Wind energy application problems in inland Estonia

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Abstract. The inland regions of Estonia have not been seen as suitable economically for deployment of wind energy systems. Prices for technological development of wind turbines are going down, while energy prices are rising constantly. Since rural regions of Estonia are underpopulated, the use of small scale wind turbine generators in these conditions is becoming more promising. Average wind speeds in mainland Estonia are 2.5–3.5 m s^{-1}. Only a very small part of the wind speed frequency distribution (~4 ppm) exceeds 12 m s^{-1}. More suitable for these regions are wind turbine generators which switch on at wind speeds less than 3 m s^{-1} and reach nominal output power at 11–12 m s^{-1}. They have similar-looking power curves, so it is possible to model the first rising part of the curve up to maximal power by second order polynomial. Because the wind speed rarely exceeds 12 m s^{-1} in inland regions there is no need to model the whole power curve. The average power curve makes it possible to estimate an approximate energy production of small scale wind turbine generators in a given region if the wind speed frequency distribution is known.

Key words: wind speed, wind energy**,** wind turbine power curve, wind speed frequency distribution

INTRODUCTION

The tradition of wind energy usage in Estonia is comparatively old. The first descriptions of windmills date from 1572. The main application of windmills for centuries was grain milling and less often for threshing and water pumping (Pajumets, 1999). The windmills in inland Estonia were also widely used but they were built higher than those on the islands and at the sea shore (Estonian Wind Power.., 2008). Currently the main use of wind energy in Estonia is for energy production. The generative power of wind farms installed in Estonia as of January 1, 2008 was 58.1 MW. The power of wind turbine generators (WTGs) at these farms is between 0.15 and 3.0 MW, with wind farm projects under development for an added 399 MW. Additionally, wind-parks are planned by the open sea and at Peipsi Lake with generative power of 700–2,100 MW (Estonian Wind Power.., 2008). Based on our own and Denmark's longer tradition of electrical energy production by high-power WTGs, it may be concluded that the output power of the WTG can change from 10 to 90 percent of installed power within a couple of hours (Kilk, 2007).

Oil shale thermal power plants produce 95% of electrical energy in Estonia and therefore it is not possible to compensate larger generated power deviations at wind farms. Development of wind farms with high-power WTGs in Estonia is becoming increaseingly expensive and complicated. Consequently, in June, 2007 new terms for connecting WTGs with the distribution network were introduced. For every MW connected to the system there should be guaranteed the existence of a local, quickly convertible compensative power source of equivalent power (Enterprise Standard, 2001; Estonian transmission …, 2008). The wind energy parks are created mostly on the islands and sea shore where the wind conditions are better than inland. But positioning wind generators inland is becoming more advisable if the following conditions are taken into account:

- the generating power of WTGs are not high (up to 100 kW) and they are not connected to the network;
- wind turbines have an energy accumulation system, a compensating energy source or consumer that can work according to the consumption schedule dictated by the wind.

If the WTG can be connected into a weak electrical network then the energy accumulation system or compensating energy source may be significantly less powerful than an autonomous WTG.

Considering the technical development of wind generators, lowering prices and constant rise of energy prices in recent years it is very likely that the usage of small-power windmills (up to 100 kW) may become economically efficient in Estonia. In this paper we examine the data of inland wind that is usually considered of small value for energy production (Tomson et al., 2002). The power curves of small-power wind generators for low and medium average wind speed regions are also analyzed in correlation with the wind data.

MATERIALS AND METHODS: THE WIND SPEED ANALYSIS

Depending on the average wind speed values and conditions, the territory of Estonia may be divided into two slightly different regions – 1) the sea shore, islands, and Peipsi Lake, and 2) the bulk of the inland. Fig. 1 shows that prevailing average wind speeds at the shore and on the islands are 5–7 m s^{-1}, and on Peipsi Lake it is a bit less - 5 m s^{-1}. Prevailing average wind speeds inland are 2.5–3.5 m s^{-1}. For example at 20 km from the western shore inland, at 10 m height the wind speed may diminish nearly 50% in comparison with the same level at sea (Tomson, 2001). The wind speed change is much smaller from the northern shore inland than from the western shore (Tomson et al., 2002). That may be the result of the sparse and lower vegetation on poor slag soil of the high northern shore regions compared to the western low shore with forests and flourishing vegetation, which provides much more resistance for the wind. This wider area of high speed winds near the northern shore is clearly visible in Fig. 1.

The generative power of the wind turbine can be described by the equation:

$$P = Sc\rho v^3 / 2 , \quad (1)$$

where P is the generator power at given wind speed, kW; S – the area of rotor blades circuit, m^2; c – the efficiency coefficient of wind generator at given wind speed; ρ – air density, kg m^{-3} and v – wind speed, m s^{-1}.

Variable parameters for specific wind generators in this equation are the wind speed and effectiveness coefficient that also depends on the wind speed – $c = f(v)$.

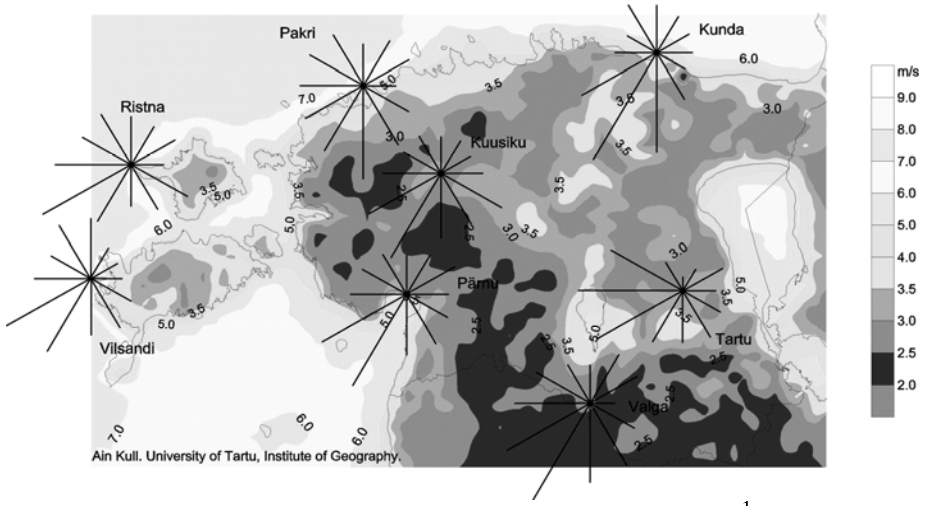

Fig. 1. The average wind speeds at different points in Estonia (m s^{-1}) (Kull, 1995).

To determine the wind turbine application possibilities it is advisable to analyze the frequency distribution of wind speeds in a given county. Five measuring points given in Table 1 are inland (Tartu, Väike-Maarja, Kuusiku, Viljandi and Valga); the rest are on the shore or islands. The wind speed of 13 m s^{-1} and more is only 0–3 ppm inland for the whole observation; on the shore and islands this parameter is 11–62 ppm. The data given in Table 1 corresponds to 10 m height above the ground level that does not necessarily give the entire overview of the wind energy at greater heights.

Table 1. The repeatability of winds with different speed at 10 m level off the ground in ppm (Kull et al.,1999).

Observation station	The repeatability in ppm of wind speed by classes (m s^{-1})													
	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
Vilsandi	10	38	85	121	131	123	105	100	84	97	62	27	11	6
Kuressaare	28	81	138	158	151	127	101	76	54	55	21	8	2	0
Pärnu	52	126	172	147	116	91	73	61	50	61	29	14	6	2
Pakri	42	105	149	151	141	115	87	78	56	51	17	6	2	0
Virtsu	29	102	172	192	165	119	82	54	34	32	11	4	1	1
Kunda	84	107	159	173	152	112	79	53	33	31	11	4	1	0
Ristna	45	124	194	193	149	95	65	48	30	31	15	7	2	1
Kärdla	54	124	171	154	165	141	77	50	32	23	5	2	1	0
Tartu	69	123	164	170	160	131	86	48	26	19	3	1	0	0
Väike-Maarja	66	120	171	187	163	121	80	45	23	20	3	0	0	0
Kuusiku	150	213	234	183	114	57	27	12	6	4	1	0	0	0
Viljandi	125	227	257	192	112	52	23	8	3	2	0	0	0	0
Valga	171	263	261	167	85	34	13	4	1	0	0	0	0	0

In December 2007 the measurements of wind speed were carried out in midland Estonia, 15 km north of Viljandi. The landscape at this measurement point is typical inland level ground with small smooth hills and opens to the winds from North, West and South (500 m of the fields). From the East there are sparsely growing high trees. As in this region the prevailing wind direction is from South-West; obstacles from the East do not influence the results of the measurements very seriously but may have increased the significance of the small wind speeds. The measurements were made by wireless weather station LaCrosse WS 2308-EL at 10 m height and the results were saved as 10 minutes average.

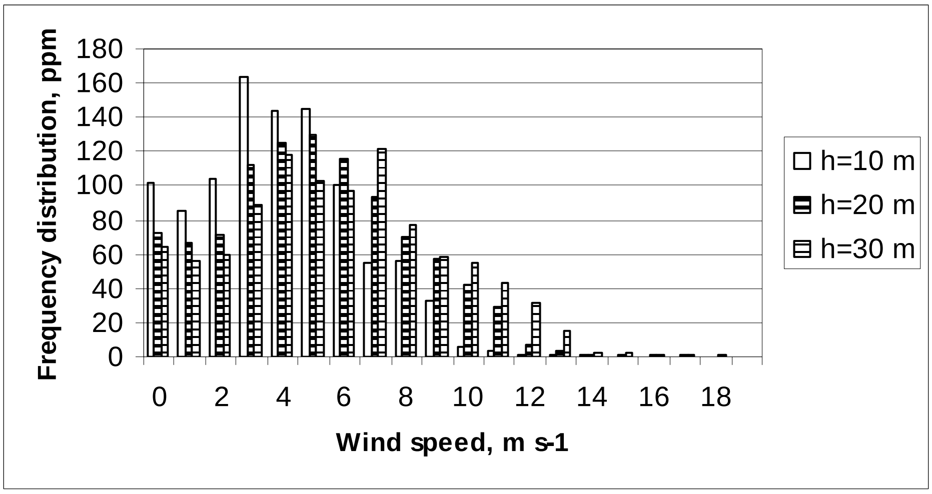

Fig. 2. The wind speed frequency distribution chart for Viljandi County in December, 2007.

Fig. 2 shows wind speed frequency distribution for measured values at 10 m height and transposed wind speed frequency distributions for 20 m and 30 m heights. Transposition was made according to the equation (Renzo, 1982):

$$v_2 = v_1 (H_2 / H_1)^{k_H} , \qquad (2)$$

where v_1 and v_2 are average wind speeds at levels H_1 and H_2. Hellman's coefficient k_H value used in calculations was $k_H = 0.29$ (Annuk & Tomson, 2005), that is best suited to characterize the landscape influence on wind speed vertical distribution in Estonia. Fig. 2 shows that frequency of occurrence of wind speeds 11–12 m s^{-1} even at 30 m height is only 44 ppm maximum. However, the wind generators with horizontal axis achieve their nominal power only at these speeds.

From the wind data analysis we may conclude that for inland regions of Estonia the wind turbines that start to generate and achieve maximum power at low wind speeds should be chosen.

The analysis of wind generator power curves

Without technical analysis we can state that the power curves of wind turbines with horizontal axis may be divided in two major groups depending on the form of the curve. The Fig. 3 shows a typical power curve (type A), characterized by a smooth rise with the wind speed increase and output power stabilization at nominal power at the wind speed of 11–16 m s^{-1}. Such a wind turbine starts to generate power at wind speeds of 2.5–5.0 m s^{-1}. As a rule the lower speed values apply to less powerful generators (up to 100 kW). The generators with this type of power curve are switched off from the network at the wind speed of ~ 25 m s^{-1}. Usually such power curve characterizes older types of wind generators (Tomson et al., 2001) or powerful devices over 1 MW. The control of such generators is achieved by pitch regulation.

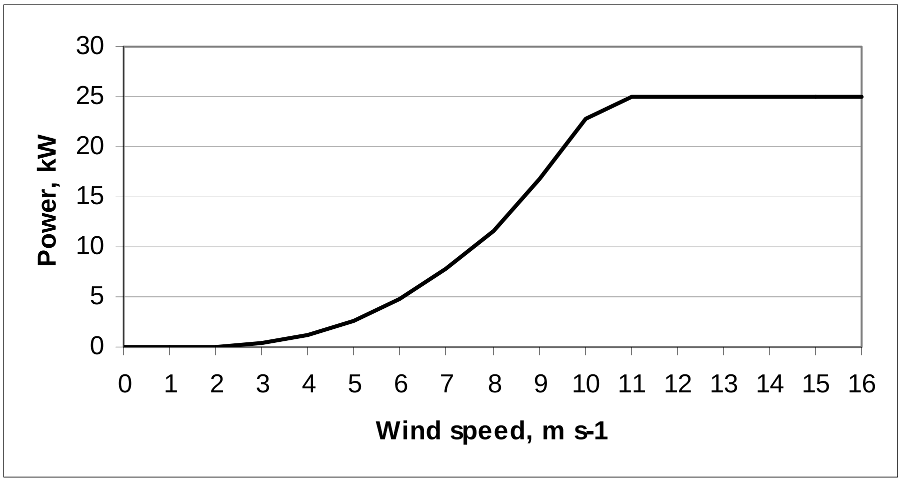

Fig. 3. Eoltec WindRunner 11-25 wind turbine generator power curve (type A) (Eoltec, 2006).

Wind generators with B type power curve shown on Fig. 4 do not have stable output power. Output power reaches maximum at the wind speeds of 11–14 m s^{-1} and starts to diminish at increased speed. In their specifications, producers of the generators with such a power curve usually suggest a smaller nominal output power than the device can produce. As Fig. 4 shows, a generator with nominal power of 20 kW can produce peak power of 25 kW and is not switched off even at high wind speeds. The specifications state that these devices can withstand wind speeds up to 65–70 m s^{-1}. The output power generation of the wind turbines with this power curve starts at wind speeds of 2.5–3.0 m s^{-1}. Usually this type of power curve characterizes smaller devices (up to 50 kW). Their control is achieved normally by stall regulation or yaw control.

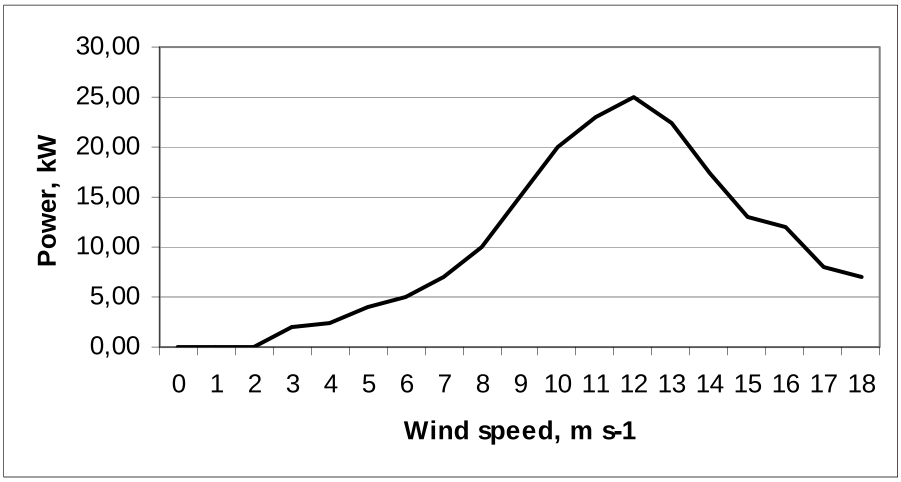

Fig. 4. WP 20 kW wind turbine generator power curve (type B) (Eoltec, 2003).

RESULTS AND DISCUSSION

Analyzing descriptions of properties of wind turbines with output power up to 100 kW, we can see that most of the devices on the market have nominal output power of 0.6–25 kW. A few have 65 and 75 kW output power. Developers of big wind generators generally use units starting from 1 MW which are meant to produce electric power for the network and are usually set up in regions with high wind speeds. Small-power wind turbines are intended for complete or partial electric energy supply for local consumers.

For more detailed analysis we choose a group of small-power generators suitable to work at comparatively low wind speeds (Table 2 (Eoltec Wind…, 2006; Eoltec Sci…, 2003; Eoltec Chi…, 2003; Proven Energy, 2007; Tech…–WP 1000…, 2007; Tech…–WP 3…, 2007)).

These devices switch on at wind speeds less than 3 m s^{-1} and achieve maximal output power at 11–12 m s^{-1}. At wind speeds less than 2 m s^{-1} even small-power turbines do not generate output power. In inland Estonia, wind speed higher than 12 m s^{-1} is comparatively rare, therefore it is advisable to use small-power wind turbines.

The data in Table 1 shows that there is only 4ppm of such winds inland. Measurement data at 10 m height (Fig. 2) indicates that there were only 2 ppm of high speed winds. Transposition of the measurement result to 30 m height gives up to 24 ppm of high speed winds at our observation point. From that we can conclude that in inland regions of Estonia it is possible to use only the rising part of the power curve of the generators corresponding to wind speeds of 2–12 m s^{-1}.

To predict the supposed energy production for a selected period, it is necessary to know the wind speed frequency distribution in a given region and the power curve of the generator. The wind speed frequency distribution corresponds most accurately with the Weibull distribution.

Taking into account the similarity of the curves it is advisable to use their normalized forms:

$$P^* = \frac{P}{P_N}, \qquad (3)$$

where P^* is normalized wind generator power, 0–1; P – measured power, kW; P_N – nominal or maximal generated power of the generator, kW.

pecifications of the wind generators under discussion are given in Table 2. It is useful to analyze A and B type curves separately.

Table 2. Specifications of small-power wind generators.

Generator type	Switching on speed, m s^{-1}	Nominal power, kW	Type of power curve	Nominal power wind speed, m s^{-1}
Eoltec WindRunner 11-25	2	25	A	11
Eoltec Scirocco 5.5-6000	2	6	A	12
Eoltec Chinook 17m-65kW	2	65	A	11
Proven 2.5	2.5	2.8 (2,5)	B	12
Proven 6 kW	2.5	6.4 (6,0)	B	12
Proven 15 kW	2.5	16.0 (15)	B	12
Tuulivoimala WP 1kW	2.5	1.65 (1)	B	12
Tuulivoimala WP 2kW	2.5	2.75 (2)	B	11
Tuulivoimala WP 3kW	2.5	4.0 (3)	B	12
Tuulivoimala WP 5kW	2.5	6.2 (5)	B	12
Tuulivoimala WP 10kW	2.5	13.0 (10)	B	12
Tuulivoimala WP 20kW	2.5	25 (20)	B	12

Figs 5, 6 show A- and B-type normalized average power curves of wind turbines for wind speeds of 2–12 m s^{-1}. Correlation coefficients for both cases are very high - $R^2 > 0.99$. So, the rising part of the power curve is very well modelled by second order polynomial. After that, we concentrate only on B-type power curves, corresponding to small scale power modern generators.

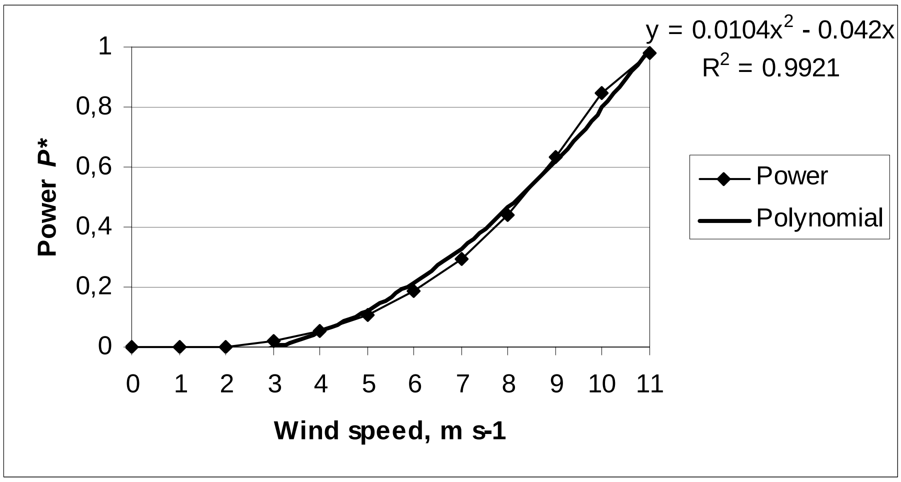

Fig. 5. Normalized averaged A-type power curve (rising part).

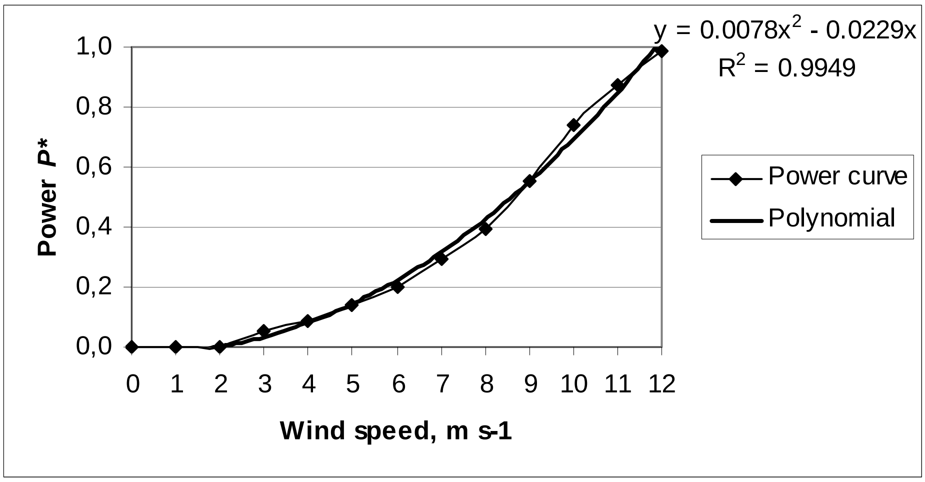

Fig. 6. Normalized averaged B-type power curve (rising part).

To model the power curve of the specific wind turbine we have to multiply the polynomial by the maximal output power of the device. Possible inaccuracy may arise from two causes: 1) not accounting for the energy produced at wind speeds over 12 m s^{-1} and, 2) mistakes of averaging power curves. We can check the error on the example of 20 kW WTG power curve, shown on Fig. 4. We take the wind speed frequency distribution example from the earlier described measurements series in Viljandi County. Table 3 shows that additional energy produced at wind speeds over 12 m s^{-1} at 30 m level are 6.7%. The measurements were conducted in December December-January are most windy months in Estonia (Tomson & Hansen, 2001), so the error for other months will be much smaller.

Table 3. WTG WP 20 electric energy calculated production in December at 10-30 m heights.

WTG's height above the ground *h*, m	Electric energy production at wind speeds 3–12 m s^{-1}, kW·h	Electric energy production at wind speeds >12 m s^{-1}, kW·h	Additional electric energy production at wind speeds >12 m s^{-1}, %
10	2374	31	1.3
20	3901	91	2.3
30	5054	340	6.7

The suggested power curve averaging error appears as standard deviation at different wind speeds. But we are most interested in the exactness of electric energy production estimation. Fig. 7 shows that power standard deviations are 3.95–38.68%. The highest standard deviation is at the wind speed of 3 m s^{-1} and diminishes at higher wind speeds, reaching minimum at 12 m s^{-1}. Power standard deviations are carried over to energy production and compensate each other to some degree. The ratio of energy production standard deviation and energy production is not greater than 2.72% at 10 m WTG positioning height and wind speed of 3 m s^{-1}. At greater heights standard deviations diminish still more and at 30 m WTG positioning height, the maximum is 1.83%.

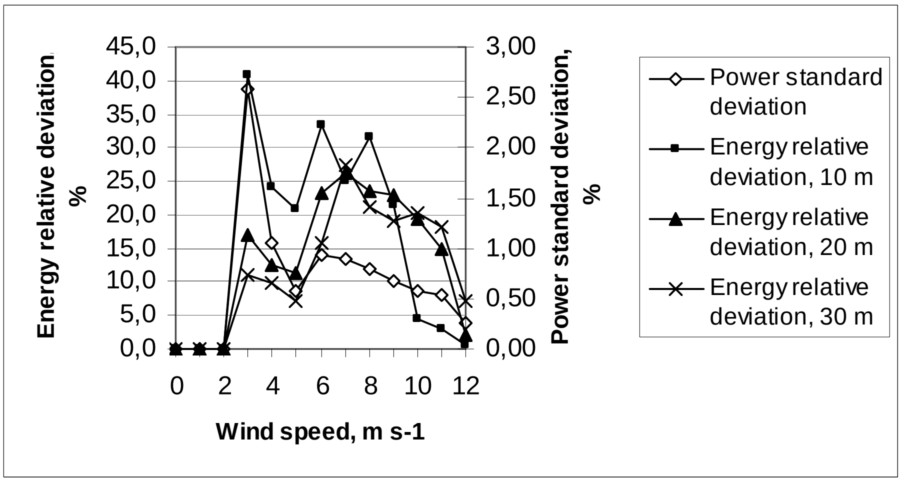

Fig. 7. Standard deviations of WTG power curves and relative deviations of electric energy production.

Power curves of wind turbines used for calculations are measured at static conditions. In actual environmental conditions where wind speed changes in a matter of seconds and the roughness of landscape is difficult to estimate, the resulting deviations are larger. The output power standard deviation of WTG's measured at normal work conditions is remarkably larger (Anahua et al., 2007) and less definite as estimated by the suggested calculations. Energy production predictions, made on the basis of wind speed measurements at 10 m height, may be up to 100% higher than real results (Tomson et al., 2004).

CONCLUSIONS

1. From the wind energy production effectiveness perspective, the most promising winds in Estonia (average 5–7 m s^{-1}) are at the sea shores and islands. The average wind speeds diminish rapidly from shore to inland, where the average wind speed is 2.5–3.5 m s^{-1}, and only minimal wind speed frequency distribution (~4 ppm) exceeds 12 m s^{-1}.
2. For electric energy production in mainland Estonia the most suitable wind turbine generators are small-power devices with horizontal axis (nominal power < 100 kW) that switch on at wind speeds < 3 m s^{-1} and reach maximal power at 11–12 m s^{-1}.
3. The power curves of small-power WTG's may be divided into two groups depending on the form of the curve after it reaches maximum. In the first, the output power stabilizes at maximum level and does not change at higher wind speeds; in the second, the power reaches maximum and then diminishes at higher wind speeds.
4. The power curves of WTG's in each group are very similar. It is useful to model only the first rising slope of the WTG power curve because wind speeds higher than 12 m s^{-1} are very rare. The rising slope of the power curve for wind speeds of 2–12 m s^{-1} is very accurately modelled by second order polynomial.

5. The ratio of energy production standard deviation and energy production is not greater than 2.72% at 10 m WTG positioning height and wind speed of 3 m s^{-1}. At higher wind speeds and greater heights this ratio diminishes. Additional electric energy production at wind speeds over 12 m s^{-1} is largest at 30 m level – 6.7% and increases at higher levels.

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