Renewable Energy 101 (2017) 51–58

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

# Optimal siting and sizing of wind farms

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ARTICLE INFO

*Article history:*
Received 17 February 2016
Received in revised form
23 May 2016
Accepted 5 August 2016
Available online 24 August 2016

*Keywords:*
Weibull distribution
Wind power density
Capacity factor
Grid integration
Linear optimization

ABSTRACT

In this paper, we propose a novel technique to determine the optimal placement of wind farms, thereby taking into account wind characteristics and electrical grid constraints. We model the long-term variability of wind speed using a Weibull distribution according to wind direction intervals, and formulate the metrics that capture wind speed characteristics at a specific location, namely the arithmetic mean of wind speed, the theoretical wind power density and the capacity factor of a prospective wind power plant, to determine the feasibility of a wind power plant establishment. Furthermore, a linear optimization formulation is provided to determine the geographical locations and the installed capacities of wind farms, in order to maximize the expected annual wind power generation, while obeying the constraints from the electrical power grid and the transmission system operator. As a case study, the proposed wind speed model and the linear optimization formulation are used to evaluate the wind characteristics and the potential wind farm sites in Turkey.



## 1. Introduction

Driven by the long-term goal to achieve a sustainable energy system, the utilization of renewable energy, especially wind power, is rising. Nevertheless, the intermittent nature of wind power challenges the stability and reliability of the power system. The wind speed characteristics at a wind farm determine the power generation from wind turbines. Therefore, for prospective investors and for power system analysts who carry out the reliability analyses, modelling the variation of wind speed is essential [1].

Many researchers have conducted case studies to investigate the distribution of wind speed for various purposes [2]: In risk analyses concerning extreme or maximum wind speeds, extreme value distributions [3] are typically used [4], whereas in grid integration studies, the Weibull distribution is widely used because of its flexibility and satisfactory results in fit tests [5,6]. This paper addresses the optimal wind power integration with a long-term focus. Consequently, the Weibull distribution is utilised to model the annual wind speed distributions.

Measurements indicate that there exists a relation between wind speed and wind direction [7–9]. Contrary to the modelling based on purely wind speed values [1,5,6], this paper models the variability of wind speed according to wind direction intervals [9], and derives the expressions for the long-term distributions of wind speed and the power output of a wind turbine. The paper further uses the metrics [10], average wind speed, wind power density, and the capacity factor of a wind power plant, to assess the wind characteristics at a geographical location, and to determine the feasible sites for the wind farms.

The main motivation for investing in a wind farm is the expected profit. On sites with strong wind, investors prefer to establish wind farms of substantial sizes. In order to avoid network congestion due to the power outputs of such wind farms, the grid operators are conservative about the integration of new power plants into the electrical grid and may impose limits on the maximum installed capacities in certain regions [11].

Various methodologies have been proposed to facilitate the determination of wind farm locations [12]. A number of these studies are based on the maximization of the profit of investors [13], which ignore the integration effects of wind farms into the electrical grid. Therefore, some studies propose methods for wind power integration according to the needs of the power grid (such as loss reduction, voltage regulation [14,15]). Nevertheless, those theoretical integration plans may fail to be realised as the proposed wind farm locations do not necessarily attract investors. To solve this wind farm placement problem, this paper presents a combined methodology for countrywide optimal wind power integration: Initially, the metrics that capture the quality of wind are utilised to

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http://dx.doi.org/10.1016/j.renene.2016.08.008
0960-1481/

assess the feasible locations for establishing wind farms from an investor's point of view. Subsequently, those feasible geographical sites are mapped on the electrical power grid, and the optimal siting and sizing of wind farms to maximize annual wind power generation, while obeying the constraints from the electrical power grid and the transmission system operator are determined. Therefore, the proposed placement of wind farms is of interest to investors, and the prospective integration of the power outputs of wind farms does not violate the transmission grid constraints.

The remainder of this paper is organised as follows: Section 2 explains the developed models for wind speed and the power output of a wind turbine. The proposed criteria for the evaluation of potential sites for wind farms are discussed in Section 3. Section 4 formulates the linear optimization problem to investigate the optimal integration of wind power plants, and the results of the optimization are presented in Section 5. Finally, Section 6 concludes the paper.

## 2. Probabilistic model for the power output of a wind turbine

This section proposes probabilistic models for wind speed and formulates the long-term variability of the power output of a wind turbine.

### 2.1. Wind speed characteristics

The annual variability of wind speed is used in assessing the integration of wind farms into the power grid [1], and typically, the Weibull distribution is used to represent the annual variation of wind speed [5,6]. The probability density function (pdf) $f_V(v)$ and the cumulative distribution function (cdf) $F_V(v)$ of the Weibull distribution are defined as

$$f_V(v) = ba^{-b}v^{b-1}e^{-\left(\frac{v}{a}\right)^b}$$
$$F_V(v) = 1 - e^{-\left(\frac{v}{a}\right)^b} \tag{1}$$

where $v$ denotes the Weibull random variable (wind speed), $a$ is a scale parameter and $b$ is a shape parameter [6].

Measurements show that wind speed characteristics depend on wind direction. In this paper, the dependence of wind speed on wind direction is incorporated into the probabilistic model of wind speed as follows: Annual wind measurement data (usually on an hourly basis) at a specific site are divided into $N_d$ intervals according to wind direction. Subsequently, the wind speed values clustered for each interval are represented by a fitted Weibull distribution and a frequency value that captures how often wind blows from this direction interval as compared to all intervals [9]. Fig. 1 illustrates a long-term wind speed model at an arbitrary site.

As a result, in the model, the probability density function of wind speed at a site is defined as

$$f_V(v) = \sum_{i=1}^{N_d} f_{V_i}(v)\omega_i \tag{2}$$

where $N_d$ is the total number of direction intervals, $f_{V_i}(v)$ is the Weibull probability density function of wind speed for the $i^{th}$ interval, and $\omega_i$ is the frequency of the $i^{th}$ interval.

### 2.2. The power output of a wind turbine

The power available in wind is converted to a useful form of energy by wind turbines. The power output of a wind turbine depends on wind speed and the characteristics of the wind turbine, such as efficiency, size and power curve. The power curve or the $p$-$v$ characteristic of a wind turbine defines how the power output of the wind turbine varies with wind speed [16]. In Fig. 2, a typical power curve of a wind turbine is illustrated.

The power curve of a wind turbine can be analysed in three regions: In order for the wind turbine to start generating power, wind speed must be greater than the cut-in speed $v_{in}$. Consequently, below the cut-in speed, in region I, the power output of a wind turbine is zero. Similarly, in region III, the wind turbine stops

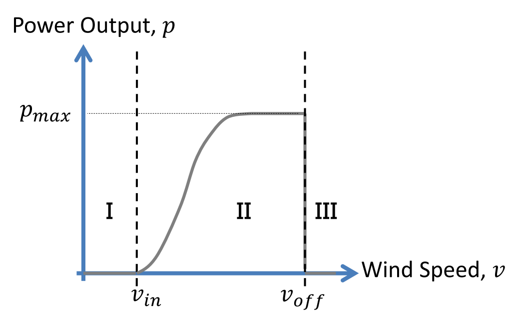


**Fig. 2.** A typical $p$-$v$ characteristic of a wind turbine.

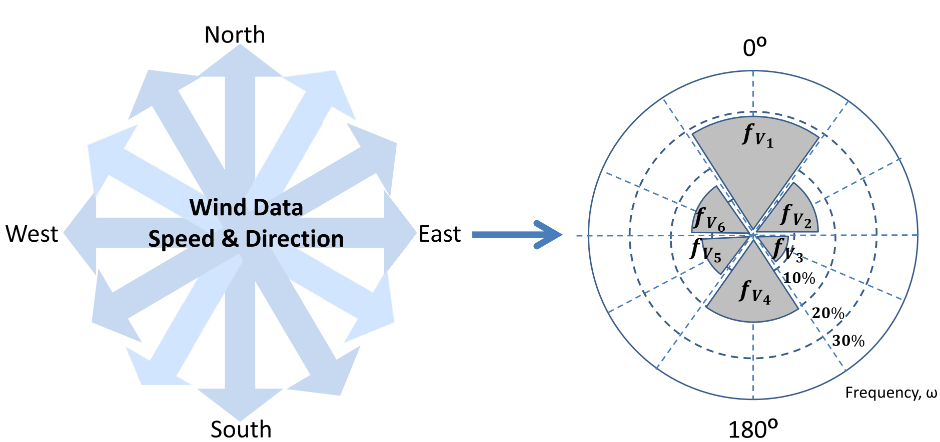


**Fig. 1.** Model for annual variability of wind speed ($N_d = 6$).