehnice și economice a două turbine eoliene, care vor fi analizate comparativ (BE6 și BE10), adoptând diferite valori pentru taxa pe emisiile de dioxid de carbon (0÷50 $/t$CO_2$), diferite înălțimi de amplasare a rotorului turbinei eoliene (18÷49 m) și folosind programul HOMER, s-au calculat următorii parametri: energia anuală produsă de turbinele eoliene, [kWh/an]; energia anuală cumpărată din rețea, [kWh/an]; energia anuală vândută în rețea, [kWh/an]; procentul din energia totală produs de turbina eoliană, [%]; emisiile anuale de CO_2, [kg/an]; valoarea anuală a costurilor și veniturilor, exclusiv costurile inițiale, OPC [$]; costul mediu pentru producerea fiecărui kWh, COE, [$/kWh]; valoarea actuală a tuturor costurilor de instalare și funcționare și a tuturor veniturilor obținute pe întreaga perioadă normală de funcționare, NPC, [$]. În funcție de COE și NPC au fost obținute următoarele valori ale înălțimii optime de amplasare pentru cele două turbine eoliene: 24-30 m pentru cazul BE10 în funcție de taxa pe emisiile de CO_2 și 24 m pentru cazul BE6.