COMPATIBILITY OF ENERGY CONSUMPTION
WITH THE CAPACITY OF WIND GENERATORS

ENERGIA TARBIMISE SOBIVUS
TUULEGENERATORITE VÕIMSUSEGA

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A Thesis
for applying for the degree of Doctor of Philosophy in Energy Use

Väitekiri
Filosoofiadoktori kraadi taotlemiseks energiakasutuse erialal

Tartu 2011
According to verdict No. 17 of May 19, 2011, the Doctoral Committee of the Engineering Sciences of the Estonian University of Life Sciences has accepted the thesis for the defence of the degree of Doctor of Philosophy in Energy Use.

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Defence of the thesis:
Estonian University of Life Sciences, room 216, Kreutzwaldi 64, Tartu on June 21, 2011, at 12:00.

Publication of this thesis is supported by the Estonian University of Life Sciences
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THE AUTHOR’S CONTRIBUTION TO THE ORIGINAL PUBLICATIONS

The contributions by the author to the papers included are as follows:

I Vahur Põder was the main author of the paper. He was responsible for literature overview and calculations. He had a major role in writing the paper.

II Vahur Põder participated in writing the paper. He was responsible for data collection and calculations. He had a minor role in writing the paper.

III Vahur Põder participated in writing the paper. He was responsible for data collection and calculations. He had a major role in writing the paper.

IV Vahur Põder was the main author of the paper. He was responsible for the literature overview and calculations. He had a major role in writing the paper.
ABBREVIATIONS

Latin script

$A_T$ rotor swept area, m$^2$
$c$ scale factor of Weibull distribution
EMHI Estonian Meteorological and Hydrological Institute
$H$ elevation, m
$H_{ref}$ reference elevation, m
$K$ von Karman constant
$k$ Weibull shape factor
$k_H$ Hellman’s exponent
$k_m$ maximum power utilization factor
$L$ scale factor
$n$ number of wind data
$P$ instantaneous power, kW
$P_a$ average power, kW
$P_m$ maximum power, kW
$P_N$ nominal power, kW
$P_r$ relative power
$t$ time period
$t_m$ average length of energy lull, h
$t_{max}$ maximum length of energy lull, h
$V$ wind speed, m/s
$V_m$ average wind speed, m/s
$V_{ref}$ average wind speed at reference elevation, m/s
$W$ energy production, GWh
$W_e$ electric energy production, GWh
$W_k$ energy content of fuels, GWh
$W_s$ heat energy production, GWh
WTG wind turbine generator
$z_0$ roughness length of surface, m

Greek script

$\beta$ consumption factor
$\rho_a$ air density, kg/m$^3$
$\eta_e$ efficiency of electrical production
$\eta_s$ efficiency of heat production
INTRODUCTION

The importance of wind energy is growing. More and more wind turbines are being erected and connected to the electrical grid. A large amount of electrical energy is generated in good wind conditions which must be consumed by the electrical system. Energy production and consumption must be in balance, it is very hard to store the surplus electric energy.

According to the approved development plan of Estonian renewable energy resources (RES) their relative importance should be 25% of total energy consumption by the year 2020 and the relative importance of electricity obtained from RES should be at least 15% (Development...2009, Development...2010).

Estonia is a good example to analyze the influence of wind speed on energy production and consumption due to the varying wind conditions in different locations. By comparing energy production and consumption charts in the energy system, the possibilities of using different sources (such as oil shale, wind, hydro) for energy production can be analyzed. One aim is to maximize the energy production of wind turbine generators. Therefore the influence of limitations must be analyzed.

Although most parts of Estonia are supplied by the national electrical grid, there are still some applications for autonomous wind power systems. Most of current grid-connected wind generators are located in areas with high average wind speed (coast area and islands). But autonomous wind energy might be needed in inland areas with lower average wind speed. Generators with low cut-in speed should be selected. The capacity of such generators is not high (up to 100 kW) and this limits the type of consumers. Constant energy supply must be guaranteed without oversizing wind turbine and storage device.
1. REVIEW OF THE LITERATURE

1.1 History of wind energy production

The earliest recorded windmills were vertical axis mills in the Afghan highlands from the seventh century BC. Windmills with horizontal axes appeared in China, Persia and Tibet in about 1000 AD. This windmill type spread, probably due to the Crusaders, from Persia and the Middle East to Central Europe and the Mediterranean countries. First records about horizontal axis windmills in England are from 1150, in France from 1180, in Germany from 1222 and in Denmark from 1259 (Ackermann 2005). The first wind electricity was produced in Denmark in the year 1890 by using a 23 m diameter wind turbine (Johnson 2006).

The capacity of installed wind turbines in Europe was 84,074 MW at the end of 2010. Wind power capacity (9259 MW) was 16.7% of new electricity generating capacity in 2010 (EWEA 2011). This was the first year since 2007 that wind power did not contribute more capacity than any other technology.

The average capacity of wind turbine generators (WTG) and the proportion of wind-generated electricity has been growing. The average capacity of an installed turbine was 394 kW in 1995 and 1,419 kW in 2008 (Nimish 2010). The penetration of wind power is highest in Denmark (24%), followed by Spain and Portugal (EWEA 2011). The instantaneous amount of wind-generated electricity depends on the relative capacities of the different power sources in electric grid. For example, a record wind energy production of 45.1% of total energy demand for almost six hours was recorded during November 7, 2009 in Spain (REVE 2009).

Most wind parks are located on the islands, off shore and on the coast, where the wind conditions are better than inland. The cost of large-scale wind energy application is high. The average installed cost of offshore wind parks built during 1991-2008 was 1632.90 €/MW (Snyder et al. 2009); the cost of onshore wind installation was 774 €/kW and offshore wind installation 1192 €/kW in 2006 (Strbac et al. 2007).
The first signs of wind energy usage are from the year 1572 in Estonia and they were used for grain milling and more seldom for grain threshing and water pumping (Pajumets 1999). The capacity of Estonian wind generation has grown quickly. The first modern 150 kW wind generator was installed in Tahkuna in 1997 and since then the total capacity of wind generators has grown to 149 MW in 2010 (Risthein 2007, EWEA 2011). During 2010 275, 862 MWh electricity was produced using wind energy resources (Elering 2011).

1.2 Energy production in Estonia

Practically almost all the electric energy consumed in Estonia, and a significant part of heat energy, is produced by electric and cogeneration power stations belonging to the uniform energy system and is transported to the consumers by the district-heating and electric networks. In the case of electric energy, there is a uniform electrical system for the whole country, while due to technical reasons, district-heating networks have limited length (for a town, village or part of it) and the capacity of district-heating plants is mostly smaller. Centrally produced electrical and heat energy is carefully measured and accounted for, and there are state-wide statistics concerning the amount of energy produced and consumed (Statistical 2009). In addition, there are also a large number of small-scale individual producers of heat energy for their own needs whose consumption rates may be estimated very roughly. In 2009 in Estonia 8,777 GWh of electric energy were produced, of which 8,549 GWh or 97.4% was produced by the thermal power stations and 227 GWh (2.6%) using wind and hydro energy. The generation of hydroelectric power stations was 32 GWh (0.4%) and wind turbines 195 GWh (2.2%). The energy content of solid fuels for electricity production was $W_k = 82,503$ TJ (22,917.5 GWh) and obtained electric energy $W_e = 8,549$ GWh (Statistical 2009). The electrical efficiency of thermal power stations can be found using:

$$\eta_e = \frac{W_e}{W_k} \times 100.$$

(1.1)

The electrical efficiency of Estonian thermal power stations was 37.3% in 2009.
At the thermal power stations and district-heating plants $W_k = 38,254$ TJ (10,626 GWh) of fuel energy was used to produce $W_s = 9,062$ GWh of heat energy (Statistical 2009). The efficiency of heat production can be found using:

$$\eta_s = \frac{W_s}{W_k} \times 100\% .$$

(1.2)

The efficiency of heat production in Estonia was 85.3% in 2009.

The proportion of oil shale in electric energy production at the thermal power stations was 97.4% and in the heat energy centralized production 13.9% (Statistical 2009). In the next 15 to 20 years there will probably be no significant reduction in the role of oil shale in Estonia (Tammeoja et al. 2008). The development plan for the Estonian electricity sector until 2018 was composed by the Ministry of Economic Affairs and Communications, with possible wind turbine capacities between 250-1200 MW in different scenarios (Estonian 2009). According to a study made by Ea Energy Analyses (Denmark), maximum 900 MW wind power can be integrated into the Estonian electricity system (Wind Power 2010).

### 1.3 Wind data measurement and wind data description

Knowledge of wind characteristics of selected sites is important for energy production estimation, because the available energy in the wind varies with the wind speed $V$ (m/s). Wind turbine generator capacity $P$ (kW) can be expressed as:

$$P = \frac{1}{2} \rho_a A_T V^3 ,$$

where 
- $\rho_a$ is the air density, kg/m$^3$; 
- $A_T$ is rotor swept area, m$^2$.

The most distinctive characteristic of wind is its variability (both geographically and temporally). Wind measurement instruments are usually located at a standard height of 10 m above open terrain, according to World Meteorological Organization (WMO) guidelines.
Most measurement systems give the average wind speed at the site, averaged over a pre-fixed time period (10 minutes are very common) and this short term data is further grouped (for example on an hourly basis) and analyzed (Mathew 2006). During the 1990s, automatic weather stations were introduced in Estonia, which enabled a dramatic increase in the accuracy of wind speed measurement (Keevallik et al. 2007).

One of the most important sources of information about the wind resources available at a certain location is its average speed $V_m$ (m/s):

$$V_m = \frac{1}{n} \sum_{i=1}^{n} V_i,$$

where $V$ is the wind speed, m/s; $n$ is the number of wind data.

The increase in wind speed due to altitude can be determined by different theoretical expressions. The Monin-Obukhov method describes the wind speed $V$ (m/s) at height $H$ (m) by means of a log-linear profile: (Johnson 2006)

$$V_z = \frac{V_f}{K} \left[ \ln \frac{H}{z_0} - \xi \left( \frac{H}{L} \right) \right],$$

where $V_f$ is the friction speed, m/s (function of surface friction and the air density); $K$ is von Karman constant (normally assumed to be 0.4); $z_0$ is the surface roughness length, m; $L$ is the scale factor (Monin-Obukhov length).

Function $x\left(\frac{z}{L}\right)$ is determined by the net solar radiation at the site.

This expression is valid for average wind speeds over short periods of time (e.g. one minute), but not for monthly or yearly means. The Monin-Obukhov method has been verified for detailed surveys at critical locations, but this method is difficult to use for general engineering studies, thus simpler expressions are used (Johnson 2006).
Wind speed increase due to altitude can be described with power law approximation according to Hellman (Hau 2006). Average wind speed \( V_m \) (m/s) at elevation \( H \) (m) can be calculated by:

\[
V_m = V_{ref} \left( \frac{H}{H_{ref}} \right)^{k_{H}},
\]

where

\( V_{ref} \) is the average wind speed at reference elevation \( H_{ref} \), m/s;

\( H_{ref} \) is the reference elevation, m;

\( k_{H} \) is the Hellman's exponent.

Value of Hellman’s exponent depends upon the coastal location and the shape of the terrain on the ground and the stability of the air. Some representative values for Hellman’s exponent are 0.10 (smooth hard ground, calm water) and 0.40 (large city with tall buildings) (Masters 2004).

Another possibility is the logarithmic wind profile law, which is widely used across Europe (Bañuelos-Ruedas et al. 2010):

\[
V_m = V_{ref} \frac{\ln \left( \frac{H}{z_0} \right)}{\ln \left( \frac{H_{ref}}{z_0} \right)},
\]

where

\( z_0 \) is the roughness length of surface, m. It can vary for example between 0.0001 m (water surfaces) and 1 m (city area) (Hau 2006).

According to climatology, the territory of Estonia may be divided into two conditionally slightly different regions – the seashore and islands (influenced by the sea) and the rest of inland (Kalamees and Kurnitski 2006). A similar distribution applies to wind. Average wind speeds on the shore and on the islands, at a height of 10 m, are 5 to 7 m/s, on Peipsi Lake 5 m/s and inland are 2.5 to 3.5 m/s (Kull 1995).

The frequency distribution of wind speeds should be analyzed to determine the wind turbine application possibilities. Wind speed repeatability for different locations in Estonia is given in Table 1.1 (Kull
et al. 1999). Five measuring points in table are located inland (Tartu, Väike-Maarja, Kuusiku, Viljandi and Valga); the rest are on the shore or islands. The wind speed of 13 m/s 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 1.1 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 1.1 The repeatability of winds with different speed at 10 m level off the ground in ppm (Kull et al. 1999)

<table>
<thead>
<tr>
<th>Observation station</th>
<th>The repeatability in ppm of wind speed by classes (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;1</td>
</tr>
<tr>
<td>Vilsandi</td>
<td>10</td>
</tr>
<tr>
<td>Kuressaare</td>
<td>28</td>
</tr>
<tr>
<td>Pärnu</td>
<td>52</td>
</tr>
<tr>
<td>Pakri</td>
<td>42</td>
</tr>
<tr>
<td>Virtsu</td>
<td>29</td>
</tr>
<tr>
<td>Kunda</td>
<td>84</td>
</tr>
<tr>
<td>Ristna</td>
<td>45</td>
</tr>
<tr>
<td>Käärdla</td>
<td>54</td>
</tr>
<tr>
<td>Tartu</td>
<td>69</td>
</tr>
<tr>
<td>Väike-Maarja</td>
<td>66</td>
</tr>
<tr>
<td>Kuusiku</td>
<td>150</td>
</tr>
<tr>
<td>Viljandi</td>
<td>125</td>
</tr>
<tr>
<td>Valga</td>
<td>171</td>
</tr>
</tbody>
</table>

In addition to the average wind speed over a period, the wind distribution is also important. Annual wind speed variations can be well characterized in terms of a probability distribution (Burton et al. 2001). The Weibull distribution has been found to give a good overview of the variations in hourly wind speed over a year in many typical locations. This distribution is a special case of the Pearson class III distribution and uses two functions to describe wind speed variation.
The probability for which the wind is at a given speed is:

\[ f(V) = \frac{k}{c} \left( \frac{V}{c} \right)^{k-1} e^{-\left( \frac{V}{c} \right)^k} \quad (1.8) \]

where

- \( k \) is the Weibull shape factor;
- \( c \) is the Weibull scale factor.

The shape factor describes the variation about the mean. The scale factor is related to the annual average wind speed:

\[ V_m = c \Gamma(1 + \frac{1}{k}) \quad (1.9) \]

The cumulative distribution function of the wind speed \( V \) describes the probability that the speed is equal to or lower than \( V \). It is described by:

\[ F(V) = \frac{\alpha}{V} \int_0^V f(V) dV = 1 - e^{-\left( \frac{V}{c} \right)^k} \quad (1.10) \]

The cumulative function can be used to estimate the time, during which the speed is within a certain speed interval. The difference of cumulative probabilities corresponding to speeds \( V_2 \) and \( V_1 \) shows the probability of wind speed being between \( V_1 \) and \( V_2 \). Thus,

\[ P(V_1 < V < V_2) = e^{-\left( \frac{V_1}{c} \right)^k} - e^{-\left( \frac{V_2}{c} \right)^k} \quad (1.11) \]

The probability that wind speed exceeds a certain value for \( V_x \) can be expressed:

\[ P(V > V_x) = 1 - \left( 1 - e^{-\left( \frac{V_x}{c} \right)^k} \right) = e^{-\left( \frac{V_x}{c} \right)^k} \quad (1.12) \]

The reliability of the Weibull distribution depends on the accuracy of \( k \) and \( c \). A substantial amount of wind measurement data over shorter time intervals are needed to determine \( k \) and \( c \) values. Sometimes the existing data contains average wind speed over a given period (daily, monthly or yearly average wind speed). In this case, a simplified case of the Weibull distribution, known as the Rayleigh distribution, can be used (Burton...
et al. 2001). In this case, shape factor $k$ is approximated to 2. Annual average wind speed is:

$$V_m = c\Gamma\left(\frac{3}{2}\right)$$ \hspace{1cm} (1.13)

and the cumulative function is thus (Burton et al. 2001):

$$F(V) = 1 - e^{-\frac{\pi}{4}\frac{V}{V_m}^2}.$$ \hspace{1cm} (1.14)

The probability of wind speed to be between $V_1$ and $V_2$ is:

$$P(V_1 < V < V_2) = e^{-\frac{\pi}{4}\left(\frac{V_2}{V_m}\right)^2} - e^{-\frac{\pi}{4}\left(\frac{V_1}{V_m}\right)^2},$$ \hspace{1cm} (1.15)

and the probability of wind to exceed wind speed $V_x$ is thus:

$$P(V > V_x) = 1 - \left(1 - e^{-\frac{\pi}{4}\left(\frac{V_x}{V_m}\right)^2}\right) = e^{-\frac{\pi}{4}\left(\frac{V_x}{V_m}\right)^2}.$$ \hspace{1cm} (1.16)

According to the European Wind Atlas, in the North European climate, $k \approx 2$ and wind speed distribution is close to the Rayleigh distribution (Keevallik et al. 2007).
1.4 Autonomous wind energy systems and storage devices

Although most locations in Estonia are supplied by the national electric grid, there are some applications for autonomous wind power systems. There are locations without any existing electric network, and building a new connection is economically unjustifiable. The cost of a fossil fuel generator can be also too expensive. Renewable energy sources, especially wind energy, can often be the primary source of energy, as they are commonly present in geographically remote and demographically sparse areas (Georgilakis et al. 2009). The stochastic output of a WTG (wind turbine generator) is one of the biggest problems in the practical usage of a small autonomous wind energy system. Some kind of backup generator or storage device is needed to ensure a constant energy supply, thus forming a hybrid system. Different energy storage alternatives, such as fuel cells, flywheels and hydraulic storage are available. The selection of storage device depends on the characteristics of the wind generation device and the consumer (Kaldellis 2006). Different simulation algorithms and methods for optimal system design are being researched, such as Simulated Annealing (Ekren & Ekren 2010) or design spaces for wind-battery systems (Roy et al. 2009).
2. AIMS OF THE STUDY

The design of wind energy system depends on different factors, such as wind conditions at the selected site, and the properties of a particular consumer. Due to the stochastic nature of wind, the output of a wind generator can change quickly (80% over two hours; Kilk 2007). Because the supply and consumption must be in balance in the energy system, some kind of compensation system is needed (hydro and pumped storage power plants, gas turbines etc). Since June 2007 a local, quickly convertible compensative power source of equivalent power is required to connect wind turbine generators (WTG) with the distribution network in Estonia (III). The most common solution to cover rapid power fluctuations is a gas turbine power plant. The running costs of gas turbines are high and therefore their working hours are kept as low as possible (Palu 2009).

The aim of this study was to find methodology to design efficient wind energy system. It means wind energy system with maximum power utilization factor and reliable energy supply, and avoiding oversizing system components (generator, storage device). In case of wind energy system connected with electric grid the influence of wind conditions and electric system energy balance must be considered. In case of autonomous system the influence of wind conditions and storage device and consumption must be considered.

List of the tasks to be solved to achieve the aim were:
1. Overview of energy production and consumption charts in the energy system.
2. Overview of wind data measurement and analysis methods.
3. Overview of power curves of different types of wind generators.
4. Analysis of wind data from different locations (with varying wind energy usage potential).
5. Devise a method to find periods without energy production (“energy lulls”) from wind data.
6. Processing of wind data to calculate energy production at different locations.
7. Estimation of the influence of consumption factor $\beta$ for different WTG/storage device/consumer combinations in autonomous energy system.
3. MATERIALS AND METHODS

3.1 Wind speed and energy production data

Estonian wind data from the EMHI (Estonian Meteorological and Hydrological Institute) and the Estonian University of Life Sciences’ measurement station (located near Viljandi) were analyzed. Measurement data contained average wind speed for a 1 h period at a height of 10 m during 2004–2008. The data was processed using SciCosLab and Microsoft Excel. Wind speed was transposed to higher height values using equations with the Hellman exponent $k_H = 0.25$ for the seashore and $k_H = 0.29$ for inland (Annuk and Tomson 2005). Distinctive locations were selected: Jõgeva, Tõravere and Viljandi for the inland area and Pakri, Tiirikoja and Virtsu for the coastal area. Energy production data of Pakri wind farm about year 2006 was obtained. It was analyzed together with consumption charts of energy system of Estonia (obtained from Eesti Energia AS).

3.2 Energy lulls

An energy lull can be defined as the period without wind or with a wind speed of less than 2.5 m/s, which is insufficient for wind turbines. Windless periods are clearly distinguishable on production charts (Fig. 3.1).

![Fig. 3.1. Normalized WTG production chart in Viljandi over two weeks in the 3rd quarter of 2006 at a height of 30 m.](image)
3.3 Energy production and consumption charts

It is useful to describe the energy production and consumption during certain period using charts. The length of the period is usually one year, one month or one day and the consumption chart characterizes electric or heat energy usage by an individual consumer, a group of consumers, or of a settlement or some other administrative unit (the whole country as well). Therefore the consumption chart is dictated by the needs of the consumers.

The growth of importance of energy production and consumption balance is caused by the widening electrical energy production based on natural phenomena not influenced directly by people (the wind, the sun and to a certain extent the water at small hydroelectric stations). The owners of such energy production systems, declaring that their energy is cost-free (when such system is already installed), try to “cram” their electrical energy into the public electric network independently of the needs of consumers (their consumption charts) making the electric power stations and network load curves more choppy. This leads to greater losses in the network and to reduced efficiency of the system. If the production peaks of such energy producers exceeds a certain level the stability of the electric energy system as a whole may become endangered (Kokin et al. 1999).

Fig. 3.2 shows the centralized electric and heat energy production data (at electric energy thermal power stations and district-heating plants) for 2006 in Estonia (II)(Statistical 2009).

![Centralized production of electric and heat energy in Estonia during 2006.](image)
From the chart, the sharply identifiable reduction of demand in the summer months is seen, especially in heat energy. It diminishes significantly the possibilities of renewable energy (wind) use for heat energy production in the summer months, because a large part of heat energy, as a by-product of electrical energy production, is not used at that time. The heat energy saving for longer periods is limited, and its efficiency is comparatively low.

For comparison, the monthly production of electric energy in 2006 by wind and hydroelectric power stations in Estonia is given in Fig. 3.3 (II) (Statistical 2009).

![Production chart of wind and hydro power stations in Estonia during 2006.](image)

**Fig. 3.3.** Production chart of wind and hydro power stations in Estonia during 2006.

According to Fig. 3.3, monthly production of wind energy is well correlated with heat and electric energy demand (Fig. 3.2). Therefore at least a portion of the (heat) energy may be produced by wind. However, as the wind at a given place may change significantly by the hour or by the minute (often even by the second), shorter period production data are needed for the analysis of the energy production dependence on the variation of wind parameters. The complex analysis of these charts should be calculated for a longer period.

The influence of hydroelectric power stations on the energy production in Estonia is very moderate. According to their energy production, it is
possible to define the periods of the snow melt in the spring and rains in the autumn (Fig. 3.3). The more specific analysis of the hydroelectric stations, and their development in the future, has been presented in the literature (Raesaar 2006).

As an example of wind energy production, the energy production of Pakri wind farm can be analyzed. This wind farm consists of eight Nordex N-90 wind turbines (each capacity 2.3 MW). The production chart of July 2006 is given in Fig. 3.4. The limitation of excess power by the control staff of the power supply system is clearly visible in the middle of the month.

![Production chart of Pakri wind farm during July 2006.](image)

In the analysis of wind turbine energy production it is practical to use the concept of the maximum power utilization factor $k_m$ that may be described as:

$$ k_m = \frac{W_{in}}{P_m t_n} \times 100, \quad (3.1) $$

where
- $W_{in}$ is the energy produced by the wind turbine during the period $t_n$, kWh;
- $P_m$ is the maximum power, kW.

Here $P_m t_n$ is the energy amount that would have been produced by the generator working at nominal power for a time $t_n$. According
to the production chart on Fig. 3.4 the output power of Pakri wind farm was periodically limited by the energy system dispatcher, and the corresponding maximum utilization factor \( k_m \) was comparatively low – 15.6%.

For calculation, the equation of the power curve that may be found using the wind turbine data (Nordex 2009) (II) is as follows:

\[
P_n = 0.0011V_n^6 + 0.0808V_n^5 - 2.1742V_n^4 + 24.297V_n^3
- 88.608V_n^2 + 90.616V_n - 0.8286
\]

(3.2)

At a wind speed \( V < 4 \) m/s the turbine output power is 0, but the equation gives us negative results, so it may be used with the additional condition:

\[
IF \ V < 4, P_n = 0
\]

(3.3)

The amount of energy produced is:

\[
W = \Sigma (P_a \Delta t_n),
\]

(3.4)

where

\( P_a \) is the average power in \( \Delta t_n \) period, kW.

The production chart of Pakri wind farm has been calculated using the wind speed data (Fig. 3.5).

Fig. 3.5. Possible production chart of Pakri wind park during July 2006.

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The maximum power utilization factor $k_m$ for this production chart is approximately 20%, nearly 4% higher than for real chart.

The daily electric energy production of Pakri wind farm for July 2006 is shown on Fig. 3.6, and it is much less informative as there are no periods with zero production, as were shown in Fig. 3.5.

![Fig. 3.6. The daily energy production of Pakri wind park during July 2006.](image)

The impact of the wind farms on the energy system is most evident from the hourly production charts. This is caused by the too short duration of sharp production variations for the large energy blocks of the power stations to follow up and to lessen their fuel consumption according to the smaller demand.

Two days – with minimum and maximum electric energy production should be compared. The hourly electric energy production by Pakri wind farm on July 3, 2006 when the consumption was minimal is given in Fig. 3.7.
The twenty-four hour calculated energy production on July 3 was 2,095 kWh and the corresponding maximum power utilization factor was 0.47%. The hourly mean power was 87.3 kW, taking into account also an 8-hour gap with nearly zero production. For a comparison, Fig. 3.8 shows the Estonian Energy system consumption chart for the same day (data obtained from Eesti Energia AS).

It is evident, that such a choppy production chart (Fig. 3.7) of the wind farm is unsuitable from the point of view of the energy system, as the work conditions for the main power generating stations are most favourable in the case of level production.

The energy production of the wind farm on July 18 (Fig. 3.9) was cut off by the energy system dispatcher approximately to 50% of the maximum power. The daily energy production was 214,560 kWh and maximum
power utilization factor 48.59%. The theoretical production chart of the same day defined by the Equation 3.2 on the basis of the wind speed data is shown in the Fig. 3.10.

![Theoretical Energy Production Chart](image1)

**Fig. 3.9.** The hourly energy production of Pakri wind park on July 18, 2006.

The energy production of the day would have been 339,293 kWh and a maximum power utilization factor of 76.8%.

![Theoretical Energy Production Chart](image2)

**Fig. 3.10.** The theoretical energy production chart of Pakri wind park on July 18, 2006 based on wind speed.
4. RESULTS AND DISCUSSION

4.1 Wind speed and energy lulls analysis

The maximum length of energy lulls $t_{max}$ (h) increases rapidly with the reduction in average wind speed (table 4.1). The standard deviation of the 5–year annual average wind speed from all locations is nearly 5%. The standard deviation of the 5–year average capacity is between 6–14% (lower values corresponds to higher average wind speeds) (I).

Table 4.1. Average wind speeds, relative wind generator capacities, means of maximum duration of energy lulls $T_m$ and the subsequent size of energy lulls with their standard deviations.

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

The largest energy lulls appeared during the autumn and winter months, with the highest probabilities in February and October (Fig. 4.1) according to the wind data (I).
Fig. 4.1. Recurrence of maximum energy lulls during 2004–2008 in six locations.

According to Pakri and Viljandi wind data, the shortest energy lulls were the most frequent (Fig. 4.2 and 4.3) (IV).

Fig. 4.2. Histogram of energy lulls during 2004–2008 in Pakri.
The correlation between the duration of maximum energy lulls and wind speed was found (Fig. 4.4).

This relation can be expressed as:

\[ t_{\text{max}} = 513.79V^{-1.683} \]  \hspace{1cm} (4.1)

The correlation coefficient for this relationship was \( r^2 = 0.85 \).
In the case of an autonomous system, the storage device should be able to ensure energy supply for the duration of the maximum energy lull. Detailed long-time wind speed measurements are needed for such a solution (Celik 2003; Kaldellis 2002). On the other hand, the probability of wind parameters can be described with the Weibull distribution (Mathew 2006; Cellura et al. 2008; Garcia et al. 1997).

According to measurement data, the relative length of an energy lull $l$ can be described using the Weibull distribution, thus the cumulative distribution function $F(l)$ is (4.2):

$$
F(l) = \frac{b}{a} \int_{a}^{b} f(t) \, dt = 1 - e^{-\left(\frac{l}{c}\right)^k},
$$

where $f(l)$ is the probability density function; $l$ is the length of the energy lull; $c$ is the Weibull scale factor; $k$ is the Weibull shape factor. The probability of a certain energy lull can be found by the cumulative distribution function. The probability between lengths $l_1$ and $l_2$ is given by:

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

The average length of an energy lull is:

$$
t_m = \frac{\sum_{i=1}^{n} t_i}{n}, 
$$

where $t_m$ is the average length of the energy lull, h; $t_i$ is the total duration of energy lulls of the same length, h; $n$ is the number of energy lulls, h.

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


The probability of a mean energy lull $P(l_m)$ is:

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

(4.5)

where $l_m$ is the duration of the mean energy lull.

There are different methods to determine the parameters $c$ and $k$. The graphical method (Mathew 2006) was used in this study. With a double logarithmic transformation the cumulative distribution function can be written as:

$$\ln\{-\ln[1 - F(l)]\} = k \ln(l) - k \ln c$$

(4.6)

The wind data from Viljandi (inland) and Pakri (near coast) from the years 2004-2008 were analyzed. This relationship is shown graphically (Fig. 4.5) and a nearly straight line can be observed (IV).

![Graph showing the relationship between ln(l) and ln(-ln[1 - F(l)])](image)

**Fig. 4.5.** Determination of $k$ and $c$ values (1–Pakri, 2–Viljandi).

According to equation 4.5, $k$ gives the slope of the line and $-k \ln c$ represents the intercept. The calculated relationships have high correlation coefficients ($r^2 > 0.95$).
The results of wind speed and energy lull analyses at heights of 30 m are given in Table 4.2.

**Table 4.2. Wind data results**

<table>
<thead>
<tr>
<th>Location</th>
<th>Average wind speed $V_m$, m/s</th>
<th>Max. lull, $t_{max}$, h</th>
<th>Mean energy lull $t_m$, h</th>
<th>Weibull shape factor $k$</th>
<th>Weibull scale factor $c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pakri</td>
<td>6.1</td>
<td>36</td>
<td>3.4</td>
<td>0.773</td>
<td>2.418</td>
</tr>
<tr>
<td>Viljandi</td>
<td>3.0</td>
<td>114</td>
<td>8.8</td>
<td>0.727</td>
<td>2.557</td>
</tr>
</tbody>
</table>

According to Table 4.2, the average wind speed has an influence on the mean and maximum energy lull lengths. The Weibull shape and scale factors for both locations were similar.

The cumulative Weibull distribution function of the Pakri and Viljandi energy lulls were calculated (Fig. 4.6). This shows the probability of the energy lull length being lower than length $l$ (IV).

![Cumulative Weibull distribution function of Pakri and Viljandi energy lulls during 2004-2008.](image)

**Fig. 4.6.** Cumulative Weibull distribution function of Pakri and Viljandi energy lulls during 2004-2008.

### 4.2 The analysis of wind generator power curves

The power curves of wind turbines with a horizontal axis may be divided into two major groups depending on the form of the curve. Fig. 4.7 shows a typical power curve (type A) (Eoltec 2006) (III).
Fig. 4.7. Eoltec WindRunner 11-25 wind turbine generator power curve (type A).

This type is characterized by a smooth rise with the wind speed increase, and output power stabilization at nominal power at a wind speed of 11−16 m/s. Such wind generators have cut-in speeds of 2.5−5 m/s, the lower speed values apply to less powerful generators (capacity up to 100 kW). Usually such a power curve characterizes powerful devices with a capacity of more than 1 MW. The generator is shut down at a wind speed of ~25 m/s.

Fig. 4.8 shows the power curve of a type B wind generator (Tuulivoimala 2007) (III).

Fig. 4.8. Tuulivoimala WP20kW wind generator power curve (type B).
These kinds of wind generators do not have stable nominal power. Output capacity reaches a maximum at wind speeds of 11–14 m/s and starts to diminish at higher speeds. The cut-in speed of these devices is 2.5–3.0 m/s. Usually, this type of power curve characterizes smaller devices (capacity up to 50 kW) and their control is normally achieved by stall regulation or yaw control. The producers of such generators usually suggest a smaller nominal output power in specifications than the device can generate. A generator with a nominal power of 20 kW can produce peak power of 25 kW (Fig. 4.8) and is not switched off even at high wind speeds. According to producers’ specifications, these wind turbines can withstand wind speeds up to 65–70 m/s.

Group of small–power wind generators, suitable for comparatively low speeds were selected (Table 4.3) (Eoltec Wind…2006; Eoltec Chi…2003; Eoltec Sci…2004; Proven Energy 2007; Tuulivoimala… 2007).

Table 4.3. Data of small–power wind generators

<table>
<thead>
<tr>
<th>Generator type</th>
<th>Cut-in speed, m/s</th>
<th>Nominal (maximum) power kW</th>
<th>Type of power curve</th>
<th>Nominal power wind speed, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eoltec WindRunner 11-25</td>
<td>2</td>
<td>25</td>
<td>A</td>
<td>11</td>
</tr>
<tr>
<td>Eoltec Scirocco 5.5-6000</td>
<td>2</td>
<td>6</td>
<td>A</td>
<td>12</td>
</tr>
<tr>
<td>Eoltec Chinook 17m-65kW</td>
<td>2</td>
<td>65</td>
<td>A</td>
<td>11</td>
</tr>
<tr>
<td>Proven 2.5</td>
<td>2.5</td>
<td>2.5 (2.8)</td>
<td>B</td>
<td>12</td>
</tr>
<tr>
<td>Proven 6</td>
<td>2.5</td>
<td>6 (6.4)</td>
<td>B</td>
<td>11</td>
</tr>
<tr>
<td>Proven 15</td>
<td>2.5</td>
<td>15 (16)</td>
<td>B</td>
<td>11</td>
</tr>
<tr>
<td>Tuulivoimala WP1000W</td>
<td>2.5</td>
<td>1 (1.65)</td>
<td>B</td>
<td>9</td>
</tr>
<tr>
<td>Tuulivoimala WP2000W</td>
<td>2.5</td>
<td>2 (2.75)</td>
<td>B</td>
<td>10</td>
</tr>
<tr>
<td>Tuulivoimala WP3KW</td>
<td>2.5</td>
<td>3 (4)</td>
<td>B</td>
<td>10</td>
</tr>
<tr>
<td>Tuulivoimala WP5KW</td>
<td>2.5</td>
<td>5 (6.2)</td>
<td>B</td>
<td>10</td>
</tr>
<tr>
<td>Tuulivoimala WP10KW</td>
<td>2.5</td>
<td>10 (13)</td>
<td>B</td>
<td>11</td>
</tr>
<tr>
<td>Tuulivoimala WP20KW</td>
<td>2.5</td>
<td>20 (25)</td>
<td>B</td>
<td>10</td>
</tr>
</tbody>
</table>

Analyzing the properties of wind turbines with output power of up to 100 kW (Table 4.3), most of the generators on the market have a nominal output power of 0.6–25 kW. Producers of large wind generators generally make units starting from 1 MW, which are meant to produce energy for a network and are usually set up in regions with high wind speeds. Small–power wind turbines are intended for complete or partial energy supply for local consumers.
4.3 Normalized power curve of WTG

Wind energy amount can be estimated on the basis of the wind generator power curve:

\[ P = f(V) , \tag{4.7} \]

where

- \( V \) is the wind speed, m/s;
- \( P \) is the corresponding power output, kW.

Normalized power curves averaged from a group of small WTGs are used for the calculation. Normalized wind generator power curves (Fig. 4.9) can be described (I):

\[ P^* = \frac{P}{P_N} \rightarrow P^* = \{0 \text{–}1\} \tag{4.8} \]

\[ 0 < V < 2.5 \rightarrow P^* = 0 \tag{4.9} \]

\[ 2.5 \leq V \leq 12 \rightarrow P^* = 0.0078V^2 - 0.0229V + 0.0086 \tag{4.10} \]

\[ V > 12 \rightarrow P^* = \text{const} \tag{4.11} \]

where

- \( P^* \) is the relative output power;
- \( P \) is the instantaneous power, kW;
- \( P_N \) is the nominal power of generator, kW;
- \( V \) is the wind speed, m/s.
The real power curve can be obtained from the normalized curve by multiplying the ordinate value by the nominal capacity of a WTG. The normalized power curve applies to most small wind turbines, with a cut–in speed of 2.5 m/s and a cut–off speed of 25 m/s or higher, and nominal power achieved at a wind speed of 12±1 m/s. 60 data sets about the average annual wind speed and corresponding annual wind turbine capacity were calculated. Wind speed was transposed to the heights of 30 m and 50 m.

![Normalized power curve of WTG](image1)

**Fig. 4.9.** Normalized power curve of WTG.

![Average annual capacities](image2)

**Fig. 4.10.** Average annual capacities according to measured hourly wind speed (grey line) and according to average annual wind speed (bold line) (I).
Annual average WTG capacity found using measured hourly wind speed appears to be higher than capacity found using average annual wind speed (Fig. 4.10). The capacity difference between two curves is a factor of 1.3 times for a wind speed of 7 m/s and increases for lower wind speeds.

Power curve based on measured hourly values can be described by a polynomial:

\[ P^* = 0.0066V_m^2 - 0.0004V_m - 0.0208 \]  

(4.12)

The correlation coefficient for this polynomial is \( r^2 = 0.9978 \).

### 4.4 The shortage of energy in an autonomous energy system

The data from Pakri Wind Park can be analyzed as a sample case of a shortage in energy production. Energy shortage is the situation whereby the balance of energy production and usage is negative. The average annual consumption capacity has been equalized to the average annual consumption. The consumption is expected to be of constant value through the whole year because, in autonomous systems, all the energy produced must be consumed.

The variations in unit generator output and the corresponding energy balance (kWh) are given in Fig. 4.11. The energy shortage appearing in the autumns (Fig. 4.11) may be the result of lower wind speeds during the summer and lengthy energy lulls in the second half of the year. In 60% of the years recorded, the largest energy lulls were registered in September or October (Fig. 4.1).
In reality, the occurrence 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 mean consumption capacity must be less than the mean generation capacity. Thus, for a given period, the amount of energy used must be less than the amount of energy produced; their ratio is called the consumption factor $\beta$. 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, the storage device is expected to contain a sufficient amount of energy to cover the shortage.

Fig. 4.12 shows the maximum possible energy deficit for different consumption factors. In addition to Pakri, wind data from Viljandi at heights of 30 m and 50 m are included to cover a wider range of wind speeds. The energy deficit increases with annual wind speed when $\beta = 1$ (Fig. 4.12).
The linear trend lines could be used for the calculation of regression, but the correlation coefficient $r^2$ is as low as 0.6–0.7. As mentioned above in chapter 4.2, the autonomous storage system cannot function when $\beta = 1$. In the case of $\beta = 0.9$, the energy deficit would be between 0–38 kWh with higher values occurring both for lower and higher annual mean wind speeds. In the case where $\beta = 0.85$, the range is limited to 0–13 kWh. Thus, if 90% of the energy generated by a unit generator is consumed, its storage capacity can be as low as 38 kWh regardless of the annual average wind speed. The remaining 10% of energy covers the losses in the storage device, and what remains thereafter should be used for a purpose other than the calculated consumer.

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

1. The comparisons of the monthly production charts of the wind farms, and charts of electrical and heat energy demand, show some correlations between them. At least some amount of the wind energy can be used for heat production.

2. The shorter period (daily) curves comparisons show that it is difficult to fit the wind farm production with electrical energy demand.

3. According to five–year wind data, the mean duration of energy lulls is highest inland (in the case of Pakri in the coastal region–3.4 h, while in the case of Viljandi in the inland region–8.8 h) and the frequency of the shortest energy lulls is highest.

4. Similarly to wind speed, the probability of energy lulls can be described by the Weibull distribution.

5. The period of maximum energy deficit mainly appears in the second half of the year, with the majority of cases registered in September or October in Estonia.

6. The wind data recorded in Estonia over the last five years suggest that the necessary capacity of a storage device in an autonomous energy system depends on the consumption factor rather than on the average wind speeds.

7. The power curves of small-power WTG-s may be divided into two groups depending on the form of the curve after it reaches the maximum. In the first group the output power stabilizes at the maximum level and does not change at higher wind speeds, in the second group the power reaches the maximum and then diminishes at higher wind speeds. The power curves of WTG-s in each group are similar to each other. It is useful to model only the first rising slope of the WTG power curve because wind speeds higher than 13 m/s are rare in mainland Estonia. The rising slope of the power curve for wind speeds of 2 to 13 m/s is accurately modelled by the second order polynomial.
REFERENCES


SUMMARY

According to different development plans, the importance of renewable energy resources in Estonia should be growing. Of the range of different renewable resources, the proportion and growth of wind generated electricity is the highest. The electric energy generated must be distributed by the national electrical network or used by the autonomous consumer. Due to the stochastic nature of wind, the output of wind generators can change quickly, but the production and consumption in the energy system must be in balance. To ensure the stability of the electric network, one possibility is to limit the output of wind generators, which can be done by an energy system dispatcher. Such a control method reduces the production, and therefore maximum power utilization factor, of a wind farm. One opportunity is to use the surplus electrical energy for heat production.

Autonomous wind energy systems might have some applications in locations without an existing electric network. Such a system might consist of a wind turbine generator and a storage device. Some kind of additional power source (PV panel, diesel generator) may be also included. Wind data analysis is necessary to estimate the energy production of a wind generator. Momentary and average wind speeds over a specified period can be used to describe potential wind energy.

The aim of the research was to describe efficient wind energy system. It means wind energy system with maximum power utilization factor and reliable energy supply. In case of wind energy system connected with electric grid the influence of electric system energy balance must be considered. In case of autonomous system the influence of storage device (for constant energy supply) must be considered.

List of the tasks to be solved to achieve the aim were:

1. to study production and consumption charts in an energy system (II);
2. to analyze the power curves of different types of wind generators (III) and calculate the annual energy production of a unit wind generator using wind measurement data (I).
3. to analyze wind measurement data to find periods without energy production (“energy lulls”) and find a method to describe them (I, IV);
4. to analyze the relationships between a WTG, a storage device and the consumer for a reliable energy supply and possibilities to describe the ratio in proportional units (I, III, IV).

Data from a group of small-power wind generators was obtained and their power curves analyzed. A second order polynomial was created to describe the power curve of the wind generator. Annual energy production could be calculated using wind data and expected generator capacity, but it does not describe the reliability of the energy supply. Relatively long periods without wind may occur. The concept of an energy lull was introduced to describe periods without wind energy production. Storage device should be able to ensure an energy supply for the duration of a maximum energy lull.

The annual mean capacity of a small WTG was calculated by using a normalized power curve for six different locations in Estonia. The length of energy lulls was found from wind measurement data. Energy production and usage in autonomous wind energy systems in different locations was modelled. Different consumption factors $\beta$ were used in the modelling to describe the energy surplus/deficit.

Results and conclusions:

1. Maximum wind energy production is limited by the capability of an electric system to use the wind electricity generated. Some amount of the wind energy can be used for heat production.
2. The power curves of small wind generators (nominal power of < 100 kW and a cut-in speed of < 3 m/s) may be divided into two groups, according to the form of the curve after it reaches the maximum. Because wind speeds exceeding 13 m/s are rare in inland of Estonia, the first rising slope of the power curve can be accurately modelled by a second order polynomial.
3. Energy lulls are periods without wind energy production. The duration of energy lulls is highest inland, and the frequency of the shortest energy lulls is higher. The probability of an energy lull can be described by the Weibull distribution.
4. The necessary capacity of a storage device in an autonomous energy system depends on the consumption factor rather than on the average wind speed.
KOKKUVÕTE

Elektrituulikute tootmisgraafikud ja nende sobitamine tarbijaga

Taastuvenenergia osatähtsus Eestis peab erinevate arengukavade alusel kasvama. Erinevatest taastuvenenergiatootmisestalikidest on kõige kiiremini kasvanud tuule osatähtsus ja toodetud energiahulk. Tuulegeneraatorite väljundvoimsus võib tuule stohhastilise iseloomu tõttu kiirelt muutuda, aga energiasüsteemis peab tootmine ja tarbimine tasakaalus olema. Üheks võimaluseks tagada elektrisüsteemi stabilius on tuulegeneraatorite toodangu piiramine, mida saab teha energiasüsteemi dispetšer. See juhtimismeetod vähendab tuulepargi toodangut ja seega maksimaalvöimsuse kasutustegurit. Üks võimalus on kasutada liigset elektrit soojuse tootmiseks.


Selle töö eesmärgiks oli efektiivse tuuleenergiasüsteemi kirjeldamine. See tähendab tuuleenergiasüsteemi maksimaalselt kõrge võimsuse kasutusteguriga ja kindla energiaga varustusega. Elektrivõrguga ühendatud süsteemi korral tuleb arvestada elektrisüsteemi tootmis- ja tarbimisvöimsuste tasakaaluga. Autonoomse energiasüsteemi korral tuleb arvestada püsiva energiavarustuse tagamiseks vajaliku salvestusseadme mõjuga.

Töö eesmärgi saavutamiseks olid ette nähtud järgmised tegevused:
1. Uurida energiasüsteemi tootmis- ja tarbimisgraafikud (II);
2. Analüüsida erinevat tüüpi tuulegeneraatorite tunnusjooni (III) ja arvutada tuule mõõteandmete alusel ühikgeneraatori aastane energiatoodang (I);
3. Analüüsida tuule mõõteandmeid, leidmaks energiatoodanguta perioode (”energiaauke”) ja otsida meetod nende kirjeldamiseks (I, IV);

Tulemused ja järelused:
1. Maksimaalne tuuleenergia toodang on piiratud elektrisüsteemi võimega genereeritud tuuleelektrit kasutada. Osa toodetud elektrienergiast võiks kasutada soojuse tootmiseks.
2. Väikese võimsusega tuulegeneraatorite (võimsus < 100 kW ja käivitumine tuulekiirusel < 2.5 m/s) tunnusjooned on vastavalt kõvera kujule peale maksimumvõimsuse saavutamist võimalik jagada 2 gruppiga. Kuna tuulekiirused üle 13 m/s on Eesti sisemaal haruldased, on võimalik tunnusjoone tõusuosa modelleerida 2-astme polünoomiga. Energiaaugud on ajaperioodid ilma tuuleenergia toodanguta. Energiaaukude ajaline kestvus on suurem sisemaal ning lühemate aukude esinemissagedus on suurem. Energiaaukude esinemise tõenäosust on võimalik kirjeldada Weibulli jaotusega.
4. Autonoomse tuuleenergiasüsteemi salvestusseadme vajalik mahtuvus sõltub pigem tarbimistegurist kui keskmisest tuulekiirusest.
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 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 m² (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
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]

$$\begin{align*}
P^* &= \frac{P}{P_N} \rightarrow P^* = \{0 - 1\} \\
0 < v < 2.5 \text{ m/s} & \rightarrow P^* = 0 \\
2.5 \leq v \leq 12 \text{ m/s} & \rightarrow P^* = 0.0078 \cdot v^2 - 0.0229 \cdot v + 0.00866022 \\
v > 12 \text{ m/s} & \rightarrow P^* = \text{const,}
\end{align*}$$

where $P^*$ – relative output power,
$P$ – instantaneous power output, kW,
$P_N$ – nominal power, kW.
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.
The Estimation of Needed Capacity of a Storage System According to Load and Wind Parameters

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

<table>
<thead>
<tr>
<th>Location</th>
<th>Height, m</th>
<th>Wind speed $v$, m/s</th>
<th>Capacity, $P^*$</th>
<th>Max. lull, $T_m$, h</th>
<th>Std. dev. $\delta$, h</th>
<th>Std. dev. $\delta^*$, %</th>
<th>Next lull, h</th>
<th>Std. dev. $\delta$, h</th>
<th>Std. dev. $\delta^*$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viljandi</td>
<td>30</td>
<td>3.0</td>
<td>0.0363</td>
<td>93.0</td>
<td>17.7</td>
<td>19.0</td>
<td>71.6</td>
<td>13.5</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>3.5</td>
<td>0.0573</td>
<td>61.8</td>
<td>8.9</td>
<td>14.4</td>
<td>53.2</td>
<td>5.6</td>
<td>10.6</td>
</tr>
<tr>
<td>Pakri</td>
<td>30</td>
<td>6.09</td>
<td>0.2263</td>
<td>24.2</td>
<td>6.2</td>
<td>25.8</td>
<td>17.8</td>
<td>1.6</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>6.92</td>
<td>0.2889</td>
<td>20.8</td>
<td>2.4</td>
<td>11.5</td>
<td>16.0</td>
<td>1.1</td>
<td>6.9</td>
</tr>
<tr>
<td>Virtsu</td>
<td>30</td>
<td>4.84</td>
<td>0.1296</td>
<td>39.4</td>
<td>9.9</td>
<td>25.0</td>
<td>29.6</td>
<td>5.5</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>5.5</td>
<td>0.1769</td>
<td>35.0</td>
<td>9.9</td>
<td>28.4</td>
<td>23.4</td>
<td>4.2</td>
<td>18.0</td>
</tr>
<tr>
<td>Jõgeva</td>
<td>30</td>
<td>3.61</td>
<td>0.0649</td>
<td>53.4</td>
<td>8.6</td>
<td>16.1</td>
<td>46.8</td>
<td>8.2</td>
<td>17.4</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>4.19</td>
<td>0.0983</td>
<td>45.2</td>
<td>9.6</td>
<td>21.2</td>
<td>36.6</td>
<td>4.3</td>
<td>11.7</td>
</tr>
<tr>
<td>Tõravere</td>
<td>30</td>
<td>3.66</td>
<td>0.0626</td>
<td>49.0</td>
<td>6.7</td>
<td>13.7</td>
<td>43.4</td>
<td>2.5</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>4.24</td>
<td>0.0957</td>
<td>37.0</td>
<td>3.3</td>
<td>8.9</td>
<td>34.0</td>
<td>5.5</td>
<td>16.1</td>
</tr>
<tr>
<td>Tiirikoja</td>
<td>30</td>
<td>3.0</td>
<td>0.0389</td>
<td>86.2</td>
<td>28.7</td>
<td>33.3</td>
<td>60.0</td>
<td>9.6</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>3.41</td>
<td>0.0565</td>
<td>65.6</td>
<td>10.8</td>
<td>16.4</td>
<td>54.0</td>
<td>8.0</td>
<td>14.9</td>
</tr>
</tbody>
</table>

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:

$$T_m = 513.79v^{-1.683}, \quad R^2 = 0.85$$  \hspace{1cm} (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.
In reality, the occurrence 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 $\beta$. 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.
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 these 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.

Acknowledgements

Authors would like to thank EMHI for kind cooperation to obtain wind data and especially head specialist Valeria Galuškina from client service department.

REFERENCES


Received March 18, 2009
The main task of the energy system is to supply the consumers with high-quality electric and heat energy. As possibilities for accumulation of the energy and especially electrical energy in Estonia are very limited, one of the main energy parameters is its uninterrupted supply. The needs of consumers are characterized by the demand curve – the variation of load for a given time period (day, month, year). It is necessary to stress the difference between load and demand curves for the producer and consumer. Up to the recent time the producer load curve consisted of the individual consumers’ demand curves sum plus losses in the distribution elements (in electric networks). Nowadays when by economical and ecological reasons the renewable energy sources are more intensively used, the part of the energy producers using wind and solar energy is constantly rising, and they are increasingly influencing the work of the whole energy system. That complicates significantly the work of the high-powered electric energy generators (with large inertia) at power stations as, in addition to the load variations depending on demand, they have to compensate extremely stochastic production of wind turbines. In this paper the problem is discussed on the basis of load and demand curves of the Energy system of Estonia and Pakri wind farm. It is shown that these curves are not suitable for mutual compensation and that may disturb the stability of the energy system at the wind park maximum power. The result is that the Energy system dispatcher is forced to limit the production of the wind park.

Introduction

Practically almost all the electric energy consumed in Estonia and noticeable part of heat energy are produced by electric and cogeneration power stations belonging to the uniform energy system and transported to the consumers by the district-heating and electric networks. As for electric energy, since there is a uniform electrical system for the whole country, district-heating net-
works are due to technical reasons limited in length, and mostly the district-heating plants of smaller capacity (town, village or part of it) produce the heat energy. Centrally produced electric and heat energy is carefully measured and accounted for, and there is statewide statistics concerning the amount of energy produced and consumed [1]. Besides that, there are also a large number of small-scale individual producers of heat energy for their own needs whose consumption rates may be estimated very roughly. In 2007 in Estonia 12 139 GWh of electric energy were produced from which 12 024.4 GWh or 99.06 % by thermal power stations using mineral fuels, 18.9 GWh (0.15 %) by hydroelectric power stations and 95.7 GWh (0.79 %) by wind turbines [1]. The amount of the heat energy produced at electric power stations and district-heating plants in the same year was altogether 8 522 GWh. The distribution of different fuels used for the electric and heat energy production is given in Table 1.

The amount of electric energy produced in 2006 from wind and hydro-energy was 88.3 GWh that forms 0.91% of the entire electric energy production. The amount of electric energy produced from mineral fuels in 2006 $W_e$ was therefore 9 610.7 GWh (99.09%). The energy content of these fuels $W_k$ was 88 915 TJ (24 718.37 GWh). We can see that the electrical efficiency of thermal power stations in Estonia was:

$$\eta_e = \left(\frac{W_e}{W_k}\right) \times 100,$$ (1)

that means 38.9%.

**Table 1.** The fuels used for centralized production of the electric and heat energy in Estonia in 2006

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Electric energy</th>
<th>Heat energy</th>
<th>Electric and heat energy altogether</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TJ</td>
<td>%</td>
<td>TJ</td>
</tr>
<tr>
<td>Coke</td>
<td>0</td>
<td>0</td>
<td>271</td>
</tr>
<tr>
<td>Oil shale</td>
<td>83 393</td>
<td>93.75</td>
<td>5 980</td>
</tr>
<tr>
<td>Milled peat</td>
<td>102</td>
<td>0.11</td>
<td>968</td>
</tr>
<tr>
<td>Lumped peat</td>
<td>0</td>
<td>0</td>
<td>563</td>
</tr>
<tr>
<td>Peat briquettes</td>
<td>0</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>Firewood</td>
<td>0</td>
<td>0</td>
<td>519</td>
</tr>
<tr>
<td>Woodchips and wood waste</td>
<td>3</td>
<td>0</td>
<td>6 893</td>
</tr>
<tr>
<td>Wood briquettes and pellets</td>
<td>0</td>
<td>0</td>
<td>39</td>
</tr>
<tr>
<td>Natural gas</td>
<td>2 341</td>
<td>2.68</td>
<td>19 371</td>
</tr>
<tr>
<td>Liquid gas</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>1</td>
<td>0</td>
<td>224</td>
</tr>
<tr>
<td>Oil shale fuel oil</td>
<td>302</td>
<td>0.34</td>
<td>3 477</td>
</tr>
<tr>
<td>Light fuel oil</td>
<td>0</td>
<td>0</td>
<td>1 245</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>10</td>
<td>0.01</td>
<td>22</td>
</tr>
<tr>
<td>Other fuels (oil shale and biogas)</td>
<td>2 763</td>
<td>3.11</td>
<td>3 766</td>
</tr>
<tr>
<td>Altogether</td>
<td>88 915</td>
<td>100.0</td>
<td>43 358</td>
</tr>
</tbody>
</table>


Table 2. Electric and heat energy production by thermal power stations, district-heating plants, and wind and hydroelectric power stations per month in 2006 (GWh)

<table>
<thead>
<tr>
<th>Month</th>
<th>Electric energy</th>
<th>Heat energy from thermal power and district heating plants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Power stations</td>
<td>Wind plants</td>
</tr>
<tr>
<td>January</td>
<td>1 018</td>
<td>7.7</td>
</tr>
<tr>
<td>February</td>
<td>949</td>
<td>3.4</td>
</tr>
<tr>
<td>March</td>
<td>951</td>
<td>5.7</td>
</tr>
<tr>
<td>April</td>
<td>652</td>
<td>5.7</td>
</tr>
<tr>
<td>May</td>
<td>724</td>
<td>4.9</td>
</tr>
<tr>
<td>June</td>
<td>626</td>
<td>3.7</td>
</tr>
<tr>
<td>July</td>
<td>644</td>
<td>3.6</td>
</tr>
<tr>
<td>August</td>
<td>876</td>
<td>4.3</td>
</tr>
<tr>
<td>September</td>
<td>636</td>
<td>5.7</td>
</tr>
<tr>
<td>October</td>
<td>888</td>
<td>7.8</td>
</tr>
<tr>
<td>November</td>
<td>864</td>
<td>8.7</td>
</tr>
<tr>
<td>December</td>
<td>871</td>
<td>13.3</td>
</tr>
<tr>
<td>Altogether</td>
<td>9 699</td>
<td>74.5</td>
</tr>
</tbody>
</table>

The percentage of the renewable fuels in electric energy production was comparatively small, and it is not possible to define it exactly as there is no data on the amount of biogas used. In production of heat energy, the part of biofuels is larger as at district-heating plants the firewood, wood chips and wood wastes, wood briquettes and pellets form nearly 6% of the whole amount of fuels used, and at individual furnaces, the biofuels are the main energy source. At thermal power stations and district-heating plants $W_k = 43 358$ TJ ($12 043$ GWh) of fuel energy was used to produce $W_\text{s} = 8 785$ GWh of heat energy, and the efficiency of heat production was:

$$\eta_s = \left( W_\text{s}/W_k \right) \times 100 = 72.9\%.$$  \hspace{1cm} (2)

The part of oil shale in electric energy production at thermal power stations was 93.75% and in the centralized production of heat energy 13.79%. In the next 15–20 years there evidently will be no significant reduction of the oil shale role in Estonia [2]. Statewide statistical institutions have only the most general data – the monthly production and consumption. More exact shorter periods data is available from the organisations producing, distributing or consuming energy.

Production and consumption charts

As we try to show in this paper, it is useful to make difference between the producer and consumer load and demand curves presented in the form of charts. The demand curve by common terminology is a graphically described
change in electric, heat or some other load during some period [3]. The length of the period is usually one year, month or day, and the demand curve characterizes consumption of electric or heat energy by individual consumer, group of consumers, of settlement or some other administrative unit (the whole country as well), and so, the load curve is dictated by the needs of consumers.

The use of the load curve term is caused by the widening electric energy production based on natural phenomena not influenced directly by people (wind, sun and to a certain extent the water at small hydroelectric stations). The owners of such energy production systems, declaring that their energy is cost-free (when such system is already installed), try to "cram" their electric energy into the public electric network independently of the needs of consumers (their demand curves), making the load curves of electric power stations and network more choppy. That leads to greater losses in the network and to smaller efficiency of the system [4], and if the production peaks of such energy producers exceed a certain level, the stability of the electric energy system as a whole may become endangered.

The load or demand curve of the year shows usually monthly production of electric or heat energy or consumption depending in the first place on weather conditions. Figure 1 shows the centralized electric and heat energy production (at electric energy thermal power stations and district-heating plants) data for 2006 in Estonia.

From the chart, we see sharply expressed lessening of demand in summer months, especially in the heat energy part. It diminishes significantly the possibilities of using renewable energy (wind) for heat energy production in summer months, because the large part of heat energy as by-product of electric energy production is not used at that time. Saving of heat energy for longer periods is limited, and the efficiency of it is comparatively low.

For comparison, the monthly production of electric energy in 2006 by the wind and hydroelectric power stations in Estonia is given in Fig. 2.

We can see that monthly production of the wind energy is in quite good correlation with heat and electric energy demand. It means that at least a part of the (heat) energy may be produced by wind. However, as the wind at the...
given place may change significantly by the hour or minutes (even seconds often), production curves of the shorter period are needed for the analysis of the energy production dependence on the wind parameters’ variation. The complex analysis of these curves should be made for a longer period.

The influence of hydroelectric power stations on the energy production in Estonia is very moderate. By their load curve, it is possible very clearly to define the periods of the snow melting in spring and rains in autumn (Fig. 2). The more specific analysis of the hydroelectric stations and their development in the future is presented in literature [6]. Though the financing of the new projects is going on, there are many obstacles thanks to the environmental requirements becoming stricter.

As an example of wind energy production, we suggest the load curve of July 2006 (Fig. 3). It is interesting because we can clearly see the cutting off the disturbing excess power peaks in the middle of the month by the control staff of the power supply system.

In the analysis of the wind turbines work it is practical to use the concept of maximum (or nominal) power utilization factor that may be described as

\[
k_m = \frac{W_m}{P_m \cdot t_n} \cdot 100,
\]

where \(W_m\) is energy produced by the wind turbine (turbines) in time period \(t_n\), \(P_m\) – maximum power (sum of the nominal power of the of the wind
turbines). Here \( P_m t_n \) is the energy amount that would have been produced by all the generators working at nominal power for time \( t_n \).

According to the load curve in Fig. 3, the output power of Pakri wind farm was periodically limited by the Energy system dispatcher, and the corresponding power utilization factor was comparatively low – 15.6\%.

For calculation, we need an equation of the power curve that may be found using the wind turbine data [5]:

\[
P_n = 0.0011v_n^5 + 0.0808v_n^5 - 2.1742v_n^4 + 24.297v_n^3 \\
-88.608v_n^2 + 90.616v_n - 0.8286. 
\]  

(4)

At the wind speed \( v < 4 \text{ m/s} \) the turbine output power is 0, but the equation gives us negative results, so it may be used with an additional condition:

\[
\text{if } v_n < 4, \quad P_n = 0.
\]  

(5)

The energy amount produced is:

\[
W = \sum (P_n \cdot \Delta t_n),
\]  

(6)

where \( P_n \) is average power in \( \Delta t_n \) period.

The load curve of the wind farm calculated using the wind speed is shown in Fig. 4.

The maximum power utilization factor for this curve is approximately 20\%, nearly 4\% higher than for the real curve.

The daily electric energy production of Pakri wind farm for July 2006 is shown in Fig. 5, and it is much less informative as there is no periods with zero production visible as in Fig. 3.

The impact of the wind farms’ load on the work of the energy system is most evident from the hourly curves as just the sharp production variations are too short for large energy blocks of the power stations to follow up and

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Fig. 4. The possible power load curve of Pakri wind farm (July, 2006).
to lessen their fuel consumption according to the smaller demand, and their effectiveness diminishes considerably.

As an example, we shall take two days – with minimum and with maximum electric energy production. In Fig. 6 we see the hourly electric energy production by Pakri wind farm in July 3, 2006 when the load was minimal.

The twenty-four hour calculated energy production on July 3 was 2,095 kWh, and corresponding maximum power utilization factor was 0.47%. The hour average power was 87.3 kW, taking into account also an 8-hour gap with nearly zero production.

For comparison, Fig. 7 shows the load curve of the Estonian Energy system for the same day.

It is evident that such choppy load curve (Fig. 6) of the wind farm is unsuitable from the point of view of the energy system, as the work conditions for the main power-generating stations are most favourable in the case of a level load curve.

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Fig. 5. The daily electric energy production of Pakri wind farm (July, 2006).

Fig. 6. The hourly electric energy production of Pakri wind farm (July 3, 2006).
The energy production of the wind farm on July 18 (Fig. 8) was cut off by the energy system dispatcher approximately to 50% of the maximum power with resulting energy production 214 560 kWh and maximum power utilization factor 48.59%. The theoretical load curve of the same day defined by Eq. 4 on the basis of the wind speed data is shown in Fig. 9.

The energy production of the day would have been 339 293 kWh and maximum power utilization factor 76.8%.
Summary

The unfitness of energy production curves of wind farms for load curves of the Energy system and extremely stochastic character of the power output of wind farms will result in serious problems for the Estonian Energy system with the increase of wind energy production. More specifically these problems are described by Tallinn Technical University researchers [7–9].

The conclusions of this analysis are:
1. The comparison of the load curves of the wind farms and curves of electric and heat energy demand shows some correlation between them that allows to use at least some of the wind energy for heat energy production in case of sufficient accumulation possibilities.
2. At the same time the comparison of shorter period (daily) curves shows that it is difficult to fit the wind farm load with electric energy demand, and that the wind energy supply to the energy system does not lessen proportionally fuel consumption and environment pollution by power stations.
3. Equation 4 suggested by the authors makes it possible to calculate the output power of the specific wind turbine according to wind conditions.
4. One of the most real possibilities to improve the utilization of wind power from the energy system point of view is introduction of the real time tariff [10, 11] when the „excessive” wind energy utilization becomes the consumer problem.
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Received March 20, 2009

Agronomy Research 6: 169-179
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...
increasingly 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:

\[
P = \frac{SC Pv^3}{2},
\]

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; \(\rho\) – 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 – \(c = f(v)\).
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>
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<tr>
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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):

\[ v_2 = v_1 \left( \frac{H_2}{H_1} \right)^{k_H} , \]  

(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).](image)

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.
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 4 ppm 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:

\[ P' = \frac{P}{P_N}, \quad (3) \]

where \( P' \) is normalized wind generator power, 0–1; \( P \) – measured power, kW; \( P_N \) – nominal or maximal generated power of the generator, kW.

Specifications 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.

<table>
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<tr>
<th>Generator type</th>
<th>Switching on speed, m s(^{-1})</th>
<th>Nominal power, kW</th>
<th>Type of power curve</th>
<th>Nominal power wind speed, m s(^{-1})</th>
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</thead>
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<td>A</td>
<td>11</td>
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<td>6</td>
<td>A</td>
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<tr>
<td>Eoltec Chinook 17m-65kW</td>
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<td>11</td>
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<tr>
<td>Proven 2.5</td>
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<td>2.8 (2.5)</td>
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</tr>
<tr>
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<td>25 (20)</td>
<td>B</td>
<td>12</td>
</tr>
</tbody>
</table>

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.

![Normalized averaged A-type power curve (rising part).](image)

\[ y = 0.0104x^2 - 0.042x \]

\[ R^2 = 0.9921 \]
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-February-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.

<table>
<thead>
<tr>
<th>WTG’s height above the ground ( h ), m</th>
<th>Electric energy production at wind speeds 3–12 m s(^{-1}), kW·h</th>
<th>Electric energy production at wind speeds &gt;12 m s(^{-1}), kW·h</th>
<th>Additional electric energy production at wind speeds &gt;12 m s(^{-1}), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2374</td>
<td>31</td>
<td>1.3</td>
</tr>
<tr>
<td>20</td>
<td>3901</td>
<td>91</td>
<td>2.3</td>
</tr>
<tr>
<td>30</td>
<td>5054</td>
<td>340</td>
<td>6.7</td>
</tr>
</tbody>
</table>

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. 6. Normalized averaged B-type power curve (rising part).
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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Põder, V., Peets, T., Toom, K., Annuk, A. 2010
THE ESTIMATION OF WIND LULL AND CONSUMPTION
FACTOR INFLUENCE ON AUTONOMUS WIND ENERGY
SYSTEM

Agronomy Research 8: 226-235.
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 m s\(^{-1}\)) and 2) inland (average wind speed 2.5-3.5 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 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).

![Length of wind lull](image)

**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:

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

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:

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

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:

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

The average length of energy lull is:

$$t_m = \frac{\sum t_i}{n},$$  

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:
\[ P(l_m) = e^{-\left(\frac{l_m}{c}\right)^k} \]  

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:

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

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

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

<table>
<thead>
<tr>
<th>Location</th>
<th>Average wind speed $v$, m s$^{-1}$</th>
<th>Max. lull, $t_{\text{max}}$, h</th>
<th>Average energy lull $t_{\text{m}}$, h</th>
<th>Weibull shape factor $k$</th>
<th>Weibull scale factor $c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pakri</td>
<td>6.1</td>
<td>36</td>
<td>3.4</td>
<td>0.773</td>
<td>2.418</td>
</tr>
<tr>
<td>Viljandi</td>
<td>3.0</td>
<td>114</td>
<td>8.8</td>
<td>0.727</td>
<td>2.557</td>
</tr>
</tbody>
</table>
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 \( l \).

![Cumulative Weibull distribution function of energy lulls in Pakri and Viljandi.](image)

**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 \( \beta \) (Põder 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 \(\beta\) 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.

ACKNOWLEDGEMENTS. The authors would like to thank EMHI for kind cooperation in obtaining wind data and especially Valeria Galuškina, chief specialist from client service department.

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ACKNOWLEDGEMENTS

This study was carried out at the Department of Energy of the Estonian University of Life Sciences. I am most grateful to my supervisor Prof. Andres Annuk.

I would like to thank all my colleagues from the Department of Energy, who have contributed in one way to another to the manuscripts and preparation of the thesis.

Many thanks also to my family for supporting and understanding me in my studies.
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Publikatsioonid:
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