Eesti Maaülikool
Estonian University of Life Sciences

POSSIBILITIES FOR BALANCING WIND GENERATORS' OUTPUT POWER

TUULIKUTE VÄLJUNDVÕIMSUSTE BALANSSEERIMISE VÕIMALUSI

KAUPO TOOM

A Thesis
to apply for the degree of Doctor of Philosophy in Energy Use

Väitekiri
Filosoofiadoktori kraadi taotlemiseks energiakasutuse erialal

Tartu 2012

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LIST OF ORIGINAL PUBLICATIONS

This present doctoral thesis is based on the following publications, which are referred to in the text by Roman numerals. The original publications have been reproduced with the permission of the copyright holders.

I **Toom, K.**, Annuk, A., Allik, A., Uiga, J., Kabanen, T. 2012. Evaluation of wind parks output power forecast error and ways to decrease it. Engineering for rural development. 11th International Scientific Conference: 428–433. Jelgava: Latvia University of Agriculture

II **Toom, K.**, Jürjenson, K., Juhanson, T., Annuk, A. 2011. Cutting wind generator power chart peaks to mitigate power forecast error. Engineering for rural development. 10th International Scientific Conference: 294–298. Jelgava: Latvia University of Agriculture

III Annuk, A., Allik, A., Pikk, P., Uiga, J., Tammoja, H., **Toom, K.**, Olt, J. 2013. Increasing renewable fraction by smoothing consumer's power curves in grid connected wind-solar hybrid systems. Oil Shale. (Accepted)

IV Annuk, A., Allik, A., Pikk, P., **Toom, K.**, Jasinskas, A. 2012. Power Balancing Possibilities for a Small Wind-PV Panel Hybrid System for a Nearly Autonomous Unit Consumer. Silvio Košutić (Editor). Actual Tasks on Agricultural Engineering: 485–494. Opatija, Croatia: University of Zagreb, Faculty of Agriculture

THE AUTHOR'S CONTRIBUTION TO THE ORIGINAL PUBLICATIONS

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

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

II Kaupo Toom was the main author of the paper. He was responsible for literature overview and calculations. He had the major role in writing the paper.

III Kaupo Toom participated in writing the paper. He participated in data analysis and calculations. He had a minor role in writing the paper.

IV Kaupo Toom participated in writing the paper. He participated in data analysis and calculations. He had a minor role in writing the paper.

ABBREVATIONS AND UNITS

Latin script

A	rotor swept area, m^2
A_i	anisotropy index
AC	alternating current
C_S	capacity shortage
C_{FS}	capacity factor solar
C_{FW}	capacity factor wind
CHP	Combined Heat and Power
DC	direct current
EMHI	Estonian Meteorological and Hydrological Institute
EU	European Union
EWEA	European Wind Energy Association
f	horizon brightening factor
f_{PV}	PV degrading factor, %
$\overline{G}$	global radiation, kW/m^2
$\overline{G}_b$	beam radiation, kW/m^2
$\overline{G}_d$	diffuse radiation, kW/m^2
$\overline{G}_T$	solar radiation incident on the PV array in the current time step, kW/m^2
$\overline{G}_{T,STC}$	incident radiation at standard test conditions, 1 kW/m^2
GHG	greenhouse gases
H	elevation, m
H_{ref}	reference elevation, m
HDKR	Hay, Davies, Klucher, Reindl
k	Weibull shape factor
k_H	Hellman's exponent
C_F	capacity factor
L_{PV}	solar energy penetration, %
L_W	wind energy penetration, %
MAPE	Mean Absolute Percentage Error
MPE	Mean Percentage Error
P	output power, kW
P_a	actual wind park output power, MW
P_f	predicted wind park output power, MW
P_L	maximum power from the grid, kW
P_m	maximum power, kW
P_P	limit capacity of energy from grid, kW

P_{δ}	power consumption of a unit-consumer with altered dispersion, kW
P_C	power consumption of a 1 kW unit-consumer, kW
P_R	power consumption of a measured consumer, kW
P_{mean}	average capacity of a unit-consumer, kW
pu	proportional unit
PV	photo voltaic
R_b	ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface
RMSE	Root Mean Square Error
T_c	PV cell temperature in the current time step, °C
$T_{c,STC}$	PV cell temperature under standard test conditions, 25 °C
t_n	time period
TSO	transmission system operator
v	hourly averaged wind speed, m/s
v_{ref}	hourly averaged wind speed at reference elevation H_{ref}, m/s
W_B	battery capacity, kWh
W_{Bl}	energy losses in battery, kWh
W_C	energy consumption by unit consumer, kWh
W_{Gp}	energy from grid, kWh
W_{Gs}	sold energy to grid, kWh
W_m	energy production
W_{PV}	energy production from PV arrays, kWh
W_R	renewable fraction, %
W_{Sh}	capacity shortage, %
W_{St}	storage capacity, kWh
W_T	total energy, kWh
W_W	energy production from wind generators, kWh
Y_{PV}	the rated capacity of the PV array, power output under standard test conditions, kW
z_0	surface roughness

Greek script

a_p	the temperature coefficient of power, %/°C
β	slope of the surface, °
ρ	air density, kg/m^3
ϱ_g	ground reflectance, which is also called albedo, %
δ	standard deviation

INTRODUCTION

The importance of renewable energy is growing. More and more wind parks, CHP-s and biogas stations are being erected and connected to the electrical grid. Due to the stochastic nature of wind, the output of a wind generator can change quickly (80 % over two hours (Kilk 2007)). As energy production and consumption must be in balance in the energy system, some kind of compensation system is needed. Maintaining the capacity balance of an electrical power system and managing the power system in real time is one of the main tasks for the transmission system operator. Under circumstances where generation starts to fluctuate and load remains constant, other generation units must compensate it. The latter is the case for large scale wind energy.

The growing share of wind power is accompanied by an increasing need for reserve capacity, which is necessary to ensure that it is always possible to balance the entire system (Eriksen & Orths 2008). To analyse the ability of power systems to control area power balance, the interchange power changes hold the key position. More precisely the values of maximum deviations in interchange power values guarantee safe operation of power systems and quality of electricity. Generally the balancing responsible parties are all generating units or traders. All of them are required to submit day-ahead schedules to the system operator that estimate their electricity feed-in or consumption. Schedules can be modified before the fixed delivery gate closure which is generally 1-3 h before real-time delivery (Klessmann *et al.,* 2008).

The real wind power differs from the forecast one. Wind park output power is particularly difficult to forecast at wind speeds of 6–10 $m \cdot s^{-1}$ due to the fact that electricity generation of wind turbines changes markedly between these speeds. The most relevant metrics to measure forecast errors are Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE). The absolute errors of the forecast are dependent on the forecasted wind power generation.

1. REVIEW OF THE LITERATURE

1.1. Wind energy in the world and in Estonia

Energy system is a system meant for the production, transmission and distribution of power and heat energy to consumers, which consists of energy producers (power plants and CHP-s, district heating boiler houses), electrical and heating networks and consumers. This kind of system is responsible for smooth supply of high quality electrical and heat energy to consumers.

Since the vast majority of wind power plants produces electrical energy, one of the main wind power engineering problems is matching wind parks production schedules and energy production and consumption charts. Due to wind stochastic characteristics, the mentioned above charts do not particularly match and, thus, the actual fuel economy and air pollution reduction percentages are considerably smaller compared to those expected (Liik *et al.*, 2005). This problem has been thoroughly discussed by Ivo Palu in his research (Palu *et al.*, 2008; Palu *et al.*, 2009; Palu 2009).

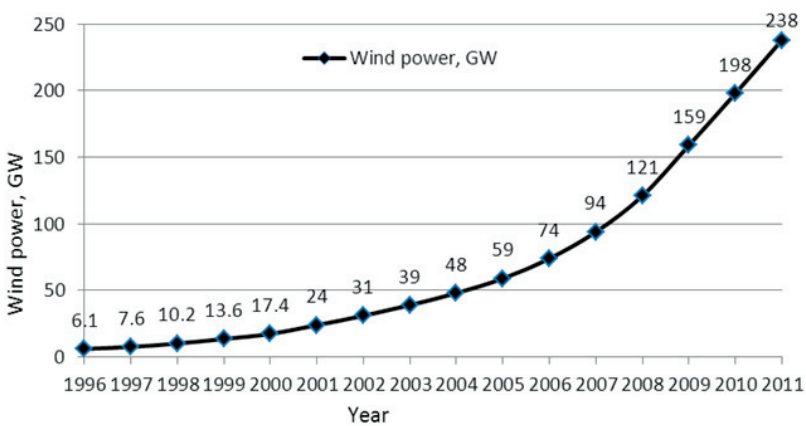

Fig. 1.1. Wind power total world capacity 1996 - 2011. (US and..., 2012).

Figure 1.1 shows, that wind energy share in the world's power engineering is constantly increasing.

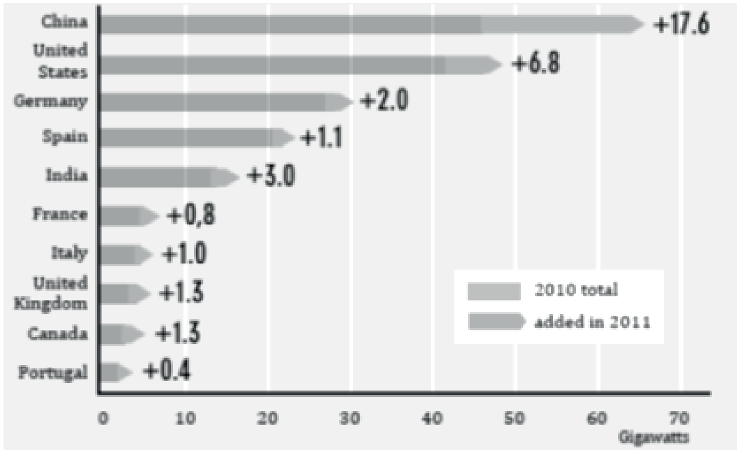

Fig. 1.2. Wind power capacity. Top 10 countries. 2011. (US and..., 2012).

Figure 1.2 shows, that in recent years, wind power engineering has considerably developed in China and the United States of America; additionally, the attention to the problems of the field has grown both in the United States of America and India. (US and..., 2012). At the same time, Denmark, as the country with the longest history of modern wind energy, is planning to have 30 % of its electricity consumption from renewable energy sources by year 2025 (Lund *et al.*, 2009) and 50% by year 2050 (Lund *et al.*, 2005, Eriksen & Orths 2008, Vision…, 2009).

The development of wind energetics is speeding up. Favourable governmental regulations and new possibilities opened up in economy to construct wind parks enhance the development of this field. At the end of 2006 European Union (EU) set its renewable energy target at 20% of overall energy consumption by year 2020 and at least 20% reduction in greenhouse gases (GHG) (A renew..., 2007). According to European Wind Energy Association (EWEA), by year 2020 the proportion of wind energy could be as high as 14.3% of EU electricity demand, 180 GW capacity of installed wind turbines (Pure..., 2009), while by the end of year 2008 the total in EU was 65 GW and it met 4.2% of EU electricity demand (Wind..., 2008). Thus, the triple increase is expected to take place within the next 11 years. All this capacity will be integrated into the grid that already includes conventional power plants like coal, oil-shale, gas or nuclear power plants.

The targets in Estonia for renewable electricity supply have been set at 5,1% (ca 400 GWh) of gross inland consumption by 2010 and 25% by

2020, while the current share of wind power in Estonia is 183.9 MW (as end of December 2011). As onshore wind power production development in Estonia is quite limited, the offshore wind park projects will have a huge role to play in the near future, if the targets set are aimed at. Also, the new Estonian Electricity Sector Development Plan of up to 2018 (Estonian..., 2009), where a 30% share of wind generation in total installed capacity is foreseen by 2018, means a substantial share of power being generated onshore and offshore in the near future.

Different EU support schemes have rendered wind energetics economically attractive and have instigated a competition between the many wind park developers to establish new facilities. The faster the project is implemented, the more advantage is gained over the competing agents. An extra-large increase in wind capacity is foreseen in offshore wind parks. The growing demand for wind generators has induced a rise in their price.

Today, in addition to the economic profitability, there is another major factor contributing to the fast growth of wind power development – that of the looming increases in the electric transmission network access fee. Meanwhile, the number of plots of good wind conditions is decreasing, and the availability of sufficient network transmission capacity has become crucial. The cost of establishing the additional electrical networks needed may be of the same range as that of a wind park itself (Landsberg *et al.,* 2005). In addition to the network related expenses, Estonian TSO requires fast-start generating units to be installed together with new connections of wind power, i.e. all new wind parks connected to the grid after 1st of July 2007, are obliged to have fast regulated power plants on Estonian territory. Up to now, the installation of wind parks meant very few additional expenses beside the initial capital costs. The later the project is started, the larger are the additional expenses involved. Although there is a theoretical possibility that one will be able to buy the balancing capacity required, its price and availability is undefined today.

Fluctuations in wind capacity are balanced by power plants of fast regulated output, such as gas turbines and hydro power plants, or storage facilities, such as pumped-storage hydro power plants and compressed air power plants. The conventional fossil fuel based thermal power plants are not easy to use for balancing large capacities of wind power and nuclear power plants are totally unsuitable in this respect. On the territory of Estonia, the resources available for balancing the wind power by oil-shale power plants are becoming exhausted, and the same is true about the hydro power plants in Latvia. The fastest way to provide for the additional fast regulated capacity is to establish gas turbine plants and a pumped-storage hydro power plant in the future.

Compensation of wind power generation with thermal generating units might not decrease but even increase the fuel cost and emissions in the power system (Electric…, 2006, Valdma *et al.,* 2009, Liik, *et al.,* 2005).

A simple means of balancing the system and reducing the grid load can be provided by the downward regulation of wind power generation in periods of substantial wind power generation. A reduction of wind power generation also makes it possible to use wind turbines for providing both upward and downward regulation (Gibescu *et al.,* 2008, Østergaard, 2008).

The increasing wind park capacities are bound to lead to the situation whereby the cheapest balancing option, i.e. the oil-shale plants will for technical reasons fail to adjust the capacities with sufficient speed.

In oil-shale power plants, the ramp-up speed of one single oil-shale generating unit is 2.5 $MW \cdot min^{-1}$, and the ramp-down speed is 7 $MW \cdot min^{-1}$. At the same time the active power balance of the electrical network is described tightly by the following equation (Keel *et al.,* 2009):

$$P_D(t)=P_G(t)+P_W(t)-P_{INT}(t), \tag{1.1}$$

where
P_D – total power demand with power losses in electrical network;
P_G – total net power generation of the traditional power plants;
P_W – total power generation of wind power plants;
P_{INT} – total interchange power with other power systems.

Even though the regulating capacity of oil-shale power plants is in the range of 50–100% of the rated power, the actual free changeable capacity falls within the range of 10–15% after the regulation by consumption is performed (Keel *et al.,* 2009). The total regulating capacity supply is proportional to the number of generators in operation and although today the oil-shale plants are able to balance the existing wind capacities, the rapid changes in production capacities decrease the efficiency of the plants, increase the CO_2 emissions, add to environmentally hazardous waste, raise specific fuel consumption and cost price (Palu *et al.,* 2009).

TSOs are authorised to reduce wind park production peaks, which they occasionally may also resort to in extreme conditions, when the balancing required cannot be achieved by other measures (Lepa *et al.,* 2009). It can be presumed that the need for cutting off peak loads is arising in future. In Estonia, the first reserve plant of 120 MW in capacity will be erected as late as 2013, and by this time, even the most conservative forecast suggests that the capacity of wind parks will have been increased to about 590 MW (Eesti..., 2009).

The method of cutting off production chart peaks could be applied systematically to correct forecast errors, whereas the energy cut off might be applicable for heat energy production in boiler houses.

1.2. Wind data description

The power of a wind generator is directly linked to the speed of wind. Wind generator output power P is in direct proportion to the cube of wind speed (Edenstein, *et al.,* 2003, Zhang, *et al.,* 2008, Goh, *et al.,* 2004, Castellanos & James, 2009) and can be expressed as:

$$P = \frac{\rho A v^3}{2}, \tag{1.2}$$

where

ρ – air density, kg/m^3;
A – rotor swept area, m^2;
v – wind speed, m/s.

Wind speed increases due to altitude increasing. Average wind speed at elevation H can be expressed by:

$$v = v_{ref}\left(\frac{H}{H_{ref}}\right)^{k_H}, \tag{1.3}$$

where

v_{ref} – average wind speed at reference elevation H_{ref}, m/s;
H_{ref} – reference elevation, m;
k_H – Hellman's exponent.

The value of Hellman's exponent depends on the location and the shape of the terrain on the ground and the stability of air. For example Hellman's exponent 0.10 means smooth hard ground or calm water and 0.40 a large city or tall buildings (Masters 2004)

Also another logarithmic wind profile law is widely used in Europe (Bańuelos-Ruedas *et al.*, 2010):

$$v = v_{ref} \frac{\ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{H_{ref}}{z_0}\right)}, \tag{1.4}$$

where

v_{ref} – roughness length of surface, m. It varies between 0.0001 m (water surfaces) and 1 m (city area) (Hau 2006).

For estimation of wind speed probability distribution used often Weibull distribution. Only average value of wind speed does not show adequate wind condition. The probability density function (1.5) and the cumulative distribution function (1.6).

The probability density function (*f (V)*) indicates the fraction of time (or probability) for which the wind is at a given velocity *V*. It is given by

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^k}, \tag{1.5}$$

Here, k is the Weibull shape factor and c is scale factor. The cumulative distribution function of the velocity *V* gives us the fraction of time (or probability) that the wind velocity is equal or lower than *V*. Thus the cumulative distribution *F*(*V*) is the integral of the probability density function. Thus,

$$F(V) = \int_0^{\alpha} f(V)dV = 1 - e^{-\left(\frac{V}{c}\right)^k}, \tag{1.6}$$

1.3. Wind solar hybrid systems

The pressure to increase the proportion of renewable energy sources in final energy consumption has grown in the last years. According to the Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources, Estonia as all other EU countries is obliged to rise the share of renewables in the final energy consumption, compared to the reference year 2005. For Estonia, the target of renewable energy share is set to 25%, as compared to 18% in 2005 (European Council, 2009).

Several sources of energy (biomass, wind power, solar radiation and ground heating) could be used for reaching the set target. Wind and solar technical resources are very convenient and available almost everywhere. The main problem is the very high stochastic level of wind.

One of the advantages of using both wind and solar energy is the possibility of producing electricity without generating heat energy. Moreover, it is characteristic to wind energy generator equipment to have the shortest energy payback period (less than 0.5 year) compared to other energy generating technologies (Matthew, 2006).

The amount of installed wind energy generating capacities is rising at an accelerating rate, therefore creating balancing properties of wind power capacities connected to the grid is needed. Despite some progress in arranging balancing measures, the development of wind capacities will exceed the grid possibilities in the near future. The best way to balance wind power units is hydropower stations. Unfortunately using hydropower as a balancing possibility is mostly limited due to lack of available necessary capacities for several reasons. Using the energy system resources of neighbouring countries is limited, because most countries are already engaged with their development of wind power.

Cutting off the production of wind park chart peaks in case of energy excess, without using peak energy (Lepa *et al.*, 2009), is one measure in emergency situations, but it is not sustainable. This does not look like a permanent solution, since more small wind and solar units connected to the grid have been set up, making the dispatch grid more complicated and therefore inducing balancing problems.

Another possible way of reducing a wind generator's effect on the grid is co-producing of energy with PV (photo voltaic) devices. Solar energy becomes more competitive due to continuously decreasing prices for PV panels (Wilkinson, 2010). Owners of wind and PV units are interested in selling more energy to the grid and purchasing as small amount of energy from the grid as possible. Evaluations show that in systems with equal capacities of wind and PV, the amount of energy supplied to and received from the grid diminishes with the increase of the relative part of wind energy and in the cases of average wind speeds 3.3-5.9 m/s stays to the range 42.3-52.6% from produced electricity (Annuk *et al.*, 2011). This shows that wind and PV units have some balancing properties when operating together. Some additional storage elements are probably needed in the system for maintaining better control of energy output. Wind power storage problems are dealt with in the article by Põder *et al.*, 2009. In case of minor consumers, chemical storages (batteries) may be used; whereas, in case of major consumers, mainly water based heat capacity storages are necessary.

The possibility to increase renewable energy penetration in one country to 50 % or more is analysed in the publication by Hoogwijk *et al.*, 2007. A technical system analysis with an increased wind power penetration in Denmark has been performed (Salgi & Lund, 2008). Proposals for being able to achieve high penetration of renewable energy are explained in Lund *et al.,* 2009, Georgilakis, 2008. It is concluded that it can only be done if energy consumption is notably reduced, other renewable energy like photovoltaic, wave and biomass installations increased and taken into use efficiently.

PV manufacturers rate the power output of their PV modules at standard test conditions (STC), meaning a radiation of 1 kW/m^2, a cell temperature of 25°C, and no wind. Standard test conditions do not reflect typical operating conditions, since full-sun cell temperatures tend to be much higher than 25°C.

The sum of beam and diffuse radiation is called global solar radiation, a relation expressed by the following equation (Homer Energy, 2011):

$$\overline{G} = \overline{G}_b + \overline{G}_d \,, \qquad (1.5)$$

where

$\overline{G}_b$ – beam radiation kW/m^2;

$\overline{G}_d$ – diffuse radiation kW/m^2.

Factor f is used to account for 'horizon brightening', or the fact that more diffuse radiation comes from the horizon than from the rest of the sky.

$$f = \sqrt{\frac{\overline{G}_b}{\overline{G}}}, \tag{1.6}$$

This term is related to the cloudiness.

The HDKR model calculates the global radiation incident on the PV array and can be expressed as follows (Duffie and Beckman 1991):

$$\overline{G}_T = (\overline{G}_b + \overline{G}_d A_i)R_b + \overline{G}_d(1 - A_i)\left(\frac{1+\cos\beta}{2}\right)[1 + f\sin^3(\frac{\beta}{2})] + \overline{G}\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{1.7}$$

where

β – slope of the surface, °;

ρ_g – ground reflectance, which is also called albedo, %;

R_b – ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface;

A_i – anisotropy index.

The most widely applied programs as HOMER and Hybrid2 for modelling hybrid renewable systems are used for the HDKR model.

2. AIMS OF THE STUDY

Wind is, compared to solar irradiation, a highly stochastic energy source; therefore forecasting wind generator output power is complicated. The aim of this study was how to better fit wind generators (their output power) into energy systems. We studied two options: cutting off wind parks output power chart peaks and combining wind generators with PV panels and batteries.

The first way to reach to aim of this study was to analyse different wind park data. Pakri and Aulepa wind parks were chosen. Pakri wind park is located in the best wind conditions in Estonia and Aulepa wind park is located in an average site in a coastal area. Analysing the wind parks data, the aim was to find ways to correct forecast error (**I, II**).

The second way to reach to aim of this study was increasing the proportion of renewable fraction, thereby reducing the need of obtaining electrical power from the grid, at different deviations of the unit consumer's graph, but at the same time the average consumption of the year stays the same. The other important variable in the calculations is the battery size. The solar irradiation data was acquired from Estonian Meteorological and Hydrological Institute (EMHI) Tõravere database and wind data from Tiirikoja database (**III, IV**).

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

1. Overview of wind energy production (**I, II**).
2. Overview of wind data analysis methods (**I, II**).
3. Analysis of different wind parks data, to find ways of correcting forecast errors (**I, II**).
4. Analysis of ways to balance power curves, using wind-solar hybrid systems (**III, IV**).

3. MATERIALS AND METHODS

3.1. Methods of forecast errors

The capacity produced by power plants at any given moment of time must be equal to the consumption capacity. With conventional fossil fuel based energy system the power balance is well maintained. The accuracy of consumption capacity forecast is high enough and it is by these charts that the output of thermal power plants is adjusted. On the contrary, the stochastic fluctuations in the wind park output power may have an amplitude as large as tens of megawatts per minute, which may result in emergency situations for the network if the need for forecast is neglected. The reason why generation is particularly difficult to forecast at wind speeds of 6–10 $m \cdot s^{-1}$ is that electricity generation of wind turbines changes markedly between these speeds.

Forecasting wind power as accurately as possible is important for wind power producers bidding in their production in an electricity market as well as to the system operator. In a market based setup the wind energy producers will normally pay for the costs of balancing the wind power. Therefore the more accurate the forecast of wind power, the lower the balancing costs to the wind power producers will be.

As a rule, wind park capacity is predicted for 24 h ahead. The time span of 24 hours enables to plan necessary changes of the reserve capacities. Nevertheless, the wind power forecast is bound to involve some error. The forecast error is estimated by three methods: Root Mean Square Error (RMSE) (3.1) (Boone, 2005, Madsen, 2004, Traiteur, 2011), Mean Absolute Percentage Error (MAPE) (3.2) and Mean Percentage Error (MPE) (3.3) (Rosen, *et al.,* 2007) (**I**).

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(P_a - P_f)^2}, \qquad (3.1)$$

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{P_a - P_f}{P_a}\right| \cdot 100, \qquad (3.2)$$

$$MPE = \frac{1}{n}\sum_{t=1}^{n}\frac{P_a - P_f}{P_a}\cdot 100 \quad , \qquad (3.3)$$

where

P_a – actual wind park output power;

P_f – predicted wind park output power.

While MPE shows the polarity of error, MAPE expresses the range of it. It is reasonable to use MPE for estimating the polarity of forecast error in the short time intervals of data-series. The MAPE values may vary significantly, but an average of 20 % can be achieved (Agabus & Tammoja, 2009).

3.2. Forecast errors in Pakri wind park and in Estonia

To evaluate forecast errors for wind park output error, we used the production chart of Pakri wind park as of 2009-2011 and the forecast data chart of average power data for 1-hour time intervals. We divided the yearly data to four quarters and chose random quarters of those three years to create a discretionary year (hereinafter "the chosen year"). The chosen year consists of quarterly data 1/1/2011–31/03/2011, 1/4/2009–30/6/2009, 1/7/2010–30/9/2010 and 1/10/2009–31/12/2009.

In Pakri wind park there are 8 Nordex N-90 2.3 MW wind units with the total capacity of 18.4 MW. The wind park is situated on the sea shore, where the wind conditions are the best, and where wind parks are built right now in Estonia (Pakri Wind Park, 2012). To generalize the results we used a proportional unit (pu). The proportional unit is a non-dimensional value, having the range of 0...1. The value 1 corresponds to the rated power of the wind park (**I**).

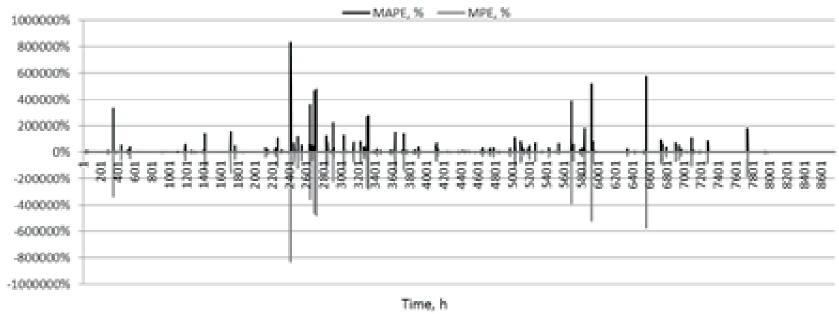

Fig. 3.1. Pakri wind park MAPE and MPE chart

Figure 3.1 shows, that MAPE and MPE are very big sometimes. Therefore we did not use extreme data values over 300%, which appears rarely for calculating MAPE average results. When we look at MAPE and other values 0…0.1 pu, then the average MAPE was 4222 % and the maximum was 828851 %. The average forecast RMSE was 0.03 pu. For example, when the data 0…0.1 were not included, only 0.1…1, then the average MAPE was already 84% and decreasing notable. But the problem is, that this is only the percent. Real capacity values are mostly small. When a rather small value is divided with a very small value, the percent is enormous. If MAPE is over 100 %, then bigger MPE values are negative. When wind power is more than 0.7 pu, then MAPE is relatively small, considering differences in the major energy amounts.

Figure 3.1 shows MPE values as mostly negative, but actually proportionally over and under forecasted values (positive and negative MPE values) are relatively equal. Our chosen year showed 51.2 % as produced more than forecasted, 47.6 % as produced less and 1.2 % precisely as forecasted (**I**).

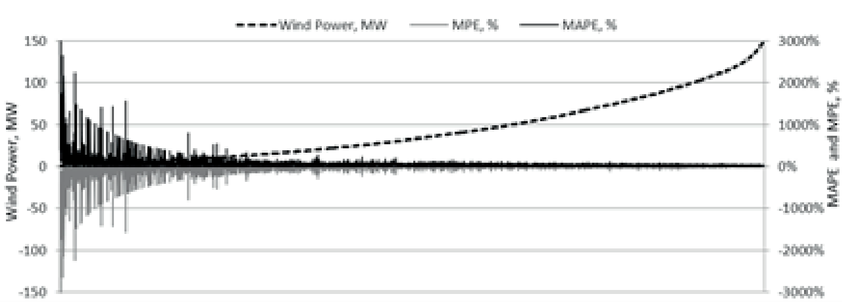

Fig. 3.2. Sorted increasing summary of wind power production, MPE and MAPE in Estonia (1/1/2011–31/12/2011) (Planned...2012).

Figure 3.2 presents the cumulative output power of Estonian wind power plants, to give a better explanation of trends. MAPE and MPE are significantly big, if the wind power is small. Also the biggest MAPE values come from negative MPE values. Negative MPE values mean, that forecast is bigger than production. Figure 3.1 and 3.2 show, that MAPE is not always the best way to analyse all wind data.

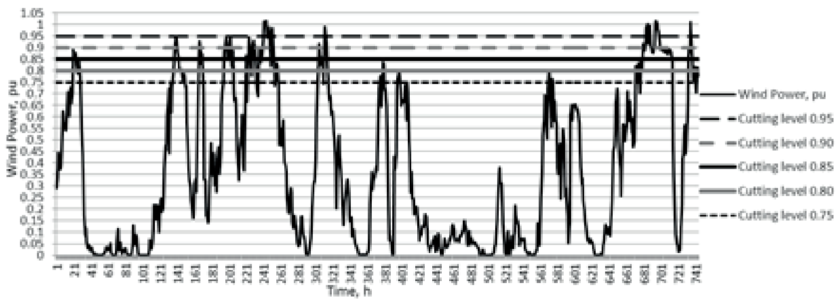

Fig. 3.3. Pakri wind park power production and cutting levels (1/1/2011–31/1/2011)

Figure 3.3 presents one option for compensating for the forecast error, which is cutting off wind park production chart peaks (Annuk, *et al.*, 2010). Cut-off energy from power peaks of production charts can be used for hydrogen production – the technology which is considered in the paper by Andrijanovitš *et al.*, 2010. By this technology it is possible to store energy, and during wind lull periods produce electrical energy again (**I**).

Wind energy usage in heat grids is observed in the paper by Lepa *et al.*, 2010. It appears that wind energy usage in heat networks compared with electrical networks is, in some aspects, simple. But some problems arise due to the different needs of production and consumption charts (different season – different consumption). As in Estonia today the bigger mounted energy storages of suitable efficiency (hydro-pumped storage stations etc.) are non-existent, we have heating networks that use local fuels or gas for district heating. In the above-mentioned study the whole amount of wind energy directed to the heat network is considered.

3.3. Forecast errors in Aulepa wind park

For estimating the forecast error of wind generators' output power we used the production chart of Aulepa Wind Park as of 2009 and the forecast data chart of average power data for 1-hour time intervals. Aulepa Wind Park includes 13 WinWind WWD-3 3 MW wind generators with the total capacity of 39 MW. For the purpose of generalization we use the proportional unit of power, pu.

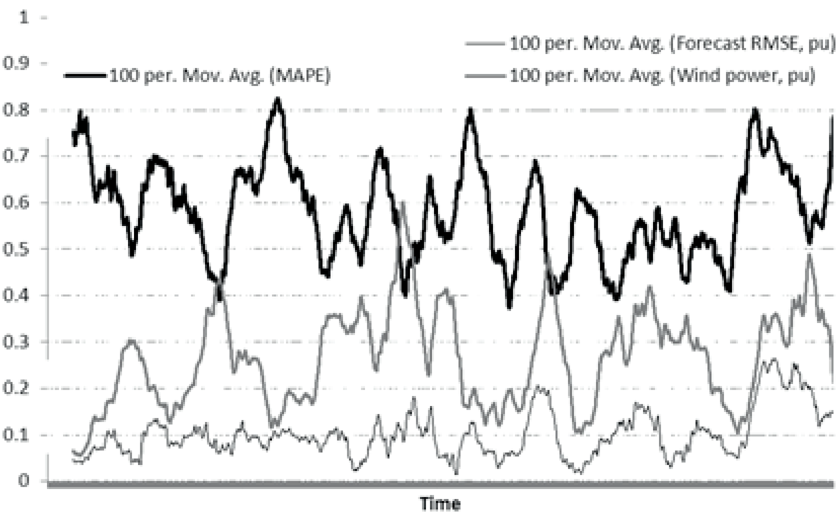

Fig. 3.4. Aulepa Wind Park production chart with forecast RMSE and MAPE chart (1/8/2009–31/12/2009)

Figure 3.4 presents the production chart of Aulepa Wind Park in proportional units of power and the corresponding forecast RMSE in percentage. The average MAPE was 58.8% and average forecast error was 0.135. We can see from the figure that the bigger the wind park output power, the smaller the MAPE, and vice versa. The forecast RMSE increases as the wind park output power increases. Figures 3.4 and 3.5 display a 100 period Trendline Moving Average to facilitate trend observation. The average wind speed in the period of 1/8/2009–31/12/2009 was 4.4 $m \cdot s^{-1}$ (**II**).

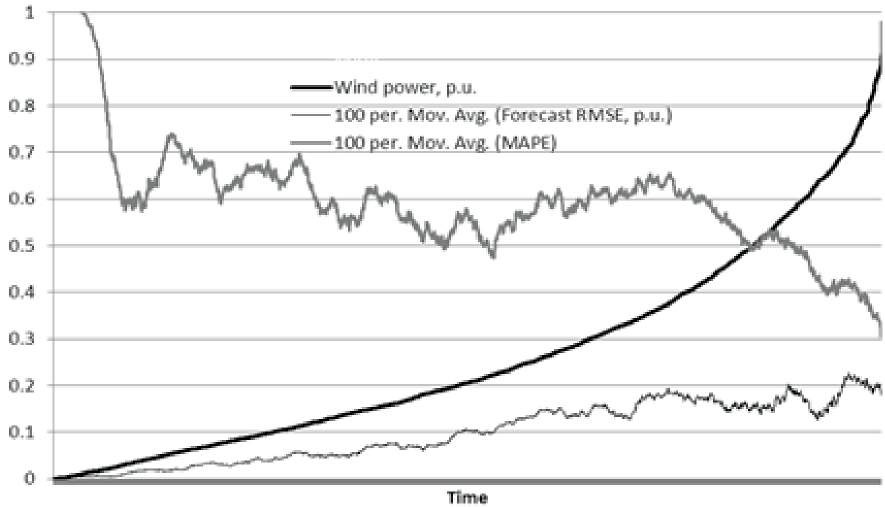

Fig. 3.5. Sorted increasing wind power in Aulepa Wind Park with forecast RMSE and MAPE chart (1/8/2009–31/12/2009)

Figure 3.5 presents the cumulative output power of the wind power plant to give a better explanation of trends. MAPE is decreasing significantly if wind power is bigger than 45%.

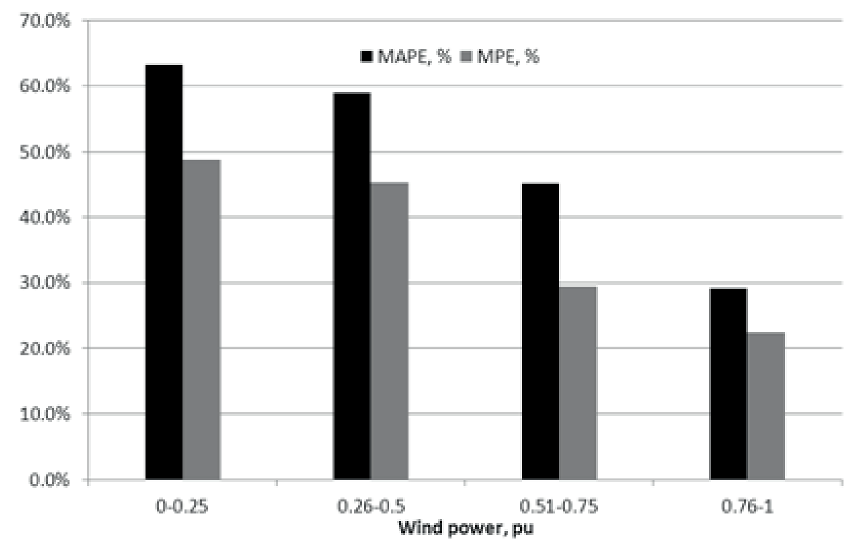

Fig. 3.6. MAPE and MPE of proportional power in Aulepa Wind Park (1/8/2009–31/12/2009)

Figure 3.6 shows by periods of time that MAPE and MPE values are higher at the lower output power of the wind park. This also means that cutting off production chart peaks makes MAPE and MPE increase.

3.4. Wind-solar hybrid system

A grid-connected integrated renewable system consisting of a consumer, wind generators, PV panels, a DC/AC converter and storage devices was studied (Fig. 3.7). The primary data processing was done by Microsoft Excel and HOMER software. One regular year of energetics, 8760 hours that includes all seasons, was the evaluation period.

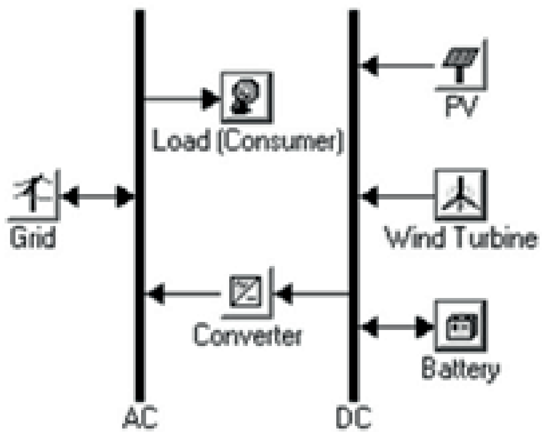

Fig. 3.7. Block diagram of the system

The annual electricity consumption data was synthesised from the measurements made by E. Jõgi in a typical Estonian countryside dwelling house during one week in February and one week in August. One peculiarity of this data is that the density and amplitude of the peak loads are higher in summer than in winter. The reason for this is that the equipment mainly utilized in rural households in summertime is used for water pumping, firewood cutting, etc and therefore more power is used, whereas electricity consumption of the base load is higher in winter because of a greater need for lighting and other applications throughout the day (Põder *et al.*, 2009).

The load profiles of the hourly average of one winter week (beginning on Monday 04.02.2008) and one summer week (beginning on Monday

28.07.2008) are shown on Fig. 3.8.. The base load occurs from 1 am to 7 am whereas the majority of the load occurs in the evening (16 pm to 1 am).

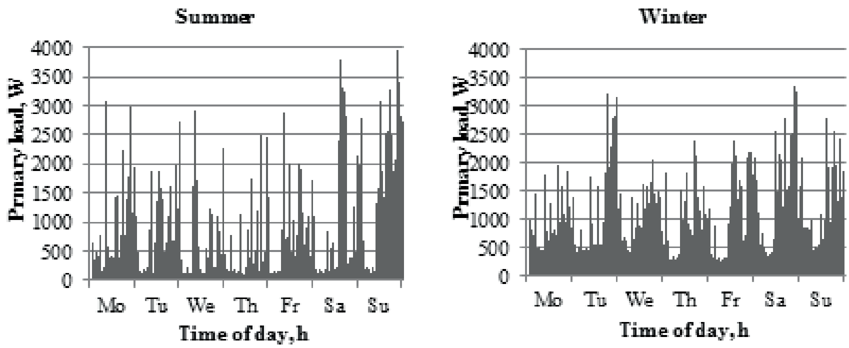

Fig. 3.8. Weekly load profile in summer and winter.

The annual average capacity of the measured consumer according to graphs presented on Fig. 3.8, is a little more than 1 kW. To use this data for scientific purposes we must generalize these. To calculate hourly data of the measured consumer chart to the unit consumer graph of average annual capacity P_{mean} = 1 kW we use the following formula:

$$P_C = \frac{\sum_{i=1}^{8760} P_R}{\sum_{i=1}^{8760} P_{meani}} \cdot P_R \quad , \tag{3.4}$$

whereas $P_{mean} = \frac{\sum_{i=1}^{8760} P_{meani}}{8760} = 1\,kW$ where

P_C – power consumption of a 1 kW unit-consumer, kW;
P_R– power consumption of a measured consumer, kW;
P_{mean}– average capacity of a unit-consumer, kW;

In the equation 3.4 used term "power consumption" means consumed hourly averaged capacity in units kW. In the same time this is described as energy consumption kWh/h. This makes the data comparable and gives us practical output. If we evaluate different consumption, we simply multiply initial data by the constant equal to the ratio of both averages of the graphs. Now we have minimum and maximum loads from all periods, which are 0.098 kW and 3.51 kW correspondingly. The random variability of the consumption graph in the sequence of daily averages is 25.5% and the difference between the hourly energy consumption data and the average daily energy usage profile is 57% according to the formulae utilized by Homer software (Homer Energy, 2011). This is a sufficiently fluctuating chart to satisfy the majority of consumer profiles (**III**).

Standard deviation was found from the annual power consumption data that was synthesized from weekly power consumption. Since the standard deviation of the consumption data in the sequence of daily averages, as the difference between the hourly data and the average daily profile, is used to assess the characteristics of the unit-consumer chart, it is reasonable to use the standard deviation δ for assessing the whole chart (Meldorf, 2008). In the current case, $\delta = 0.76$ kW. As the average power consumption $P_C = 1$ kW, the before mentioned standard deviation also characterizes relative standard deviation. In order to research consumer charts of different characteristics (*e.g.* charts with sharp-declining or gentle-declining slopes), the variation from the average value (P_C) is altered. For this an equation (3.5) is used,

$$P_\delta = P_C + (P_{mean} - P_C) \cdot \delta \,, \tag{3.5}$$

where

P_δ – power consumption of a unit-consumer with altered dispersion, kW;
P_C – power consumption of a 1 kW unit-consumer, kW;
P_{mean} – average capacity of a unit-consumer, kW;
δ – standard deviation

Global solar irradiation and wind speed data

The calculations were performed with averaged hourly wind speed and global irradiation data measured by the Estonian Meteorological and Hydrological Institute in the locations of Tõravere and Tiirikoja in 2004-2009.

The solar irradiation data was used from one location – Tõravere, by the suggestion that in Estonia the annual actinometrical resource in the area changes up to 5.5% 890-990 kWh/year and the data from Tõravere describes the average irradiation from the Sun in Estonia (Tomson, 2000).

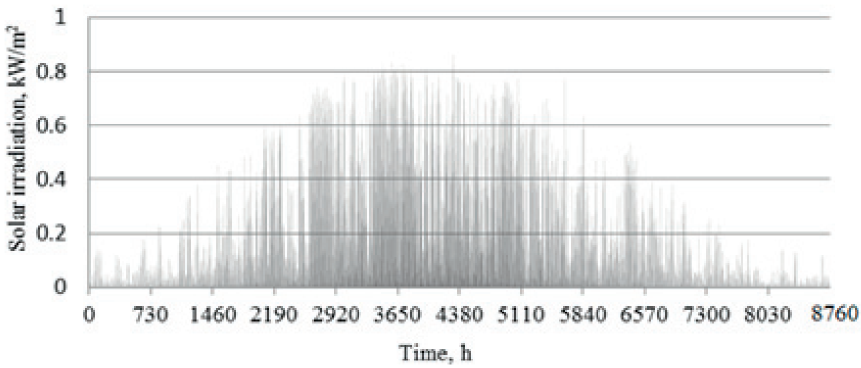

Fig. 3.9. Solar irradiation data in Tõravere 2008 (EMHI)

In Fig. 3.9 the solar irradiation data in Tõravere from the sample year 2008 is presented. Wintertime actinometrical resources are relatively insufficient, especially in December and January. In February and March the situation becomes better, because of diffused radiation reflected from snow. The proportion of direct and diffused radiation in winter months is small, 0.2-0.6. In summer months it is in the range of 0.6-1.2 (Annuk *et al.*, 2011; Russak & Kallis, 2003). In spite of the stable annual actinometrical resources, when comparing the years, solar irradiation behaviour is hard to determine due to diffused radiation during the day. For the PV panels we use devices with 12% efficiency at standard test conditions.

According to some authors (Beausoleil-Morrison *et al.*, 2011; Tomson, 2000) the slope of 45 degrees is used to get maximum power output from PV panels in northern countries. Taking into consideration the opening electricity market in 2013, it will be reasonable to produce as much energy as possible in colder seasons. In this thesis we evaluate panels without a tracking system; therefore the panels have an azimuth of 0 degrees to south.

The most commonly recommended PV array angle is equal to the latitude, because this gives the most even production chart through the year (Beausoleil-Morrison *et al.*, 2011; Tomson, 2000). The third option is an angle that is best suited for PV production in winter (also in spring and autumn). To calculate the best angle of tilt in the winter season, the latitude is multiplied by 0.89, and 24 degrees added (Al-Karaghouli *et al.,* 2007). The latitude of the measuring point is 58.26° and according to the cited above, the optimal tilt for winter conditions is 75.85°. We use a degrading factor f_{PV} = 90% (Al-Karaghouli *et al.,* 2007). The result is the angle from the horizontal at which the panel should be tilted. The reason is that in winter most of the solar energy comes at midday, so at noon the panel should be pointed almost directly to the sun.

To calculate the output of the PV panel we use the following equation (Homer Energy, 2011) (**IV**):

$$P_V = Y_{PV} f_{PV} \frac{\overline{G}_T}{\overline{G}_{T,STC}} [1 + \alpha_P (T_c - T_{c,STC})], \tag{3.6}$$

where

Y_{PV} – the rated capacity of the PV array, power output under

standard test conditions, kW;
f_{PV} – the PV degrading factor, %;
$\overline{G}_T$ – the solar radiation incident on the PV array in the current time step, kW/m^2;
$\overline{G}_{T,STC}$ – the incident radiation at standard test conditions, 1 kW/m^2,
a_p – the temperature coefficient of power, %/°C;
T_c – the PV cell temperature in the current time step, °C;
$T_{c,STC}$ – the PV cell temperature under standard test conditions, 25 °C.

Due to cold climate in the evaluated region and for simplifying the calculations we did not consider the temperature effect, $a_p = 0$.

The power output of the wind turbine is calculated every hour. This entails a two-step process to first calculate the wind speed at the hub height of the wind turbine, then to calculate how much power the wind turbine would produce at certain averaged hourly wind speed.

By using wind speed hourly averaged data we analysed the Weibull´s shape factor *k* in different locations on the territory of Estonia. The wind speed data was measured at the anemometer height 10 m and average sea level (100 m in this thesis). It became obvious from the analysis that the average shape factor *k* = 1.77 with standard relative deviation δ = 0.06. The database consists of 30 measurements of 6 years and 5 different places (coastal and inland regions). Therefore it is eligible to use the wind data of Tiirikoja (EMHI observatory) (Fig. 3.10) from the year 2006 because this year has the closest to the abovementioned Weibull shape factor.

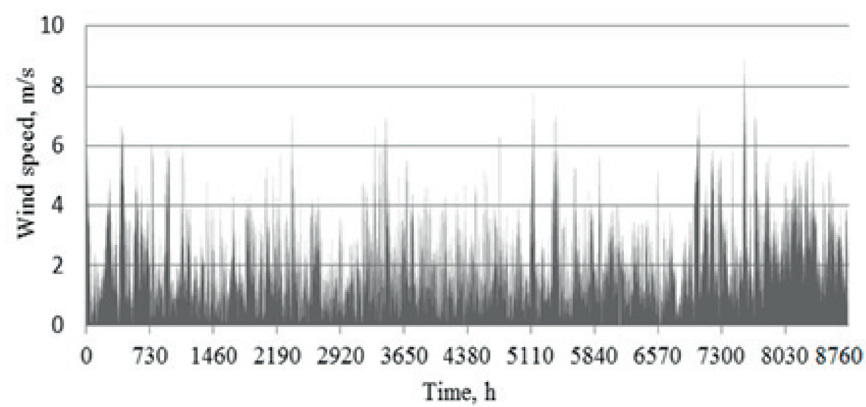

Fig. 3.10. Wind speeds in Tiirikoja, 2006

The power curve (3.7) of this virtual generator is averaged from several wind turbines that are most suitable for mild wind conditions wind generator charts. It should also be noted that this normalized power curve has the following limiters: if the wind speed $v<2.5$ m/s $P = 0$ kW and when $v > 12$ m/s, $P = 1$ kW (Põder *et al.*, 2009).

$$P=0.0078\cdot v^2 - 0.0229\cdot v + 0.00866022, \tag{3.7}$$

where

v – hourly averaged wind speed, m/s;
P – output power, kW.

The hub height of 30m was chosen. A logarithmic relation is used for transforming the wind speed data to the chosen height of 30 m. The surface roughness of $z_0 = 0.25$ was chosen since it is characteristic for landscapes in the countryside, where there are many trees, but not many buildings.

DC/AC converter with the efficiency of 90% is used. Sealed deep-cycle lead-acid batteries with the minimal state of charge SOC = 40% and the capacity of 200 Ah i.e 2.4 kWh and roundtrip efficiency of 80% are used as storage. Batteries are connected to strings by four pieces, with 48 V output voltages (**IV**).

The energy balance of a hybrid system given in Fig. 3.7 is the following:

$$W_C = W_w + W_{PV} + W_{Gp} - W_{Bl} - W_{Gs}\,, \tag{3.8}$$

where

W_C – energy consumption by unit consumer, kWh/year;
W_W – energy production from wind generators, kWh/year;
W_{PV} – energy production from PV arrays, kWh/year;
W_{Gp} – purchased energy from grid, kWh/year;
W_{Bl} – energy losses in battery, kWh/year;
W_{Gs} – sold energy to grid, kWh/year.

A unit consumer's average demand is 1 kW, this means a 8760 kWh consumption per year. The capacity factors are correspondingly solar and wind devices C_{fS}=0.084 and C_{fW}=0.115. The capacity factors stay constant during the study, but capacities change. To cover losses in the storage equipment, wiring and inverter, we suggest using enough wind generators and PV arrays to cover at least:

$$W_W + W_{PV} \rightarrow 10000 \text{ kWh/ year}, \tag{3.9}$$

It should be noted, that average productivity from renewable energy sources must be tightly tied with consumption in order to avoid extensive overproduction. In order to comply with the perquisite (3.8) in the chosen wind and solar conditions, a wind 7 kW wind generator and PV panels of 4.12 kW power in total are used.

4. RESULTS AND DISCUSSION

4.1. Forecast errors in Pakri wind park and Estonia

The results of cutting off production chart peaks in different levels are given in Table 4.1 (**I**).

Table 4.1. Cutting off production chart peaks

Cutting level, pu	Wind power, pu	Remaining energy, %	MAPE, %	Forecast RMSE, pu	Forecast RMSE decreasing %
No cutting	0.277	100	52.2	0.125	-
0.95	0.267	94.8	52.4	0.124	2.9
0.90	0.261	92.0	52.6	0.122	4.3
0.85	0.245	84.3	53.3	0.119	6.8
0.80	0.234	79.0	53.7	0.116	9.0
0.75	0.218	71.2	54.8	0.115	10.3

In Table 4.1 the remaining energy, average wind power, forecast RMSE and MAPE are calculated at different cutting levels. the forecast error decreases when the cutting off production chart peaks. MAPE does not change significantly. The average forecast RMSE in Pakri wind park without cutting was 0.125 pu. The average forecast RMSE in Estonia is about 0.134 (Wind power in Estonia, 2010). For example the forecast RMSE in Germany is 0.106 and Denmark is 0.084 (Wind power in Estonia, 2010). This is due to bigger total wind parks output power, also developers have more experience in prediction.

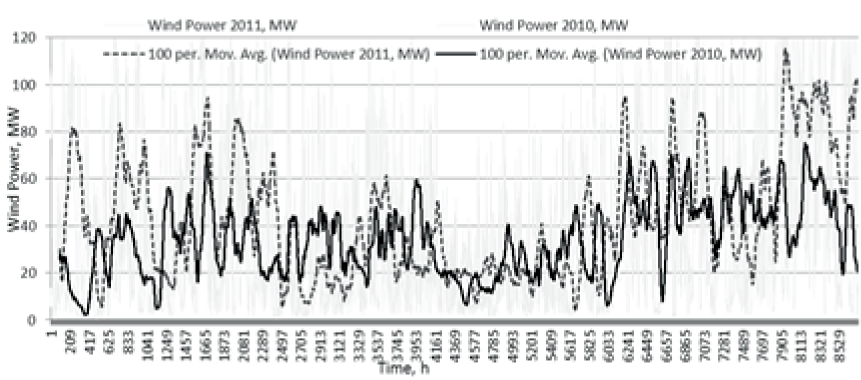

Fig. 4.1. Summary of wind power production in Estonia (1/01/2010–31/12/2011)

Figure 4.1 displays a 100 period trendline moving average to facilitate trend observation. The figure shows, that for Estonian wind parks the year 2011 was more productive than 2010. In summer the production is lower than during the rest of the year. Table 4.2 gives the summary of those 2 years. The third row is the wind data from TransnetBW GmbH, who is TSO in Baden-Württemberg (South Germany). The actual and forecasting data were all integer numbers, but the magnitude is still valid (Wind power in South-Germany, 2012) (**I**).

Table 4.2. Summary of year 2010 in Estonia, 2011 in Estonia and Germany

Year	Average wind power, MW	Maximum wind power, MW	Average MAPE, %	Average forecast RMSE, MW	Maximum forecast RMSE, MW
2010 Estonia	34.2	127.8	50.5	11.7	92.4
2011 Estonia	43.3	161.7	53.0	11.4	83.6
2011 Germany	48.0	458.0	46.6	15.5	230.0

Table 4.2 shows that the maximum forecast error can sometimes be about 72% of the actual total output power of Estonian wind parks. In Pakri wind park the maximum was 74%. But the average forecast RMSE is considerably worse than for German wind parks.

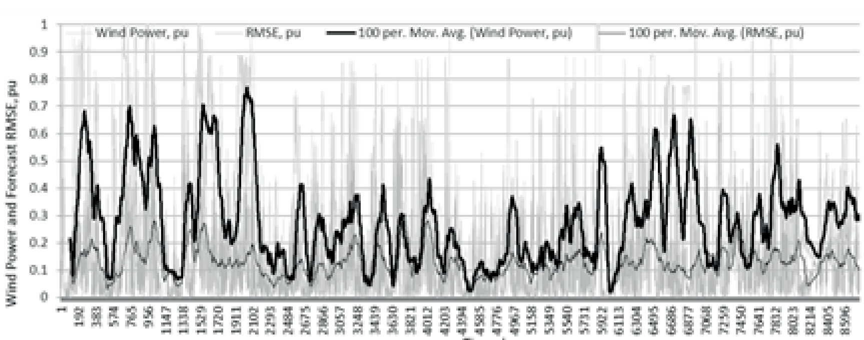

Fig. 4.2. Forecast RMSE in pu by periods of time

Figure 4.2 shows, that Pakri wind park output power is similar to all wind parks summary in Estonia (Figure 3.4 and Figure 4.1).

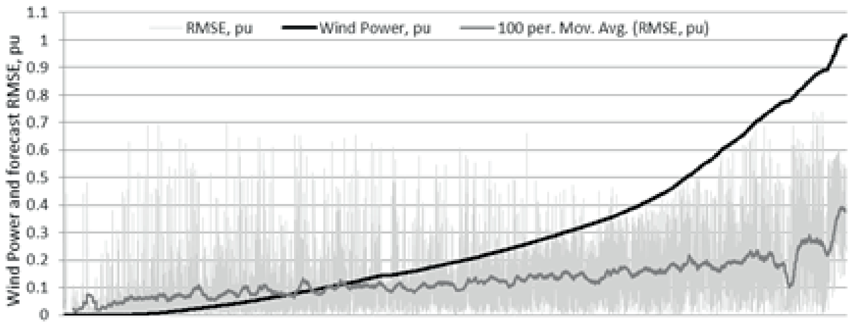

Fig. 4.3. Sorted increasing summary of wind power production and forecast RMSE

Figure 4.3 displays a sorted increasing wind power and forecast RMSE 100 period trendline moving average to facilitate the trend observation. The figure shows, that RMSE values often exceed the 0.5 line (168 hours per year – 2 %). The maximum RMSE is 0.74. In Table 4 the presented average forecast RMSE is divided into four ranges.

Table 4.3. Average forecast RMSE

Wind Power, pu	0–0.25	0.25–0.5	0.5–0.75	0.75–1
Average forecast RMSE, pu	0.0860	0.1509	0.1941	0.2557
Number of hours of Wind Power, %	58.2	21.3	11.2	9.3

Table 4.3 shows that for 79.5 % of the year the wind park output power is under 0.5 pu. If we are cutting on level 0.9 pu, then the number of hours of wind power is 2.3 %.

4.2. Forecast errors in Aulepa wind park

The results of cutting off production chart peaks in different levels are given in Table 4.5 (**II**).

Table 4.4. Cutting off production chart peaks

Cutting level, pu	Remaining energy, %	Forecast RMSE, pu	MAPE, %	MPE, %
0.80	94.5	0.134	59.3	45.0
0.70	86.2	0.130	60.0	45.6
0.60	74.1	0.123	61.1	46.5
0.50	61.5	0.112	61.9	47.7
0.40	47.6	0.098	62.7	48.9
0.30	32.4	0.077	62.8	49.2

In Table 4.4 the cut off energy, forecast RMSE, MAPE and MPE are calculated at different cutting levels. Forecast RMSE decreases when cutting off production chart peaks. MAPE and MPE do not change significantly. The average forecast RMSE in Aulepa Wind Park without cutting was 0.135. The average forecast RMSE in Estonia is about 0.13.

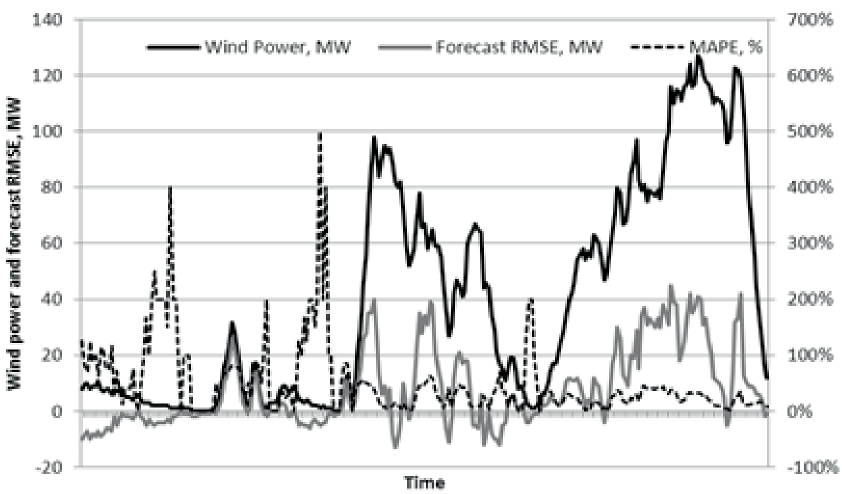

Fig. 4.4. Summary of wind power production, forecast RMSE and MAPE in Estonia (20/01/2011–30/01/2011).

During the period of time in Fig. 4.4., the average MAPE of Estonian wind generators is 51 % with the maximum wind park output power of 127 MW and the maximum forecast error of 45 MW within the given period (Planned …, 2012). The figure also shows that for a long period, the forecast RMSE is more than 30 MW. All over Estonia there are similar trends to those of Aulepa Wind Park, given in previous figures.

In the analysis of the performance of wind turbines it is feasible to apply the concept of capacity factor usage (Annuk, *et al.*, 2010) that may be described as

$$C_F = \frac{W_m}{P_m \cdot t_n} \cdot 100 \quad , \tag{4.1}$$

where W_m is energy produced by the wind turbine in the time period t_n, and P_m is maximum power (sum of the nominal power 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. During this period at Aulepa, the capacity factor was 26 %. This is the average result in Estonian wind parks.

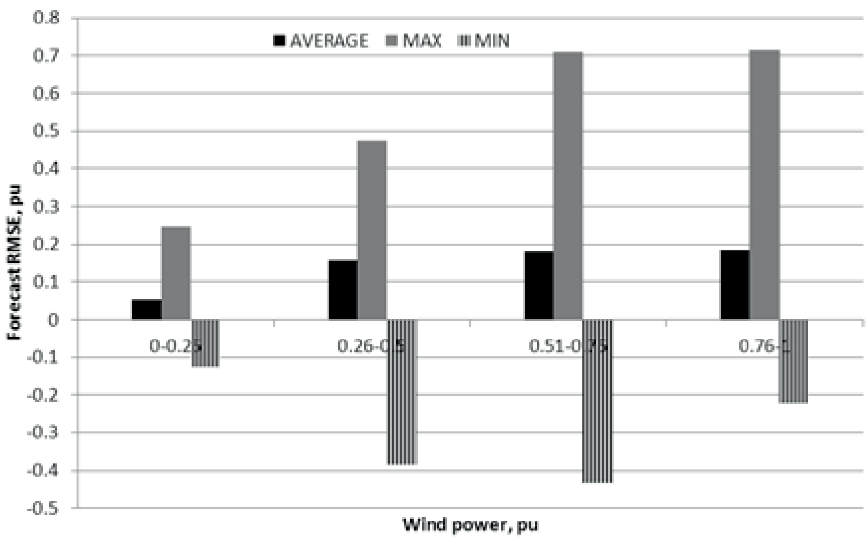

Fig. 4.5. Forecast RMSE in pu by periods of time.

Figure 4.5 shows that there are greater forecast RMSE values if the wind park output power exceeds 0.5. The maximum forecast RMSE (even up to 0.71) were at wind park output power being 0.5–0.8 or at wind speed being about 9–11 $m \cdot s^{-1}$.

4.3. Wind-solar capacities without batteries

To find the optimal configuration of wind-PV capacities without batteries, different combinations in diverse amounts of produced energy are calculated according to the equation (3.9). The indicators used were wind and solar penetration levels L_W and L_{PV} accordingly, and relative energies W_{Gp} and W_{Gs} from the grid and supplied to the grid. The results are shown in Table 4.5 and Fig. 4.6 (**IV**).

Table 4.5. Dependencies of energy indicators from share of solar energy in system.

Share of solar energy, W_{PV}, %	Energy from grid, W_{Gp}, %	Supplied to grid energy, W_{Gs}, %	Renewable fraction, W_R, %	Solar energy penetration, L_{PV}, %	Wind energy penetration, L_W, %
0	34	38	66.1	0	115
10	33	37	67	11.4	103
20	33	37	67.4	22.8	91.6
30	32	37	67.5	34.3	80.2
40	33	37	67.3	45.7	68.7
50	33	37	67	57.1	57.3
60	34	38	66.4	68.5	45.8
70	34	39	65.6	79.9	34.4
80	35	40	64.5	91.3	22.9
90	37	41	63	103	11.5
100	39	43	61.1	114	0

From Table 4.5 it can be seen that solar and wind penetration levels may become higher than 100%, this is due to the chosen conditions that were explained in equation 3.8.

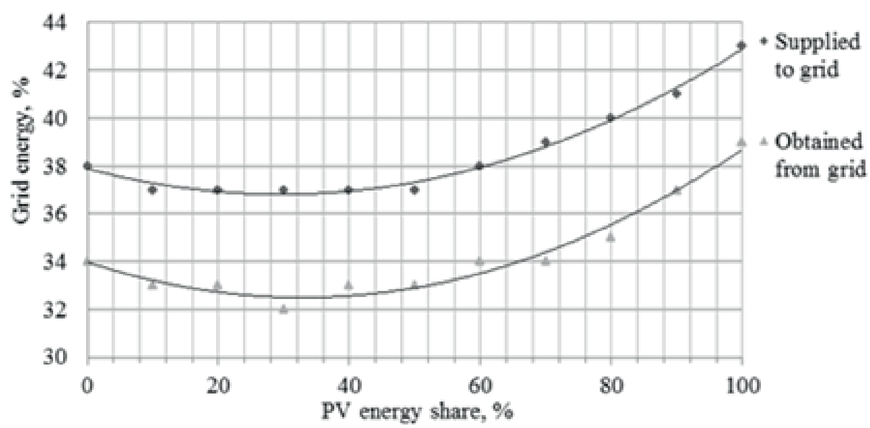

Fig. 4.6. Dependencies of grid obtained and supplied energy W_{Gp}, % and W_{Gs}, % accordingly to produced energy by different solar energy shares W_{PV}, %.

All relative indicators are given in proportion to the consumed energy 8760 kWh, except the renewable fraction W_R, which is calculated by using the following formula:

$$W_R = \frac{W_{PV} + W_W}{W_C + W_{Cp}} \quad , \tag{4.2}$$

From Fig 4.6 we see that the energy sold to the grid exceeds the precentage of electricity purchaced from it. In case of minimal energy from the grid, energy produced by PV panels and wind generators has a ratio of 3/7 correspondingly. Using this ratio we have the best balancing possibilities (e.g. the highest share of renewable fraction W_R the highest shown in Table 4.5. This result is very close to sources (Annuk, 2011; Caralis, 2011).

This ratio was now used in calculations, where batteries are included to decrease the amount of electricity from the grid. In order to do that, we must limit the capacities from the grid. In our calculations the following set of limited capacities for purchasing energy from the grid were in the range of 1-3 kW, by the step 0.5 kW. Due to the chosen battery configuration the series of storage amounts are in the range of 0-576 KWh by the step 9.6 kWh.

Table 4.6. Storage needs on different levels of limiting capacities for energy from grid

Limit. capacity of energy from grid, P_p, kW	Storage capacity, W_{S}, kWh	Obtained energy from grid, W_{Gp}, %	Renewable fraction, W_R, %	Capacity shortage, W_{Sh}, %
3	0	32	68	0.46
	9.6	32	68	0
	19.2	32	68	0
2.5	0	31	68	1.92
	9.6	30	69	0
	19.2	30	70	0
2	0	31	69	5.57
	38.4	27	73	0.21
	48	26	74	0
	57.6	26	74	0
1.5	0	29	71	12.7
	67.2	21	79	1.4
	76.8	21	79	1.19
	86.4	21	79	0.99
1	0	25	75	25
	86.4	16	84	4.77
	480	13	87	1.13
	576	13	87	0.64

As we see in Table 4.6 (**IV**), adding storage capacities helps to increase the renewable fraction and decrease energy obtained from the grid. Limiting from-grid capacity without storage elements rises the capacity shortage rapidly.

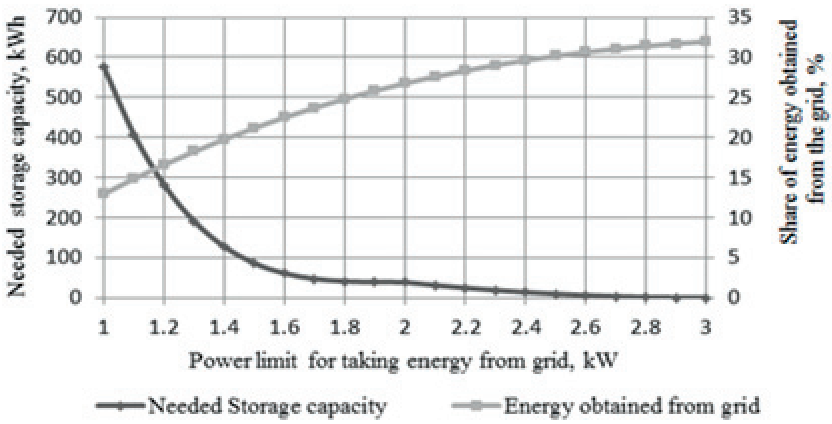

Fig. 4.7. Dependencies of limiting power from grid

Fig 4.7 shows the suggestion, when the capacity shortage is near zero $W_{Sh} \leq 1\%$, the used storage capacities amounts and share of obtained energy from grid. In the case of limiting the capacity up to 1.6 kW, the needed storage capacity rises exponentially and it is not reasonable to use values above it. As a generalisation to the results given in Fig. 4.7, it is reasonable to limit the obtained capacity near the 1.6 kW treshold, then the needed storage capacity is 59 kWh and the share of energy from the grid is 23%.

4.4. Renewable fraction

As follows, the possibilities of increasing the renewable fraction for different standard deviations of the consumer chart were researched. The power obtained from the grid P_L is limited (capacity shortage $C_S < 0.1\%$) and the number of batteries is correspondingly increased. The results, when the standard deviation $\delta = 0.76$ kW are presented in Table 4.7. (**III**)

Table 4.7. The parameters of the system when δ = 0.76 kW

Battery, capacity W_B, kWh	Energy from grid, W_{Gp}, kWh	Total energy received W_T, kWh	Energy fed to the grid W_{Gf}, kWh	Maximal power from the grid P_L, kW	Renewable fraction W_R	W_{Bl}, kWh
0	4803	14843	5079	0	0.676	1004
5.76	4524	14564	4731	2.5	0.689	996
11.52	4257	14297	4397	2.4	0.702	989
17.28	3945	13984	4010	2.2	0.718	983
23.04	3637	13676	3628	2	0.734	972
28.8	3470	13509	3421	1.9	0.743	967
34.56	3423	13462	3360	1.9	0.746	966
40.32	3392	13431	3319	1.9	0.747	965

W_T is the total energy from the wind generator, PV panels and from the grid (4.3).

$$W_T = W_W + W_{PV} + W_{Gp}, \tag{4.3}$$

Renewable fraction W_R is calculated by using the following formula:

$$W_R = \frac{W_{PV} + W_W}{W_T}, \tag{4.4}$$

It can be seen from Table 4.7 that adding batteries increases the renewable fraction W_R, is reducing the need for energy from the grid W_{Gp} and reduces the amount of energy fed to the grid W_{Gf}. When the capacity of the batteries is increased further, the effect diminishes, while the losses in the batteries are reduced as well. The correlations described in Table 4.7 can be seen in Fig. 4.8.

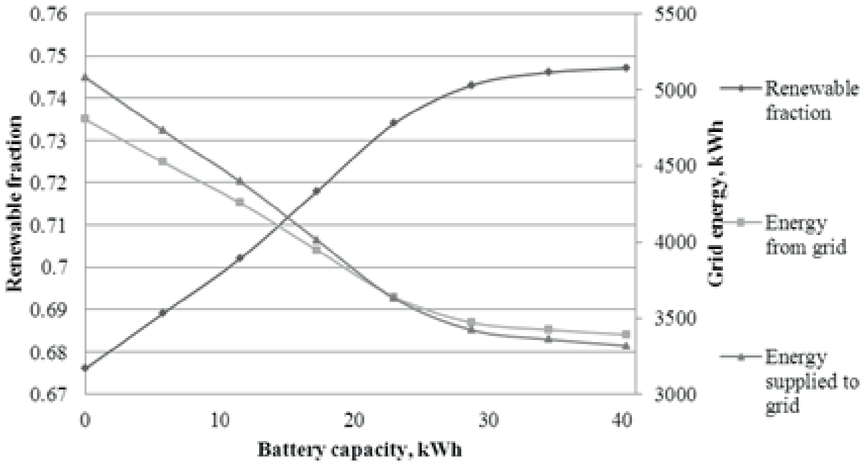

Fig 4.8. Renewable fraction, energy from the grid and to the grid dependency on the batteries added, with maximum dispersion 0.76 kW of the consumption chart.

The escalation of renewable fraction by adding batteries is linear until 23.0 kWh, at the same time the power received from the grid is being reduced to a value that is smaller than the power fed to the grid.

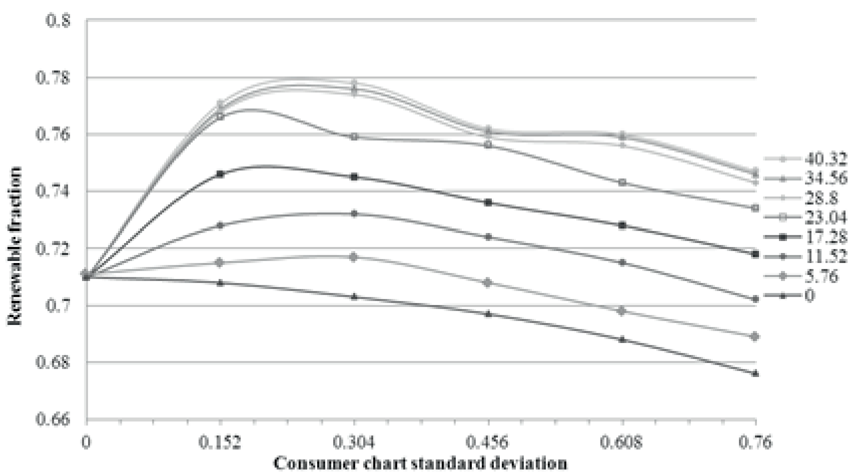

Fig 4.9. Influence of battery capacity to renewable fraction in several standard deviations values of consumption curve.

The consumer-chart shown in Fig. 4.9 describes the renewable fraction in cases of different consumer chart standard deviations and variable amounts of battery capacities. It can be seen, that if the standard deviation is increaced without adding any batteries to the system, the renewable fraction is reduced. When batteries are added, the renewable fraction starts increacing and reaches its maximal value $W_R = 0.779$ when $\delta = 0.25 \pm 0.05$ kW. Adding batteries with the total accumulation capacity exceeding 23 kWh, does not remarkably increace the renewable fraction.

5. CONCLUSIONS

1. The higher the wind park output power, the lower becomes MAPE, and vice versa. The forecast RMSE increases as the wind park output power increases. MAPE is relative and RMSE is absolute error.

2. Forecast RMSE decreases as the production chart peaks are cut off. MAPE and MPE do not change significantly.

3. The highest forecast RMSE could be observed when the wind park output power was in the range of 0.5–0.8 pu. In this range is most difficult to forecast wind park output power.

4. Capacity factor of Estonian wind parks is approximately 25%, but this indicator is in Germany two times smaller. While the average forecast RMSE is in Estonia wind parks considerably smaller than for Germany.

5. In case of grid-connected wind-PV systems without batteries the renewable fraction has a falling trend when the standard deviation of the consumption curve increases.

6. When batteries are added to the grid-connected wind-PV system, the renewable fraction is the highest at the standard deviation $\delta = 0.25 \pm 0.05$ kW of the unit consumer consumption curve. If the value is higher or lower, the renewable fraction decreases. Therefore the consumption curve should not be too flat.

7. In case of the standard deviation $\delta = 0$ the battery capacity has no influence on the renewable fraction.

8. It is important for a grid-connected PV-wind hybrid system to minimize energy from the grid and to have the highest share of renewable fraction possible, while having an optimal configuration and not using other fuels. It is important, since by doing so energy dependence is decreased and therefore energy security is increased.

9. It is reasonable to use storage elements to increase the renewable fraction and decrease the amount of energy from the grid. In

the case of a unit consumer it is reasonable to limit the capacity from the grid near the 1.6 kW threshold. In this case the system needs a storage amount of 59 kWh and the share of energy from the grid is lowest, 23%. If the capacity from the grid is limited further, the amount of storage capacity needed will increase exponentially.

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SUMMARY

The importance of renewable energy is growing. More and more wind parks, CHP-s and biogas stations are being erected and connected to the electrical grid. Of the range of different renewable resources, the proportion and growth of wind generated electricity is the highest. Due to the stochastic nature of wind, the output of wind generators changes quickly, but the production and consumption in the energy system must be in balance. The actual production from wind generators and the forecasted energy are usually different and this energy must be obtained somewhere else, which means extra expense. Wind generator output power is harder to forecast than for example heat power plant output. Errors in forecasting should be minimized.

The aim of the research was to find ways to balance wind generators' output power. Wind generators with greater power must forecast their production and send information to TSO. To reduce errors on forecasting, wind generators production chart peaks could be cut. To balance small wind generators, PV panels and batteries could be added to systems.

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

1. Overview of wind data analysis methods (**I, II**).

2. Analysis of different wind parks' data, to find ways to correct forecast errors (**I, II**).

3. Analysis of ways to balance power curves, using wind-solar hybrid systems (**III, IV**).

Data from Pakri and Aulepa wind park was collected and analysed from different angles. At the beginning of the research the data series were shorter. Then methodology and hypotheses were developed, which were also confirmed on long data series. Forecast errors were calculated and the results compared with wind parks in Estonia, Germany and Denmark. Single wind park results are comparable with Estonian wind parks total.

Wind data was also collected form Tiirikoja (EMHI), solar irradiation data was collected from Tõravere (EMHI) and annual electricity consumption data from an Estonian typical countryside dwelling (E. Jõgi). Data have been used in a system, where a wind generator, PV panel and battery are

added. Different parts of the system and their sizes, also their production, are explored and analysed, so that the system would be optimal to the unit consumer.

Results and conclusions:

1. The forecast error is estimated by three methods: Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE) and Mean Percentage Error (MPE).

2. The biggest forecast errors could be observed when the wind park output power was in the range of 0.5–0.8. The higher the wind park output power, the lower is MAPE, and vice versa. The forecast error increases as the wind park output power increases. the forecast error decreases as the production chart peaks are cut off. MAPE and MPE do not change significantly.

3. Nowadays PV-wind hybrid systems are used in two ways: autonomous and grid connected. It is important for a grid-connected system to minimize energy from the grid and to have the highest share of renewable fraction possible, while having an optimal configuration and not using other fuels. It is important, since by doing so energy dependence is decreased and therefore energy security is increased. When batteries are added to the grid-connected wind-PV system, the renewable fraction is the highest at the standard deviation is $\delta = 0.25 \pm 0.05$ kW of the consumption curve. If the value is higher or lower, the renewable fraction decreases. Therefore the consumption curve should not be too flat.

KOKKUVÕTE

Taastuvenergia tähtsus on kasvamas. Järjest enam tuuleparke, koostootmisjaamasid ja biogaasijaamasid ehitatakse ning ühendatakse elektrivõrku. Erinevatest taastuvenergia liikidest on kõige kiiremini kasvanud tuule osatähtsus ja toodetud energia hulk. Tuulegeneraatorite väljundvõimsus muutub tuule stohhastilise iseloomu tõttu kiirelt, aga energiasüsteemis peab tootmine ja tarbimine tasakaalus olema. Tuulegeneraatorite poolt tegelikult toodetud ja ennustatud võimsuse puudujääk tuleb võrgu tasakaalus püsimiseks hankida kusagilt mujalt, mis toob kaasa lisakulutusi. Tuulegeneraatoritelt saadavat võimsust on palju raskem ennustada, kui näiteks soojuselektrijaama puhul. Ennustamisel tekkivaid vigu tuleks minimaliseerida.

Selle töö eesmärgiks oli leida viise tuulegeneraatorite väljundvõimsuste balansseerimiseks. Suurema võimsusega tuulegeneraatorid peavad oma toodangut prognoosima ning seda võrgu operaatorile edastama. Ennustamisel tekkivate vigade vähendamiseks võiks tuulegeneraatori toodangu tippe lõigata. Väiksemate tuulegeneraatorite puhul võiks balansseerimiseks lisada neile päikesepaneeli ning aku.

Töö eesmärgi saavutamiseks olid ette nähtud järgmised tegevused:

1. Uurida tuuleandmete analüüsi meetodeid (**I, II**).
2. Analüüsida erinevate tuuleparkide andmeid, et leida viise vähendada ennustamise vigu (**I, II**).
3. Analüüsida viise, et balansseerida toodangu kõveraid, kasutades tuule-päikese hübriid süsteemi (**III, IV**).

Töö käigus on kogutud Pakri ja Aulepa tuulepargi andmeid ning neid analüüsitud erinevate nurkade alt. Uurimustöö alguses olid andmeread lühemad ning siis sai välja töötatud metodoloogiad ning püstitatud hüpoteesid, mis leidsid pikkade andmeridade puhul ka tõestust. Andmete põhjal on arvutatud ennustamise vead ning võrreldud neid kogu Eesti ning Saksamaa ja Taani tulemustega. Üksiku tuulepargi tulemused on suurusjärkudes võrreldavad kogu Eesti tuuleparkide tendentsidega.

Töö käigus on kogutud ka tuule andmeid Tiirikojast (EMHI), päikese kiirguse andmeid Tõraverest (EMHI) ning elektri tarbimise andmeid tüüpilisest Eestimaa maakoha elamust (E. Jõgi). Andmeid on käsitletud süsteemis, kus on tuulegeneraator ja päikesepaneel ning lisatud on ka aku. Vaadeldud ja analüüsitud on süsteemi osade erinevaid suuruseid ning nende toodangumahtusid, et optimeerides neid kasutades ühiktarbijat.

Tulemused ja järeldused:

1. Prognoosi viga hinnatakse peamiselt kolme meetodi abil: Ruutkeskmine viga (RMSE), keskmine absoluutne protsentuaalne viga (MAPE) ja keskmine protsentuaalne viga (MPE).

2. Kõige rohkem ja kõige suuremad ennustamise vead on tuulepargi väljundvõimsuse vahemikus 0.5 – 0.8 pu (suhtelist ühikut). Mida suurem on tuulepargi väljundvõimsus, seda väiksem tuleb MAPE (keskmine absoluutne protsentuaalne viga) ja vastupidi. Ruutkeskmine viga (RMSE) suureneb tuulepargi väljundvõimsuse suurenemisega. Tuulepargi tootmisgraafiku tippude lõikamisel ruutkeskmine viga väheneb, keskmine absoluutne protsentuaalne viga (MAPE) ja keskmine protsentuaalne viga (MPE) ei muutu väga palju.

3. Tänapäeval kasutatakse tuule-päikese hübriidsüsteemi kahel viisil: autonoomselt ja võrku ühendatuna. On väga oluline võrku ühendatud süsteemis, et minimaalselt kasutatakse energiat võrgust ja saavutada niimoodi võimalikult suur taastuvenergia osakaal, samas saavutatakse optimaalne konfiguratsioon ja välditakse teiste kütuste kasutamist. Samuti energia sõltuvus väheneb ning seega energia julgeolek suureneb. Kui akud on lisatud võrku ühendatud tuule-päikese süsteemi, siis taastuvenergia osa on suurim standardhälbega $\delta = 0.25 \pm 0.05$ kW tootmiskõverast. Kui väärtus on suurem või väiksem, siis taastuvenergia osa väheneb. Seega tarbimiskõver ei tohiks olla liiga lame.

I

ORIGINAL PUBLICATIONS

Toom, K., Annuk, A., Allik, A., Uiga, J., Kabanen, T. 2012. EVALUATION OF WIND PARKS OUTPUT POWER FORECAST ERROR AND WAYS TO DECREASE IT. Engineering for rural development. 11-th International Scientific Conference: 428 - 433. Jelgava: Latvia University of Agriculture

EVALUATION OF WIND PARKS OUTPUT POWER FORECAST ERROR AND WAYS TO DECREASE IT

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Abstract

From a socio-economic perspective, better forecasting will reduce the total generation costs due to the more optimal dispatch of power plants. The operators of the wind parks integrated into the transmission network are responsible for presenting a 24h-forecast of their output power to the transmission system operator (TSO). The real wind power differs from the forecast one. This difference needs balancing by the rest of the energy system. In Estonian conditions, it means regulating the capacity of oil-shale-fuelled power plants, which induces an accelerated wear, additional emissions and fuel consumption of the power plants.

Wind park output power is particularly difficult to forecast at wind speeds of 6–10 $m \cdot s^{-1}$ due to the fact that electricity generation of wind turbines changes markedly between these speeds. The most relevant metrics to measure forecast errors are Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE). The absolute errors of the forecast are dependent on the forecasted wind power generation. Thus, most of the prediction problems lie in the higher end of wind output values.

Keywords: wind park, wind power, forecast error, production charts

Introduction

Fluctuations in wind capacity are balanced by power plants of fast regulated output, such as gas turbines and hydro power plants, or storage facilities such as pumped-storage hydro power plants and compressed air power plants. The conventional fossil fuel based thermal power plants are not easy to use for balancing large capacities of wind power, and nuclear power plants are totally unsuitable in this respect. In the territory of Estonia, the resources available for balancing the wind power by oil-shale power plants are becoming exhausted, and the same is true about the hydro power plants in Latvia. The fastest way to provide for the additional fast regulated capacity is to establish gas turbine plants and a pumped-storage hydro power plant in the more distant future.

TSOs are authorised to reduce wind park production peaks, which they occasionally also resort to in extreme conditions, when the balancing required cannot be achieved by other measures [1]. It can be presumed that the need for cutting off peak loads is increasing fast. In Estonia, the first reserve plant of 120 MW in capacity will be constructed as late as 2013, and by this time, even the most conservative forecast suggests that the capacity of wind parks will have been increased to about 590 MW [2]. The method of cutting off production chart peaks could be applied systematically to correct forecast errors, whereas the energy cut off might be applicable for heat energy production in boiler houses.

Materials and methods

The capacity produced by power plants at any given moment of time must be equal to the consumption capacity. With conventional fossil fuel based energy system the power balance is well maintained. The accuracy of consumption capacity forecast is high enough and it is by these charts that the output of thermal power plants is adjusted. On the contrary, the stochastic fluctuations in the wind park output power may have an amplitude as large as tens of megawatts per minute, which may result in emergency situations for the network if the need for forecast is neglected. The reason why generation is particularly difficult to forecast at wind speeds of 6–10 $m \cdot s^{-1}$ is that electricity generation of wind turbines changes markedly between these speeds.

Forecasting wind power as accurately as possible is important to wind power producers bidding in their production in an electricity market as well as to the system operator. In a market based setup the wind power producers will normally pay for the costs of balancing the wind power. Therefore the more accurate the forecast of wind power, the lower the balancing costs to the wind power producers will be.

As a rule, wind park capacity is predicted for 24 h ahead. The time span of 24 hours enables to plan necessary changes to the reserve capacities. Nevertheless, the wind power forecast is bound to involve some error. The forecast error is estimated by three methods: Root Mean Square Error (RMSE) (1), Mean Absolute Percentage Error (MAPE) (2) and Mean Percentage Error (MPE) (3) [3].

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(P_a - P_f)^2}\ , \tag{1}$$

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{P_a - P_f}{P_a}\right| \cdot 100\ , \tag{2}$$

$$MPE = \frac{1}{n}\sum_{t=1}^{n}\frac{P_a - P_f}{P_a} \cdot 100, \tag{3}$$

where P_a – actual wind park output power;
P_f – predicted wind park output power.

While MPE shows the polarity of error, MAPE expresses the range of it. It is reasonable to use MPE for estimating the polarity of forecast error in the short time intervals of data-series. The MAPE values may vary significantly, but an average of 20 % can be achieved [4].

To evaluate forecast errors for wind park output error, we used the production chart of Pakri wind park as of 2009-2011 and the forecast data chart of average power data for 1-hour time intervals. We divided the yearly data to four quarters and chose random quarters of those three years to create a discretionary year. The year (hereinafter "the chosen year") consists of quarterly data 1/1/2011–31/03/2011, 1/4/2009–30/6/2009, 1/7/2010–30/9/2010 and 1/10/2009–31/12/2009.

In Pakri wind park there are 8 Nordex N-90 2.3 MW wind units with the total capacity of 18.4 MW. The wind park is situated on the sea shore, where the wind conditions are the best, and where wind parks are built right now in Estonia [5]. To generalize the results we used a proportional unit (pu). The proportional unit is a non-dimensional value, having the range of 0...1. The value 1 corresponds to the rated power of the wind park.

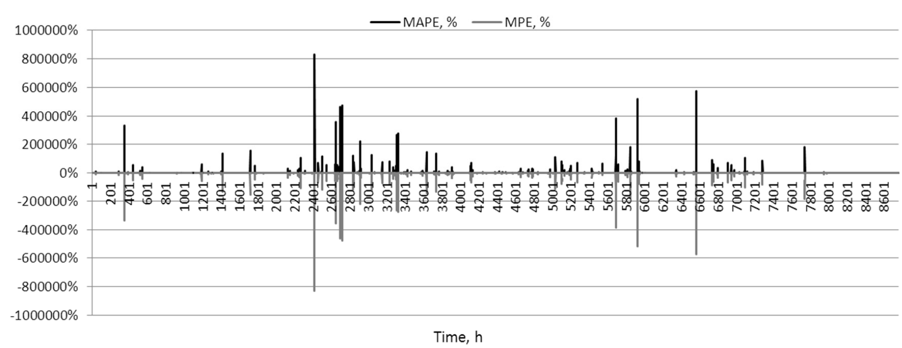

Fig. 1. **Pakri wind park MAPE and MPE chart**

Figure 1 shows, that MAPE and MPE are very big sometimes. Therefore we did not use extreme data values (only the values, which were smaller than 300 %) for calculating MAPE average results.

When we look at MAPE and other values 0…0.1 pu, then the average MAPE was 4222 % and the maximum was 828851 %. The average forecast RMSE was 0.03 pu. For example, when the data 0…0.1 were not included, only 0.1…1, then the average MAPE was already 84 % and increasing fast. But the problem is, that this is only the percent. Real energy values are mostly small. When a rather small value is divided with a very small value, then the percent is enormous. If MAPE is over 100 %, then bigger MPE values are negative. When wind power is more than 0.7 pu, then MAPE is relatively small, considering differences in the major energy amounts.

The figure shows as if MPE values are mostly negative, but actually proportionally over and under forecasted values (positive and negative MPE values) are relatively equal. Our chosen year showed 51.2 % as produced more than forecasted, 47.6 % as produced less and 1.2 % precisely as forecasted (0 MW forecasted and 0 MW produced).

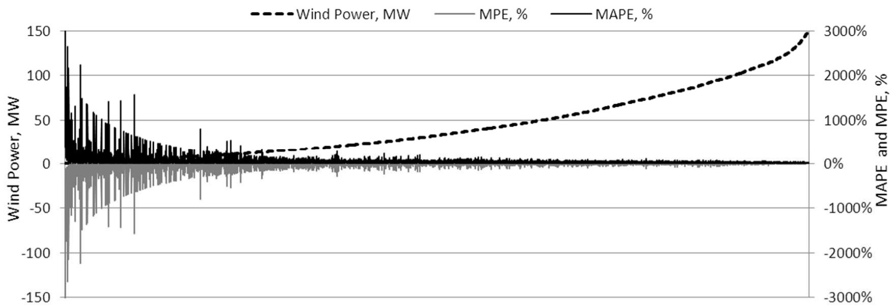

Fig. 2. **Sorted increasing summary of wind power production, MPE and MAPE in Estonia (1/1/2011–31/12/2011) [6].**

Figure 2 presents the cumulative output power of Estonian wind power plants, to give a better explanation of trends. MAPE and MPE are significantly big, if the wind power is small. Also the biggest MAPE values come from the negative MPE values. Negative MPE values mean, that forecast is greater than production. Figure 1 and 2 show, that MAPE is not always the best way to analyse all wind data.

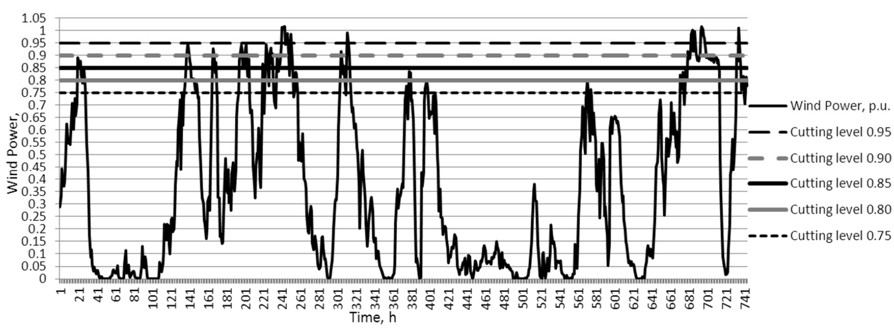

Fig. 3. **Pakri wind park power production and cutting levels (1/1/2011–31/1/2011)**

Figure 3 presents one option for compensating for the forecast error, which is cutting off wind park production chart peaks [7, 8]. Cut-off energy from power peaks from production charts can be used for hydrogen production – the technology which is considered in the paper [9]. By this technology it is possible to storage energy, and during wind lull periods to produce electrical energy again.

Wind energy usage in heat grids is observed in the present paper [10]. It appears, that wind energy usage in heat networks compared with electrical networks is, in some aspects, somehow simple. But now some problems arise due to the different needs of production and consumption charts (different season – different consumption). As in Estonia today the bigger mounted energy storages with suitable efficiency (hydro-pumped storage stations etc.) are non-existent, we have heating networks that use local fuels or gas for distant heating. In the above-mentioned study the whole amount of wind energy directed to heat network is considered.

Results and discussions

The results of cutting off production chart peaks in different levels are given in Table 1.

Table 1

Cutting off production chart peaks

Cutting level, pu	Wind power, pu	Remaining energy, %	MAPE, %	Forecast RMSE, pu	Forecast RMSE decreasing %
No cutting	0.277	100	52.2	0.125	-
0.95	0.267	94.8	52.4	0.124	2.9
0.90	0.261	92.0	52.6	0.122	4.3
0.85	0.245	84.3	53.3	0.119	6.8
0.80	0.234	79.0	53.7	0.116	9.0
0.75	0.218	71.2	54.8	0.115	10.3

In Table 1 the remaining energy, average wind power, forecast RMSE and MAPE are calculated at different cutting levels. Forecast error decreases when the cutting off production chart peaks. MAPE does not change significantly. The average forecast RMSE in Pakri wind park without cutting was 0.125 pu. The average forecast error in Estonia is about 0.134. For example the forecast RMSE in Germany is 0.106 and Denmark is 0.084 [11]. This is due to bigger total wind parks output power, also developers have more experience in prediction.

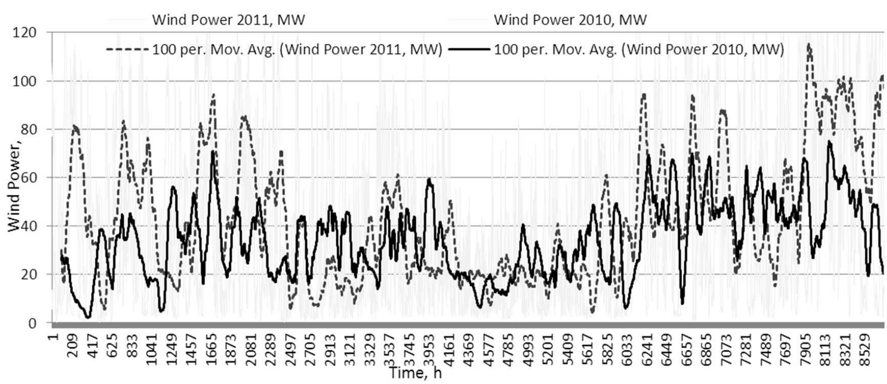

Fig. 4. **Summary of wind power production in Estonia (1/01/2010–31/12/2011)**

Figure 4 displays a 100 period trendline moving average to facilitate trend observation. Figure shows, that for Estonian wind parks the year 2011 was more productive than 2010. In summer months the production is lower than during the rest of the year. In Table 2 there is the summary of those 2 years. The third row is the wind data from TransnetBW GmbH, who is TSO in Baden-Württemberg (South Germany). The actual and forecasting data were all integer numbers, but the magnitude is still valid [12].

Table 2

Summary of year 2010 and 2011

Year	Average wind power, MW	Maximum wind power, MW	Average MAPE, %	Average forecast RMSE, MW	Maximum forecast RMSE, MW
2010	34.2	127.8	50.5	11.7	92.4
2011	43.3	161.7	53.0	11.4	83.6
2011 Germany	48.0	458.0	46.6	15.5	230.0

Table 2 shows that maximum forecast error can sometimes be about 77 % of Estonian wind parks actual total output power. In Pakri wind park the maximum was 74 %. But the average forecast RMSE is considerably worse than for German wind parks.

In Table 3 there are examples of wind power in different wind parks in Estonia.

Table 3

Largest wind parks in Estonia

Wind park	Wind power, MW	Rated power, MW
Pakri	15.03	18.4
Viru-Nigula	20.89	24
Esivere	3.03	8
Rõuste	6.56	8
Aulepa	25.94	39
Tooma	8.99	16
Virtsu	5.08	6.9
SUM	**85.52**	**120.3**

The data is collected from Estonian TSO SCADA 3/3/2012 on 20:54.

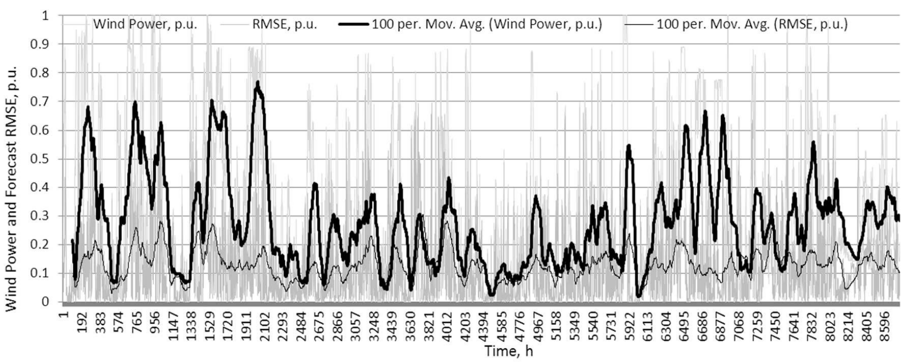

Fig. 5. **Forecast RMSE in pu by periods of time**

Figure 5 shows, that Pakri wind park output power is similar to all wind parks summary in Estonia (Figure 4).

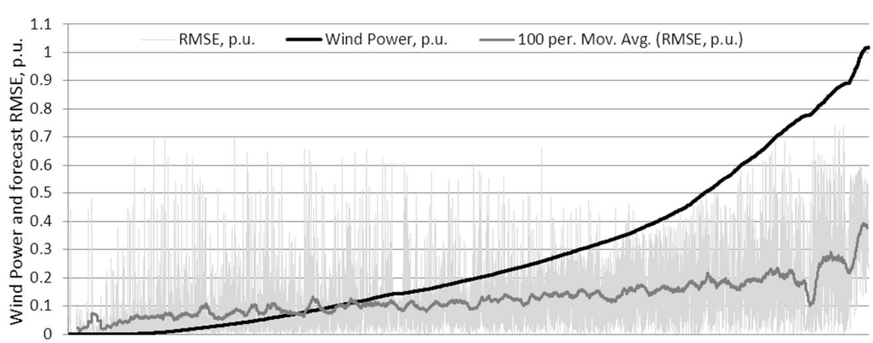

Fig. 6. **Sorted increasing summary of wind power production and forecast RMSE**

Figure 6 displays a sorted increasing wind power and forecast RMSE 100 period trendline moving average to facilitate trend observation. The figure shows, that RMSE values often exceed 0.5 line (168 hours per year – 2 %). The maximum RMSE is 0.74. In Table 4 the presented average forecast RMSE is divided into four ranges.

Table 4

Average forecast RMSE

Wind Power, pu	0–0.25	0.25–0.5	0.5–0.75	0.75–1
Average forecast RMSE, pu	0.0860	0.1509	0.1941	0.2557
Number of hours of Wind Power, %	58.2	21.3	11.2	9.3

Table 4 shows that for 79.5 % of the year the wind park output power is under 0.5 pu. If we are cutting in level 0.9 pu, then the number of hours of wind power is 2.3 %.

Conclusions

1. According to measurement data in Pakri wind park, the average MAPE was 52.2 % and the average forecast RMSE was 0.128 pu.
2. The higher the wind park output power, the lower becomes MAPE, and vice versa. The forecast error increases as the wind park output power increases.
3. 79.5 % of the year, Pakri wind park output power was under 0.5 pu.
4. Forecast error decreases as the production chart peaks are cut off. MAPE and MPE do not change significantly.
5. Estonian average wind power is better than in Germany, considering the size of wind parks. But the average forecast RMSE is considerably worse than for German wind parks.

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II

Toom, K., Jürjenson, K., Juhanson, T., Annuk, A. 2011.
CUTTING WIND GENERATOR POWER CHART PEAKS TO
MITIGATE POWER FORECAST ERROR.
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CUTTING WIND GENERATOR POWER CHART PEAKS TO MITIGATE POWER FORECAST ERROR

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Abstract. Under certain circumstances, the transmission system operator (TSO) can face the need to reduce the power output of the wind parks. In a market based setup the wind power producers will normally pay for the balancing costs of wind power. Therefore, the more accurate the forecast of wind power, the lower the balancing costs for the wind power producers will be. From a socio-economic perspective, better forecasting will reduce the total generation costs due to the more optimal dispatch of power plants. The operators of the wind parks integrated into the transmission network are responsible for presenting a 24h-forecast of their output power to TSO. The real wind power differs from the forecast one. This difference needs balancing by the rest of the energy system. In the Estonian conditions, it means the regulation of the capacity of oil-shale-fuelled power plants which induces an accelerated wear, additional emissions and fuel consumption of the power plants. The reason why wind park output power is particularly difficult to forecast at wind speeds of 6-10 $m \cdot s^{-1}$ is due the fact that electricity generation of wind turbines changes markedly between these speeds.

Keywords: wind park, wind power, forecast error, production charts.

Introduction

Fluctuations in wind capacity are balanced by power plants of fast regulated output, such as gas turbines and hydro power plants, or storage facilities such as pumped-storage hydro power plants and compressed air power plants. The conventional fossil fuel based thermal power plants are not easy to use for balancing large capacities of wind power, and nuclear power plants are totally unsuitable in this respect. In the territory of Estonia, the resources available for balancing the wind power by oil-shale power plants are becoming exhausted, and the same is true about the hydro power plants in Latvia. The fastest way to provide for the additional fast regulated capacity is to establish gas turbine plants and a pumped-storage hydro power plant in the further future.

TSOs are authorised to reduce wind park production peaks, which they occasionally also resort to in extreme conditions, when the balancing required cannot be achieved by other measures [1]. It can be presumed that the need for cutting off peak loads is increasing fast. In Estonia, the first reserve plant of 120 MW in capacity will be erected as late as 2013, and by this time, even the most conservative forecast suggests that the capacity of wind parks will have been increased to about 590 MW [2]. The method of cutting off production chart peaks could be applied systematically to correct forecast errors, whereas the energy cut off might be applicable for heat energy production in boiler houses.

Materials and methods

The capacity produced by power plants at any given moment of time must be equal to the consumption capacity. With a conventional fossil fuel based energy system the power balance is well maintained. The accuracy of consumption capacity forecast is high enough and it is by these charts that the output of thermal power plants is adjusted. On the contrary, the stochastic fluctuations in the wind park output power may have amplitude as large as tens of megawatts per minute, which may result in emergency situations for the network if the need for forecast is neglected. The reason why generation is particularly difficult to forecast at wind speeds of 6-10 $m \cdot s^{-1}$ is due the fact that electricity generation of wind turbines changes markedly between these speeds.

Forecasting wind power as accurately as possible is important to wind power producers bidding in their production in an electricity market as well as to the system operator. In a market based setup the wind power producers will normally pay for the costs of balancing the wind power. Therefore, the more accurate the forecast of wind power, the lower will the balancing costs to the wind power producers be.

As a rule, wind park capacity is predicted for 24 h ahead. The time span of 24 hours enables to plan the necessary changes to the reserve capacities. Nevertheless, the wind power forecast is bound to involve some error. The forecast error (FE) (1) is estimated by two main methods: Root Mean Square

Error (RMSE) and Mean Absolute Percentage Error (MAPE) (2) [3]. In this paper we also report on the use of Mean Percentage Error (MPE) (3).

$$FE = \frac{1}{n}\sum_{t=1}^{n} P_a - P_f \, , \tag{1}$$

$$MAPE = \frac{1}{n}\sum_{t=1}^{n} \left| \frac{P_a - P_f}{P_a} \right| \cdot 100 \, , \tag{2}$$

$$MPE = \frac{1}{n}\sum_{t=1}^{n} \frac{P_a - P_f}{P_a} \cdot 100 \, , \tag{3}$$

where P_a – actual wind park output power;
P_f – predicted wind park output power.

While MPE shows the polarity of error, MAPE expresses the range of it. It is reasonable to use MPE for estimating the polarity of forecast error in the short time intervals of data-series. The MAPE values may vary significantly, but an average of 20 % can be achieved [4].

For the estimation of the forecast error of wind generators output power we used the production chart of Aulepa Wind Park as of 2009 and the forecast data chart of average power data for 1-hour time intervals. Aulepa Wind Park includes 13 WinWind WWD-3 3 MW wind generators with the total capacity of 39 MW. For the purpose of generalization we use the proportional unit of power, p.u.

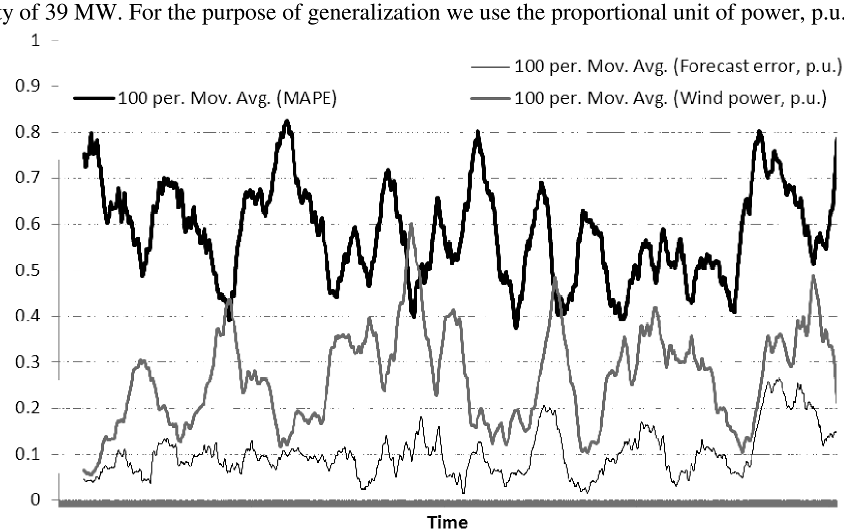

Fig. 1. **Aulepa Wind Park production chart with forecast error and MAPE chart (01.08.2009-31.12.2009)**

Figure 1 presents the production chart of Aulepa Wind Park in proportional units of power and the corresponding forecast errors in percentages. The average MAPE was 0.588 and average forecast error was 0.135. We can see from the figure that the larger the wind park output power, the smaller turns MAPE, and vice versa. The forecast error increases as the wind park output power increases. Figures 1 and 2 display a 100 period Trendline Moving Average to facilitate the trend observation. The average wind speed in the period of time 1.8.2009–31.12.2009 was 4.4 m·s^{-1}.

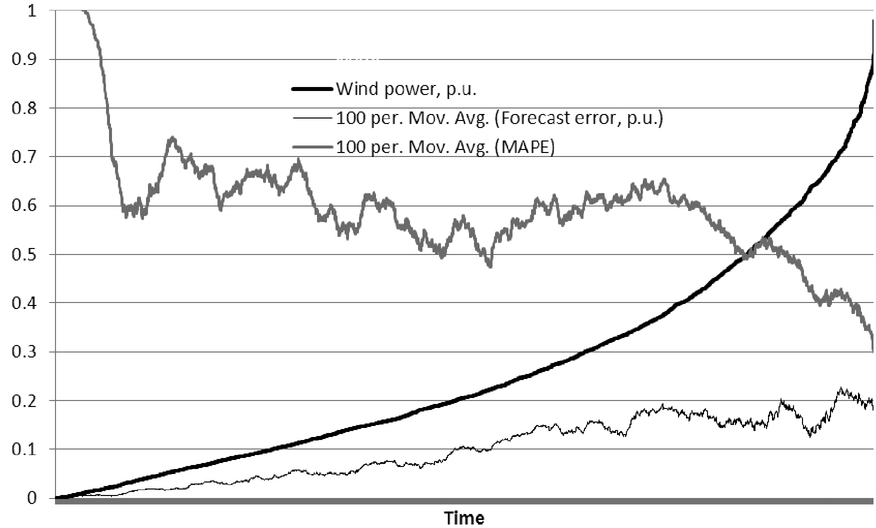

Fig. 2. **Sorted increasing wind power in Aulepa Wind Park with forecast error and MAPE chart (1.8.2009-31.12.2009)**

Figure 2 presents the cumulative output power of the wind power plant to give a better explanation of trends. MAPE is decreasing significantly if the wind power is greater than 0.45.

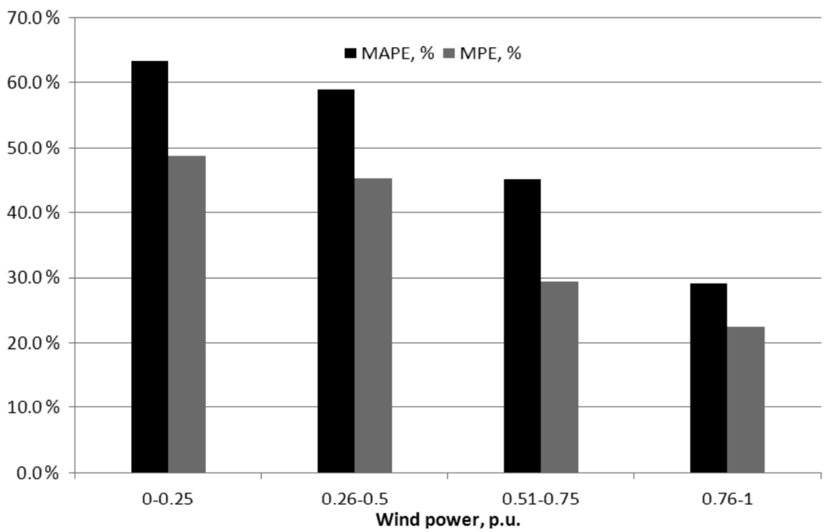

Fig. 3. **MAPE and MPE of proportional power in Aulepa Wind Park (01.08.2009-31.12.2009)**

Figure 3 shows by periods of time that MAPE and MPE values are higher at the lower output power of the wind park. This also means that cutting off production chart peaks makes MAPE and MPE increase.

Results and discussions

The results of cutting off production chart peaks on different levels are given in Table 1. The cut off energy, forecast error, MAPE and MPE are calculated on different cutting levels. The forecast error decreases when cutting off production chart peaks. MAPE and MPE do not change significantly. The average forecast error in Aulepa Wind Park without cutting was 0.135.

Table 1

Cutting off production chart peaks

Cutting level, %	Cut off energy, %	Forecast error, p.u.	MAPE, %	MPE, %
30	67.6	0.077	62.8	49.2
40	52.4	0.098	62.7	48.9
50	38.5	0.112	61.9	47.7
60	25.9	0.123	61.1	46.5
70	13.8	0.130	60.0	45.6
80	5.5	0.134	59.3	45.0

The average forecast error in Estonia is about 0.13. For example, in Germany and Denmark the forecast error is about 0.08-0.10 [5]. This is due to bigger total wind park output power and developers have more experience in prediction.

During this period of time (see Fig. 4), the average MAPE of Estonian wind generators is 51 % if the maximum wind park output power was 127 MW and the maximum forecast error was 45 MW within the given period [6]. The figure also shows that for a long period of time, the forecast error is more than 30 MW. All over Estonia there are similar trends to those of Aulepa Wind Park given in previous figures.

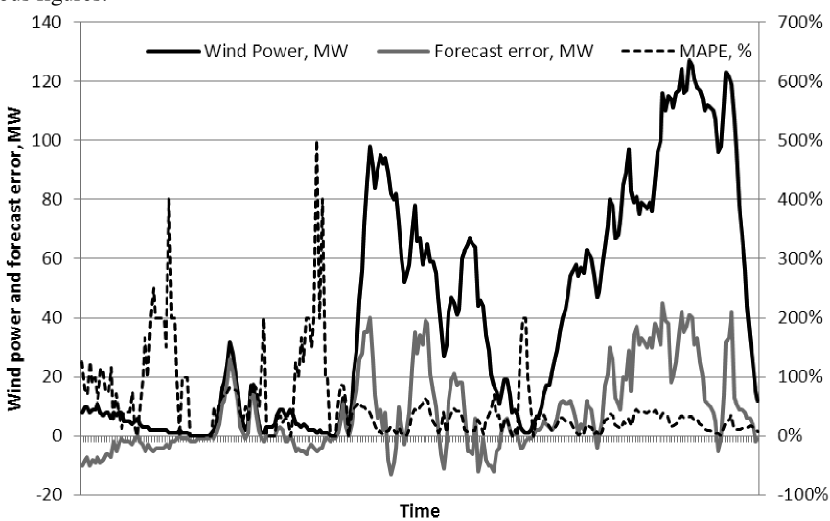

Fig. 4. **Summary of wind power production, forecast error and MAPE in Estonia (20.01.2011-30.01.2011)**

In the analysis of the performance of wind turbines it is feasible to apply the concept of the coefficient of maximum (or nominal) power usage [7] that may be described as

$$k_m = \frac{W_m}{P_m \cdot t_n} \cdot 100, \tag{4}$$

where W_m is energy produced by the wind turbine in the time period t_n, and P_m is the maximum power (sum of the nominal power 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. During this time period at Aulepa, the coefficient of nominal power usage was 26 %. This is the average result in Estonian wind parks.

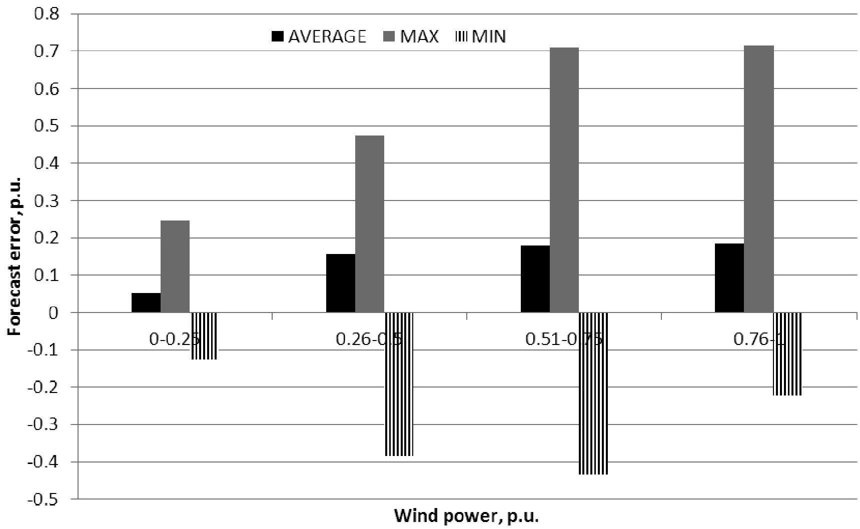

Fig. 5. **Forecast error in p.u. by periods of time**

Figure 5 shows that there are greater forecast errors if the wind park output power exceeds 0.5. The most and the greatest forecast errors (even up to 0.71) were at the wind park output power being 0.5-0.8 or at the wind speed being about 9-11 $m \cdot s^{-1}$.

Conclusions

1. According to the measurement data in Aulepa Wind Park, the average MAPE was 58.8 % and the average forecast error was 0.135.
2. The higher the wind park output power, the lower becomes MAPE, and vice versa. The forecast error increases as the wind park output power increases.
3. During the period of time 01.08.2009–31.12.2009 at Aulepa, the coefficient of nominal power usage was 26 %. This is an average result in Estonian wind parks.
4. The forecast error decreases as the production chart peaks are cut off. MAPE and MPE do not change significantly.
5. The most and the greatest forecast errors could be observed when the wind park output power was in the range of 0.5-0.8.

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III

Annuk, A., Allik, A., Pikk, P., Uiga, J., Tammoja, H.,
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INCREASING RENEWABLE FRACTION BY SMOOTHING CONSUMER´S POWER CURVES IN GRID CONNECTED WIND-SOLAR HYBRID SYSTEMS

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Wind and solarirradiation are highly stochastic energy sources. Nevertheless, to some degree, both are usable almost everywhere and therefore are very convenient energy sources. In the current paper a small wind-photovoltaic (PV) panel hybrid system connected to the grid with or without a storage equipment is estimated. The main purpose is to research the augmentation of the renewable fraction, thereby reducing the need of obtaining electrical power from the grid, at different deviations of the unit consumer's graph, but at the same time the average consumption of the year stays the same. The other important variable in the calculations is the battery size. The weather data is acquired from meteorological databases.

Introduction

The pressure to increase the proportion of renewable energy sources in final energy consumption has been growing in the last years. According to the Directive 2009/28/EC of the European Parliament of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources, Estonia as all other EU countries is obliged to rise the share of renewables in the final energy consumption compared to the reference year 2005. For Estonia, the target of renewable energy share is set to 25%, as compared to 18% in 2005 [1].

Several sources of energy (biomass, wind power, solar radiation and ground heating) could be used for reaching the set target. Wind and solar resources are very convenient and available almost everywhere. The main problem is the very high stochastic nature of wind and solar energy.

It is characteristic to the wind energy generator equipment to have the shortest energy payback period (less than 0.5 year) compared to other energy generating technologies [2].

The amount of installed wind energy generating capacities is rising at an accelerating rate; therefore it is needed to create balancing properties of wind power capacities connected to the grid. For example the operating variables of currently operational oil-shale based power plants are not meant for balancing the rapidly changing stochastic electrical power inputs to the grid [3]. The development of wind capacities will exceed the balancing possibilities currently available in the grid in the near future. The best way to balance wind power units is hydropower stations. Unfortunately using hydropower as a balancing possibility is mostly limited due to the lack of available necessary capacities for several reasons. Using the energy system resources of the neighbouring countries is limited as well, because most countries are already engaged with development of wind power.

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Another possible way of reducing a wind generator's effect on the grid is co-producing energy with PV devices. Solar energy becomes more competitive due to continuously decreasing prices for PV panels [4]. Owners of wind and PV units are interested in selling more energy to the grid and purchasing as small amounts of energy from the grid as possible. Research shows that the energy needed to obtain from the grid is minimal if the ratio of wind-PV cogenerated power is 70% – 30% correspondingly [5, 6]. This shows that wind and PV units have some balancing properties when operating together. Some storage elements are probably needed in the system for maintaining control of energy flows.

The goal of the paper is to evaluate the possibilities for diminishing the amount of purchased energy from the grid in cases of different standard deviations characterizing the unit-consumer graph while various accumulation capacities are used.

System architecture of a wind – PV system

In the current article a grid-connected integrated renewable system consisting of a consumer, wind generators, PV panels, a DC/AC inverter and storage devices (Fig. 1) is assessed. The primary data processing was implemented by Microsoft Excel and Homer software. One regular year of 8760 hours that includes all seasons was used as the evaluation period. The energy received from the grid was limited in a way that the capacity shortage would not exceed 0.1%. At the same time the size of wind and PV energy generation equipment was chosen in order to follow the ratio of produced energy 70% and 30% mentioned above.

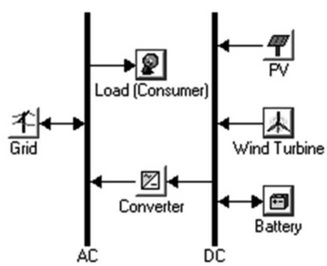

Fig 1. Block diagram of the system architecture.

Load analysis of a consumer

The annual electricity consumption data was synthesised from the measurements made in an Estonian typical countryside dwelling house during one week in February and one week in August. One peculiarity of this data is that the density and amplitude of the peak loads are higher in summer than in winter. The reason for this is that the equipment mainly utilized in rural households in the summertime it is used for water pumping, firewood cutting, etc and therefore more electrical power is used whereas electricity consumption of the base load is higher in winter because of a greater need for lighting and other applications throughout the day.

The load profile of the hourly average of one week in winter (beginning on Monday 04.02.2008) is shown in Fig. 2. From Fig. 3 we can follow the load profile of the summer week (beginning on Monday 28.07.2008). The base load occurs from 1 am until 7 am whereas the majority of the load occurs during the evening (16 pm to 1 am).

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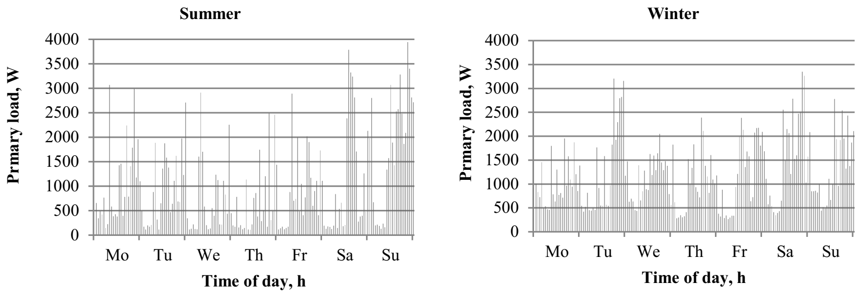

Fig. 2. Weekly load profile in summer and winter.

As can be seen from Fig. 2 and Fig. 3 minimum and maximum loads from all periods are 0.098 kW and 3.51 kW correspondingly. The random variability of the consumption graph in the sequence of daily averages is 25.5% and the difference between the hourly energy consumption data and of the average daily energy usage profile is 57% according to formulas utilized by Homer software [7]. This is a sufficiently fluctuating chart to satisfy the majority of consumer profiles.

Standard deviation was found from the annual power consumption data that was synthesized from weekly power consumption. Since the standard deviation of the consumption data in the sequence of daily averages, as the difference between the hourly data and the average daily profile, is used to assess the characteristics of the unit-consumer chart, it is reasonable to use the standard deviation δ for assessing the whole chart [8]. In the current case, δ = 0.76 kW. As the average power consumption P_C = 1 kW, the before mentioned standard deviation also characterizes relative standard deviation. In order to research consumer charts of different characteristics (*e.g.* charts with sharp-declining or gentle-declining slopes), the variation from the average value (P_c) is altered. For this equation (1) is used.

$$P_{\delta} = P_C + ((P_{mean} - P_C) \cdot \delta \,, \tag{1}$$

where P_{δ} – power consumption of a unit-consumer with altered dispersion, kW;
P_C – power consumption of a 1 kW unit-consumer, kW;
P_{mean} – average power consumption of a unit-consumer P_{AVG} = 1 kW;

Global solar irradiation and wind speed data

The calculations were based on averaged hourly wind speed and global irradiation data measured by the Estonian Meteorological and Hydrological Institute (EMHI) in the locations of Tõravere and Tiirikoja in 2004-2009.

The solar irradiation data was used from one location – Tõravere, by the suggestion that in the territory of Estonia, the annual actinometrical resource changes up to 5.5%, which corresponds to 890-990 kWh/year [9]. Therefore the data from Tõravere is used, as it describes sufficiently the average global solar irradiation from the Sun in Estonia.

In Fig. 3 the solar radiation data in Tõravere for the sample year 2008 is presented. It can be seen, that in wintertime, this actinometrical solar irradiation resource is uneconomical for producing household electricity (especially in December and January). In February and March the amount of solar radiation increases, because of the less cloud coverage and more diffused radiation reflected from snow. The relation of direct to

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diffused radiation in winter months is 0.2-0.6. In summer months it is in the range of 0.6-1.2 [5, 10]. For the PV panels the system efficiency of 12% at standard test conditions is used.

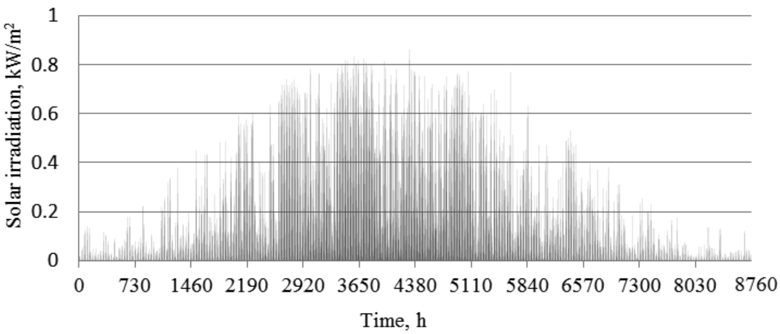

Fig.3. Solar irradiation data in Tõravere 2008 (EMHI).

The most commonly recommended PV array angle is equal to the latitude, because this gives the most even production chart through the year [9, 11]. Taking into consideration the opening electricity market in 2013, it will be reasonable to produce as much energy as possible in colder seasons.

To calculate the best angle of tilt in the winter season (months October until March), the latitude is multiplied by 0.89, and 24 degrees added [11]. The latitude of the measuring point is 58.26˚ and according to the cited above, the optimal tilt for winter conditions is 75.85˚. The result is the angle from the horizontal at which the panel should be tilted.

In this paper, a derating factor f_{PV} = 90% [12] is used for panels without a tracking system; therefore the panels have an azimuth of 0 degrees to south.

To calculate the output of the PV panel the following equation is used [7]:

$$P_V = Y_{PV} f_{PV} \frac{\overline{G}_T}{\overline{G}_{T,STC}} [1 + \alpha_P (T_c - T_{c,STC}] , \quad (2)$$

where Y_{PV} – the rated capacity of the PV array, power output under standard test conditions, kW;

f_{PV} – the PV degrading factor, %;

$\overline{G}_T$ – the solar radiation incident on the PV array in the current time step, kW/m^2;

$\overline{G}_{T,STC}$ – the incident radiation at standard test conditions, 1 kW/m^2;

a_P – the temperature coefficient of power, %/°C;

T_c – the PV cell temperature in the current time step, °C;

$T_{c,STC}$ – the PV cell temperature under standard test conditions, 25 °C.

The power output of the wind turbine is calculated every hour. This entails a two-step process to first calculate the wind speed at the hub height of the wind turbine, then to calculate how much power the wind turbine would produce at certain averaged hourly wind speed.

By using wind speed hourly averaged data the Weibull´s shape factor k in different locations on the territory of Estonia was analyzed. The wind speed data used was measured at the height of 10m from the surrounding surface, which is around 90 m from the sea level in our study. It was calculated from the database, that the average k = 1.77 with relative standard deviation δ = 0.06. The database consists of 30 measurements of 6 years (2004-2009) and 5 different places (coastal and inland regions): Tiirikoja, Jõgeva, Pakri, Tõravere, Viljandi. Although the Weibull shape factors for wind speeds are rather similar in these locations, it cannot be said about other locations in Estonia. For example in Virtsu and in Sõrve, the shape factor is considerably higher, reaching the value $k = 2$. The wind data of Tiirikoja (Fig. 4) from the year 2006 is used because this year has the abovementioned Weibull shape factor of $k = 1.77$.

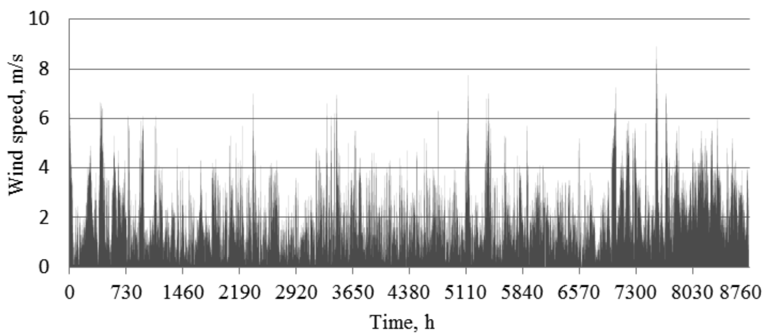

Fig. 4. Wind speed hourly data in location Tiirikoja, 2006.

The power curve (3) of a wind generator is averaged from several wind generators that are most suitable for moderate wind conditions. It should also be noted that this normalized power curve has the following limiters: if the wind speed $v < 2.5$ m/s $P = 0$ kW and when $v > 12$ m/s, $P = 1$ kW [13].

$$P = 0.0078 \cdot v^2 - 0.0229 \cdot v + 0.00866022, \quad (3)$$

where v – hourly averaged wind speed, m/s;
P – output power, kW.

The hub height of 30 m was chosen. For transforming the wind speed data to the chosen height, a logarithmic relation was used for transforming the wind speed data to the chosen height of 30 m. The surface roughness of $z_0 = 0.25$ was chosen since it is characteristic for landscapes in the countryside, with many trees, but few buildings.

The inverter and storage selection

A DC/AC inverter with the nominal power of 10 kW and efficiency of 90% is used. Losses in the inverter are around 900 kWh per year. Sealed deep-cycle lead-acid batteries with minimal state of charge SOC = 40% and the capacity of 200 Ah i.e useable 1.44 kWh and roundtrip efficiency of 80% is used as storage device. Batteries are connected to strings by four pieces, with 48 V output voltages in total.

The energy balance of the system

The energy balance of a hybrid system given in Fig. 1 is the following:

$$W_C = W_W + W_{PV} + W_G - W_{Bl} - W_{GS} - W_{Il} \quad (4)$$

where W_C – energy consumption by unit consumer, kWh/year;
W_W – energy production from wind generators, kWh/year;

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W_{PV} – energy production from PV arrays, kWh/year;
W_{Gp} – purchased energy from grid, kWh/year;
W_{Bl} – energy losses in battery, kWh/year;
W_{Il} – energy losses in inverter, kWh/year;
W_{Gf} – energy fed to the grid, kWh/year.

A unit consumer's average demand is 1 kW, this means a 8760 kWh consumption per year. The capacity factors are correspondingly solar and wind devices CF_S=0.084 and CF_W=0.115. The capacity factors stay constant during the study, but the capacities change. To cover losses in the storage equipment, wiring and inverter, we suggest to use enough wind generators and PV arrays to cover at least:

$$W_W + W_{PV} \to 10000 \text{ kWh/year,} \tag{5}$$

It should be noted, that the average productivity from renewable energy sources must be tightly tied with consumption in order to avoid extensive overproduction. In order to comply with the perquisite (5) in the chosen wind and solar conditions, a wind 7 kW wind generator and PV panels of 4.12 kW power in total are used.

Renewable fraction of the total electrical energy produced

As follows, the possibilities of increasing the renewable fraction for different standard deviations of the consumer chart are researched. The power obtained from the grid P_L is limited (capacity shortage C_S < 0.1 %) and the number of batteries is correspondingly increased. The results, when the standard deviation δ = 0.76 kW are presented in table 1.

Table 1. **The parameters of the system when δ = 0.76 kW**

Battery, capacity W_B, kWh	Energy from grid, W_{Gp}, kWh	Total energy received W_T, kWh	Energy fed to the grid W_{Gf}, kWh	Maximal power from the grid P_L, kW	Renewable fraction W_R	W_{Bl}, kWh
0	4803	14843	5079	0	0.676	1004
5.76	4524	14564	4731	2.5	0.689	996
11.52	4257	14297	4397	2.4	0.702	989
17.28	3945	13984	4010	2.2	0.718	983
23.04	3637	13676	3628	2	0.734	972
28.8	3470	13509	3421	1.9	0.743	967
34.56	3423	13462	3360	1.9	0.746	966
40.32	3392	13431	3319	1.9	0.747	965

W_T is the total energy received from the wind generator, PV panels and from the grid (6).

$$W_T = W_W + W_{PV} + W_{Gp} \tag{6}$$

Renewable fraction W_R is calculated by using the following formula:

$$W_R = \frac{W_{PV} + W_W}{W_T} \tag{7}$$

It can be seen from Table 1 that adding batteries increases the renewable fraction W_R, is reducing the need for energy from the grid W_{Gp} and reduces the amount of energy fed to

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the grid W_{Gf}. When the capacity of the batteries is increased further, the effect diminishes, while the losses in the batteries are reduced as well. The correlations described in Table 1 can be seen in Fig. 5.

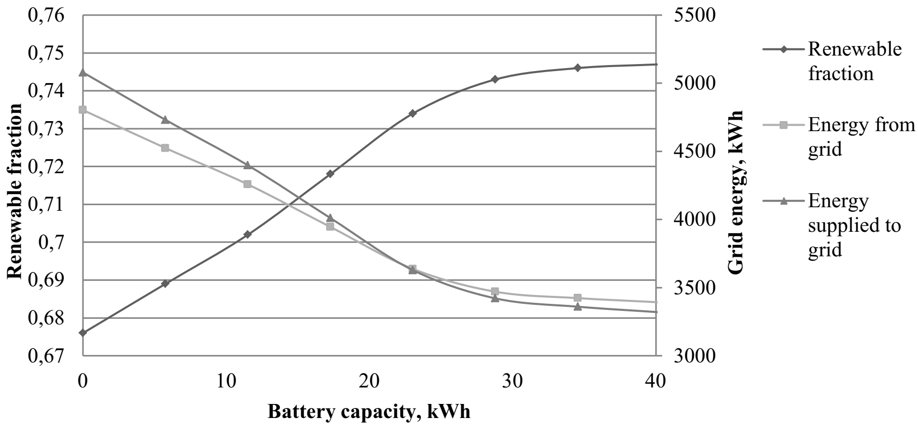

Fig 5. Renewable fraction, energy from the grid and to the grid dependency on the batteries added, with maximum dispersion 0.76 kW of the consumption chart.

The escalation of renewable fraction by adding batteries is linear until 23.0 kWh at the same time the power received from the grid is being reduced to a value that is smaller than the power fed to the grid.

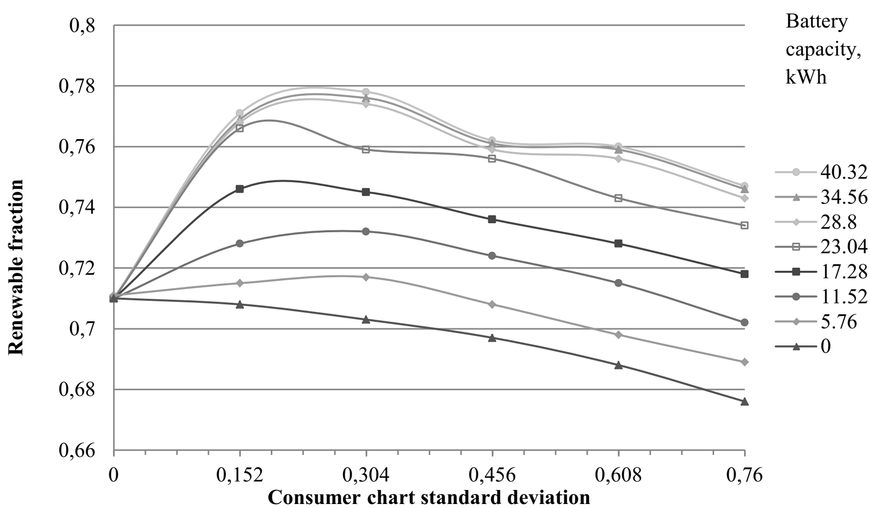

Fig 6. Influence of battery capacity to renewable fraction in several standard deviations values of consumption curve.

The consumer-chart shown in Fig. 6 describes the renewable fraction in cases of different standard deviations and variable amounts of battery capacities. It can be seen, that if the standard deviation is increaced without adding any batteries to the system, the renewable fraction is reduced. When batteries are added, the renewable fraction starts increacing and reaches its maximal value W_R = 0.779 when δ = 0.25 ± 0.05 kW. Adding batteries with total accumulation capacity exceeding 23 kWh, does not remarkably increace the renewable fraction.

Conclusions

In the current article, measures for increasing grid-connected wind-PV system's renewable fraction (ratio of energy produced from wind and solar to total obtained energy i.e. energy from grid) and therefore reducing the amount of energy received from the grid were investigated. A unit consumer with the average power consumption of 1 kW was used for analysing the system. The unit consumer was created by reducing the power consumption of an actually measured consumer. Different standart deviation charts where created from this unit consumer chart. The most representative wind and solar data was used. The methology used in this research can be used for the development of real wind-PV systems connected to the grid by using smart-grid solutions.

From the results presented in this article, the following conclusions can be drawn:

1. In case of grid-connected wind-PV systems without batteries the renewable fraction has a falling trend when the standard deviation of the consumption curve increases.
2. When batteries are added to the grid-connected wind-PV system, the renewable fraction is the highest at the standard deviation δ = 0.25 ± 0.05 kW of the consumption curve. If the value is higher or lower, the renewable fraction decreases. Therefore the consumption curve should not be too flat.
3. In case of the standard deviation δ = 0 then the battery capacity has no influence to the renewable fraction.

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IV

Annuk, A., Allik, A., Pikk, P., **Toom, K.**, Jasinskas, A. 2012.
POWER BALANCING POSSIBILITIES FOR A SMALL
WIND-PV PANEL HYBRID SYSTEM FOR A NEARLY
AUTONOMOUS UNIT CONSUMER.
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485 - 494. Opatija, Croatia: University Of Zagreb,
Faculty of Agriculture

POWER BALANCING POSSIBILITIES FOR A SMALL WIND-PV PANEL HYBRID SYSTEM FOR A NEARLY AUTONOMOUS UNIT CONSUMER

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ABSTRACT

Wind is, compared to solar irradiation, a highly stochastic energy source. Nevertheless, both are usable (to some degree) almost everywhere and therefore are very convenient energy sources. There are several possible configurations for a system with renewable energy sources, for example standalone and grid connected. In the current paper we estimate a small wind-PV panel hybrid system connected to the grid, with or without a storage equipment. It is important to find correlation between the rated capacities of wind and solar PV equipment. Besides, sizing a storage equipment is important, as it is expensive. The main goal of estimation is minimizing the amount of electrical energy from the grid by using the minimal amount of storage equipment. In the calculations, the weather data acquired from meteorological databases (hourly time series data over 6 years from several locations), a 1 kW unit consumer, normalised wind generators, standard PV-panels and batteries are used.

Key*words:* *wind-PV energy, energy storage, renewable energy penetration, system optimization*

INTRODUCTION

The pressure to increase the proportion of renewable energy sources in final energy consumption has been grown in the last years. According to the Directive 2009/28/EC of the European Parliament of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources, Estonia as all other EU countries is obliged to rise the share of renewables in the final energy consumption compared to the reference year 2005. For Estonia, the target of renewable energy share is set to 25%, as compared to 18% in 2005 (European Council, 2009).

Several sources of energy (biomass, wind power, solar radiation and ground heating) could be used for reaching the set target. Wind and solar technical resources are very convenient and available almost everywhere. The main problem is the very high stochastic level of wind.

One of the advantages of using both wind and solar energy is the possibility of producing electricity without generating heat energy. Moreover, it is characteristic to the wind energy generator equipment to have the shortest energy payback period (less than 0.5 year) compared to other energy generating technologies (Matthew, 2006).

The amount of installed wind energy generating capacities is rising at accelerating rate, therefore creating balancing properties of wind power capacities connected to the grid is needed. Despite some progress in arranging balancing measures, the development of wind capacities will exceed the grid possibilities in the near future. The best way to balance wind power units is hydropower stations. Unfortunately using hydropower as a balancing possibility is mostly limited due to lack of available necessary capacities for several reasons. Using the energy system resources of neighbouring countries is limited, because most countries are already engaged with development of wind power.

Cutting off the production of wind park chart peaks in case of energy excess, without using peak energy (Lepa *et al*., 2009), has become one of the balancing measures in the last years. This does not look like a permanent solution, since more small wind and solar units connected to the grid have been set up, making the dispatch grid more complicated and therefore inducing balancing problems.

Another possible way of reducing a wind generator's effect on the grid is co-producing of energy with PV (photo voltaic) devices. Solar energy becomes more competitive due to continuously decreasing prises for PV panels (Wilkinson, 2010). Owners of wind and PV units are interested in selling more energy to the grid and purchasing as small amount of energy from the grid as possible. Evaluations show that in systems with equal capacities of wind and PV, the amount of energy supplied to and received from the grid diminishes with the increase of the relative part of wind energy and in the cases of average wind speeds 3.3-5.9 m/s stays to the range 42.3-52.6% from produced electricity (Annuk *et al*., 2011). This shows that wind and PV units have some balancing properties when operating together. Some storage elements are probably needed in the system for maintaining control of energy flows.

The goal of the paper is to evaluate the possibilities for diminishing the amount of purchased energy from the grid by changing the ratio of the rated capacities of wind and PV units with varying minimised storage amounts. We look into possibilities to operate this system in off-grid regime. This is important for energy security. We use a unit consumer with the average capacity 1 kW by evaluating the behaviour of a system consisting of producers (wind-PV hybrid system), storage and a consumer. Economical aspects are not used in the calculations.

MATERIALS AND METHODS

In the present paper is assessed a grid-connected integrated renewable system consisting of a consumer, wind generators, PV panels, a DC/AC converter and storage devices (Fig. 1). The primary data processing was implemented by Microsoft Excel and HOMER software. One regular year of 8760 hours that includes all seasons was the evaluation period.

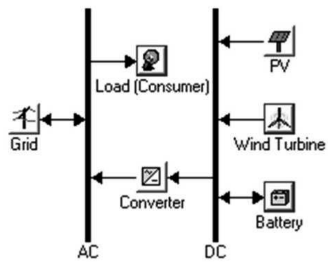

Fig. 1. Block diagram of the system

The annual electricity consumption data was synthesised from the measurements made in an Estonian typical countryside dwelling during one week in February and one week in August. It shows as one peculiarity that the daily and weekly peak loads are higher in summer than in winter. The reason for this is the equipment that is used in rural households in the summertime for water pumping, firewood sawing, etc. The daily averages and base loads are higher in winter because of a greater need for lighting and other applications.

Minimum and maximum loads are 0.098 kW and 3.51 kW correspondingly. The standard deviation in the sequence of daily averages is 25.5% and the difference between the hourly data and the average daily profile is 57%. This is a sufficiently rapid chart to satisfy the majority of consumer profiles.

The calculations were performed averaged hourly wind speed and global irradiation data measured by the Estonian Meteorological and Hydrological Institute in the locations of Tõravere and Tiirikoja in the years 2004-2009.

The solar irradiation data was used from one location – Tõravere, by the suggestion that in Estonia the annual actinometrical resource in the area changes up to 5.5% 890-990 kWh/year and the data from Tõravere describes the average irradiation from the Sun in Estonia (Tomson, 2000).

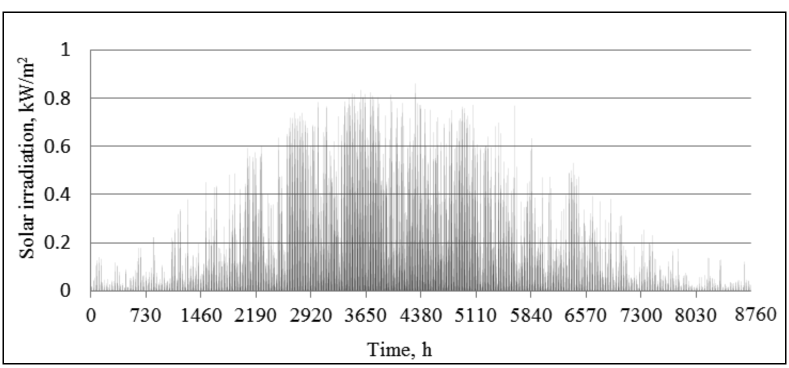

Fig. 2. Solar irradiation data in Tõravere 2008 (EMHI)

In Fig. 2 the solar irradiation data in Tõravere from the sample year 2008 is presented. Wintertime actinometrical resources are relatively insufficient, especially in December and January. In February and March the situation becomes better, because of diffused radiation reflected from snow. The proportion of direct and diffused radiation in winter months is small, 0.2-0.6. In summer months it is in the range of 0.6-1.2 (Annuk *et al*., 2011; Russak&Kallis, 2003). In spite of the stable annual actinometrical resources, when comparing the years, solar irradiation behaviour is hard to determine due to diffused radiation during the day. For the PV panels we use devices with 12% efficiency at standard test conditions.

According to some authors (Beausoleil-Morrison *et al*., 2011; Tomson, 2000) the slope of 45 degrees is used to get maximum power output from PV panels in northern countries. Taking into consideration the opening electricity market in 2013, it will be reasonable to produce as much energy as possible in colder seasons. In this paper we evaluate panels without a tracking system; therefore the panels have an azimuth of 0 degrees to south.

The most commonly recommended PV array angle is equal to the latitude, because this gives the most even production chart through the year (Beausoleil-Morrison *et al*., 2011; Tomson, 2000). The third option is an angle that is best suited for PV production in winter (also in spring and fall). To calculate the best angle of tilt in the winter season, the latitude is multiplied by 0.89, and 24 degrees added (Al-Karaghouli *et al.,* 2007). The latitude of the measuring point is 58.26° and according to the cited above, the optimal tilt for winter conditions is 75.85°. We use a derating factor f_{PV} = 90% (Al-Karaghouli *et al.,* 2007). The result is the angle from the horizontal at which the panel should be tilted. The reason is that in winter most of the solar energy comes at midday, so at noon the panel should be pointed almost directly to the sun.

To calculate the output of the PV panel we use the following equation (Homer Energy, 2011):

$$P_V = Y_{PV} f_{PV} \frac{\overline{G}_T}{\overline{G}_{T,STC}} [1 + \alpha_P (T_c - T_{c,STC}] , \tag{1}$$

where

Y_{PV} – the rated capacity of the PV array, power output under standard test conditions, kW;

f_{PV} – the PV degrading factor, %;

$\overline{G}_T$ – the solar radiation incident on the PV array in the current time step, kW/m^2;

$\overline{G}_{T,STC}$ – the incident radiation at standard test conditions, 1 kW/m^2,

a_P – the temperature coefficient of power, %/°C;

T_c – the PV cell temperature in the current time step, °C;

$T_{c,STC}$ – the PV cell temperature under standard test conditions, 25 °C.

Due to cold climate in the evaluated region and for simplifying the calculations we did not consider the temperature effect, $a_P = 0$.

The power output of the wind turbine is calculated every hour. This entails a two-step process to first calculate the wind speed at the hub height of the wind turbine, then to calculate how much power the wind turbine would produce at certain averaged hourly wind speed.

By using wind speed hourly averaged data we analyzed the Weibull´s shape factor k in different locations on the territory of Estonia. The wind speed data was measured at the anemometer height 10 m and average sea level (100 m in our study). It became obvious from the analysis that the average shape factor $k = 1.77$ with standard relative deviation $\delta = 0.06$. The database consists of 30 measurements of 6 years and 5 different places (coastal and inland regions). Therefore it is eligible to use wind data of Tiirikoja (Fig. 3) from the year 2006 because this year has the abovementioned Weibull shape factor.

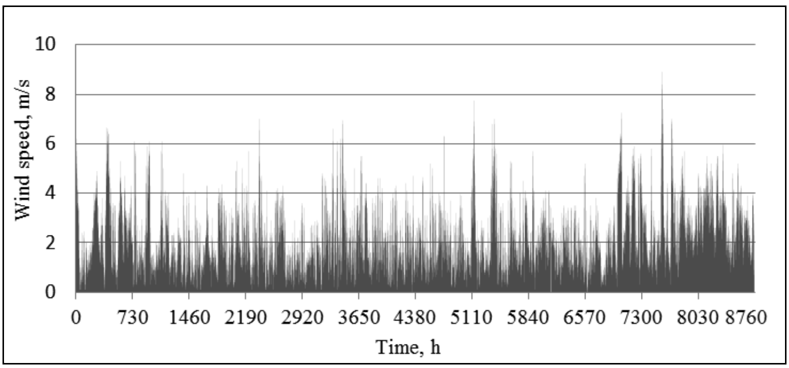

Fig. 3. Wind speeds in Tiirikoja, 2006

The power curve (2) of this virtual generator is averaged from several wind turbines, that are most suitable for mild wind conditions wind generator charts. It should also be noted that this normalized power curve has the following limiters: if the wind speed v<2.5 m/s $P = 0$ kW and when $v > 12$ m/s, $P = 1$ kW (Põder et al., 2009).

$$P = 0.0078 \cdot v^2 - 0.0229 \cdot v + 0.00866022 \quad (2)$$

where

v – hourly averaged wind speed, m/s;

P – output power, kW.

The hub height of 30m was chosen. A logarithmic relation is used for transforming the wind speed data to the chosen height of 30 m. The surface roughness of $z_0 = 0.25$ was chosen since it is characteristic for landscapes in the countryside, where many trees, but not many buildings are situated.

DC/AC converter with the efficiency of 90% is used. Sealed deep-cycle lead-acid batteries with minimal state of charge SOC = 40% and the capacity of 200 Ah i.e 2.4 kWh and roundtrip efficiency of 80% are used as storage. Batteries are connected to strings by four pieces, with 48 V output voltages.

The energy balance of a hybrid system given in Fig. 1 is the following:

$$W_C = W_W + W_{PV} + W_G - W_{Bl} - W_{GS}, \quad (3)$$

where

W_C – energy consumption by unit consumer, kWh/year;
W_W – energy production from wind generators, kWh/year;
W_{PV} – energy production from PV arrays, kWh/year;
W_{Gp} – purchased energy from grid, kWh/year;
W_{Bl} – energy losses in battery, kWh/year;
W_{Gs} – sold energy to grid, kWh/year.

A unit consumer's average demand is 1 kW, this means a 8760 kWh consumption per year. The capacity factors are correspondingly solar and wind devices CF_S=0.084 and CF_W=0.115. The capacity factors stay constant during the study, but capacities change. To cover losses in the storage equipment, wiring and inverter, we suggest to use enough wind generators and PV arrays to cover at least:

$$W_W + W_{PV} \rightarrow 10000 kWh/year. \quad (4)$$

It should be noted, that average productivity from renewable energy sources must be tightly tied with consumption in order to avoid extensive overproduction.

RESULTS AND DISCUSSIONS

To find the optimal configuration of wind-PV capacities without batteries, different combinations in diverse amounts of produced energy are calculated by the suggestion of the equation (4). The indicators used were wind and solar penetration levels L_W and L_{PV} accordingly, and relative energies W_{Gp} and W_{Gs} from the grid and supplied to the grid. The results are shown in Table1 and Fig. 4.

Table 1. Dependencies of energy indicators from share of solar energy in system.

Share of solar energy, W_{PV}, %	Energy from grid , W_{Gp}, %	Supplied to grid energy, W_{Gs}, %	Renewable fraction, W_R, %	Solar energy penetration, L_{PV}, %	Wind energy penetration, L_W, %
0	34	38	66.1	0	115
10	33	37	67	11.4	103
20	33	37	67.4	22.8	91.6
30	32	37	67.5	34.3	80.2
40	33	37	67.3	45.7	68.7
50	33	37	67	57.1	57.3
60	34	38	66.4	68.5	45.8
70	34	39	65.6	79.9	34.4
80	35	40	64.5	91.3	22.9
90	37	41	63	103	11.5
100	39	43	61.1	114	0

From Table 1can be seen that solar and wind penetration levels may become higher than 100%, this is due to the chosen conditions that were explained in equation 4.

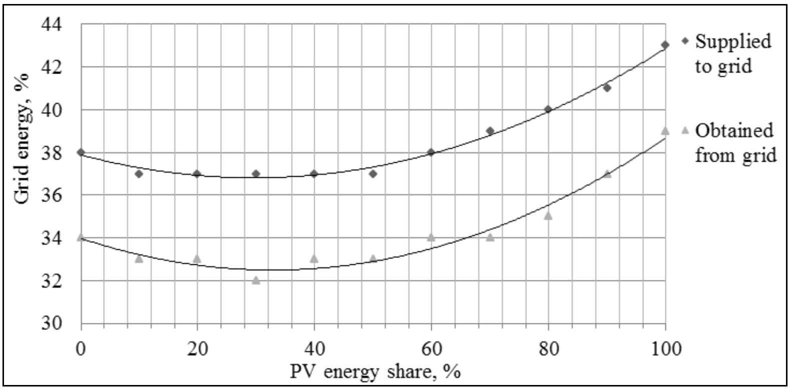

Fig. 4. Dependencies of grid obtained and supplied energy W_{Gp}, % and W_{Gs}, % accordingly to produced energy by different solar energy shares W_{PV}, %.

All relative indicators are given in proportion of the consumed energy 8760 kWh, except the renewable fraction W_R, which is calculated by using the following formula:

$$W_R = \frac{W_{PV} + W_W}{W_C + W_{Cp}} \tag{5}$$

We see that the energy sold to the grid exceeds the precentage of electricity purchaced from it. In case of minimal energy from the grid, energy produced from PV panels and wind generators has a ratio of 3/7 correspondingly. Using this ratio we have the best balancing possibilities (e.g. the highest share of renewable fraction W_R the highest shown in Table 1. This result is very close as in sources (Annuk, 2011; Caralis, 2011).

This ratio was now used in calculations, where batteries are included to decrease the amount of electricity from the grid. In order to do that, we must limit the capacities from the grid. In our calculations the following set of limited capacities for purchasing energy from the grid were in the range of 1-3 kW, by the step 0.5 kW. Due to the chosen battery configuration the series of storage amounts are in the range of 0-576 KWh by the step 9.6 kWh.

Table 2. Storage needs on different levels of limiting capacities for energy from grid

Limit capacity of energy from grid, P_P, kW	Storage capacity, W_{St}, kWh	Obtained energy from grid, W_{Gp}, %	Renewable fraction, W_R, %	Capacity shortage, W_{Sh}, %
3	0	32	68	0.46
	9.6	32	68	0
	19.2	32	68	0
2.5	0	31	68	1.92
	9.6	30	69	0
	19.2	30	70	0
2	0	31	69	5.57
	38.4	27	73	0.21
	48	26	74	0
	57.6	26	74	0
1.5	0	29	71	12.7
	67.2	21	79	1.4
	76.8	21	79	1.19
	86.4	21	79	0.99
1	0	25	75	25
	86.4	16	84	4.77
	480	13	87	1.13
	576	13	87	0.64

As we see in Table 2, adding storage capacities helps to increase the renewable fraction and decrease energy obtained from the grid. Limiting from-grid capacity without storage elements rises the capacity shortage rapidly.

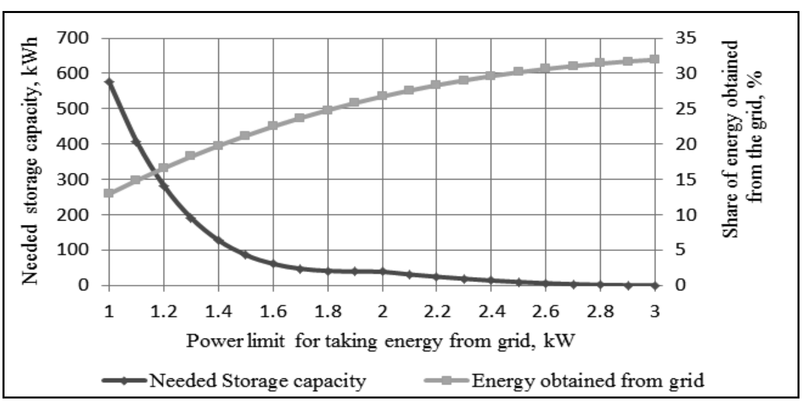

Fig. 5. Dependencies of limiting power from grid

Fig 5 shows the suggestion that when the capacity shortage is near zero $W_{Sh} \approx 1\%$, the used storage capacities amounts and share of obtained enegy from grid. In the case of limiting the capacity up to 1.6 kW, the needed storage capacity rises exponentially and it is not reasonable to use values above it. As a generalisation to the results given in Fig. 5 it is reasonable to limit the obtained capacity near the 1.6 kW treshold, then the needed storage capacity is 59 kWh and the share of energy from the grid is 23%.

CONCLUSIONS

In the example of a wind and PV panel system using a unit consumer with certain properties connected to grid, it is possible to find out the best possible electricity ratio, produced by wind and solar devices having the best balancing possibilities. The measure of the balancing possibilities is the amount of energy from the grid. Decreasing the amount of energy from the grid was the main goal of the study. Storage amounts have additional balancing properties. Storage amounts need to be minimized by minimizing the share of energy obtained from the grid and maximizing the renewable fraction.

The following generalizations can be made.

1. Nowadays PV-wind hybrid systems are used in two ways: autonomous and grid connected. It is important for a grid-connected system to minimize energy from the grid and to have the highest share of renewable fraction as possible, while having an optimal configuration and not using other fuels. It is important, since by doing so energy dependence is decreased and therefore energy security is increased.
2. Over dimensioning of a system is another issue to be observed. It is reasonable to limit the amount energy from installed capacities near the consumption energy taking into account the losses in devices. Rated capacities of devices are possible to be found according to climate conditions.
3. It is reasonable to use storage elements to increase the renewable fraction and decrease the amount of energy from the grid. In the case of a unit consumer it is reasonable to limit the capacity from the grid near the 1.6 kW threshold. In this case the system needs a storage amount of 59 kWh and the share of energy from the grid is lowest 23%. If the capacity from the grid is limited further, the amount of storage capacity needed will increase exponentially.

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