

The Estimation of Wind Lull and Consumption Factor Influence on Autonomous Wind Energy System

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Abstract. Due to the stochastic output of wind generators, some kind of storage device will be necessary to ensure a constant energy supply by an autonomous energy system. The necessary storage capacity depends on wind data and consumption factor. The latter describes the ratio between average production capacity and average usage capacity. In addition to average wind speed, the frequency and duration of windless periods must be considered as well. The concept of energy lulls has been outlined to describe the influence of duration, frequency and distribution of windless periods on a wind energy system. Location has strong influence on energy lull length; the difference in average duration between a coastal area and inland is more than two fold. Weibull distribution can be used to describe the probability of energy lulls.

Key words: Wind speed, wind energy, consumption factor, wind lull, energy lull, autonomous power system

INTRODUCTION

Although most of Estonia is supplied by the national electric grid, there are some applications for autonomous power systems. There are locations which lack electric network and where building a new connection would be economically unjustifiable. The cost of a fossil fuel generator may be also too expensive. Renewable energy sources, especially wind energy, can often be the primary sources of energy, as they are usually available in geographically remote and demographically sparse areas (Georgilakis et al., 2009). The stochastic output of WTG (wind turbine generator) is one of the biggest problems while using a small autonomous wind energy system. A backup generator or storage device will be necessary to ensure constant energy supply. The selection of the storage device depends on the characteristics of wind generation device and the consumer. Different simulation algorithms and methods for optimal system design are being researched, e. g. Simulated Annealing (Ekren & Ekren, 2010) or design spaces for wind-battery systems (Roy et al., 2009). Wind energy can be described in terms of momentary and average speed during some period. Average wind speed can describe potential wind energy in some location but nevertheless, it does not provide an overview of wind energy parameters. Annual energy production calculation based on wind data and the expected generator capacity found according to consumption might not provide the necessary energy supply reliability. The prediction of annual energy production according to the power curve of generator

might be insufficient. There may occur relatively long periods without wind. The concept of energy lull has been introduced to describe periods without wind energy production (Põder et al., 2009). 5-year wind data from two different locations have been analyzed to find out the length of energy lulls and the capacity of storage device.

MATERIALS AND METHODS

WTG output depends on wind speed. For example, Estonia can be divided into two areas with different wind speeds at standard measurement height 10 m: 1) islands, seashores and Lake Peipsi (average wind speed $5-7 \text{ m s}^{-1}$) and 2) inland (average wind speed $2.5-3.5 \text{ m s}^{-1}$) (Kull, 1995). Wind data from years 2004-2008 was obtained from EMHI (Estonian Meteorological and Hydrological Institute) where average wind speed for 1 h period at 10 m height was measured. Small wind generators (impeller's circle area up to 200 m^2 and power up to 50 kW) were considered; therefore, wind speeds were transposed to their typical 30 m height (EVS, 2006). Hellman power law with exponent $k_H = 0.25$ for seashore and $k_H = 0.29$ for inland was used for this purpose (Annuk & Tomson, 2005). Wind data was divided into quarters according to the seasons. In total 19 quarters were analyzed. As average wind speed does not provide a good overview of wind energy parameters, the concept of energy lulls is being introduced. Most small wind turbines have the cut-in speed 2.5 m s^{-1} or higher and the cut-out speed 25 m s^{-1} (Annuk et al., 2008). A wind lull can be described as a period without any wind. An energy lull can be defined as a period without wind or with wind speed less than 2.5 m s^{-1} that is inapplicable for wind turbines (Põder et al., 2009). Wind speeds more than 25 m s^{-1} were not considered due to low frequency (Annuk et al., 2008). As wind speed measurement interval is 1 h, the shortest energy lull length is 1 h. Wind data from Pakri (located in coastal area) and Viljandi (located inland) were analyzed (Fig. 1).

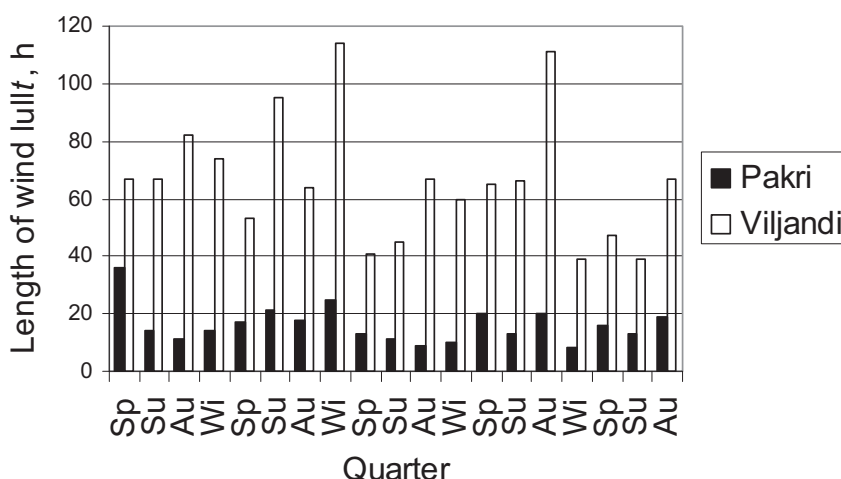


Fig. 1. The extreme values of energy lulls according to seasons (Sp – spring, Su – summer, Au – autumn, Wi – winter) during 2004-2008.

In case of an autonomous system, the storage device should be able to ensure energy supply for the duration of maximum energy lull. Detailed long-time windspeed measurements are needed for such a solution (Celik, 2003; Kaldellis, 2002). On the other hand, the probability of wind parameters can be described with Weibull distribution (Mathew, 2006; Cellura et al., 2008; Garcia et al., 1997). According to our measurement data, the relative length of energy lull l can be described using Weibull distribution, thus the cumulative distribution function is:

$$F(l) = \int_a^b f(l) dl = 1 - e^{-\left(\frac{l}{c}\right)^k}, \quad (1)$$

where $F(l)$ – cumulative probability distribution function, $f(l)$ – probability density function, l – relative length of energy lull, c – Weibull scale factor, k – Weibull shape factor.

The Weibull distribution function $f(l)$ of energy lull can be mathematically expressed as:

$$f(l) = \left(\frac{l}{c}\right)^k \frac{k}{l} e^{-\left(\frac{l}{c}\right)^k}. \quad (2)$$

The probability of a certain energy lull can be found by the cumulative distribution function. The probability between lengths l_1 and l_2 , when $1 \leq l \leq 48$ is given by:

$$P(l_1 < l < l_2) = e^{-\left(\frac{l_1}{c}\right)^k} - e^{-\left(\frac{l_2}{c}\right)^k}. \quad (3)$$

The average length of energy lull is:

$$t_m = \frac{\sum_{i=1}^n t_i}{n}, \quad (4)$$

where t_m – average length of energy lull, h; t_i – total duration of energy lulls with same length; n – total sum of energy lulls.

The duration of relative energy lull is equal to minimum length of energy lull based on wind speed measurements 1 h, thus $l_m = t_m$.

The probability of average energy lull is:

$$P(l_m) = e^{-\left(\frac{l_m}{c}\right)^k}, \quad (5)$$

where $P(l_m)$ – probability of average energy lull, l_m – duration of average energy lull.

There are different methods to determine parameters c and k . In this study the graphical method is used (Mathew, 2006). With a double logarithmic transformation of cumulative distribution function $F(l)$ can be written as:

$$\ln\{-\ln[1 - F(l)]\} = k \ln(l) - k \ln C. \quad (6)$$

Graphically the relationship gives an almost straight line (Fig. 2).

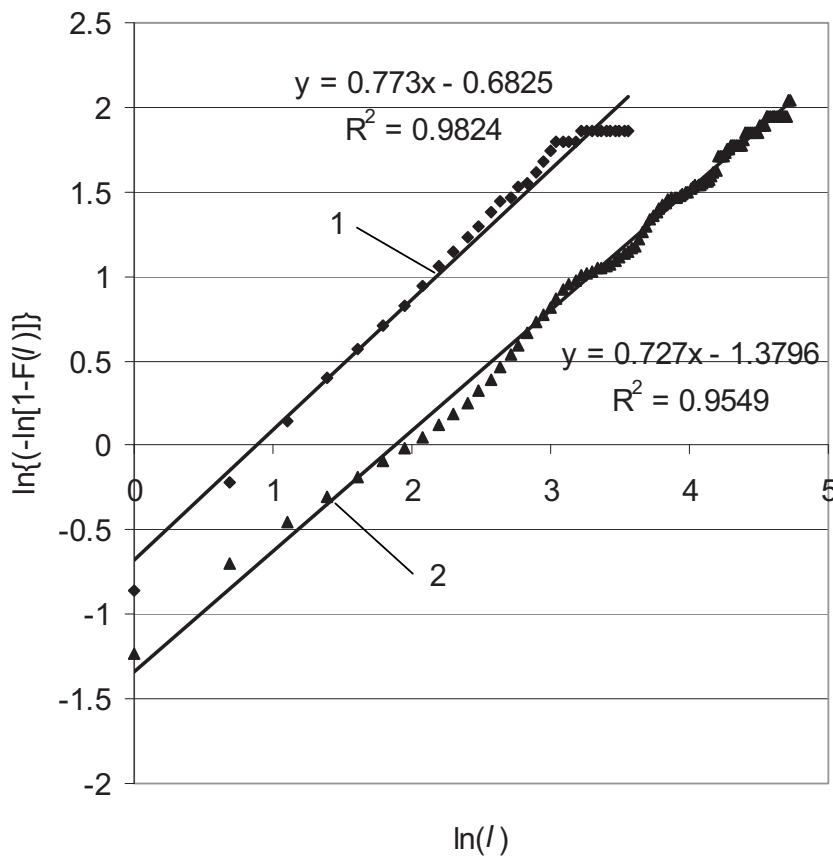


Fig. 2. Determination of k and c values (1 – Pakri, 2 – Viljandi).

According to equation 6, k gives the slope of the line and $-k \ln c$ represents the intercept. Obtained relationships have high correlation coefficients ($R^2 > 0.95$).

RESULTS AND DISCUSSION

Histograms were found for energy lulls in Pakri and Viljandi (Figs. 3-4). The frequency of shortest energy lulls is highest.

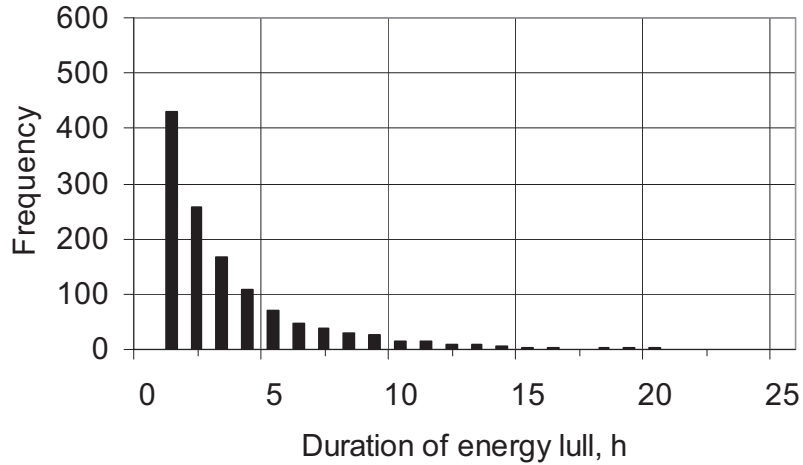


Fig. 3. Histogram of energy lulls during 2004-2008 in Pakri.

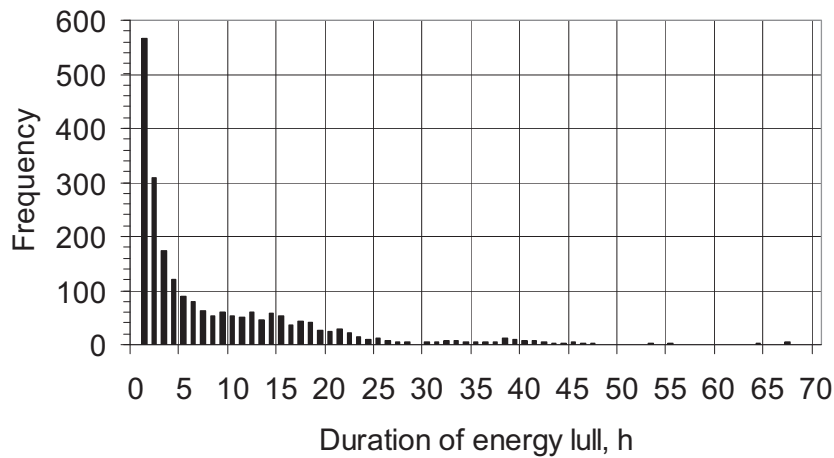


Fig. 4. Histogram of energy lulls during 2004-2008 in Viljandi.

The results of wind speed and energy lull analyses at 30 m height are given in Table 1.

Table 1. Wind data results

Location	Average wind speed v , m s^{-1}	Max. lull, t_{max} , h	Average energy lull t_m , h	Weibull shape factor k	Weibull scale factor c
Pakri	6.1	36	3.4	0.773	2.418
Viljandi	3.0	114	8.8	0.727	2.557

According to Table 1, average wind velocity has influence on average and maximum energy lull length. Weibull shape and scale factors are similar for both locations.

The cumulative Weibull distribution function of Pakri and Viljandi energy lulls was calculated (Fig. 5). This shows the probability of energy lull length being lower than l .

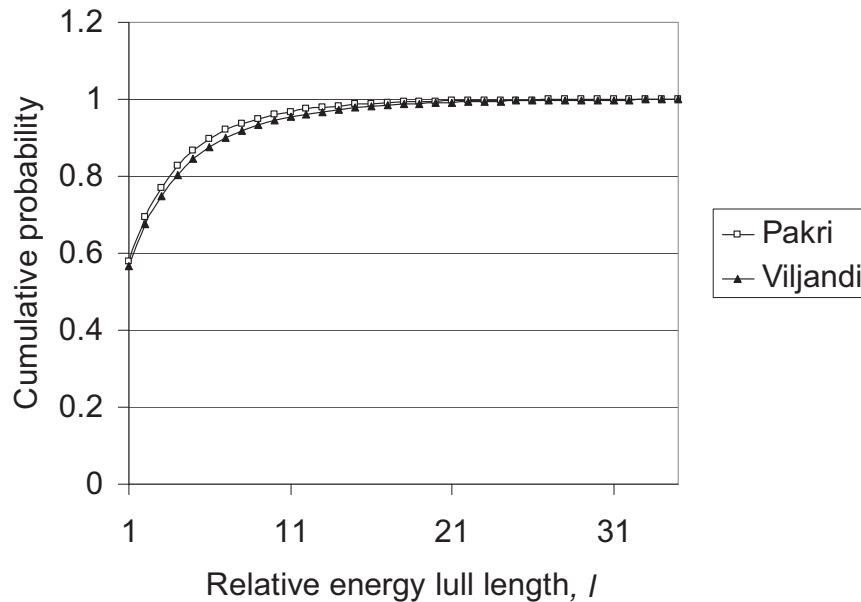


Fig. 5. Cumulative Weibull distribution function of energy lulls in Pakri and Viljandi.

Pakri and Viljandi wind data can be analyzed as a sample case of energy balance in an autonomous energy system. Energy shortage is a situation where the balance of energy production and usage is negative. The load is expected to be constant throughout the whole year, because in an autonomous system all the energy produced must be consumed.

In a real world energy system the occurrence of equal generation and usage capacities cannot appear due to losses in generation and storage process. For compensation, the average generation capacity must be higher than average consumption capacity. During a given period, the amount of energy used must be less than the amount of energy produced whereas the ratio is called consumption factor β (Pöder et al., 2009). The storage device must be able to store a sufficient amount of energy to cover the maximum possible shortage of energy. Therefore, it follows that prior to applying the consumption load, the storage device is expected to contain a sufficient amount of energy to cover the shortage. Variations in generated and stored energy together with different consumption factors in Pakri and Viljandi are calculated (Figs. 6-9). The average annual consumption capacity has been equalized with the average annual load. Data from quarters 1-15 is included because of the longest location of energy lulls.

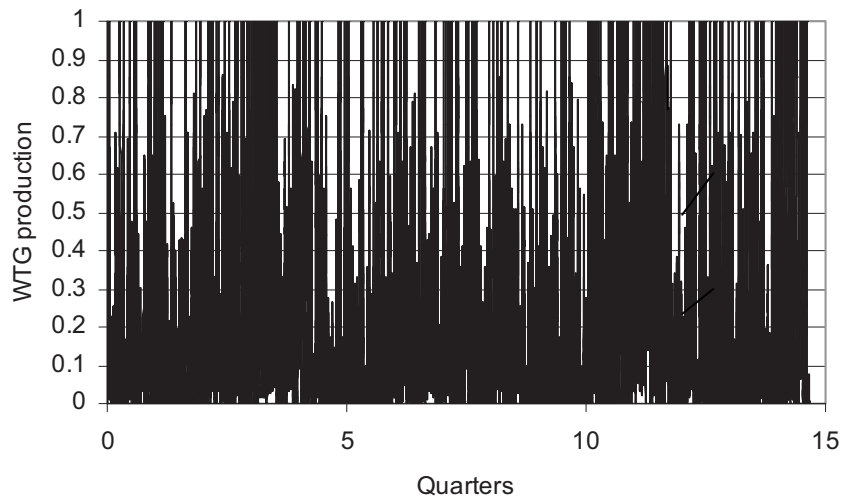


Fig. 6. Variation in WTG energy production in Pakri during 2004-2008 at 30 m height.

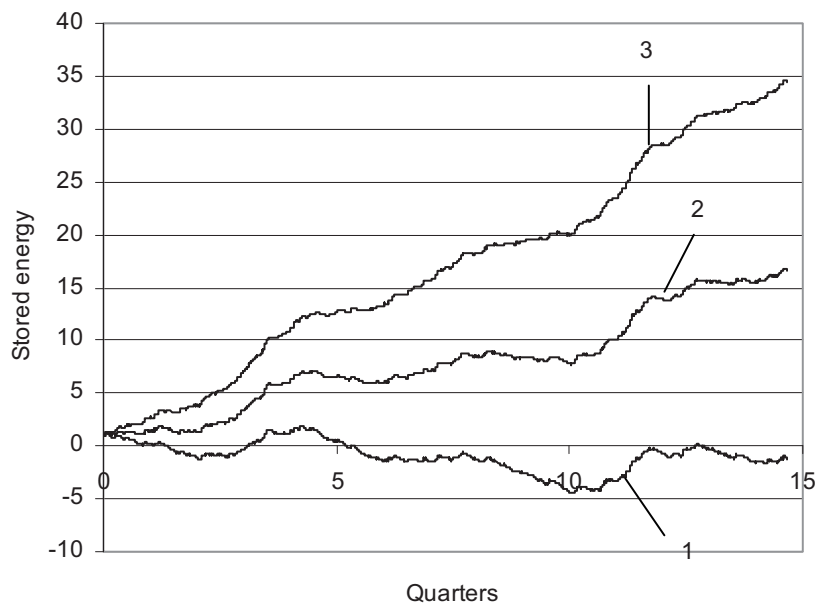


Fig. 7. Variation in stored energy in case of different consumption factors ($1-\beta = 1.0$; $2-\beta = 0.75$; $3-\beta = 0.5$) in Pakri during 2004-2008 at 30 m height.

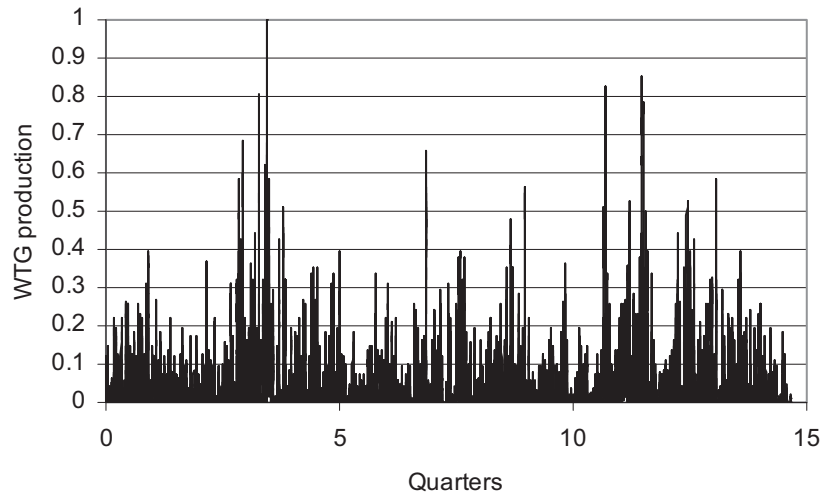


Fig. 8. Variation in WTG energy production in Viljandi during 2004-2008 at 30 m height.

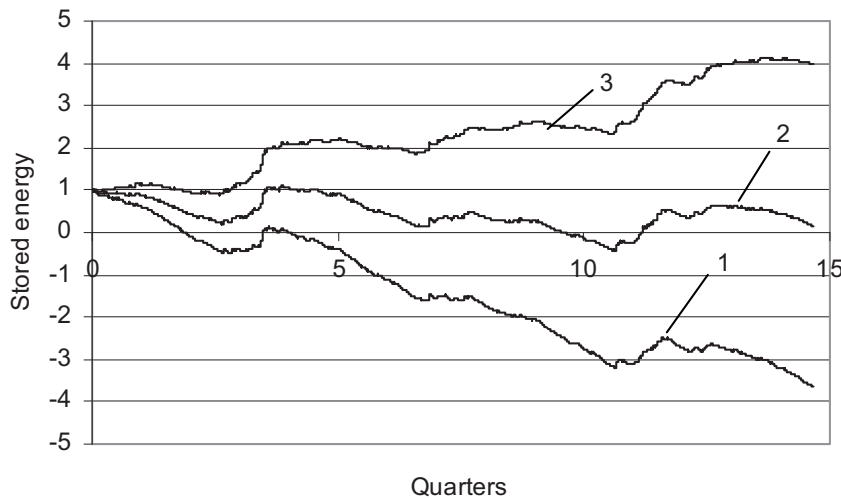


Fig. 9. Variation in stored energy in case of different consumption factors (1- $\beta=1.0$; 2- $\beta=0.75$; 3- $\beta=0.5$) in Viljandi during 2004-2008 at 30 m height.

According to Figs. 6 and 8, the amount of generated energy depends on site wind data (Pakri has higher average wind speed than Viljandi). Wind velocity has also strong influence on energy production and consumption balance (Figs. 7 and 9). In case of Pakri consumption factor $\beta=0.75$ ensures constant energy supply (balance is positive), in Viljandi it not enough (storage is empty during certain time periods). $\beta=0.5$ ensures continuous energy supply in Viljandi. The consumption factor β must be evaluated to ensure continuous energy supply in case of an autonomous wind energy system.

CONCLUSIONS

1. According to measurement data, the frequency of shortest energy lulls is highest.
2. According to 5-year wind data, the average duration of energy lulls is highest inland (Pakri – 3.4 h, Viljandi – 8.8 h).
3. The probability of energy lulls can be described by Weibull distribution function with factors $k = 0.727$, $c = 2.557$ for inland and $k = 0.773$, $c = 2.418$ for coastal area in Estonia.
4. During the sizing of storage devices for autonomous wind energy systems, it will be useful to consider the probability of energy lulls in addition to wind speed probability.
5. Time of the year does not influence the length of energy lulls.

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