International Journal of Smart Grid and Clean Energy

Economic sensitivity analysis for the improvement in the energy capture of wind turbine generator

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Abstract

Recently, the installed capacity of wind power generators (WTGs) has significantly increased as an effort to reduce greenhouse gas emissions. The current technology for a WTG may utilize only 80% of theoretically maximum wind energy, and thus, related studies have been conducted to maximize its electricity production. If the price of a WTG becomes expensive due to advanced technologies, the improved profitability of a wind plant project is not a natural outcome from the increased energy yield. However, the economic analysis related to the increased wind energy capture has not been sufficiently addressed. Therefore, in this study, we perform the economic sensitivity analysis for the improvement in the energy capture of a WTG. Specifically, we examine the decrease in the levelized cost of energy (LCOE) due to the increased energy production; then, we analyze the acceptable increase in the capital cost of a WTG in the view of economic feasibility. The results show that both the reduction in LCOE and the acceptable increase in the capital cost are linearly proportional to the percent increase in the energy production of a WTG. Further, it is found that the economic effect is possibly the best for time-of-use (TOU) electricity pricing scheme.

Keywords: Wind turbine generator, economic analysis, sensitivity analysis, cost of energy

1. Introduction

Global warming due to greenhouse gas (GHG) emissions is a worldwide issue that threatens the survival of human being. As one of the measures against the problem, many studies on and applications of renewable energy sources (RESs) have recently been done in the electric sector. Among RESs except hydropower, wind power is the largest proportion of approximately 53%, of which the globally cumulative installed capacity has exponentially increased during the last 10 years from 93,924 MW in 2007 to 539,123 MW in 2017 [1, 2]. The global wind power generation in 2017 was 1,123 TWh, about 4.4% of total world electricity generation, although the installed capacity was about 7.5% [3].

Such discrepancy between the aspects of energy production and power capacity occurs mostly due to the variability and intermittency of wind. However, there is also a technology factor. According to Betz's law, the theoretically maximum energy extracted from wind is approximately 59% of the wind kinetic energy [4]. In contrast, the current technology for a wind turbine generator (WTG) may utilize only 80% of the theoretically maximum energy [5]. Therefore, there is still room for technological improvement, and related studies have been conducted to maximize electricity production from wind power.

The research on the maximization of wind energy capture has been done in two respects; one is the wind turbine itself and the other is the control strategy of the WTG. The previous studies on the wind turbine itself are as follows. In [6], blades are optimally designed to maximize the energy production, and accordingly minimize the cost of energy. In [7], a method to determine the geometric parameters of the blade is presented for the objective of maximizing the energy production. The airfoil of large wind turbine blades is optimally designed to achieve a large power coefficient in [8]. It is shown in [9] that the energy

* Manuscript received March 3, 2019; revised February 3, 2020.
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doi: 10.12720/sgce.9.2.330-337

production can be increased by maximizing the aerodynamic performance of a wind turbine blade. In a different aspect, there are attempts to integrate the superconducting generator with low loss and high reliability, which lead to the increase in energy production [10, 11].

Various control and operational schemes for WTGs have been presented to maximize the energy capture. An adaptive control algorithm for maximum power point tracking (MPPT) is proposed in [12]. A MPPT method using hill climbing searching without speed sensors is proposed in [13]. An efficient universal MPPT control without predetermined turbine characteristics and a nonlinear MPPT control based on feedback linearization are presented in [14] and [15], respectively. In [16], a robust output feedback controller is proposed to maximize the energy production in the presence of uncertainties in the parameters and dynamics of a wind turbine. In [17], the highest output power is achieved by determining the optimal angle of attack using computational fluid dynamic methodology. A nonlinear predictive controller asymptotic output tracking scheme is proposed in [18] to maximize the energy production.

Since the construction of a wind plant, particularly an offshore wind plant, is a project with huge capital, such technological advancement should be meaningful if it leads to improving the economic feasibility of the project. Moreover, if the price of a WTG becomes expensive due to the advanced technologies, the improved profitability of the project is not a natural outcome from the increased energy yield. In that situation, the issue of economic feasibility assessment becomes more important. However, the economic analysis related to the increased wind energy capture has not been sufficiently addressed in the literature. Therefore, in this study, we perform the economic sensitivity analysis for the improvement in the energy capture of a WTG. Specifically, first, we examine how much the levelized cost of energy decreases due to the increase in energy production of a WTG; second, we analyze how much the captital cost of a WTG is allowed to increase in the view of economic feasibility. These analyses are performed using the sensitivity analysis function of HOMER software.

The remainder of this paper is organized as follows. The modeling of a WTG and its economic charateristics are described in Section 2. The simulation parameters, such as wind speed and electricity prices, are also presented in Section 3. The simulation results and the associated economic analyses are presented in Section 3. Finally, concluding remarks are given in Section 4.

2. Modeling and Simulation Setup

2.1. Characteristics of WTG

A generic 10 kW wind turbine model with the rated speed of 15 m/s, cut-in speed of 3 m/s, and cut-out speed of 24 m/s is selected. The power curve with respect to wind speed is given in Fig. 1. Its initial capital cost and operation and maintenance (O&M) cost are set to $20,000 and $200 per year, respectively, considering the data in [1]. The lifetime is 20 years. The capacity of converter system is 10 kW, and its initial capital cost is set to $300. The efficiency and the lifetime of the converter are 95% and 15 years, respectively.

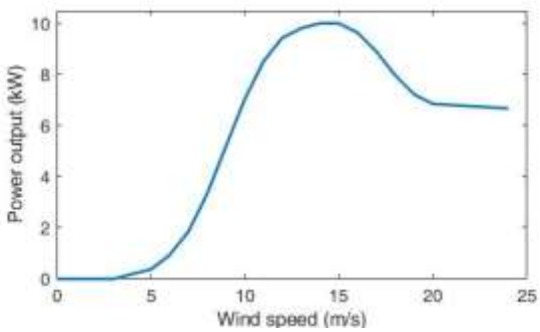

Fig. 1. Power output curve for the selected 10 kW wind turbine.

The location is set at 35 degrees latitude and 126 degrees east longitude, which corresponds to West

Sea area of South Korea. The wind speed is composed for the location using the NASA surface meteorology and solar energy database [19] by scaling at the annual average of 5 m/s. The box plots and hourly profiles for annual wind speed and wind power output are shown in Fig. 2. The total energy production in this condition is calculated as 8,321 kWh per year except the loss due to the converter.

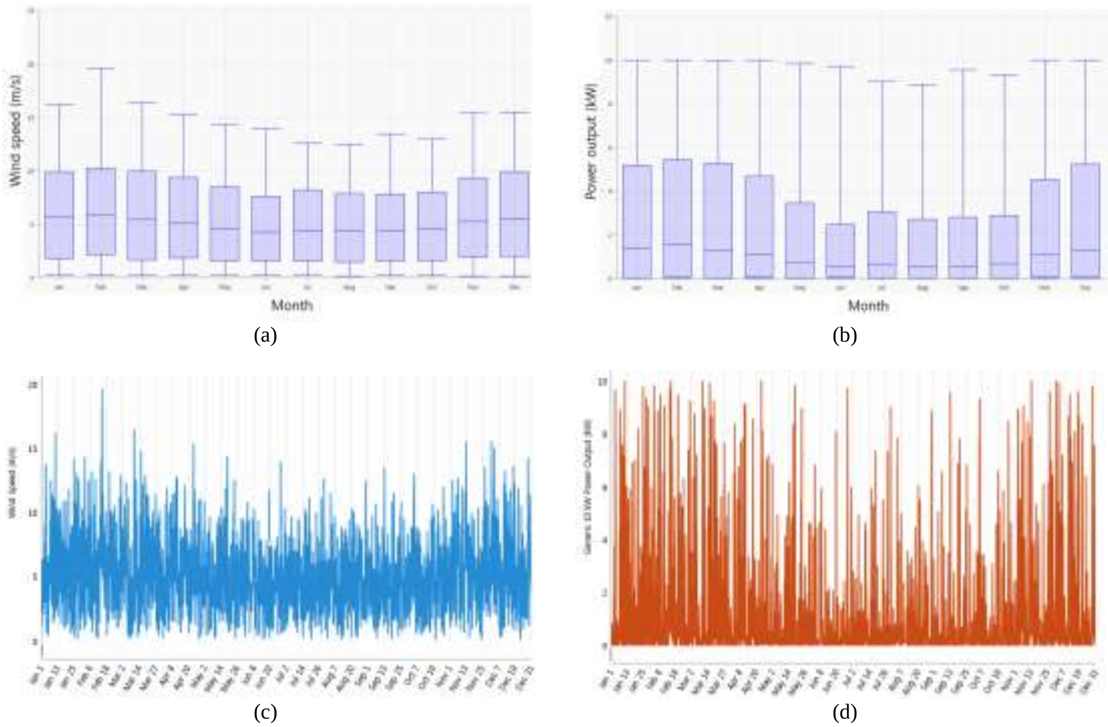

Fig. 2. Monthly statistical data of (a) wind speed in m/s and (b) wind power output in kW, and hour profiles of (c) wind speed in m/s and (d) wind power output in kW.

2.2. Economic parameters

Three kinds of rate schemes for the electricity price are considered; uniform, time-of-use (TOU), and real-time pricing (RTP). The price values for TOU pricing and RTP are taken from Korean data of [20] and [21], respectively. The hourly prices of all the rate schemes are adjusted such that the average hourly price is equal to $0.1/kWh. The specific prices of the schemes are shown in Fig. 3.

The economic analysis is based on the net present cost and levelized cost of energy (LCOE), which are calculated by the HOMER software. The related parameters are discount rate and project lifetime, which are set to 6% and 25 years, respectively.

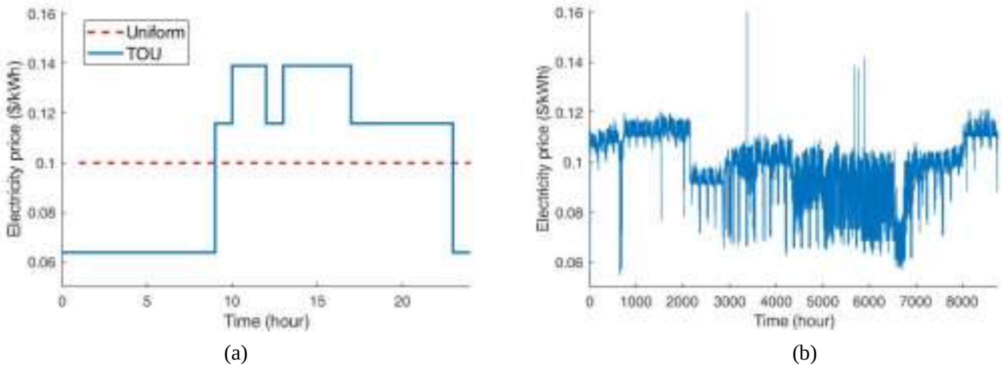

Fig. 3. Electricity prices: (a) Uninform pricing (dotted) and TOU pricing (solid), and (b) Real-time pricing (RTP).

2.3. Simulation cases

The improvement in the energy production of a WTG is modeled as the change of the power curve in Fig. 1. For example, a WTG which can generate 5% more electricity is composed by multiplying the base power curve in Fig. 1 by the value of 1.05. Thus, other characteristics of a WTG, such as rated speed and converter efficiency, are used unchanged.

The base WTG and ten improved WTGs from 1% to 10% improvement in energy production are considered in the simulations. The annual average of wind speed and the average hourly electricity price are set to 5 m/s and $0.1/kWh, respectively. In the first simulations, the LCOE is calculated and compared for each WTG. In the second simulations, the sensitivity analyses are performed to examine the acceptable increase in the capital cost of WTG. Further, in the second simulation, two value of the annual average of wind speed, 4 m/s and 6 m/s, are additionally considered to investigate the effects of the worse and better weather condition, respectively. Three pricing schemes in Fig. 3 are separately applied in all the simulations.

3. Results and Discussion

3.1. Changes in LCOE

The values of LCOE for all the simulation cases are listed in Table 1. The LCOE decreases by approximately the same value of $0.002/kWh as the energy production of WTG increases by 1% for all the pricing schemes. In other words, the reduced value of LCOE is linearly proportional to the percent increase in the energy production. The reason for the similar reduction in LCOE is that the increase in energy production is the same for each 1% improvement, which results in the same change in the revenue by selling the electricity. However, it should be noted that the reduction of LCOE does change for each 1% improvement because the total energy production is placed in the denominator when the LCOE is calculated and it changes for each improved WTG case. If the reduction of LCOE is expressed as a ratio, it corresponds to the decrease by about 1.3%–1.4% every 1% increase in the energy production.

It can be seen from Table 1 that the LCOE for TOU pricing scheme is lower than those of uniform pricing and RTP schemes. It happens because the electricity prices are higher at the time of more electricity generation of a WTG for the TOU pricing. This presumption can be quantitatively verified by computing the correlation coefficient between the electricity prices and the electricity generation of a WTG. The correlation coefficient is equal to zero for the uniform pricing according to its definition. The correlation coefficients for TOU pricing and RTP are 0.2174 and 0.1711, respectively. The correlation coefficient for TOU pricing is the largest. Consequently, the LCOE for the TOU pricing scheme becomes the lowest in this study.

Table 1. LCOE of base WTG and improved WTGs.

WTG	LCOE ($/kWh)		
Pricing scheme	Uniform	TOU	RTP
Base WTG	0.154	0.142	0.150
1%-improved	0.152	0.139	0.148
2%-improved	0.149	0.137	0.145
3%-improved	0.147	0.134	0.143
4%-improved	0.145	0.132	0.140
5%-improved	0.142	0.130	0.138
6%-improved	0.140	0.127	0.136
7%-improved	0.138	0.125	0.134
8%-improved	0.136	0.123	0.131
9%-improved	0.133	0.121	0.129
10%-improved	0.131	0.119	0.127

3.2. Changes in GHG emissions

The estimated GHG emissions, such as carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen oxides (NOx), for all the simulation cases are listed in Table 2. The estimated GHG emissions are simulated with HOMER software assuming that the hourly wind generation is supplied with that from a 10kW diesel generator. Therefore, a value in Table 2 means that a WTG may reduce a corresponding GHG emission by that amount if it is used instead of the diesel generator.

Table 2 shows the base WTG can reduce considerable amount of GHG emissions. In addition, 5% and 10% improvement in energy capture of WTG may achieve the additional reduction in CO2 emission by 0.88% and 1.74%, respectively. A corresponding reduction in other GHG emissions can also be achieved with the improved WTG. Although the absolute reduction of approximately 1% is not so remarkable, it is noteworthy that this environmental benefit can be achieved by improving only one property. Further, if the reduction in GHG emissions is translated into monetary value in an emission trading market, an additional decrease in the LCOE of WTG may be obtained. Therefore, it can be verified that the improvement in energy capture of WTG can make not only the positive environmental effects, but also the economic effect from decreased LCOE.

Table 2. Possible reduction in GHG emissions with base WTG and improved WTGs.

WTG	GHG emissions (kg/yr)			
	CO_2	CO	SO_2	NOx
Base WTG	21,589	163	53.0	186
1%-improved	21,627	164	53.1	186
2%-improved	21,665	164	53.2	186
3%-improved	21,704	164	53.3	187
4%-improved	21,741	164	53.3	187
5%-improved	21,779	165	53.4	187
6%-improved	21,816	165	53.5	188
7%-improved	21,854	165	53.6	188
8%-improved	21,891	166	53.7	188
9%-improved	21,928	166	53.8	189
10%-improved	21,965	166	53.9	189

3.3. Acceptable increase in WTG capital cost

The acceptable increase in the capital cost of WTG can be found by comparing the LCOE of a new expensive WTG with that of the base WTG. For example, if the LCOE of an improved WTG with higher capital cost is greater than the LCOE of base WTG, the improved WTG is considered unacceptable from the economic point of view. This kind of economic analysis can be done using the sensitivity plot of the HOMER software. As a demonstration, the sensitivity plots of 5%-improved WTG and 10%-improved WTG in the base condition for the TOU pricing scheme are shown in Fig. 4, where the annual average of wind speed is 5 m/s.

The area on the left side of the middle-inclined line means that the LCOE of the improved WTG is lower than that of the base WTG, and thus, the improved WTG is acceptable in the view of economic feasibility. The Homer software deals with the captital cost and the replacement cost after lifetime as different variables. Thus, two variables constitute the two axes in Fig. 4. However, there is no reason to make a difference between the capital and replacement cost except that the latter should be forecasted. Therefore, we will find the point where two costs are equal. Consequently, it can be derived from Fig. 4 that the increase in the capital cost is acceptable by 2.56% for the 5%-improved WTG and by 5.03% for the 10%-improved WTG.

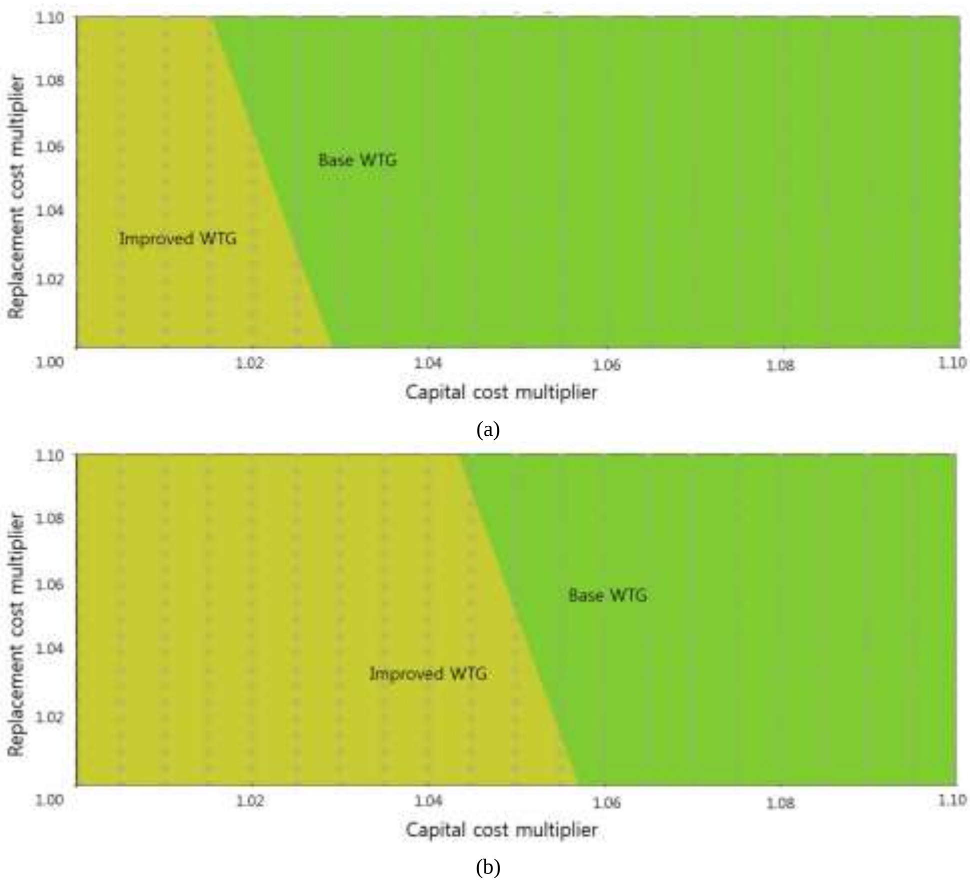

Fig. 4. Sensitivity plots: (a) 5%-improved WTG and (b) 10%-improved WTG. The inclined line indicates the boundary for the economic acceptability of the improved WTG.

The procedures to find the point of acceptable increase in the capital cost are performed for all the improved WTGs and pricing schemes, and the results are summarized in Fig. 5. As can be inferred from the results for LCOE, the acceptable increase in the capital cost is also linearly proportional to the percent increase in the energy production of a WTG. In addition, the acceptable increase is largest for TOU pricing. The difference between the pricing schemes increases according to the percent increase in the energy production. This is because the correlation coefficient between the electricity prices and the electricity generation of a WTG is maintained, and thus, the increased production translates into the increase difference between the pricing schemes.

It can be clearly seen from Fig. 5 that the higher wind speed not only increases the acceptable increase in the capital cost, but also enlarges its difference between the pricing schemes. Consequently, it can be suggested that the budget for the improved WTG should be justified in relation to both the current pricing scheme and the weather condition. Further, if the expected degree of technical improvement in terms of energy production not large enough, the acceptable increase in the capital cost of the advanced WTG will be marginal. Then, it needs to be seriously considered, at least from the economic point of view, whether to proceed with the research and development (R&D) of the technology.

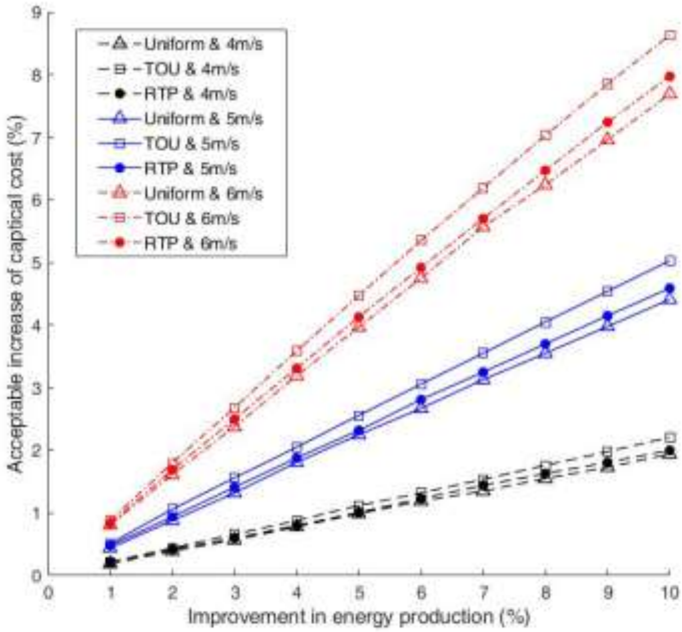

Fig. 5. Values of acceptable increase in the capital cost of a WTG for the combinations of the improvement in energy production, pricing scheme, and average wind speed.

4. Conclusion

In this paper, the economic analyses were performed for an improved WTG in terms of energy production. Various values of degree of technical improvement, pricing schemes, and average wind speed were considered. It was found that both the reduction in LCOE and the acceptable increase in the capital cost are linearly proportional to the percent increase in the energy production of a WTG. The correlation coefficient between the electricity prices and the electricity generation of a WTG happens to be the largest for TOU pricing, which results in the largest economic effect. Such difference between the pricing schemes needs to be investigated with different data sets. The weather condition was obviously a significant factor for determining the economic effect.

The analyses in this study may be practically utilized when planning an R&D of a WTG technology with consideration for the budget constraint. In other words, some technology improvement in energy production may be rejected to proceed with if the technical improvement is marginal, such that the resulting increase in the capital cost is greater than the acceptable increase. Further research with other types of WTG and weather conditions is suggested.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Wonseok Yang and Chung Kyu Lee set up the simulation environment, performed the simulations, and drafted the manuscript; Young Gyu Jin designed the study, performed the analysis, and thoroughly revised the paper; all authors had approved the final version.

Acknowledgements

This research was supported by Korea Electric Power Corporation. (Grant number:R18XA03)

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