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THE ESTIMATION OF NEEDED CAPACITY OF A STORAGE SYSTEM ACCORDING TO LOAD AND WIND PARAMETERS

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One of the most important problems of the Estonian energy system is the compensation of power fluctuations of wind parks. The possibilities of energy system stabilization by Estonian oil shale power plants are limited. At the same time the use of wind energy has not led to the expected reduction in oil shale consumption. Autonomous wind energy systems with some storage devices are one possible way to develop wind energy usage. A system consisting of a wind generator and storage device is analyzed in this article. The storage device might be a fuel cell with hydrogen storage, pumped storage, flywheel or battery. A unit generator and the normalized and averaged power curve of small wind turbine generators are used for the analysis of wind data. Average hourly wind speeds are measured in different locations of Estonia. The duration, frequency and distribution of windless time periods are analyzed. The estimated principles of storage device selection are given according to wind data and power curves.

Introduction

The main problem of wind energy usage is the stochastic output of power generation devices. Two different situations can be differentiated: the wind generator is connected with the electric network, or it is an autonomous unit equipped with a storage and backup supply system. The latter belongs mostly to a small-scale energy supply. Wind turbines with the fan area of up to 200 m^2 (power up to 50 kW) are categorized as small wind generators [1]. There are some applications for small wind generators in Estonia. There are still locations without any existing electric network, and building a new connection is economically unjustifiable. Such locations can be supplied with small WTGs (wind turbine generator). The countryside of Estonia is relatively sparsely populated, and requirements for installation of small

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WTGs are lower than those for the big ones. Secondly, the small WTGs can positively contribute to the development of distributed generation.

Small wind turbines might be either connected to the electric network or work autonomously. The main problem in either case, though, is the compensation for energy shortage caused by wind speed fluctuations. This is unlike high-capacity wind turbines, which have also problems with peak capacity regulation, especially in the electric grid containing relatively high amount of wind electricity. Characteristically, the power output of wind can be only reduced [2]. Power output increase can be achieved only by using additional power supplies or storage devices. Wind energy is described in terms of momentary speed and average speed during some period. Average wind speed describes the potential wind energy in some location but it does not provide an overview of wind energy parameters. To describe wind as an energy flow system, it is hereby suggested that the concept of *energy lull*, hereafter energy lull, be introduced. Energy lull could be defined as the time period of no wind or of wind speed less than 2.5 m/s that is not applicable for wind turbines. Energy lulls caused by very high wind speeds (more than 25 m/s) are not described here.

Wind characteristics in Estonia

According to climatology, the territory of Estonia may be divided into two slightly different regions – that of seashore and islands (influenced by the sea) and the inland [3], the distribution that also applies to wind. The average wind speeds are 5–7 m/s at the shore and on the islands and 2.5–3.5 m/s in inland [4]. Wind energy production is considered economically feasible for seashores and islands. Some wind turbine generators have already been built in inland for commercial production. As a rule, it is used units that are installed.

When considering the increasing energy prices the installation of small wind turbines is going to be more and more profitable. Due to technical requirements, it is not economically feasible today to connect the small WTG with distribution network. In the case of a distant electric network, a small wind generator supplying a small autonomous network is most suitable. Therefore, the questions about the capacities of wind generators and storage devices or additional power supplies are raised.

Annual energy production calculated according to wind data and the expected generator capacity found according to consumption might not provide the energy supply reliability needed. The oversizing of generator and storage system would lead to a significant rise in their cost. The prediction of annual energy production according to the power curve of a generator is not sufficient. There might be relatively long time periods without wind (energy lulls) in Estonia, during which the backup system must ensure energy supply. This problem has not been investigated in this way.

The calculation of installed capacity of wind turbine and storage device is appropriate when there is not enough wind data about selected location available [5]. There are different methods for the optimization of generator capacities in energy systems in the case of partial information [6], in the case of cogeneration [7] and for cooperation of wind turbines with oil shale plants [8]. These methods have been developed for the continuous power production and consumption schedules and do not involve storage devices. Models of LOLP (Loss of Load Probability) and EENS (Expected Energy Not Supplied) have been used for the estimation of the reliability of the hybrid system (wind generator + diesel generator + storage device) but this model does not include the capacity of storage device [9]. The LOLP model has been used to study a similar system (wind generator + diesel generator + storage) but average wind speed of 7.5 m/s was used and longer wind-free periods were not taken into consideration [10].

Data and methods

Wind measurement data from EMHI (Estonian Meteorological and Hydrological Institute) was analyzed where average wind speed for 1 h time period had been measured at the height of 10 m during the last 5 years. The data was processed using Scilab and Microsoft Excel. Distinctive locations were selected: Jõgeva, Viljandi, Tõravere for the inland area and Virtsu, Pakri and Tiirikoja (near Lake Peipsi) for the shore area.

The data was transposed to higher height values using Hellman equation with coefficient $k_H = 0.25$ for seashore [11] and $k_H = 0.29$ for inland [12]. Wind energy amount could be estimated on the basis of the wind generator power curve $P = f(v)$ where v is the average speed of 1 h time periods and P is the corresponding power output. In our calculations, we use the normalized power curve averaged from a group of small WTG-s. Normalised wind generator power curves (Fig. 1) could be described as [13]

$$P^* = \frac{P}{P_N} \rightarrow P^* = \{0 - 1\}$$

$$0 < v < 2.5 \text{ m/s} \rightarrow P^* = 0 \tag{1}$$

$$2.5 \le v \le 12 \text{ m/s} \rightarrow P^* = 0.0078 \cdot v^2 - 0.0229 \cdot v + 0.00866022$$

$$v > 12 \text{ m/s} \rightarrow P^* = \text{const},$$

where P^* – relative output power,
P – instantaneous power output, kW,
P_N – nominal power, kW.

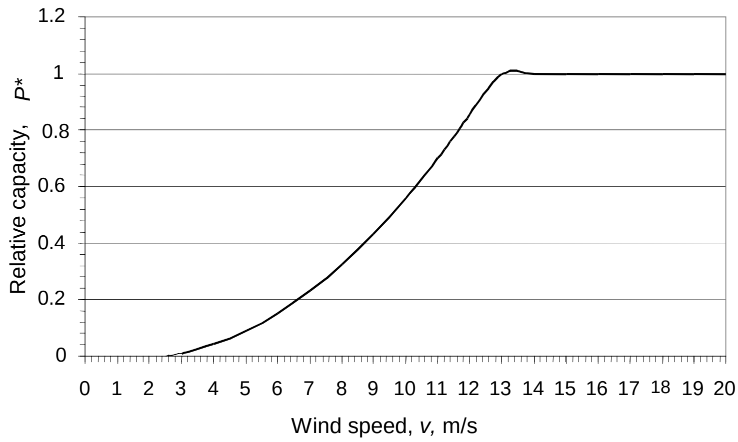

Fig. 1. Normalized power curve of wind turbine generator.

Average hourly generator output

Equation (1) describes the power curve of wind generator, where capacity $P*$ is expressed in relative units. The real power curve can be obtained by multiplying the ordinate value by the nominal capacity of an existing WTG. This unified power curve applies to most small wind turbines, with a start-up speed of 2.5 m/s or higher and with the nominal power achieved at wind speed 12 m/s ± 1 m/s. With measurement data about 5 years from 6 different locations and average wind speeds transposed to the heights of 30 m and 50 m we have 60 data points of average annual wind speed and the corresponding annual wind turbine capacity. From Fig. 2 it appears that the annual average WTG capacity based on the hourly averages is higher (grey line) than the capacity fund using power curve data (dashed line). The capacity difference between the two curves is 1.3 times on wind speed 7 m/s and increases on lower wind speed. Power curve based on measured hourly values can be described by polynomial:

$$P^{*} = 0.0066 \cdot v^{2} - 0.0004 \cdot v - 0.0208, \quad (2)$$

$$R^{2} = 0.9978,$$

where P^{*} – normalized relative hourly output of wind generator,
v – average hourly wind speed, m/s,
R – correlation coefficient.

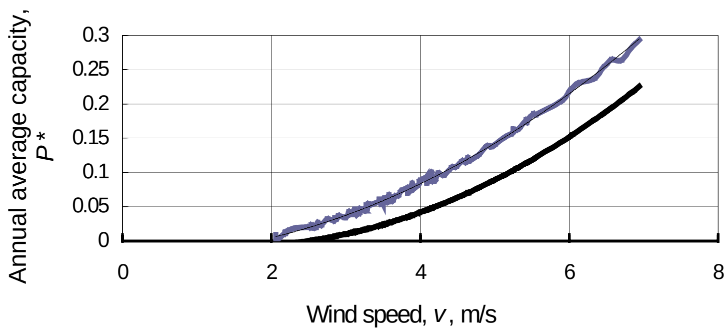

Fig. 2. WTG average annual capacities according to real hourly wind speed (grey line with trend line) and according to mean annual wind speed data (bold line).

Occurrence and duration of energy lulls

Figure 3 shows that time periods without wind are clearly distinguishable. The selected 3rd quarter was a period of the least wind values during 2006. Time period with the wind speed between 0–2.49 m/s is important for energy production because WTG is not generating energy.

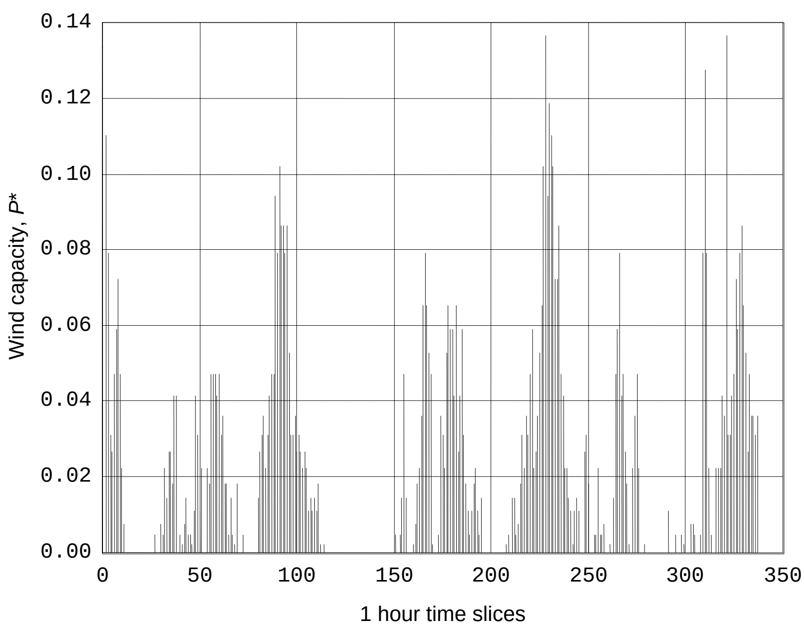

Fig. 3. Normalized WTG capacity changes in Viljandi during two weeks in 3rd quarter of 2006 at a height of 30 m.

Table 1 shows that the maximum average duration of energy lulls T_m in five years is usually bigger by one standard deviation than the following average energy lull. The maximum length of energy lull T_m increases quickly with the reduction of average wind speed. The standard deviation of all 5-year annual average wind speed in all locations is near 5%. The standard deviation of 5-year average capacity is between 6–14% (smaller values at higher average wind speed).

According to Fig. 4, the largest energy lulls are appearing during autumn and winter months, with the highest probabilities for large energy lulls in February and October.

Table 1. **The values of five years: average wind speeds, average of maximum duration of energy lulls T_m and the following size of energy lulls with their standard deviations**

Location	Height, m	Wind speed v, m/s	Capa-city, P^*	Max. lull, T_m, h	Std. dev. δ, h	Std. dev. δ^*, %	Next lull, h	Std. dev. δ, h	Std. dev. δ^*, %
Viljandi	30	3.0	0.0363	93.0	17.7	19.0	71.6	13.5	18.9
	50	3.5	0.0573	61.8	8.9	14.4	53.2	5.6	10.6
Pakri	30	6.09	0.2263	24.2	6.2	25.8	17.8	1.6	9.0
	50	6.92	0.2889	20.8	2.4	11.5	16.0	1.1	6.9
Virtsu	30	4.84	0.1296	39.4	9.9	25.0	29.6	5.5	18.5
	50	5.5	0.1769	35.0	9.9	28.4	23.4	4.2	18.0
Jõgeva	30	3.61	0.0649	53.4	8.6	16.1	46.8	8.2	17.4
	50	4.19	0.0983	45.2	9.6	21.2	36.6	4.3	11.7
Tõravere	30	3.66	0.0626	49.0	6.7	13.7	43.4	2.5	5.8
	50	4.24	0.0957	37.0	3.3	8.9	34.0	5.5	16.1
Tiirikoja	30	3.0	0.0389	86.2	28.7	33.3	60.0	9.6	16.0
	50	3.41	0.0565	65.6	10.8	16.4	54.0	8.0	14.9

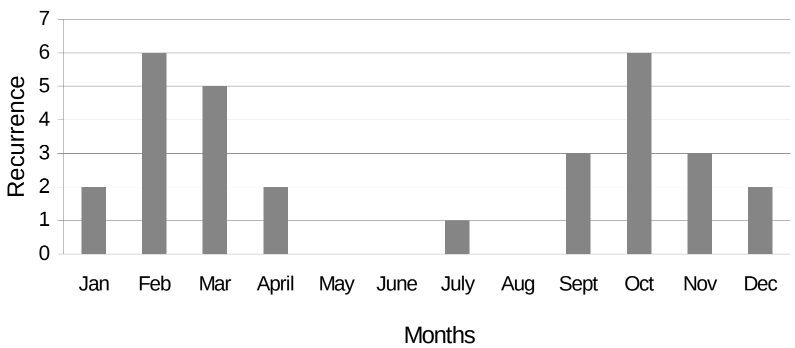

Fig. 4. Recurrence of maximum energy lulls during different month of 2004–2008 in 6 locations.

The correlation between the duration of maximum energy lulls for all measurement points and years is given in Fig. 5. The distinct power function between the duration of energy lulls and annual average wind speed is made explicit:

$$T_m = 513.79v^{-1.683}, \qquad R^2 = 0.85 \tag{3}$$

The maximum duration of energy lulls T_m at low wind speeds is more than 200 hours and at higher wind speeds it stays around 18 hours. For wind speeds of less than 4 m/s the maximum duration of energy lulls T_m is more than 50 hours.

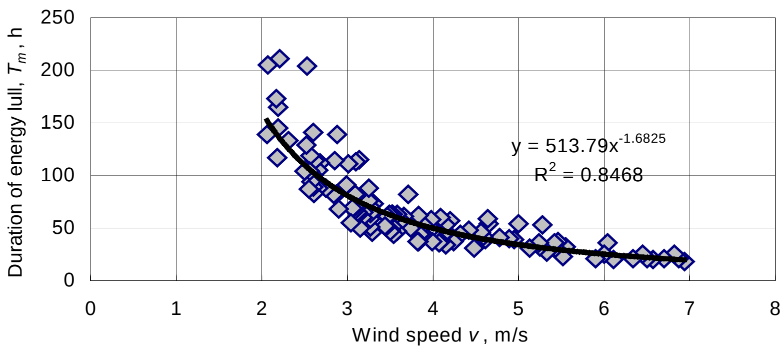

Fig. 5. The correlation between the duration of maximum energy lulls and annual average wind speed.

The shortage of energy in autonomous energy system

The Pakri Wind Park data can be analyzed as a sample case of shortage in energy production. Energy shortage is the situation whereby the balance of energy production and usage is negative. The average wind speed over the last 5 years is $v = 4.6$ m/s at height 10 m in Pakri which well corresponds to the average wind speed of the last 40 years. We hereby expect the load to be of constant value through the whole year because in autonomous systems all the energy produced must be consumed. The energy shortage appearing in autumn (Fig. 6) may be the result of lower wind speeds during summer [14] and the lengthy energy lulls in the second half of the year. During 60% of the years recorded, the largest energy lulls are registered in September or October. The variations in unit generator output and the corresponding energy balance (kWh) are given in Fig. 6. The average annual consumption capacity has been equalized to average annual load.

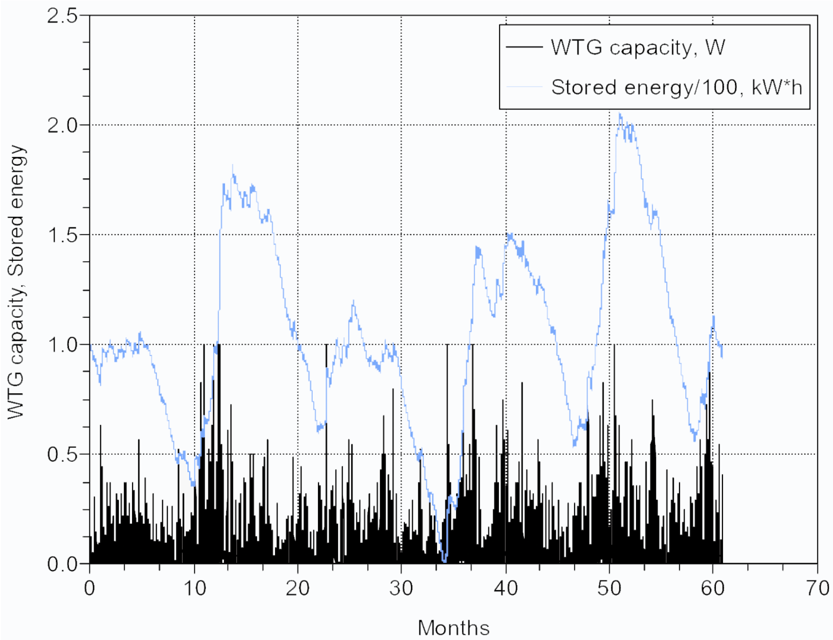

Fig. 6. Variation in WTG capacity and energy to be stored in Viljandi of 2004–2008 at a height of 50 m.

In reality, the occurence of equal generation and usage capacities could not appear when only storage devices are used and the losses in storage are not included. Losses occur during the storage process, and for compensation the average usage capacity must be less than average generation capacity. Thus, for a given period the amount of energy used must be less than the amount of energy produced whereas their ratio is called consumption factor β. A storage device must be able to store a sufficient amount of energy to cover the maximum possible shortage of energy. It therefore follows that prior to applying the consumption load the storage device is expected to contain a sufficient amount of energy to cover the shortage.

Figure 7 shows the maximum possible energy deficit for different consumption factors. In addition to Pakri the wind data from Viljandi at heights 30 m and 50 m are included to cover a wider range of wind speeds. According to Fig. 7 the energy deficit increases with annual wind speed when $\beta = 1$. The linear trend lines could be used for the description of regression but the correlation coefficient R^2 is as low as 0.6–0.7. As mentioned above, the autonomous storage system cannot function when $\beta = 1$. In the case of $\beta = 0.9$, energy deficit would be between 0–38 kWh with higher values occurring both for lower and higher annual average wind speeds. In the case of $\beta = 0.85$, the range is limited to 0–13 kWh.

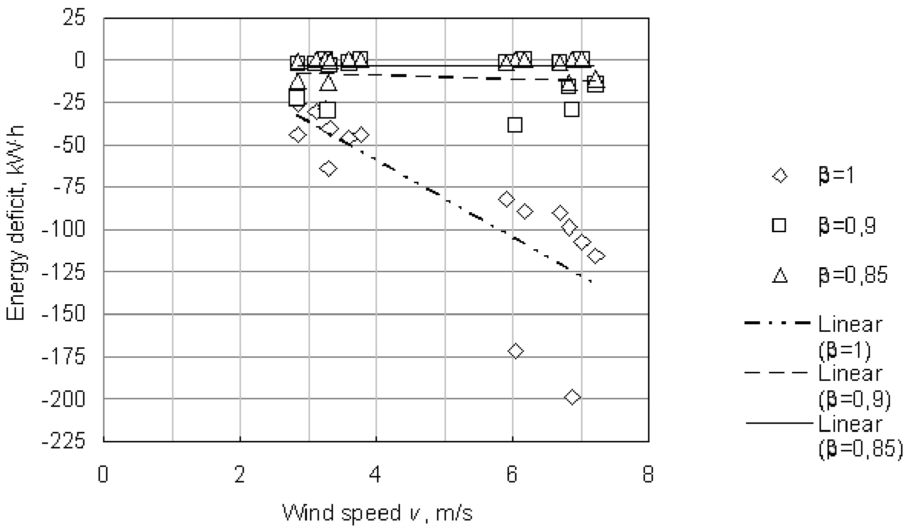

Fig. 7. Maximum energy deficit for different annual average wind speeds during one year in Viljandi and Pakri at the heights of 30 m and 50 m with consumption factors $\beta = 1; 0.9; 0.85$.

Thus, if 90% of energy generated by a unit generator is consumed, its storage capacity can be as low as 38 kWh regardless of the annual wind speed average. The remaining 10% of energy cover the losses in the storage device, and what remains thereafter should be used outside the calculated consumer, for instance saved by a thermal energy storage device, whereas the load factor selected must match the efficiency of the storage device applied (can be as low as ~40%).

However, the above energy deficit values do not apply for all measurement points. For example, in Virtsu at the height of 30 m and 50 m the values in the case of $\beta = 0.9$ and $\beta = 0.85$ are 73 kWh and 32 kWh, respectively, and the annual average wind speeds of theses 5 years are between 4–6 m/s that is in the range of that between Viljandi and Pakri. Thus the values of energy deficit do not depend on the annual average wind speed.

Conclusions

1. The longest energy lulls are longer than the second longest lulls by a standard deviation. While the maximum duration of energy lulls T_m in coastal area at heights 30 m and 50 m is within the range of 18–54 hours, in inland the maximum is 37–114 hours in length. 20% of the maximum energy lulls T_m occur in March, another 20% in October, and 17% in April.

2. The period of maximum energy deficit is mainly appearing in the second half of the year with the majority of cases registered in September or October.
3. The actual annual average generator capacity at the wind speed of 7 m/s is 1.3 times higher than that calculated from the generator power curve, and the difference increases at lower wind speeds.
4. The wind data recorded in Estonia over the last 5 years suggest that the necessary capacity of a storage device in an autonomous energy system depends on the consumption factor rather than on the wind speed averages.

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