CONFIGURATION OF INTEGRATED ENERGY SYSTEM ACCORDING TO PROBABILISTIC INFORMATION

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Abstract. The current article analyzes a system consisting of a small wind generator and PV panels with an electricity and heat storage system. We presume that the wind generator and the PV panels work jointly in autonomous mode. Systems of the given configuration are used mainly in remote sites or islands, where it is not economically reasonable to establish an electrical grid. The existing wind generator systems are mostly over-dimensioned to provide maximum energy supply reliability, hence their high cost as a rule. Wind and solar conditions are unique for any certain area. Nowadays it is possible to get climate data for a longer period due to which it is possible to rely on an analysis of real conditions. The longer the data row, the more true results it is possible to achieve. If 100 % reliability is aimed at, it will be necessary to guarantee certain capacity of electrical storage. Compromises in reliability might result in a decrease in electrical storage capacity, which will make the system cheaper. In our paper we have not targeted at an economic analysis; however, we will present a methodology for sizing and optimizing the components of a wind-PV energy system according to certain climate conditions.

Keywords: wind and PV energy, integrated energy system, energy supply probability, heat storage.

Introduction

Wind generators can be roughly divided into two: small and large wind generators according to their capacity [1]. In both cases balancing the stochastic effects of wind power may pose a problem. Cooperation with other energy creation installations and/or the presence of energy accumulation is of great importance. A consumer who has varying power can also assist to balancing power fluctuations. In most cases, other energy producers are not perfect while reacting quickly to fluctuating power. The best among these would be a hydroelectric plant, but this kind of resource is rarely available for small autonomous wind parks. Wearing down of fossil fuel power plants accelerates; moreover, expenses on fuel and emissions do not decrease proportionally with the balanced production. Gas turbine plants are mostly used to balance peak capacities, which is expensive. The choice of accumulation equipment for large and small scale wind energy is slightly different. It has proven expedient in large scale energy to use pumped storage hydro plants if location permits. Lead accumulators with a deep discharge cycle are the most common energy storage equipment in small scale wind energy. But it must be said that if the power amounts to tens of kilowatts, the necessary battery availability and cost of autonomous solutions are huge, reaching hundreds of kilowatt hours.

We have mostly envisioned the niche usage of small power wind generators (up to 50 kW) in places lacking electrical power systems; however, a trend is developing with small wind turbines which are installed switched into the network. On the other hand, when a small wind turbine is switched into the network, in most cases it has not been installed to produce energy only for sale; its main aim is to provide the local consumer with electrical energy and enhance power system reliability, as the economic effect of energy sale is insignificant. As a result of this, as much energy as possible should be utilised on site.

This system should be able to function as an energy island. Thus, the problems of both autonomous and switched solutions are rather similar. One independent energy source to mitigate wind power fluctuations could be solar energy. PV (photo voltaic) panels can be installed without restrictions; in addition, their maintenance costs, such as those of the wind generators are low. Their price is still high today, but we can expect a quick fall in price. In addition, the economic efficiency of PV panels is reduced by the low intensity of solar radiation in winter at the Nordic latitudes which significantly decreases the maximum energy performance coefficient of PV panels.

Materials and methods

In the current paper, we are analysing the need for accumulation capacities in case of wind generator-PV-panel cooperation at different reliability and consumption factors. Measuring data on wind speed and solar radiation over longer periods is available nowadays. If the wind speed of the measuring data can be derived into wind power density corresponding to the installation height of the wind generator, using the power curve of the generator [2], then in case of solar radiation the problem is more complicated. Solar radiation flow to the horizontal surface is recorded as total radiation. Total radiation mainly consists of two components: direct radiation and diffuse radiation. PV panels are usually inclined to the horizon at an angle and have a certain azimuth. Diffuse radiation has shorter wave length than direct radiation, which makes the effect of PV panels different. The indefinite alteration of diffuse radiation due to climatic factors and the position of PV panel pose a problem. The amount of diffuse radiation depends on the transparency of the atmosphere, the reflection coefficient of the ambient surface, and the position of the panel. The share of diffuse radiation at the Estonian latitudes is lower in summer and higher in winter; as an average annual, it forms approximately half of the total radiation balance [3]. There are data in the literature [4] which have considered also the share of diffuse radiation, but owing to the lack of corresponding measuring data this is not possible. The measuring data of PV panel output power [5] have also been used. This kind of data is usually not available over a longer period.

Studies indicate that even in good wind conditions which could guarantee a more or less serious security of supply, the necessary battery capacity per a 1 kW nominal power wind turbine exceeds 100 kWh; however, a quarter of the energy produced by the wind turbine must be converted into lower quality energy, such as heat [6]. The fluctuation of PV panel output power is periodical in a twenty-four hour period; still, the wind has a weak periodical component only in summer near water bodies. Wind and solar power densities are not in correlation. Based on the last year data, for instance, we have calculated the respective correlation coefficients $R^2 = 0.1886$ and $R^2 = 0.1376$ in Estonian mainland and coastal areas. Thus, the PV panels should have a positive impact on the balancing process of the output power of a small wind turbine. We have used hourly average wind speed and total solar radiation Q data on Pakri, obtained from EMHI (Estonian Meteorological and Hydrological Institute) in 2007-2009, as the source data.

The wind data were transposed to higher height value 30m using Hellman equation with the coefficient $k_H = 0.25$ for seashore [7] and $k_H = 0.29$ for inland [8]. 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 1 h time periods and P is the corresponding power output. In our calculations, we use the normalized power curve averaged from a group of typical small WTG-s. Normalised wind generator power curves could be described as [2]

$$P_W^* = \frac{P_W}{P_N} \rightarrow P^* = \{0\ldots1\}$$

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

$$2.5 \le v \le 12 \text{ m}\cdot\text{s}^{-1} \rightarrow P^* = 0.0078\cdot v^2 - 0.0229\cdot v + 0.00866022 \quad (1)$$

$$v > 12 \text{ m}\cdot\text{s}^{-1} \rightarrow P^* = \text{const},$$

where P_W^* – relative output power;

P_W – hourly average power output, kW;

P_N – rated power, kW.

As the solar radiation data include the aforementioned uncertainties of measurement, we use them as an imitation of a periodical energy source which changes according to time of day and season. We convert the data into relative units:

$$P_S^* = \frac{P_S}{P_{S\max}} \rightarrow P_S^* = \{0\ldots1\} \quad (2)$$

where P_S^* – relative output power;

P_S – hourly average radiation density, kW·m^{-2};

$P_{S\max}$ – maximum radiation density, kW·m^{-2}.

Adding up the hourly average simultaneous data on wind and solar, we get the following combined graph:

$$P_S^* + P_W^* = \{0...2\} \tag{3}$$

In this case we have equal maximum capacities, i.e., wind power penetration level L_W = 50 %. The average relative power is 0.34. While processing the data, we also change the energy consumption factor β [10]. If the energy consumption factor is $\beta = 1$, the produced and consumed energy during the given period are equal. In order to perform load imitation, we observe two cases, in which the consumption is homogeneous and the consumption follows the consumption curve of a real small farm.

The continuity of energy supply is estimated by the theory of reliability. Reliability is the probability that a device will perform its intended function during a specified period of time under stated conditions. Mathematically, this may be expressed as:

$$R(t)\,\Pr\{T > t\} = \int_t^{\infty} f(x)dx, \tag{4}$$

where $f(x)$ – failure probability density function;
t – length of the period of time.

For evaluating energy supply reliability we use value as availability of the integrated wind system, used for evaluating reliability of power stations [9]. The availability A of the integrated wind energy system is defined as follows:

$$A = ((T_a - T_l)/T_a), \tag{5}$$

where T_a – total hours of availability period;
T_l – total hours of outage due to energy lulls.

Nowadays automatically registered trustworthy wind data for longer periods are increasingly available. Therefore, it is possible to use wind time series data for evaluating the reliability of an integrated wind energy system and determining the capacities of the equipment. The longer the period, the more trustworthy the results of the analysis are. We use three year series data with the above mentioned properties.

We evaluate the system: wind generator, PV panel, consumer, electricity and heat storage. The heat storage is used as dump load for balancing energy flows. Therefore, the energy balance of the system in the three year period may be expressed as follows:

$$W_g = \beta \cdot W_c + W_h + W_l, \tag{6}$$

where W_g – energy produced by wind generator and PV panel;
β – energy consumption factor (0...1);
W_c – energy consumed for energy supply;
W_h – energy to heat storage (including other losses);
W_l – losses in electricity storage (efficiency of storage as 75 %).

In any moment the system must correspond to the following conditions:

$$P_{gi} = P_{c\,i} = P^*, \tag{7}$$

where P_{gi} – capacity from the wind generator + PV panel, any time point;
P_{ci} – consumed capacity by system of consumer and storages.

The consumer capacity P_c as a constant or averaged real consumption curve that can be expressed by the following expression:

$$P_c = \frac{\sum_{i=1}^{n} W_{gi}}{n}, \tag{8}$$

where W_{gi} – hourly amount of generated energy,

n – amount of hours.

In calculations we consider the following conditions:

$$W_s < \beta \sum_{i=1}^{n} W_{ci} ,$$

$$\text{if } W_s = 0, \text{ then } P_{ci} = 0; \text{ if } W_c > W_s, \text{ then } W_{hi} > 0, \quad (9)$$

where W_s – capacity of electricity storage.

The time interval, when $P_{ci} = 0$, is accounted as interruption time of energy supply.

Results and discussion

In our calculations we imitate two types of consumers, one with a constant load and another following the load curve of a real consumer. Figure 1 presents the weekly loads of a real consumer in summer and winter. By winter we meant the period from October to April and by summer the rest of the year.

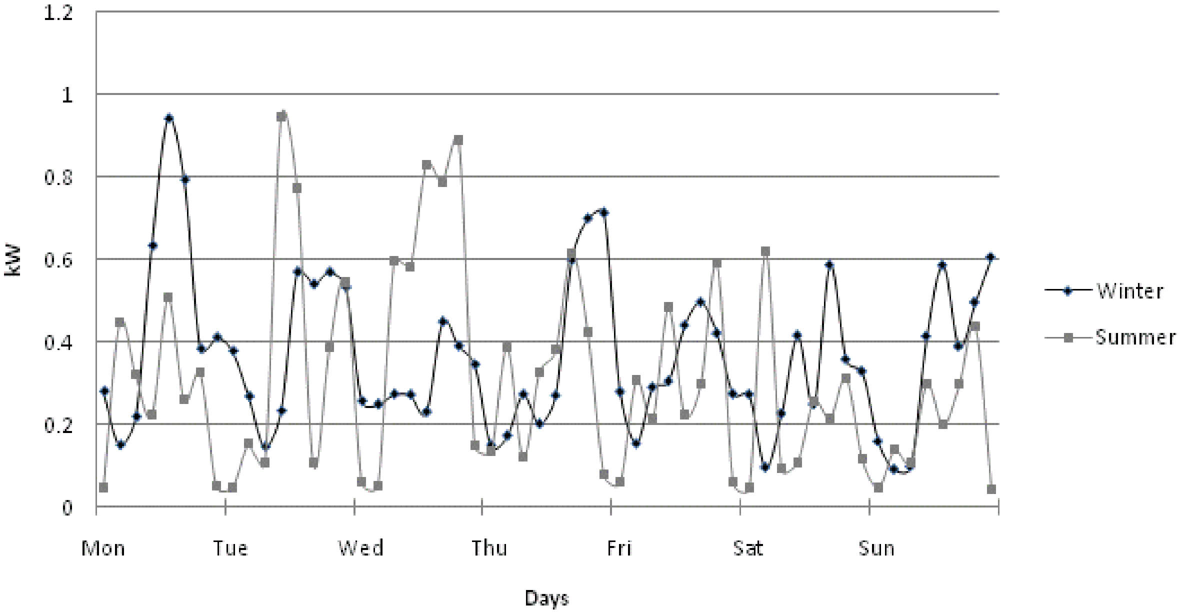

Fig. 1. **Weekly load curve of a real consumer in summer and winter**

For better illustration we calculated (Tab. 1) the ratio of heat energy to the total produced energy. Here it is clearly seen that the amount of heat energy depends on the consumption factor β and in the given case may exceed 25 % of the produced energy by $\beta = 0.75$. In the case of a real consumption curve, the necessary accumulator availability $A = 1$ and the consumption factor $\beta = 0.75$ are 1.5 times higher than in the case of a flat consumption curve; the difference decreases as A decreases and β increases (Figure 2).

The energy spent on heat does not change considerably when we compare the two consumer cases. If we compare the data with a situation where an analogous solution [6] functioned only with the wind generator and only a flat curve case was observed, the necessary accumulation availability has decreased by 45 % in the case of $\beta = 1$ and $A = 1$ (Figure 3). Although the given source for the observation period is five years, the previous calculations indicate that in the case of a 3 and 5 year period the accumulation reliability is the same, however, lower in a 1 year period.

Table 1

Dependencies on availability A to capacity of electricity storage and heat energy amount during a three year evaluation period by flat and real consumption curves

Availability A	Storage capacity W_s, kWh				To heat W_h, kWh (%)			
	Flat curve		Real curve		Flat curve		Real curve	
	β = 1	β =0.75	β = 1	β = 0.75	β = 1	β = 0.75	β = 1	β =0.75
0.95	172	50	232	65	620.4 (7.0)	2586.1 (29.2)	707.0 (8.0)	2650.2 (29.9)
0.96	190	58	263	73	552.4 (6.2)	2529.6 (28.5)	599.2 (6.8)	2594.6 (29.3)
0.97	222	66	301	82	456.8 (5.2)	2473.8 (27.9)	485.2 (5.5)	2533.1 (28.6)
0.98	255	75	337	97	357.4 (4.0)	2411.0 (27.2)	377.3 (4.3)	2468.0 (27.8)
0.99	288	83	374	113	258.6 (2.9)	2355.5 (26.6)	266.2 (3.0)	2400.2 (27.1)
1.00	323	94	408	144	157.9 (1.8)	2298.8 (25.9)	165.1 (1.9)	2310.1 (26.1)

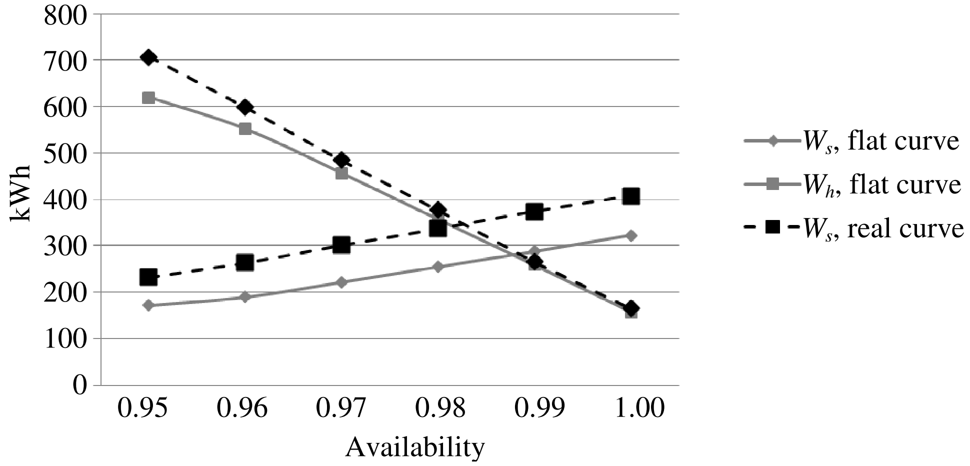

Fig. 2. **Necessary storage capacity and heat energy according to availability, when β = 1 wind+solar solution by flat and real consumption curves**

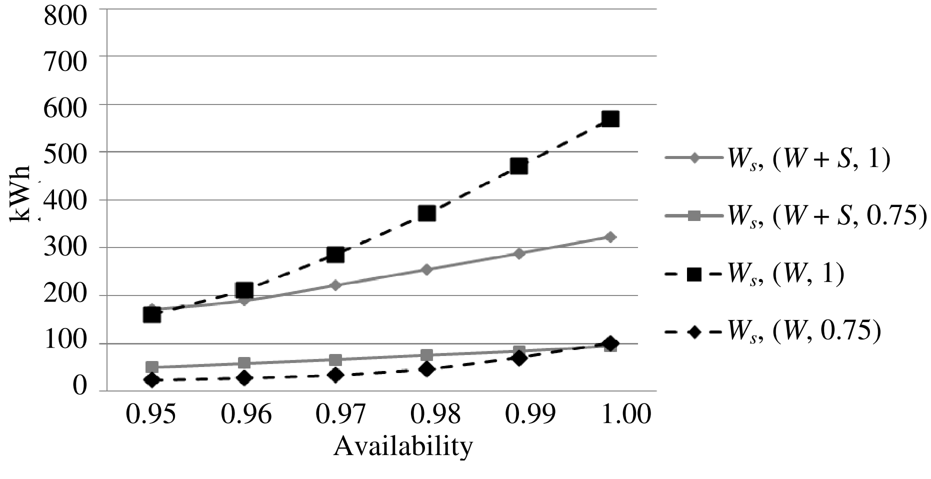

Fig. 3. **Necessary accumulation availability W_s by different consumption factors β = 0.75 and β = 1.0 in case of two solutions: only wind (*W*) and wind+solar (*W*+*S*)**

From Fig. 2 and 3 it can be seen that the necessary storage capacity is in inverse correlation with the amount of heat energy. Keeping both values to the minimum is essential. But finding the minimum of storage capacity is primary, as storages are expensive and of a relatively short working age. It is possible to get heat energy by cheaper methods than using the current configuration of a wind generator system, thus excessive heat energy amount decreases the economy efficiency of the system by expanding equipment capacities. From the graphs it is seen that decreasing the consumption factor increases the availability influence about values near 1 to values of the storage capacity.

Conclusions

1. Compared to the flat consumption curve, the need for accumulation appliances increases in case of wind+solar solutions approximately by one third if we have a real consumption graph with the consumption factor $\beta = 1.0$. When the consumption factor β decreases to 0.75, the difference grows by 1.5 times. This fact indicates that the shape of the consumption curve affects the capacitance of the accumulation equipment; consequently, when changing the shape of the consumption curve, it is possible to change the accumulation equipment capacity.
2. If a solar energy source is added to the wind power solution, it will decrease the accumulation equipment capacity up to 45 % in a situation when $A = 1.0$ and $\beta = 1.0$. But in the case of lower A values, the need for accumulation equipment capacitances relating to wind+solar solution is higher than while using solely wind power. The major impact is made by reduction of β, as a result of which the need for accumulation equipment in case of wind+solar solution may even be twice as high as in case of only wind power solution on conditions $A = 0.95$ and $\beta = 0.75$. The use of the wind+solar solution is justified at the consumption factors and availability close to 1.
3. The given evaluation is a methodological survey of the options for the choice of a storage device capacity, which has currently become possible due to reliable wind speed and solar data available for longer periods. The longer the time series data period, the higher the reliability of calculations.
4. Even with relatively high average wind speeds and adding solar energy source the necessary values of storage capacities proved to be very high. In the given example, when the average capacity consumed given per unit generators solution wind+solar is 0.34 kW, the value of the necessary storage capacities in favourable conditions is over 100 kWh. If we need to provide a bigger consumer with energy supply of reasonable reliability, we multiply the capacity of a unit generator by the necessary coefficient. The value of the storage capacity will change accordingly.
5. The storage capacity needs decreases quickly if the reliability of supply is reduced, and could even be around two times with the value of availability 0.95. The question arises if the consumer agrees to have such long power interruption periods (annually 438 h). By availability level 0.99 it is 0.7 times smaller, which means 87.6 h of energy supply interruption a year.
6. The given methodology enables us to add energy producers, consumers and storage equipments to the system in order to study the influence on the necessary value of the storage capacity or the amount of heat energy.

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