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# Optimum hub height of a wind turbine for maximizing annual net profit

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ABSTRACT

The optimization method of the hub height, which can ensure the economic feasibility of the wind turbine, is proposed in this study. Annual Net Profit is suggested as an objective function and the optimization procedure is developed. The effects of local wind speed and wind turbine power characteristics on the optimum hub height are investigated. The optimum hub height decreased as the mean wind speed and wind shear exponent increased. Rated power had little effect on optimum hub height; it follows that the economies of scale are negligible in the rated power range of 0.75–3 MW. Among the wind turbine power characteristics, rated speed and cut-out speed most strongly affected the optimum hub height.



## 1. Introduction

Wind power is an effective solution to environmental issues, such as air pollution and the exhaustion of fossil fuels, because it is pollution-free and renewable. It can be also utilized as a distributed power source that can reduce peak loads in an electrical power system. Due to these advantages, wind power capacity is increasing globally. According to the Global Wind Energy Council (GWEC) [1], the cumulative worldwide wind power capacity was 318.1 GW at the end of 2013 and is increasing continuously. Particularly, Asia is the largest wind power market worldwide, and the wind power capacity in Asia increased by about 18.2 GW in 2013, based on China, India, Japan, and South Korea [1]. Wind capacity increased by about 1 GW in the US, for a total cumulative capacity of 61.1 GW at the end of 2013 [2]. In Europe, 11.2 GW of wind power were installed in 2013 and wind power accounted for 8% of the total electricity consumption [3]. Due to this global trend, research on wind turbine issues is being conducted in various fields.

Many studies have been reported on the optimal site matching of wind turbines [4–8], because wind power depends highly on location. Jowder [4] performed site matching study in Kingdom of Bahrain using the measured wind speed data. Adaramola et al. [5] conducted the assessment of wind power along the coast of Ghana. EL-Shimy [6] studied optimal site matching for the wind turbines in the Gulf of Suez region. Dong et al. [7] conducted assessment of wind potential and selected suitable wind turbine in Huitengxile of Inner Mongolia, China. Chang et al. [8] assessed the wind resources in various regions by using a normalized turbine performance index. Though these site matching studies provide useful results, their scope was limited to the appropriate choice of specific wind turbine products for particular region, and the design optimization of the wind turbine components were not carried out in those studies.

The importance of site matching of wind turbines is attributed to the fact that the vertical wind speed characteristics vary with the location. From this point of view, the optimization of hub height of the wind turbine is important, since hub height determines the wind speed applied on the wind turbine generator. Specifically, the power characteristics of wind turbines are invariant in terms of hub height, and wind speed increased with altitude. Thus, energy production can increase with the increase of the hub height as long as the hub height does not affect the operation of a wind turbine, because the wind turbine do not operate in the conditions of excessive wind speed for safety. Considering the fact that the hub height also affects the initial capital cost of a wind turbine, it is an important factor that affects both energy production and initial capital cost. The hub height should be optimized in a way that maximizes the net profit, which can be calculated by converting the amount of energy production and the initial capital cost into an appropriate common unit.

Although several studies were reported on optimizing the wind turbine hub height [9–16], there were the limitations that the economic feasibility could not be ensured as the net profit was not considered in the objective function. Al-Hadhrami [9] recommended suitable hub height for small wind turbines under 80 kW based on Capacity Factor (*CF*). Similarly, Alam et al. [10]

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**Nomenclature**

| | | | |
|---|---|---|---|
| $AEP$ | amount of annual energy production (kW h) | $P_r$ | rated power of the wind turbine (kW) |
| $ANP$ | annual net profit ($) | $P(\upsilon)$ | wind turbine power output |
| $c_e$ | electricity selling price per 1 kW h ($/kW h) | $T$ | hours of one year |
| $c_{O\&M}$ | operation and Maintenance costs per 1 kW h ($/kW h) | $\upsilon$ | wind speed (m/s) |
| $c_{P_r}$ | installation cost per 1 kW ($/kW) | $\bar{\upsilon}$ | mean wind speed (m/s) |
| $FCR$ | fixed charge rate | $\bar{\upsilon}_{ref}$ | mean wind speed measured at $h_{ref}$ (m/s) |
| $f(\upsilon)$ | wind probability density function | $V_{in}$ | wind turbine cut-in speed (m/s) |
| $h$ | wind turbine hub height (m) | $V_{out}$ | wind turbine cut-out speed (m/s) |
| $h_{opt}$ | optimum hub height (m) | $V_r$ | wind turbine rated speed (m/s) |
| $h_{ref}$ | reference altitude for wind speed measurement (m) | $\alpha$ | wind shear exponent |
| $ICC$ | initial capital cost ($) | | |

obtained the optimum hub height for 600–2500 kW sized wind turbine by calculating energy production using *CF*. However, they could not ensure economic feasibility because initial capital cost was not considered in the *CF*. Rehman et al. [11] obtained the optimum hub height using the amount of energy production and initial capital cost. However, the calculation was not accurate because they simply compared the amount of energy production with the initial capital cost as percentages, without converting the values into appropriate common units. Mirghaed et al. [12] optimized wind turbine design using Cost of Energy (*COE*) as an objective function and Maki et al. [13] also developed the multi-level system design algorithm for wind turbines based on *COE*. Though *COE* considers the initial capital cost as well as energy production, the net profit is not calculated; thus, it cannot judge the economic feasibility. More recently, Albadi et al. [14] proposed the turbine-site matching index (*TSMI*) as an objective function for optimizing the wind turbine systems. Chen et al. investigated the wind turbine tower height matching problem in the wind farm [15] and developed an iteration method for the same problem [16] using *TSMI*. However, *TSMI* cannot be used as an objective function to judge the economic feasibility. Therefore, In order to evaluate the economic feasibility of the wind turbines, the new objective function is needed that can calculate the net profit.

The purpose of this study is to optimize the hub height to ensure economic feasibility by calculating the net profit. The net profit of a wind turbine involves subtraction of the initial capital costs from the profit from energy production. To calculate the net profit of a wind turbine, annual net profit (*ANP*) is used as an objective function to optimize hub height. Hub height optimization procedure considering *ANP* is described briefly, and the effects of the local wind speed and wind turbine power characteristics on the optimum hub height are investigated.

## 2. Annual Net Profit

To calculate *ANP*, the profit from energy production and the costs are converted into 1-year units. The annual profit is calculated by converting annual energy production into annual electricity sale revenue, and the annual cost is calculated by adding annual operating and maintenance costs and initial capital costs, converted into 1-year units.

The operating and maintenance costs can be expressed considering the rated power or the amount of energy production of the wind turbine [17]. It is assumed that the operating and maintenance costs are proportional to the amount of energy production. In this study, the effects of economies of scale, which result from many factors, such as, reduced material consumption and civil works, are also considered. Such effects were shown in many wind turbine installation cases [18]. The major assumptions when calculating *ANP* are as follows:

(1) All electricity from a wind turbine is sold.
(2) Operating and maintenance costs are proportional to the amount of energy production.
(3) Initial capital cost increases linearly with hub height.
(4) Initial capital cost per unit capacity decreases linearly with the rated power of a wind turbine.

*ANP* is expressed based on these assumptions as follows:

$$ANP = (c_e - c_{O\&M})AEP - FCR \cdot ICC \tag{1}$$

Here, *AEP* is the amount of annual energy production, *FCR* is the fixed charge rate, and *ICC* is the initial capital cost. $c_e$ and $c_{O\&M}$ are the electricity selling price and the operating and maintenance costs per 1 kW h, respectively. *FCR* is a factor by which the *ICC* is multiplied to convert the initial capital cost into an annual cost. This factor is determined by a comprehensive consideration that includes the wind turbine lifespan, interest rate, and state of capital [19]. *AEP* is determined by the power characteristics and the wind distribution, and *ICC* is determined by the rated power and hub height of a wind turbine.

### 2.1. AEP

*AEP* is calculated using the wind probability density function $f(\upsilon)$ and wind turbine power output $P(\upsilon)$.

$$AEP = T \cdot \int_0^\infty f(\upsilon)P(\upsilon)d\upsilon \tag{2}$$

where $T = 8760$ to convert the units of *AEP* from hours to years, and the integral term denotes the expected power.

$f(\upsilon)$ can be expressed as a Rayleigh distribution [20], determined by $\bar{\upsilon}$, via the following formula:

$$f(\upsilon) = \frac{\pi}{2}\frac{\upsilon}{\bar{\upsilon}}\exp\left\{-\frac{\pi}{4}\left(\frac{\upsilon}{\bar{\upsilon}}\right)^2\right\} \tag{3}$$

where $\upsilon$ is the wind speed and $\bar{\upsilon}$ denotes the mean wind speed. Fig. 1 shows the shape of $f(\upsilon)$ at various $\bar{\upsilon}$. In a wind turbine, $\bar{\upsilon}$ is determined by hub height. The vertical distribution of $\bar{\upsilon}$ with altitude is usually modeled with a logarithmic law or a power law. A logarithmic law had disadvantage in that it was difficult to be applied for general engineering studies [21]. In this study, a power law is used, because it is valid over a wide altitude range (30–300 m) [22], and is more frequently used in engineering problems [23]. The power law can be written as follows:

$$\bar{\upsilon} = \bar{\upsilon}_{ref}\left(\frac{h}{h_{ref}}\right)^\alpha \tag{4}$$

Here, $h_{ref}$ is the reference altitude where the wind speed is measured, and $\bar{\upsilon}_{ref}$ is the mean wind speed measured at $h_{ref}$. $h$ is the