Wind & Photovoltaic Hybrid Energy System Design on the Basis of Standard Workload Graphs of Estonian Small Consumers

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***Abstract*— This article investigates the use of standard workload chart factors of the Estonian Utility Grid to determine the optimal design of a Wind and PV hybrid system design for a small consumer. Different natural conditions are considered for the designs and real measured consumer data was used to control the designs.**

I. Introduction

Raising energy prices, public awareness, availability of technologies and subsidies is causing the usage of renewable energy sources to become more feasible. Renewable energy solutions are commonly distributed geographically. In the concept of distributed energy solutions the local generation and demand should be in balance and therefore it is preferable to consume as much energy as possible on-site. The problem with the planning of a micro generation solution, where the producer should have the best conformity with the consumer, is not only that the total consumption is required, it is also necessary to know the specific characteristics of the consumption distribution in time. This hourly consumption data is often not available.

The hourly consumption distribution factors [1][2] (standard workload factors) that are used by power companies to estimate the characteristics of consumers that do not have hour-based remote reading systems, could be used. On the basis of those factors, that reflect the amount of electricity consumed by the customer in each calendar month by the hour, the data for the design of renewable energy solutions could be derived. The necessary parameter to know is the annual electricity demand from where the probable values of each of the 8760 hours in a year could be calculated.

Unlike other commodities, electricity cannot be stored efficiently. Therefore, delicate balance must be maintained between the generation and consumption for 8760 hours a year [3]. To restrain fluctuations the optimal combination of wind and solar applications should be used to utilize their compensating property to each other and a certain amount of batteries should be added to the system.

II. Material and Methods

A. Consumer

The definition of a small consumer in this case is a household or business that has a main fuse of 63A or less, has no electrical heating and a maximal annual consumption of 4000 kWh or less [1]. From this definition the maximal annual consumtion value is used in the simulations. grid. The assumed monthly consumption distribution can be seen on Fig 1.

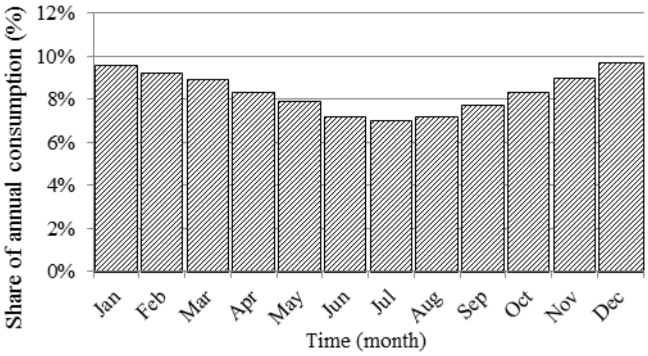

Fig. 1. Standard monthly proportions of annual consumption [1].

To calculate the hourly consumption estimated by the standard workloads, the following equation was used,

$$P_{i,}\, j = Wa \cdot Fm_j \cdot Fh_{i,j}\,, \quad (1)$$

where:

$P_{i,n}$ – The average consumption power of the i-th hour of the j-th month, kW;

Wa – the annual energy consumption, kWh/a;

Fm_j – the consumption factor of the j-th month in a year [1];

$Fh_{i,j}$ – the hourly consumption factor of the i-th hour of the j-th month [4].

An one week long fragment of the results that represent the consumption can be seen on Fig. 2.

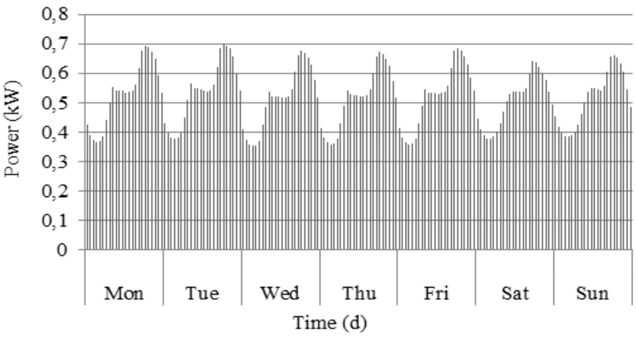

Fig. 2. Calculated winter week load curve on the basis of the standard consumer chart factors.

As can be seen from Fig. 2, the workload graph is smoother than the characteristic of a real consumer. For example the peak loads of a real household consumer (Fig. 3), are higher than 0,7 kW and the consumption is more fluctuating.

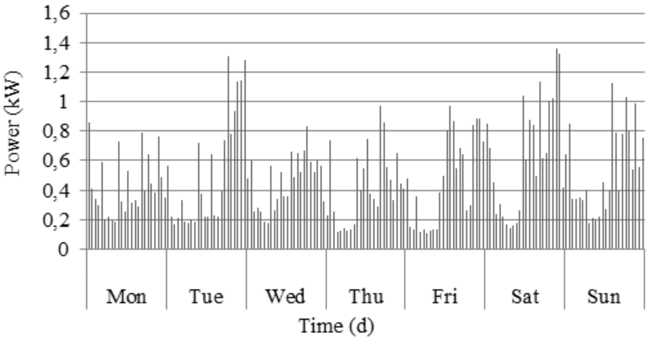

Fig. 3. Measured winter week load curve of a 4000kWh/a household electricity consumer.

The relative smoothness of the standard workload graph (Fig. 2) in comparison to the real consumers' load curve (Fig 3) is due to the usage of averaged data for the compilation of the factors and because of the fact that the power companies take into account the consumption simultaneity factors.

B. System Design

A grid-connected integrated renewable system consisting of a consumer, wind generators, PV panels, a DC/AC inverter and batteries was simulated for the synthetic consumer described in the previous chapter. The results were controlled by implementing the same calculations with the data of a real measured consumer.

The generation and storage units have DC outputs and are connected to the load and grid by converter as can be seen in Fig. 4.

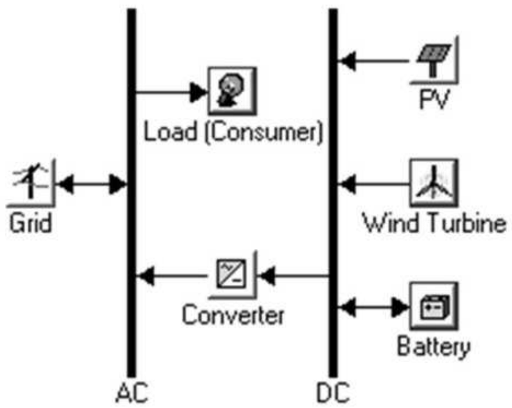

Fig. 4. Simulation setup diagram [5].

To determine the optimal design of a Wind and PV hybrid system design for a small consumer the wind generator and solar array nominal capacities were analyzed with a 1 kW step. The goal of the system design is to acieve an optimal energy balance, ignoring financial aspects [5]. A constraint was set to produce at least 80% of renewable energy in the total energy balance. The missing share is obtained from the grid. Another assumption was to have at least 1 kW nominal capacity of both energy generation technologies. This constraint was made to enable the analysis of the compensating property of each resource to the other.

Batteries were considered in the system to use most of the on-site generated renewable energy. A system without batteries generates also more disorders in the main grid. Sealed deep-cycle lead-acid batteries with minimal state of charge SOC = 40% and the capacity of 200 Ah are used as storage devices. The total battery capacity of the system is chosen to be 9,6 kWh in the calculations. Batteries are connected to strings by 24 pieces, with 48 V output voltages in total [7].

C. Wind Resource

In the simulations the average the wind speed is taken as the main variable to estimate different hybrid system setups for consumers in different locations.

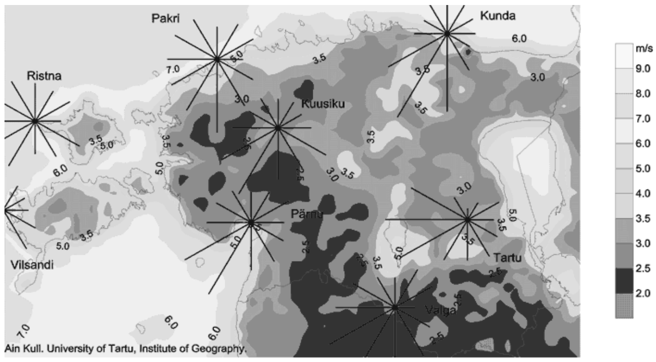

Fig. 5. Average Wind speeds in Estonia [8].

In Estonia the yearly average wind speeds (Fig. 5) range from 2,7 m/s to 6,6 m/s [8]. To determine the system desings for the different wind conditions the data was scaled to different annual averages with a step of 1 m/s. In the calculations average wind speed steps were considered ranging from 2 m/s to 7 m/s. The wind speed data used in the modeling process was measured in Tõravere in 2010 (Fig. 6).

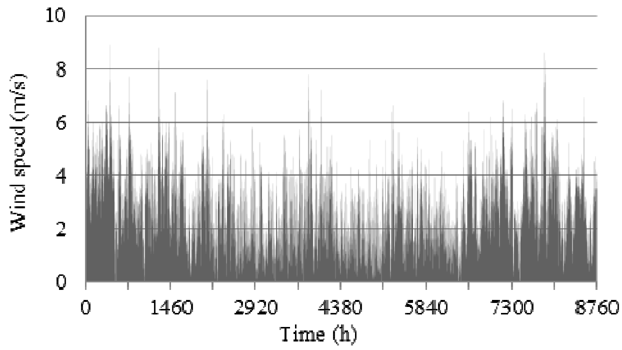

Fig. 6. Hourly wind speed data in location Tõravere, 2010 [9].

The power curve (2) of the normalized wind generator is averaged from several wind turbines that are most suitable for mild 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*. The wind generator power curve is the following [10]:

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

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

D. Solar Resource

The annual solar irradiation does not differ much throughout Estonia, the annual actinometrical resource can vary up to 5,5% (890 kWh/m^2/a to 990 kWh/m^2/a) [13].

Therefore the same solar irradiation data was considered for all of the system setups utilized for evaluating the influence of wind speeds. The irradiation data from a location with a moderate value (Tõravere) was chosen. The irradiation is typically better in locations where also the wind speed is greater and vice versa, so as the critical parameter is taken the average wind speed that has a greater variety in the borders of the country. There is a positive correlation in Estonia between the average wind speeds and the solar conditions, this is due the proximity of the coast [13].

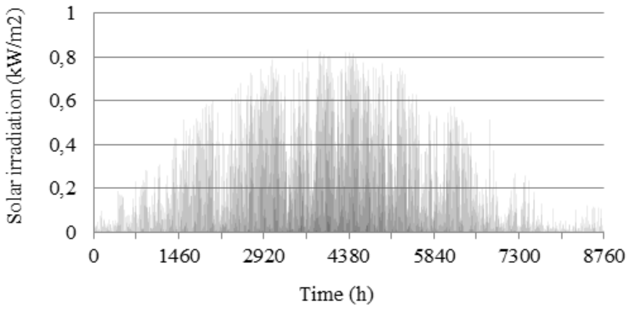

Fig.7. Solar irradiation data in Tõravere 2010 [9].

As the solar panel inclination was taken 45 degrees on the basis of a Canadian case study in a similar latitude as in Estonia [14].

To calculate the output of the PV panel the following equation was used [6],

$$P_{PV} = Y_{PV}\, f_{PV} \frac{G_T}{G_{T,STC}} \left[1+\alpha_p (T_c - T_{c,STC})\right], \quad (3)$$

where

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

f_{PV} – the PV degrading factor, %;

G_T – the solar irradiation incident on the PV array in the current time step, kW/m^2;

$G_{S,STC}$ – the incident radiation at standard test conditions, 1 kW/m^2,

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

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

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

It is prefered to utilize maximally the locally produced renewable energy by the consumer itself. The batteries are installed to balance the dicrepancies of production and consumption. In time steps when the state of charge of the batteries is not suitable to receive or deliver energy the system feeds the excess to the main grid or obtains the deficit from it. The share of renewable energy (renewable fraction) from the total amount of energy obtained is calculated by using the following formula [6]:

$$f_{ren} = \frac{W_{PV} + W_W}{W_{Gp} + W_{PV} + W_W}, \quad (4)$$

where:

f_{ren} – Renewable fraction, %;

W_{PV} – energy received by the consumer from PV arrays, kWh/year;

W_W – energy received by the consumer from wind generators, kWh/year;

W_{Gp} – energy purchased from grid, kWh/year.

The energy balance of a hybrid system given in Fig. 4 is the following [6]:

$$W_W + W_{PV} + W_{Gp} = W_C + W_{Bl} + W_{Il} + W_{Gf}, \quad (5)$$

where

W_C – energy consumption by consumer, kWh/year;

W_{Bl} – energy losses in batteries, kWh/year;

W_{Il} – energy losses in the inverter, kWh/year;

W_{Gf} – energy fed to the grid, kWh/year.

III. Results and Discussions

The system designs that are calculated on the basis of the natural conditions described above can be seen for the standard load curve in Table I and for the real consumer in Table II. By comparing the tables can be seen that the found designs are the same under the respective conditions but the renewable fraction is up to 1,5% lower with the real consumer. That shows that the greater diurnal fluctuations have an influence on the system performance but it is insignificant. The battery bank contributes to leveling of the diurnal fluctuations and reduces the energy exchange with the grid.

TABLE I
System Structures on the Basis of Synthetic Consumer Data

Aver-age wind speed (m/s)	Wind generator		Photovoltaic array		Grid		Renewable fraction
	Capacity (kW)	Annual energy production (kWh)	Capacity (kW)	Annual energy production (kWh)	Annual energy obtained (kWh)	Excess supplied to grid (kWh)	%
2	1	171	7	5938	1406	3042	81.3
3	4	2337	3	2545	1162	1560	80.8
4	3	4123	2	1697	944	2253	86.0
5	2	4519	1	848	951	1829	85.0
6	2	6122	1	848	549	2962	92.7
7	1	3675	1	848	710	723	86.4

TABLE II
SYSTEM STRUCTURES ON THE BASIS OF REAL CONSUMER DATA

Average wind speed (m/s)	Wind generator		Photovoltaic array		Grid		Renewable fraction
	Capacity (kW)	Annual energy production (kWh)	Capacity (kW)	Annual energy production (kWh)	Annual energy obtained (kWh)	Excess supplied to grid (kWh)	%
2	1	171	7	5938	1481	3151	80.5
3	4	2337	3	2545	1238	1915	80.6
4	3	4123	2	1697	1063	2395	84.6
5	2	4519	1	848	1056	1949	83.6
6	2	6122	1	848	636	3042	91.6
7	1	3675	1	848	802	799	84.9

The influence of the consumer chart deviation and battery bank capacity can be found in [7]. It has to be considered that in cases where the real consumer load is extremely fluctuating the optimal system design can differ from the design resulting from the synthetic data. One indicator for this is, that the grid purchases and excess electricity shares are bigger in the simulations with the data of the real consumer because of the more frequent and extensive fluctuations in the consumption.

For the specific location where the weather data originates a system with a 4 kW wind turbine and a 3 kW photovoltaic array was found as the most suitable solution for this kind of consumer chart. The typical size for a grid connected renewable micro producer in Estonia is 11kW, because of the 3x16A main circuit breaker that is set as threshold capacity for small private producers to connect to the grid with simplified requirements[15]. For the consumer type handled in this article this capacity is more than needed.

Since this type of consumer load curve is also applicable for apartment buildings and the individual flats in them [1], this approach could be used when establishing Energy Cooperatives. Whereby the respective capacities mentioned above could be multiplied with the number of individual consumers to get an estimation how much installed capacity such a cooperative would need to be self-sufficient.

The methodology could find use in cases where the renewable energy solution is designed together with planning of a new building and therefore no real data is available.

IV. CONCLUSIONS

The standard workload graphs where used to estimate a hybrid energy system design. A consumer with the annual power consumption of 4000 kWh was used for analysing the system. The unit consumer chart was created by combining daily and monthly shares that are representant for the household and small business consumers in Estonia. The most representative wind and solar data was used to finde the needed nominal capacities to cover the energy demand.

Control calculations where made with a real measured consumer. Though the real consumer is more fluctuating than the consumption estimated with the standard workload graph, the proposed system designs are in the analysed cases the same. The methology used in this research can be used for the development of real wind-PV systems connected to the grid. The most changing variable for these applications in different locations in the borders of Estonia is the average wind speed. The optimal nominal power of the energy producers itself are dependent on the location of the system because the wind conditions differ strongly in the borders of Estonia.

In unfavorable weather conditions the share of excess electricity raises because if it is desired to cover the same annual consumption then more capacity needs to be installed. This greater capacity in turn creates for short time periods more production, a part of this cannot be consumed or stored.

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