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Value of wind power – Implications from specific power

V. Johansson*, L. Thorson, J. Goop, L. Göransson, M. Odenberger, L. Reichenberg, M. Taljegard, F. Johnsson

Department of Energy and Environment, Chalmers University of Technology, 412 96 Gothenburg, Sweden

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This paper investigates the marginal system value of increasing the penetration level of wind power, and how this value is dependent upon the specific power (the ratio of the rated power to the swept area). The marginal system value measures the economic value of increasing the wind power capacity. Green-field power system scenarios, with minimised dispatch and investment costs, are modelled for Year 2050 for four regions in Europe that have different conditions for renewable electricity generation. The results show a high marginal system value of wind turbines at low penetration levels in all four regions and for the three specific powers investigated. The cost-optimal wind power penetration levels are up to 40% in low-wind-speed regions, and up to 80% in high-wind–speed regions. The results also show that both favourable solar conditions and access to hydropower benefit the marginal system value of wind turbines. Furthermore, the profile value, which measures how valuable a wind turbine generation profile is to the electricity system, increases in line with a reduction in the specific power for wind power penetration levels of >10%. The profile value shows that the specific power becomes more important as the wind power penetration level increases.

1. Introduction

Global generation of electricity by wind power has increased rapidly since the beginning of the 21st Century, and wind power is expected to play a significant role in the future energy system with low levels of carbon emissions [1]. According to Wiser and Bolinger [2], wind turbines have increased in height, diameter, and generator capacity in the period 1998–2014, which has led to increased electricity generation per wind turbine [2]. This has resulted in a decreasing trend for the average specific power (the ratio of the rated power to the swept area) of new wind turbines, during that time period. The decrease in average specific power, together with increased tower heights, has led to continuous improvements of the capacity factors for wind turbines. The specific power of the average new installation in USA in Year 2014 was 250 W/m^2, as compared to 390 W/m^2 in Year 1998 [2]. In some areas of the USA, 50% of the wind turbines installed in Year 2014 had a specific power in the range of 190–220 W/m^2. In addition, in the time period of 1998–2014, there was an increase in the number of installations at low-wind-speed sites (IEC class IIIA/B,[1] with an average wind speed of 7.5 m/s) [2]. Chabot [3] refers to this transition towards lower wind speed sites and low specific power as the “silent wind power revolution”. According to Chabot, an important target for the development of the wind power industry is to design wind turbines with low specific power (i.e., low-wind-speed turbines) and place them at sites with medium or high wind speeds (IEC class IIA/B and IEC class IA/B, with average wind speeds of 8.5 m/s and 10 m/s, respectively), thereby creating even higher capacity factors.

Molly [4] compares the levelised cost of electricity (LCOE) for wind turbines with different specific power values for different average wind speeds, and discusses the positive effects of low specific power, such as higher grid utilisation and increases in the guaranteed electricity output. Molly also argues that wind turbines with low specific power are especially important for power systems with high penetration levels of wind power. Hirth and Müller [5]

* Corresponding author.
E-mail address: vikjo@chalmers.se (V. Johansson).

[1] International standard notation for wind speed sites, according to IEC 61400 [30].

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investigated the electricity market features of wind power. They found that a reduction in specific power increased the value factors and reduced the self-cannibalisation of wind turbines. Johansson and Thorson [6] performed a study similar to that of Hirth and Müller [5], investigating differences in the economics of wind turbines with different specific power values using historical wind and electricity spot price data. Johansson and Thorson [6] also analysed the effects of wind turbines with reduced specific power values within the power system. They found that the green-field electricity systems with the lowest overall costs for investments and electricity generation gave wind power penetration levels as high as 60% and 80% in parts of the future Swedish and Danish electricity systems, respectively.

The scientific literature reports a wide range of costs for wind turbines, and most sources of investment costs are presented per MW, regardless of the specific power of the wind turbines [1,2,7,8]. An exception to this trend is the report of Moné et al. [9], which presents the investment costs for wind turbines across a range of modern specific powers, from which Johansson and Thorson [6] extrapolated the costs for wind turbines with even lower specific power. In contrast, Hirth and Müller [5], Molly [4], and Chabot [3] have used cost data, for which the link to the specific power is not clear, together with arguments regarding the positive effects on the system of low specific power. Ueckerdt et al. [10] investigated the integration costs associated with increasing the share of intermittent renewable technologies through the use of system Levelised Cost of Energy (system LCOE) for the electricity generation system. Their method involved allocating the increasing LCOE of the non-renewable part of the electricity system to the renewable technologies. The increased costs of the non-renewable part were due to decreased utilisation of base-load technologies and increased investment costs in flexible generation. However, the work of Ueckerdt et al. only included wind turbines with one specific power.

In order to quantify the benefits of reduced specific power of wind turbines, results from modelling of wind turbine cases covering a sufficient geographical area and with different specific power need to be compared. Thus, the aim of this study is to quantify the marginal system value of onshore wind turbines with different specific powers, and to analyse how this value depends on the wind power penetration level. The marginal system value is the economic value of increasing the wind power capacity, which could be interpreted as the willingness to pay for additional wind turbines. The reason for choosing the marginal system value to quantify the difference between the specific power, is motivated by the fact that costs for wind turbines with low specific power remain uncertain. Wind turbines with different specific power values are compared using the profile value, which is a measure of how valuable a wind turbine generation profile is to the electricity system. Thus, the profile value is used to compare differences between wind turbines with different specific power values, rather than comparing the competitiveness of wind power to those of other electricity generation technologies.

The marginal system values and profile values are quantified using a linear optimisation model, which is performed for different shares of wind power and with different specific powers of the wind turbines. Future scenarios for Year 2050 are modelled for four regions in Europe, each with different conditions for renewable electricity generation, including wind, solar, and hydropower.

2. Methodology

2.1. Definitions of marginal system value and profile value

The method used is to increase linearly the potential wind power penetration level[2] (i.e., the share of the yearly demand that could have been covered by wind power if none of the generation from wind power was curtailed), which acts to include predetermined capacity of wind power in each simulation. Since the potential penetration level of wind power is predefined in every model run, the wind turbine cost does not affect the investment decisions. Therefore, since the costs are uncertain, no investment costs are attributed to the wind turbines in the modelling [operations and maintenance (O&M) costs are, however, included also for wind power], although the calculated marginal system value of the wind turbines is compared to a reference cost function.

The value derived from increasing the capacity of wind power, which is linked to the changes in investment and variable costs for the electricity generation, can be designated as the marginal system value of the wind turbines. The reason to define marginal system value rather than to use the similar measure "marginal LCOE", defined by Ueckerdt et al. [10], is because the system LCOE needs a predefined investment cost, whereas marginal system value instead estimates the willingness to pay for different wind turbines at different penetration levels of wind power. The annual system value, $C'(pen, PS)$, for a specific effective wind power penetration level (i.e., the share of the yearly demand that is covered by wind power), pen, and for a wind turbine with the specific power, P_S, is described as follows:

$$C'(pen,P_S)\approx\frac{\Delta C(pen,P_S)}{\Delta Cap(pen,P_S)}=\frac{C(pen-x/2,P_S)-C(pen+x/2,P_S)}{Cap(pen+x/2,P_S)-Cap(pen-x/2,P_S)}, \quad (1)$$

where $\Delta C(pen, P_S)$ is the difference in the annual system costs and $\Delta Cap(pen, P_S)$ is the difference in the installed capacity of wind power between the different wind power penetration levels. The annual marginal system value is approximated by step-wise changes in the effective penetration level of wind power at intervals of x. The marginal system value, $MSV(pen, P_S)$, is obtained by dividing the annual marginal system value by the annuity factor, AF, as follows:

$$MSV(pen, P_S) = \frac{C'(pen, P_S)}{AF}. \quad (2)$$

The annual system costs and installed capacity of wind power at different penetration levels are calculated using a power curve model and a power system model.

Wind turbines with lower specific power generate more electricity per MW compared to wind turbines with higher specific power. This difference in magnitude of generation between wind turbines with different specific power should be accounted for when analysing generation profiles of wind turbines. The profile value, P, is here defined as a measure for comparing how valuable the different wind turbine generation profiles are to the electricity system. It is calculated from the marginal system value by normalising the electricity generation per MW between the wind turbines with different specific power values. In this study, 200 W/m^2 is used as the reference specific power for the profile value.

$$P(pen, P_S) = MSV(pen, P_S)*\frac{Cap(pen, P_S)}{Cap(pen, 200)}. \quad (3)$$

[2] Throughout this paper two different definitions of penetration level are used: (i) potential penetration level which is the share of the yearly demand which could have been covered by a variable generation technology if no electricity generation was curtailed and (ii) actual penetration level which is the share of the yearly demand which is covered by the technology in the model results.