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Performance of wind-solar integrated grid connected energy system

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Abstract. In this work the system of wind generator and PV panel connected to the grid is discussed. The unit wind generator and indicative solar data converted to relative values were used. The ratio between energy amount going to the grid and produced energy was analysed for different energy demands in case of varying wind power levels and solar irradiation intensities. In case of produced and consumed in site yearly energy is equal, the amount of energy supplied to grid and consumed is approximately equal to 50% of energy production. With the increase of wind energy part, this ratio diminishes. Wind – PV panels' solution is most effective in case of energy selling to the grid at low demand periods. The possibility of Photovoltaic Geographical Information System (PVGIS) database application for solar data modelling was also analysed. For summer months the differences between the PVGIS database and measured data from Estonian Meteorological and Hydrological Institute (EMHI) do not exceed 5%, though in winter months it reaches 25%. But as on the latitude of Estonia the PV panels' energy production in winter is marginal compared to summer then its influence on the energy balance is very small.
Key words: wind power penetration, solar database, consumption factor

INTRODUCTION

It is possible to divide solar and wind energy production into large- and small-scale production units. Generally, in large-scale production the installed power is measured in megawatts and in case of small-scale production the power is limited by tens of kilowatts. In wind energy systems this grouping is also supported by standard 200 m^2 area of impeller´s circle corresponding to approximately 50 kW (Estonian Standard, 2006). The main problem in wind and solar energy production is stochastic character of output power. To compensate that, the close association with other power plants and/or storage systems is needed. By large-scale energy production the most reasonable is to use hydro-pumping power stations for electric energy accumulation whenever it is possible (Hamburg & Valdma, 2011). In most cases the fossil fuel or hydro power stations are used for that. The potential of hydro power plants is quite limited and do not allow to use for new wind generators. To balance the output power of small-scale wind and solar power plants the rechargeable batteries are used if the power units are autonomous. If the system is connected to the grid, the resources and demand of other producers may be used for balancing. The market for so-called peak-power is emerging, where the price of electrical energy may be several times higher than ordinary tariff (Kuhi-Thalfeldt & Valtin, 2011). For the grid-connected small-scale units the following principles should be used: the produced energy should be consumed in close vicinity; the energy output balancing should be performed locally, with minimum support of the grid; the appliances should be able to work as an energy island (Annuk et al., 2011). It is not yet possible nowadays to sell the electricity produced by small-scale wind and solar units to the energy grid in Estonia. The overproduced energy simply goes to the grid but the additional absent energy should be bought from the grid. The easiest solution today is to choose the nominal power of the wind and solar units to be equal to the minimum demand. But in this case the consumable capacity is marginal as minimal power demand is very small usually. It is important to investigate the influence of different configurations of wind and solar solutions on the quantities of energy sent to the grid and received from it, to be able to make decisions whether to sell the energy or to concentrate on the energy supply of the own consumers.

MATERIALS AND METHODS

Output power fluctuation of PV panels depends on solar radiation and is periodic by nature. The wind periodic component is comparatively week and exists only on summer near lakes and other water sources. There is no correlation between wind and solar power, e.g. according to year 2009 data the calculated correlation coefficients R^2 for inland and seashore in Estonia were 0.1886 and 0.1376, correspondingly. We may conclude that PV panels should have positive effect in balancing the small-scale wind generator output power. The calculations were performed using EMHI (Estonian Meteorological and Hydrological Institute) averaged hourly wind speed and global solar irradiation data (Tõravere, Harku, Tiirikoja) from year 2009.

The wind data was transposed to higher height (30 m) using Hellman equation with the coefficient k_H = 0.25 for seashore (Tomson & Annuk, 2005) and k_H = 0.29 for inland (Annuk & Tomson, 2005). Wind energy amount could be estimated on the basis of the wind generator power curve $P = f(v)$ where v is the average speed of wind for one hour time periods and P is the corresponding power output. In calculations we used the normalized power curve averaged from a group of typical small WTG-s. Normalized wind generator power curves could be described as (Annuk et al., 2008):

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

$$0 \prec v \prec 2.5 m/s \rightarrow P^* = 0 \qquad (1)$$

$$0 \le v \le 2.5 m/s \rightarrow P^* = 0.0078 \cdot v^2 - 0.0229 \cdot v + 0.00866022$$

$$v \succ 12 m/s \rightarrow P^* = const$$

where P_W^* – relative output power,

P_W – hourly average power output, kW

P_N – rated power, kW.

The radiation flow data of the Sun is usually presented as energy flow (flux) density in Wm^{-2} or Wh $m^{-2}day^{-1}$ on the horizontal plane. The real conditions at installation of PV panels are different. On the other hand, the available data is also presented not as energy flow density but as Global Solar Irradiation (*Q*), which is the sum of direct (*S´*) and diffuse (*D*) solar irradiation that is falling on the horizontal surface of the ground (Russak & Kallis, 2003). The solar radiation that passes through directly to the earth's surface is called Direct Solar Radiation. Diffuse Solar Radiation is the part of the solar radiation scattered by the atmosphere and travelling long way before reaching the surface. Scattering is strongly wavelength dependent: the short wavelengths of blue and violet light are strongly deflected, whereas the longer-wavelength red, orange, and yellow are largely unaffected. So, diffuse solar radiation has in general shorter wavelengths than direct radiation and its effect on PV panels is different. This radiation component is not monitored constantly. The relative roles of the direct and diffused radiation are different for each month, but in yearly average, almost the same. In the summer, the direct radiation prevails and in the winter months the diffused radiation part is more considerable as presented on Fig. 1.

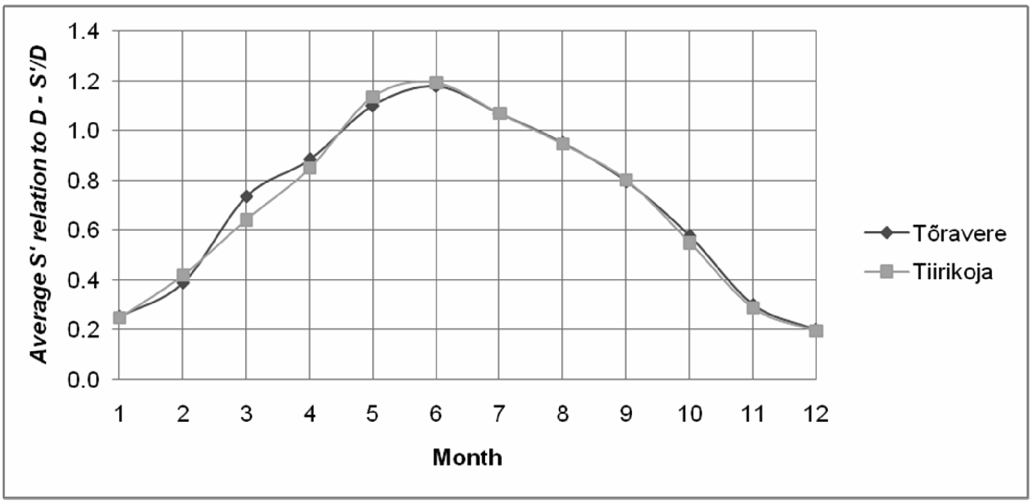

Figure 1. The mean ratio of direct (*S'*) to diffuse (*D*) radiation at Tõravere (1955–2000) and Tiirikoja (1975–2000) in different months.

The diffuse radiation depends on the sun elevation angle, air molecules in atmosphere, evaporation of water, propellants and ability of earth's surface to reflect light. Part of the direct sunlight is diffused on the way through the earth's atmosphere and therefore travelling a long way before reaching the earth's surface. Therefore, the prediction of the amount of diffused light is complicated and not straightforward.

To use global solar radiation (Q) data for later experiments we need to evaluate the different available sources. For this, we are comparing meteorological data from Estonian Meteorological and Hydrological Institute (EMHI) and Photovoltaic Geographical Information System (PVGIS) databases (Photovoltaic…, 2011). These two sources both give information of global solar radiation measurement results among others for two different locations in Estonia, Tõravere and Tiirikoja. The corresponding charts are presented on Figs 2 and 3. The global irradiation data ratio of EMHI and PVGIS is given as Ratio (R):

$$R = 100\% \left(\frac{Q_{EMHI}}{Q_{PVGIS}} - 1 \right) \tag{2}$$

where Q_{EMHI} – global irradiation data of one month from EMHI database,
Q_{PVGIS} – global irradiation data of one month from PVGIS database.

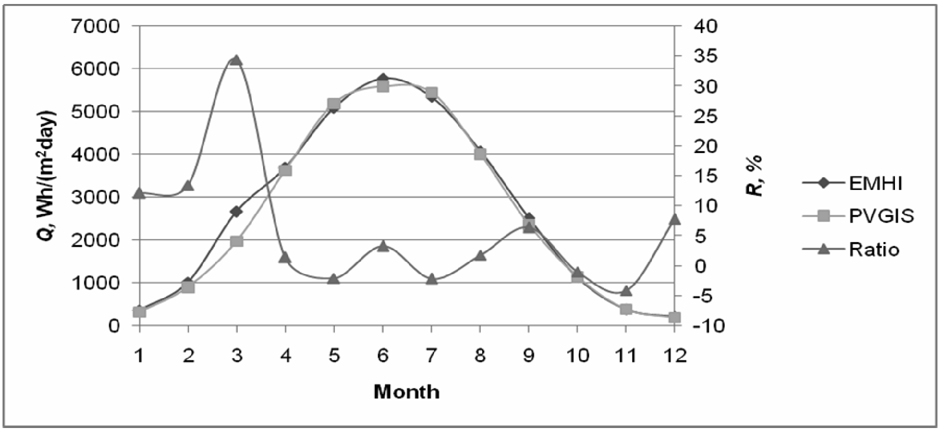

Figure 2. Ratio of global irradiation data for the location Tõravere of EMHI and PVGIS databases in 2009.

According to the figures, the global irradiation data is almost similar in the two different databases. The major dissimilarity is noticeable in winter months, with relative error up to 20% for Tõravere and up to 25% for Tiirikoja in March. The main reason for such high deviations is the diffuse light component in measurement results. Usually PVGIS uses measured irradiation data, but if the data has not been measured, the system makes generalizations and the values may vary. As the PVGIS gives lower values for global radiation in winter months, we can be sure that in future calculations we shall not overestimate the produced energy of the solar system. In summer months the difference of EMHI and PVGIS is less than 5%. Taking into account that a standard deviation (σ) in measurements is typically 5 to 10% (Russak & Kallis, 2003), we can conclude, that PVGIS method is good enough to use for long term measurement results in summer and in winter.

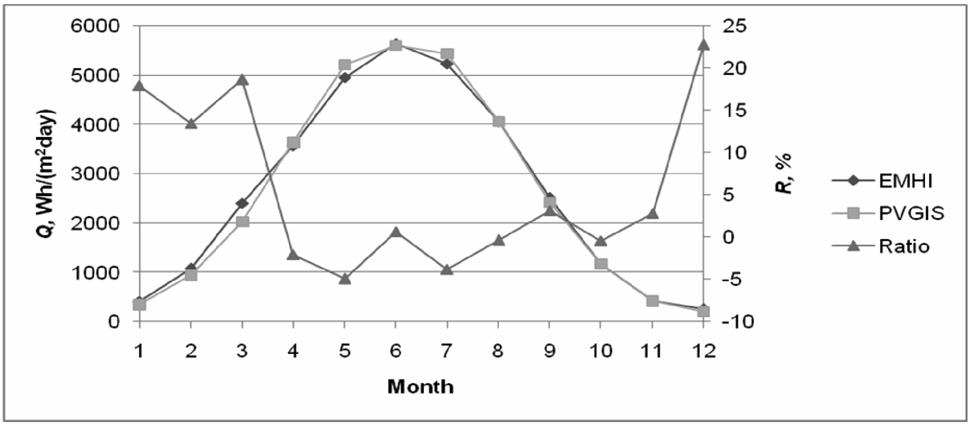

Figure 3. Ratio of global radiation data for the location Tiirikoja from EMHI and PVGIS databases in 2009.

In this work we do not discuss the properties of PV panels and their technical specifications, and look only at the global solar radiation (Q) relative data. To find the area of real PV panel the exact technical properties of the specific panel type should be taken into account (Friesen et al., 2007). The power output curve of the solar panel is very similar to the solar radiation curve with largest uncertainties in winter period on the latitude of Estonia. But this does not have very significant effect as the average monthly production of the PV panels from October to February is less than one fifths of the production in June, that is noticeable also on Figure 2 and 3 (Gottschalg et al., 2005).

As the solar radiation data includes before-mentioned uncertainties we may try to use these as an imitation of periodic energy source varying according to the time of the day and season of the year. The data can be transformed into relative units as follows:

$$P_S^* = \frac{P_S}{P_{S\max}} \rightarrow P_S^* = \{0...1\} \quad (3)$$

where P_S^* – relative output power,

P_S – hourly average radiation density, W/m^2

$P_{S\max}$ – maximum radiation density, W/m^2.

Sums together hourly average data of wind and sun, we get the resulting equation:

$$P_S^* + P_W^* = \{0...1\} \quad (4)$$

In this case the maximum power levels are equal, it means that wind power penetration level is L_W = 50%. In further analysis we can change that proportion. Similar method is used for interaction analysis of wind and wave energy solutions

(Stoutenberg et al., 2010). In data analysis process we change also the consumption factor β (Põder et al., 2009), that is the ratio of energy W_c supposedly consumed at the observation period and energy W_p produced at the same period:

$$\beta = \frac{W_C}{W_P} \tag{5}$$

The interaction analysis of wind and solar solutions on energy quantities supplied to the electric grid and received from it, is performed on the basis of Harku Meteorological Station data in 2009 as these are illustrating the good inland conditions most effectively.

RESULTS AND DISCUSSION

In Table 1 the grid-connected integrated wind and solar system´s parameters for different locations in Estonia are shown. The installed unit power of both wind and solar systems equals to one. The quantities of produced and consumed energy are equal. We can see that the solar irradiation maximum Q_{max} and the capacity factor k_s (Hamburg & Valdma, 2011; Annuk et al., 2010) of the PV panel are very similar at different locations. The capacity factor k_w of the wind generator strongly depends on the average

Table 1. Grid connected integrated wind and solar systems data in 2009.

Location	v, ms^{-1}	k_w	k_s	Q_{max}, Wm^{-2}	W_w, kWh	W_s, kWh	ΣW	W_{def}, %	W_w, %
Tõravere	3.3	0.045	0.130	968	396	1137	1533	52.6	25.8
Harku	4.0	0.087	0.127	936	757	1109	1866	49.7	40.6
Pakri	5.9	0.211	0.127	936	1846	1109	2955	42.3	62.5

wind speed v. Relative importance of the energy received from the grid W_{def} diminishes with the average wind speed v increase and in Pakri where the average wind speed v is best equals 42.3%, and the wind energy penetration level W_w is 62.5%. Though, in the southern parts Europe, the same process is just opposite (Tina et al., 2006).

For further estimation we use averaged hourly wind speed and global solar irradiation time-series data at Harku and Pakri from year 2009. On Fig. 4 the relative (to produced energy W_p) energy received from the grid W_{def} and the whole system capacity factor k are shown depending on L_w. We can see that at L_W levels of 0 and 1 the proportion of energy received from the grid W_{def} is the same though the capacity factors k are different. On this chart W_{def} is minimal when L_W = 70%.

On Fig. 5 the charts of energy supplied to (W_{over},%) and received from the grid (W_{def},%) for varying values of consumption factor β are shown. When the consumption factor is β = 1, the energy amounts supplied to and received from the grid are equal. We can see that it is more efficient to use wind – PV panels' solution in case of smaller energy capacity factor values and if possible, to sell the energy to the grid. In case of large values β of as 2 we have to consume from the grid as much energy, as the wind – PV panels system produces. As we see from Figure 5 increasing β energy supplied to (W_{over},%) grid diminishes to 0 and all energy received from grid.

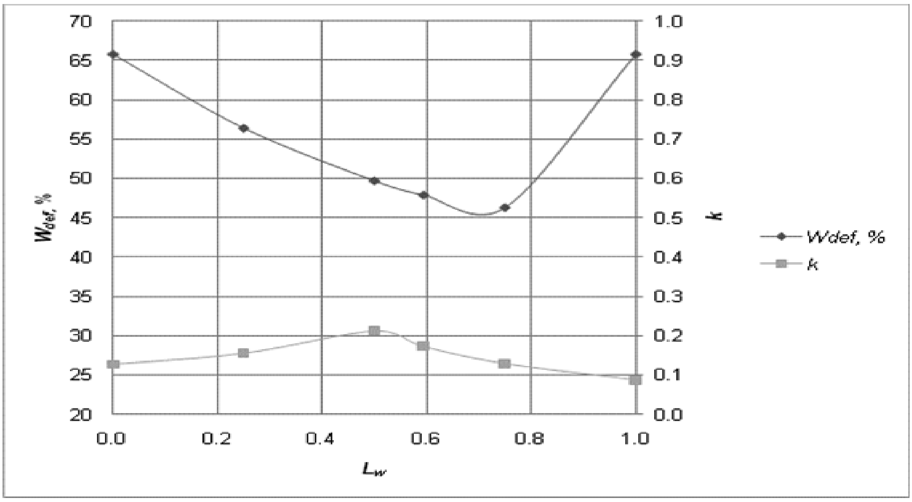

Figure 4. The capacity factor k and energy received from the grid W_{def} at different wind power penetration levels L_{W}.

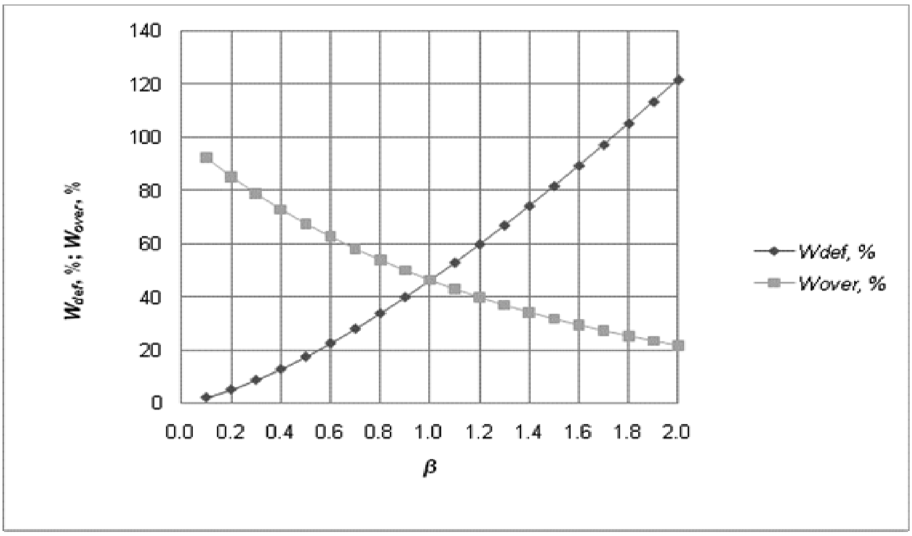

Figure 5. Energy supplied to and received from the grid for varying β values, accordingly W_{over},% and W_{def},%.

CONCLUSIONS

1. In case of the grid-connected wind – PV panels' solution without the storage system the amounts of energy supplied to and received from the grid are equal at the consumption factor β = 1, and correspond to approximately one halve of the produced energy.
2. The amount of energy supplied to and received from the grid diminishes with the increase of the wind energy relative part and in the observed cases is 42.3–52.6%.

3. The data from PVGIS database is applicable with little compromise for modelling of the solar radiation on our latitude. The global irradiation data ratio of EMHI and PVGIS is mostly less than 5% except winter months when it reaches 25%.
4. It is more efficient to use wind – PV panels' solution with smaller consumption factor β values and to sell the energy to the grid. In case of large values of β the amount of energy consumed from the grid may be as large as produced energy amount.
5. The results of this work are of indicative value and additional research is needed for different PV panels' installation angles and varying consumption power values for more durable observation period.
6. The grid-connected wind – PV panels' solution could include controllable consumer, such as heat accumulator, though that will increase the payback period.

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