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Sizing of an Islanded Wind-Solar-Battery Hybrid Power System for a Zero-Energy House in Afyon Turkey

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Abstract- Renewable energy systems offer sustainable solutions for the energy need of the world. Hybrid systems can be an alternative for remote off-grid houses that do not have connection to the electricity grid. This study examines sizing of an islanded wind-solar-battery power system for a zero-energy house that does not have a grid connection in Afyon Turkey. For this remote house, continuous power supply is an essential requirement and the designed system must guarantee reliable uninterrupted supply of power to the house. In an off-grid wind-solar-battery hybrid system, if different rated wind turbines and/or different number of solar panels are used in the system, the minimum number of batteries needed in the hybrid system would be different in order the meet the uninterrupted continuous power supply requirement. In practice it is the usual case that, due to incompatible hybrid system components the consumers suffer from no electric power occasionally. In this study, using power consumption data of the considered remote house and actual wind and solar measurement data of Afyon site, sizing analysis for a hybrid wind-solar-battery power system is done. For a sizing analysis, calculations that use actual small-time interval data are essential to ensure uninterrupted continuous power from a hybrid system.

Keywords Wind solar hybrid power system, isolated stand-alone system, off grid remote application, sizing hybrid power system, power reliability

1. Introduction

Today as people's concerns regarding the potential consequences of global warming and climate change increase, there is an increased awareness for supporting and using renewable energy sources. Among many renewable energy sources most probably solar and wind energy getting the most public attention all around the world. Aside being abundant, the wind and solar energy do not pollute the environment, reduce emissions of greenhouse gases and contribute to sustainable development. While the use of solar and wind energy for large scale power generation increases all around the world through the use of large wind turbines and solar array farms, distributed or isolated small to medium scale residential microgeneration also increases. With increased incentives and advantageous electric feed-in tariffs, on-grid residential microgeneration with net metering increases in residential consumers. In remote areas for houses which are far away from the central electricity network, off-grid residential microgeneration offers a solution for the energy demand, since connecting the houses to the central electricity network is usually economically unjustifiable. Sustainable reliability of power supply is important in most stand-alone off-grid systems. Even though solar and wind are inexhaustible and affordable energy sources while they are intermittent therefore highly unpredictable, they also vary greatly according to geographic location and local climate. Since climatic conditions are always changing in time, energy systems that depend on solely a single energy sources have the disadvantage of not being capable of meeting the demand. Hybrid application systems that include energy generation equipment which uses different renewable energy sources and electrical energy storage systems usually diminish unwanted instability of each single energy sources.

Stand-alone hybrid systems that include a wind turbine, photovoltaic solar panels and energy storage batteries are used by numerous isolated applications worldwide. For example, these systems are used in telecommunication stations, road lightings and signals, water supply systems and etc. as well as in isolated remote houses. Hybrid systems are combinations of different components and each different combination exhibits different technical and economical characteristics. Also, the output of these different components strictly depends on the local climatic conditions, such as solar irradiance, air temperature, wind speed and etc. A hybrid power system should be analyzed and designed according to the local solar and wind characteristics for better utilization of the whole system.

In the literature it is possible to find many studies on analysis of off-grid renewable hybrid energy systems that contains a wind turbine, photovoltaic panels for power generation and batteries for energy storage for different geographic locations of the world. As for example studies from the literature that consider wind/solar/battery hybrid systems, Kose *et al.* [1] investigated a renewable hybrid power system for pumping applications for agricultural irrigation in Konya Turkey. Alvarez *et al.* [2] simulated a hybrid system for electric power generation in the locality of Molleturo in Ecuador. Using a MATLAB/SIMULINK simulation, Rajini *et al.* [3] presented the performance of a hybrid system to be used in Chennai district in the Indian state of Tamilnadu. Maouedj *et al.* [4] presented a hybrid power system to power a small remote house in Adrar Region in Algeria based on solar radiation and wind speed measurement data. Vieira *et al.* [5] investigated the performance of a standalone hybrid system to supply power to a reverse osmosis (RO) desalination unit to be used in a rural or remote region in Brazil. Ronad *et al.* [6] investigated the optimal cost analysis of hybrid systems to power irrigation pumps installed in Energy Park, Basaveshwar Engineering College (Autonomous), Bagalkot, India. Zhang *et al.* [7] investigated the optimal sizing of stand-alone hybrid systems for remote area in Davarzan, Khorasan in northeastern Iran. Icaza *et al.* [8] modelled and simulated a hybrid energy conversion system for the Hill Curiquinga of Quingeo in Ecuador and also compared the results with the experimental data of the site. Sinha *et al.* [9] studied optimum configurations of a hybrid system for a low windy locations in Western Himalayan region of India. Ioakimidis *et al.* [10] presented an analysis for energy needs of the small Spanish village of Uruena. Anoune *et al.* [11] analyzed analytically and also experimentally a hybrid system in the campus of International University of Rabat, Morocco. Gursoy *et al.* [12] investigated the optimal sizing of an off-grid hybrid system for a remote area in Texas USA based on meteorological data. Paragond *et al.* [13] designed and simulated an isolated hybrid system using the realistic data obtained from the Innovation Centre, Manipal Institute of Technology Manipal in India. Merzic *et al.* [14] analyzed the sustainable supply of power to a tourist center in Rostovo in Bosnia and Herzegovina using hybrid power systems. Grgić *et al.* [15] presented a hybrid generation system for autonomous load supply that will ensure reliable and stable electricity supply and also an MPPT algorithm that will ensure stable system operation. Tutkun *et al.* [16] investigated the daily cost minimization for an off-grid renewable microhybrid system installed to a residential home in Turkey. Saidi *et al.* [17] proposed a new energy management strategy based on Fuzzy Logic to optimize the power flow in a standalone hybrid power generated system and simulated the hybrid system using real meteorological data detected in Adrar region Algeria. Vazquez *et al.* [18] developed a wi-fi monitored and controlled IoT-based hybrid power generation system for constant power supply for remote or rural areas. Icaza *et al.* [19] investigated the usefulness of a hybrid system for lightning of a Christmas tree and crib located in the city of Cuenca in Ecuador. Mercado *et al.* [20] used a Genetic Algorithm to optimally size a hybrid renewable energy system using the climate data and load data from Barranquilla, Colombia. For a brief review on stand-alone hybrid wind-solar power generation systems with battery storage, the reader is referred to the following review papers [21][22].

Especially, if the reliability of the power or in other words uninterrupted continuous power is an essential requirement in a hybrid system, then the size of each component in the hybrid system should be chosen considering the whole hybrid system to satisfy the load demand on the basis of power reliability. Different combinations of the hybrid system components with different sizes can be a hybrid system solution for the house that can satisfy the requirements. Therefore, configuring the hybrid system itself is actually an optimization problem that depends on the requirements of the specific project and the resources that are available in the considered geographic location.

This study examines the sizing of an islanded wind-solar-battery hybrid power system for an off-grid house in Afyon Turkey that do not have a connection to the electricity grid. With assuming that the life expectancy of small wind turbines is about 20 years, for this house it is required that the hybrid system should strictly be able to supply the consumption of the house uninterruptedly for 20. In the market it is possible to find many different brand wind turbines that have different power curves, many photovoltaic solar panels with different electrical specifications and also many batteries with different technical specifications. In an off-grid hybrid system for every different chosen wind turbine model and for every chosen different number of solar panels, a different number of batteries is required in the system in order to satisfy the continuous uninterrupted power supply requirement. In the practice it is the common case that after doing a rough estimation of power production and consumption based on long-term (i.e. yearly) averages, the components of the hybrid systems are chosen smaller than necessary such that the consumer suffers from not getting enough power from the system occasionally. The chosen hybrid system components based on long time averages cannot guarantee instantaneous power at any time. Only a study that takes into consideration of power balance for small time intervals can guarantee instantaneous power at any time [23]. In this study, for an off-grid zero energy house in Afyon Turkey, a hybrid power system that includes a wind turbine, solar panels and batteries will be sized. We base our analysis on actual 10-minute averaged measured wind and solar data for power production as well as on actual 10-minute averaged measured power consumption data of the house. It is strictly required that the chosen hybrid system should be able to supply uninterrupted continuous power at all times. We note that among many different combinations for hybrid system that may ensure reliability requirement of the demand power, the one with the lowest cost would be the optimum combination. Since hybrid system components have different prices in different countries, it might be misleading to consider the cost of different systems, thus our analysis will not include a price analysis

2. Methodology and Calculations

2.1. Site Information and Hybrid System Components

The considered remote off-grid house is located in Afyon city in Turkey and Fig. 1 shows the location of the house on the map. In this study the used solar and wind data comes from a 12-meter wind-solar measurement tower near by the house. The measurement tower has a wind speed anemometer, a wind direction vane, a temperature sensor, a barometric pressure sensor, a relative humidity sensor and also a solar pyranometer. At every 10 minutes, the data logger records 10-minute averaged sensor data together with minimum and maximum data and also standard deviation. The solar power potential in Afyon city is good with high solar irradiance together with rather low temperature [24]. The yearly average of our measured solar irradiance data is 209.1 W/m^2 with an average temperature of 13.2 °C which shows a good potential for a solar power investment. However, the wind potential of Afyon city is rather low. The yearly average of our measured wind speed is 4.1 m/s. We also note that the humidity in Afyon is high with a yearly average relative humidity of 55%.

Fig. 1. Location of Afyon on the map.

The schematics of the considered wind-solar-battery system for the grid-isolated remote house in Afyon is given in Fig. 2. The array of solar panels in the off-grid system generates DC electricity. The array of solar panels is connected to a controller which charges the battery bank. We consider that the solar charge controller has 95% efficiency which is an average efficiency for solar charge controllers in the market. In the system there is also a small wind turbine. Usually small wind turbines generate three phase AC electricity with voltage and frequency that changes with the RPM of the wind turbine rotor. There is a controller after the wind turbine which converts the three phase AC to DC and in order to charge the batteries. We also consider that the wind charge controller has 95% efficiency. A dump load is considered in the designed system and in cases when the batteries are full and also when the generated wind turbine power exceeds the demand power, the dump load dissipates the excess power in order to avoid over speeding of the wind turbine. In Turkey the grid voltage and frequency are 220V AC with 50 Hz frequency. In the considered hybrid system, there is a DC-AC inverter in order to supply the house. Similarly considering different DC-AC inverters in the market as an average we assume that the DC-AC inverter has 90% efficiency.

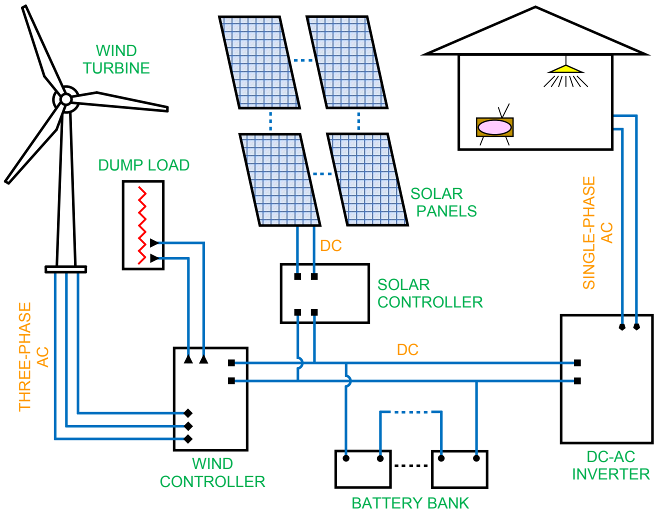


Fig. 2. Schematic view of the considered wind-solar-battery system.

In the considered hybrid system, the priority sources are the solar panels and the wind turbine. For example, at the times when the combined solar panel and wind turbine total power generation is greater than or equal to the demand power, they supply the house and the excess power charges the battery bank. At the times when the solar panels and wind turbine combined total power generation is less than the demand power, the battery bank is used to match the remaining needed power. As an essential requirement, the designed off-grid wind-solar-battery hybrid system is expected to supply uninterrupted continuous power for 20 years.

2.2. Considered wind turbines and wind power calculations

For the wind turbine in the hybrid system, using the internet we choose 7 different candidate horizontal axis wind turbines. The chosen wind turbines and their AWEA Rated Powers are given in Table 1. The "AWEA Rated Power" is the wind turbine's power output at 11 m/s wind speed defined in IEC 61400-12-1 standard by the American Wind Energy Association (AWEA).

Table 1. Considered wind turbine models in the present study and their rated powers.

Wind Turbine Model Name	AWEA Rated Power
Air-X [25]	0.148 kW
Swift [26]	0.9 kW
Pika T701 [27]	1.5 kW
Skystream 3.7 [28]	2.1 kW
Fortis Montana [29]	3.3 kW
Kingspan KW6 [30]	5.2 kW
Excel 10 [31]	8.9 kW

The wind turbine power curves that are published in the wind turbine's certifications are given all together in Fig. 3. The chosen wind turbines in this study cover a range of rated powers between 148 W to 8.9 kW.

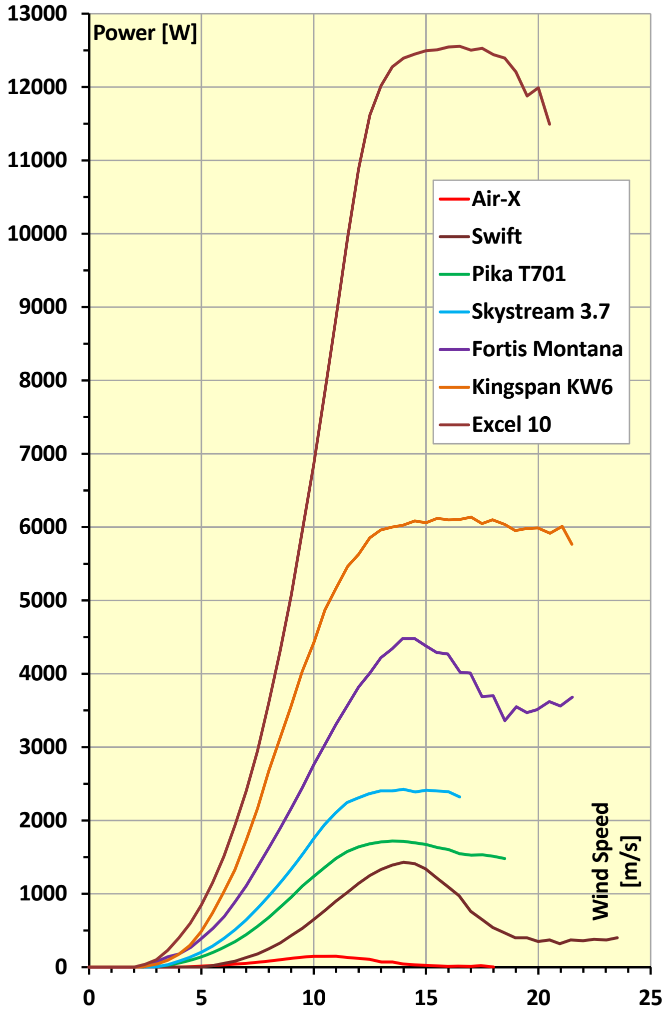


Fig. 3. Wind turbine's power curves.

The wind measurements are taken at 12 meters height therefore we assume that the considered small wind turbine will also have a 12 m tower. The wind turbine power curves are usually normalized with the air density at sea level (1.225 kg/m3). Since we are using the wind turbine's power curves in calculating the wind turbine power, we must correct the power curve with the instantaneous density. We note that the density of air is not a measurable quantity, therefore we must calculate it. The density of air changes with respect to the temperature, barometric pressure as well as the relative humidity. For humid air the density is written as

$$\rho = \frac{P_d}{R_d\,T} + \frac{P_v}{R_v\,T} \tag{1}$$

where the subscript d refers to dry air and v refers to water vapor also ρ is in [kg/m^3], P_d and P_v are in [Pa] and T is in Kelvin [K]. The water vapor and the dry air gas constants are given as

$$\begin{aligned} R_d &= 287.058 \quad [\text{J/(kg K)}] \\ R_v &= 461.495 \quad [\text{J/(kg K)}] \end{aligned} \tag{2}$$

The barometric pressure sensor gives the total air pressure (P). The Dalton's law state that the moist air pressure is equal to the sum of the partial pressures of the water vapor (P_v) and the dry air (P_d)

$$P = P_d + P_v \tag{3}$$

First, we calculate the saturation vapor pressure (P_{sat}) using the following equation

$$P_{sat} = \frac{6.1078}{p^8} \tag{4}$$

where P_{sat} is in [mBar] and the definition of p is given as

$$\begin{aligned} p = c_0 + T(c_1 + T(c_2 + T(c_3 + T(c_4 \\ +T(c_5 + T(c_6 + T(c_7 + T(c_8 + T.c_9)))))))) \end{aligned} \tag{5}$$

Here the temperature is in Celsius degrees [°C] and also the coefficients in the equation are defined as

$$\begin{aligned} c_0 &= 0.99999683 \\ c_1 &= -0.90826951 \ \times 10^{-2} \\ c_2 &= 0.78736169 \ \times 10^{-4} \\ c_3 &= -0.61117958 \ \times 10^{-6} \\ c_4 &= 0.43884187 \ \times 10^{-8} \\ c_5 &= -0.29883885 \ \times 10^{-10} \\ c_6 &= 0.21874425 \ \times 10^{-12} \\ c_7 &= -0.17892321 \ \times 10^{-14} \\ c_8 &= 0.11112018 \ \times 10^{-16} \\ c_9 &= -0.30994571 \ \times 10^{-19} \end{aligned} \tag{6}$$

This approximation is valid for -50 °C < T < 100 °C (see pp. 351-353 in [32]). Using the relative humidity sensor readings ($\emptyset$), the water vapor pressure (P_v) is obtained as

$$P_v = \emptyset\, P_{sat} \tag{7}$$

Then using the water vapor pressure (P_v), first the dry air pressure (P_d) and then the air density (ρ) is calculated. This calculated air density is used in correcting the normalized power curves (see [33][34]).

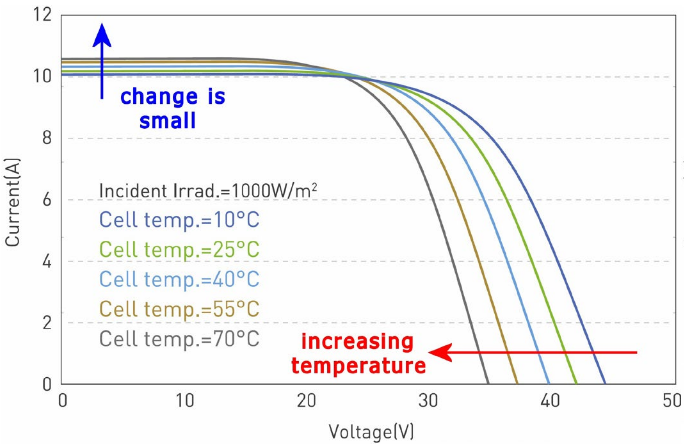
2.3. Solar panels and solar power calculations

After a search for the manufacturers and photovoltaic panel models on the internet, we decided to use the GCL-M3/60H photovoltaic panel model [35] in the solar panel array. The electrical specifications of the chosen solar panel at Standard Test Conditions STC (Irradiance 1000 W/m^2, Module Temperature 25 °C, Air Mass 1.5 spectra) and also at Nominal Operating Cell Temperature NOCT (Irradiance 800 W/m^2, Ambient Temperature 20 °C, wind speed 1 m/s) are given in Table 2.

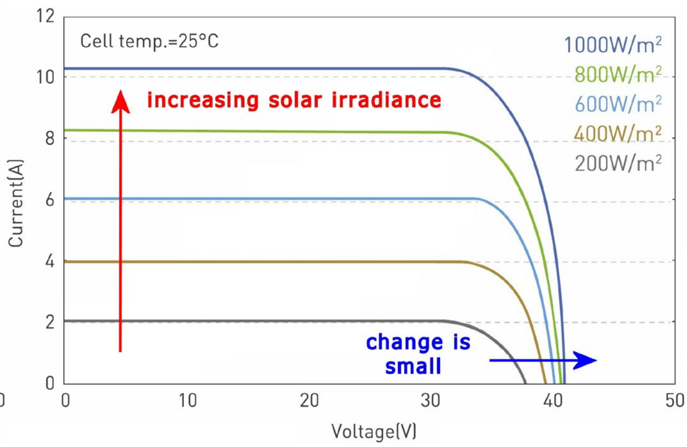
During operation, the instantaneous output of solar panels depends on both the cell temperature and the solar irradiance [36]. To reflect the real operating conditions, in our calculations we consider the effect of the cell temperature and the solar irradiance on the power output of the solar panels. The influence of the cell temperature and the solar irradiance on the solar panel characteristics are shown in manufacturer's I-V curves in Fig. 4. In Fig. 4a, as the cell temperature increases the open circuit voltage decreases almost linearly. When the cell temperature increases the short circuit current increases slightly also, however this increase is small. The changes in the cell temperature affect the open circuit voltage significantly but have comparatively small effect on the short circuit current. In our calculations we neglect the effect of the cell temperature increase on the short circuit current and only consider that the cell temperature has an influence on the open circuit voltage. Also as seen in Fig. 4b, as the solar irradiance increases the short circuit current increases linearly. We also see that the increasing solar irradiance increases the open circuit voltage in a logarithmic relationship, however this change is small compared to the change in the short circuit current. The changes in the solar irradiance affect the short circuit current significantly but have comparatively small effect on the open circuit voltage. For this reason, in our calculations we neglect the effect of increasing solar irradiance on the open circuit voltage and consider that the solar irradiance has an influence on the short circuit current. We note that as the ambient air temperature changes the cell temperature changes also. With including the effect of the ambient temperature and the solar irradiance on the output power our calculations reflect the real operating conditions accurately.

Table 2. Solar panel specifications.

Electrical Specifications STC	
Maximum Power P_{MAX}	325 W
Maximum Power Voltage V_{MP}	34.2 V
Maximum Power Current I_{MP}	9.51 A
Open Circuit Voltage V_{OC}	41.1 V
Short Circuit Current I_{SC}	9.88 A
Module Efficiency	19.3 %
Electrical Specifications NOCT	
Maximum Power P_{MAX}	241.39
Maximum Power Voltage V_{MP}	32.1 V
Maximum Power Current I_{MP}	7.52 A
Open Circuit Voltage V_{OC}	38.2 V
Short Circuit Current I_{SC}	7.99 A
Temperature Ratings	
Nominal Operating Cell Temperature	44 °C
Temperature Coefficient of V_{OC}	-0.3 %/°C



(a) Effect of cell temperature



(b) Effect of solar irradiance

Fig. 4. The effect of increasing cell temperature and solar irradiance on I-V curves.

In calculating the solar panel power output, it is important to calculate the operating temperature of the solar cells, since higher operating temperatures typically result in lower power outputs and efficiencies. In solar cells, the temperature difference of solar cell and the ambient air changes almost linearly with respect to the solar irradiance. The cell temperature is calculated as the following [37]

$$T_{cell} = T_{air} + (\mathrm{NOCT} - 20°\mathrm{C}) \frac{G}{800 \frac{\mathrm{W}}{\mathrm{m}^2}} \tag{7}$$

where temperatures are in Celsius degrees [°C], G is the measured solar irradiance in [W/m^2] and NOCT is the Nominal Operating Cell Temperature of the photovoltaic solar panel.

As seen in Fig. 4a, change in the cell temperature affects the open circuit voltage linearly and this linear relationship is specified by the manufacturers. For the chosen photovoltaic panel, the Temperature Coefficient of V_{OC} given in Table 2 defines the linear relationship between the cell temperature and the open circuit voltage as percentage. Using the values given in Table 2, the open circuit voltage at a calculated cell temperature is obtained using the following expression

$$V_{OC}(T_{cell}) = V_{OC}(25°\mathrm{C}) + (T_{cell} - 25°\mathrm{C}) \left(V_{OC}(25°\mathrm{C}) \frac{\Delta V_{oc}}{\Delta T} \right) \tag{8}$$

Also as seen in Fig. 4b, the solar irradiance affects the short circuit current of the solar cells. The short circuit current of the solar cell at a measured solar irradiance is obtained using the following equation [38]

$$I_{SC}(G) = I_{SC}\left(1000 \frac{\mathrm{W}}{\mathrm{m}^2}\right) \frac{G}{1000 \frac{\mathrm{W}}{\mathrm{m}^2}} \tag{9}$$

Solar controllers operate with maximum power point tracking (MPPT) algorithm to maximize the output power of solar panels. The Fill Factor (FF) of a solar cell is defined as the ratio of the maximum power from the solar cell to the product of the open circuit voltage and the short circuit current [38]

$$FF = \frac{P_{MP}}{V_{OC}\, I_{SC}} = \frac{V_{MP}\, I_{MP}}{V_{OC}\, I_{SC}} \tag{10}$$

Using the values in Table 2 and also using the calculated open circuit voltage at the cell temperature ($V_{OC}(T_{cell})$), short circuit current at a measured solar irradiance ($I_{SC}(G)$) and also the Fill Factor (FF), the maximum power from the solar cell (P_{MP}) is calculated (see [39]).

2.4. Power consumption of the house

For the considered house in Afyon we do not have continuous power consumption measurements, however we have many electric meter readings obtained at different times. From these readings we see that the power consumption has daily variations such that in the evenings when everybody is at home the consumption increases compared to the daytime consumption. Also, when everybody is at sleep after midnight the power consumption decreases. The power consumption has seasonal variations also where the consumption is higher in wintertime compare to the consumption in summertime.

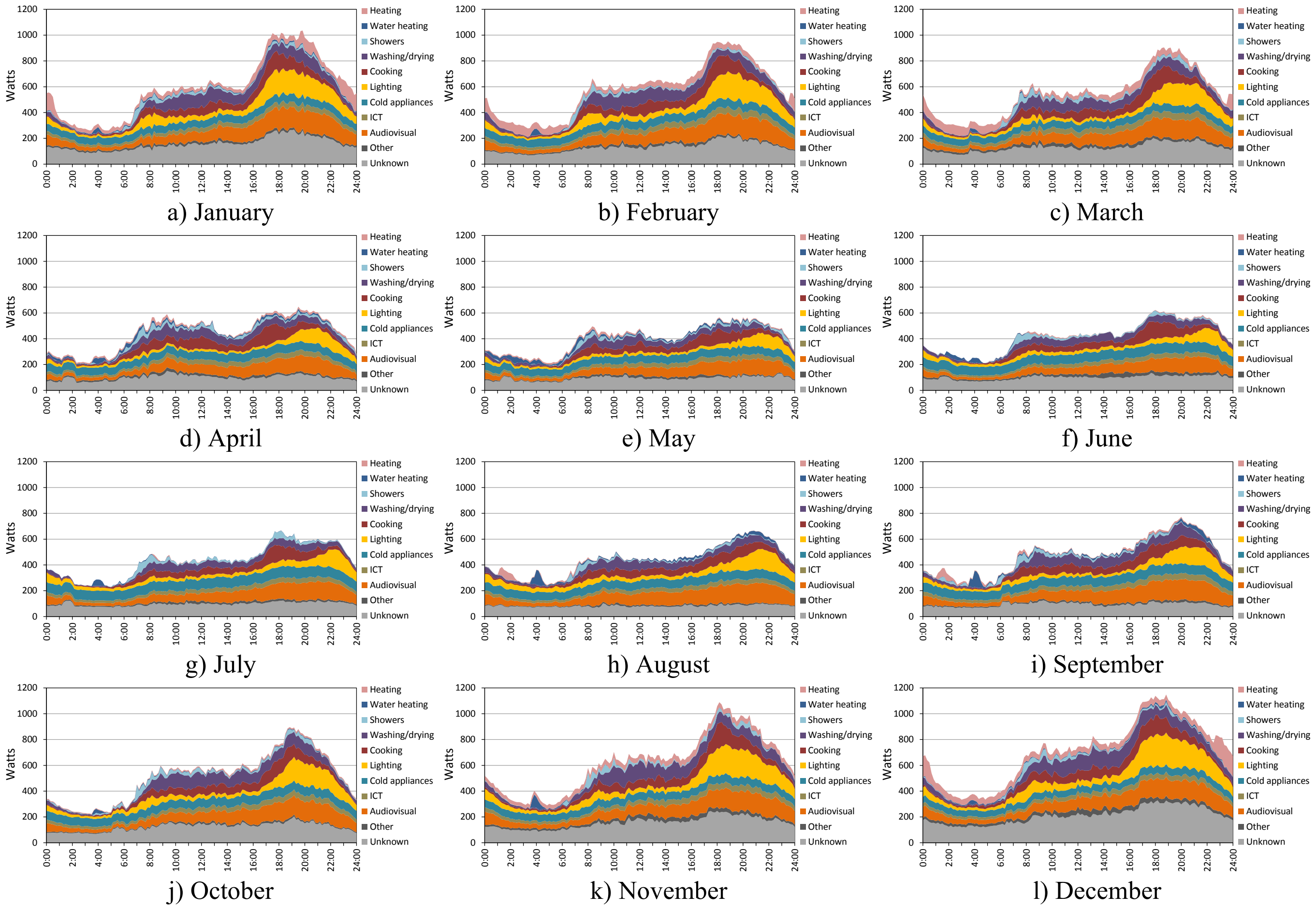


Fig. 5. Daily power consumption for different months.

In Household Electricity Survey monitoring study, carried out by United Kingdom Department of Energy & Climate Change, power consumption was monitored at appliance level in 250 houses across England between May 2010 and July 2011. The measured data is publicly available in [40] as 10-minutes data. In Fig. 5, the average daily power consumption is given for each month in a year.

The measured data in [40] match very closely with the electric meter readings we collected. For the considered house in Afyon we estimate that the published data in [40] can represent the power consumption within an estimated error less than ± 5%. For this reason, in our analysis, for considered house we use the published power consumption data in [40] as representative consumption. We assume that these daily consumption profiles repeat everyday in the corresponding month.

2.5. Batteries

Batteries are electrochemical energy storage devices that can store energy in a chemical form and convert that stored chemical energy into electrical energy when needed. The battery capacity represents the maximum amount of energy that can be extracted from the battery under certain specified conditions. The most common measure of battery capacity is Ah (Ampere Hour). For batteries Ah rate shows the number of hours for which a battery can provide a current equal to the discharge rate at the nominal voltage of the battery. According to Peukert's law, the battery's available capacity decreases as the discharge rate increases. In the market there are different type of batteries [41] and in the present study we consider deep-cycle gel batteries (100 Ah) in our calculations, which are usually preferred in renewable energy applications.

3. Calculations, Results and Discussions

The algorithm we follow in our calculations is given in Fig. 6.

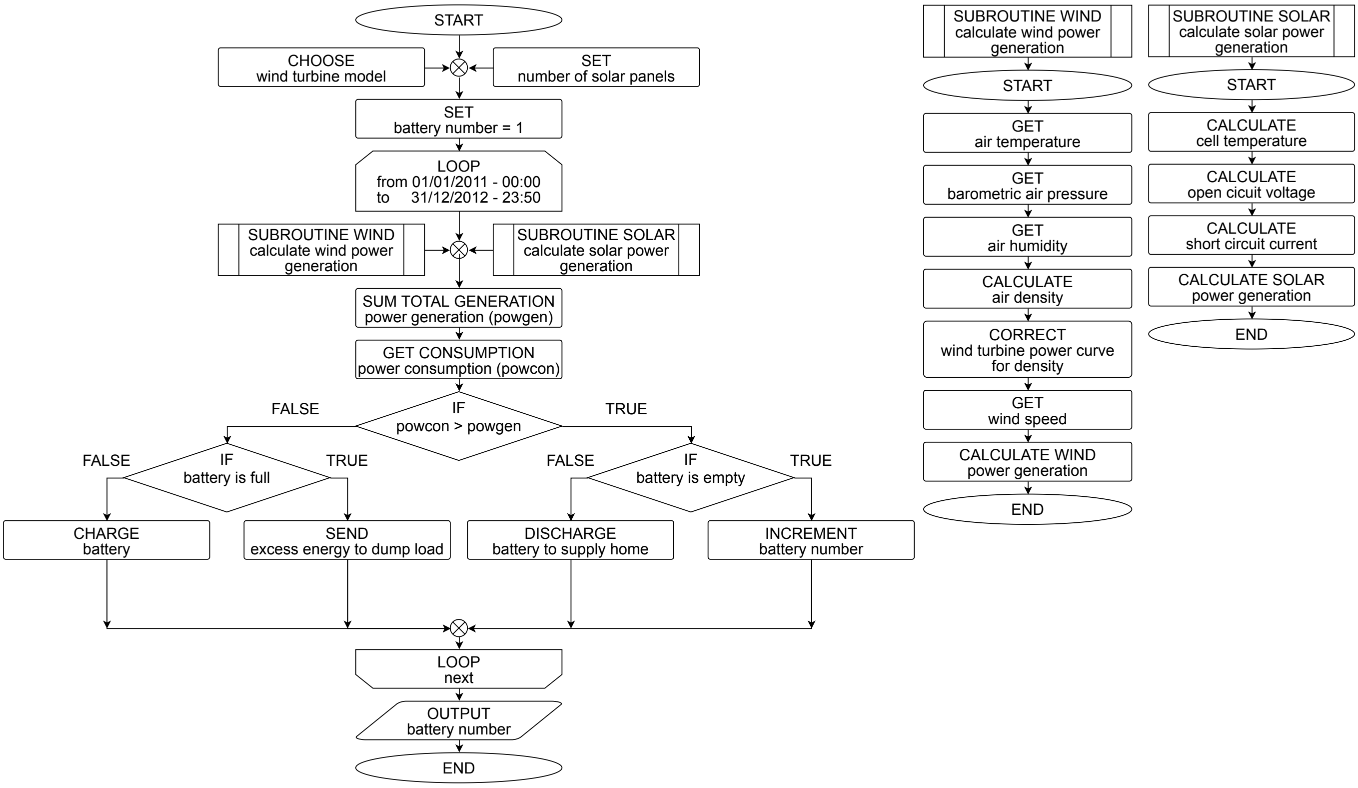
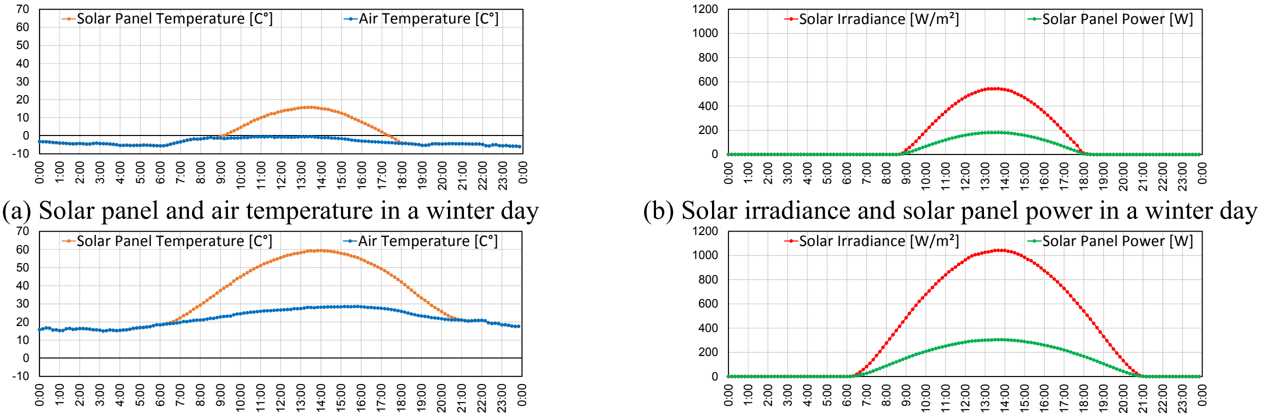


Fig. 6. Algorithm followed in present calculations.

First, we select the number of solar panels and also a wind turbine model for the hybrid system. Second, we guess a number for the batteries to be used in the battery bank, however this number changes during calculations. Using the measure wind and solar data, for every 10 minutes we calculate wind turbine power generation and also the solar panel power generation. In wind turbine power calculations, the wind turbine's power curve is used. As mentioned earlier the wind turbine power curves are normalized with the air density at the sea level (1.225 kg/m3). Following the procedure described in Section 2.2, we calculate the air density using the relative humidity, air pressure and ambient temperature data for every 10 minutes and with this we correct the wind turbine's power curve. Finally, the wind turbine power generation is obtained using the measured wind speed data and also the corrected power curve for every 10-minutes. In calculating the solar panels power generation, we include the effect of the ambient air temperature and the solar irradiance on the photovoltaic solar panels. Following the procedure described in Section 2.3, first we calculate the cell temperature of the solar panels and then calculate the open circuit voltage of the solar panels at this cell temperature. Then the short circuit current of the solar panels at a measured solar irradiance is calculated. Finally, by using the fill factor we calculate the power generated by the solar panels at every 10 minutes. For the considered remote house, we also have the power consumption for every 10 minutes. In every 10 minutes if the power generated by the solar panels and the wind turbine are greater than the consumed power, the solar panels and the wind turbine supply the power need. The exceeding power is used to charge the batteries. In the case if the batteries are full then the power is dissipated in the dump load. For the considered 10 minutes if the power generated by the solar panels and the wind turbine are less than the consumption power, the battery bank must supply the remaining needed amount of power. During the calculations at any 10 minutes, if the hybrid power system cannot supply the power demand this shows that storage capacity of the system is not enough to support the considered house. When this happens, we go back and increase the number of batteries by one and then restart the calculations from the beginning again. In our analysis we assume that the power consumption and also the solar and wind statistics repeats the same every year. With this we carry on our calculations for 20 years.

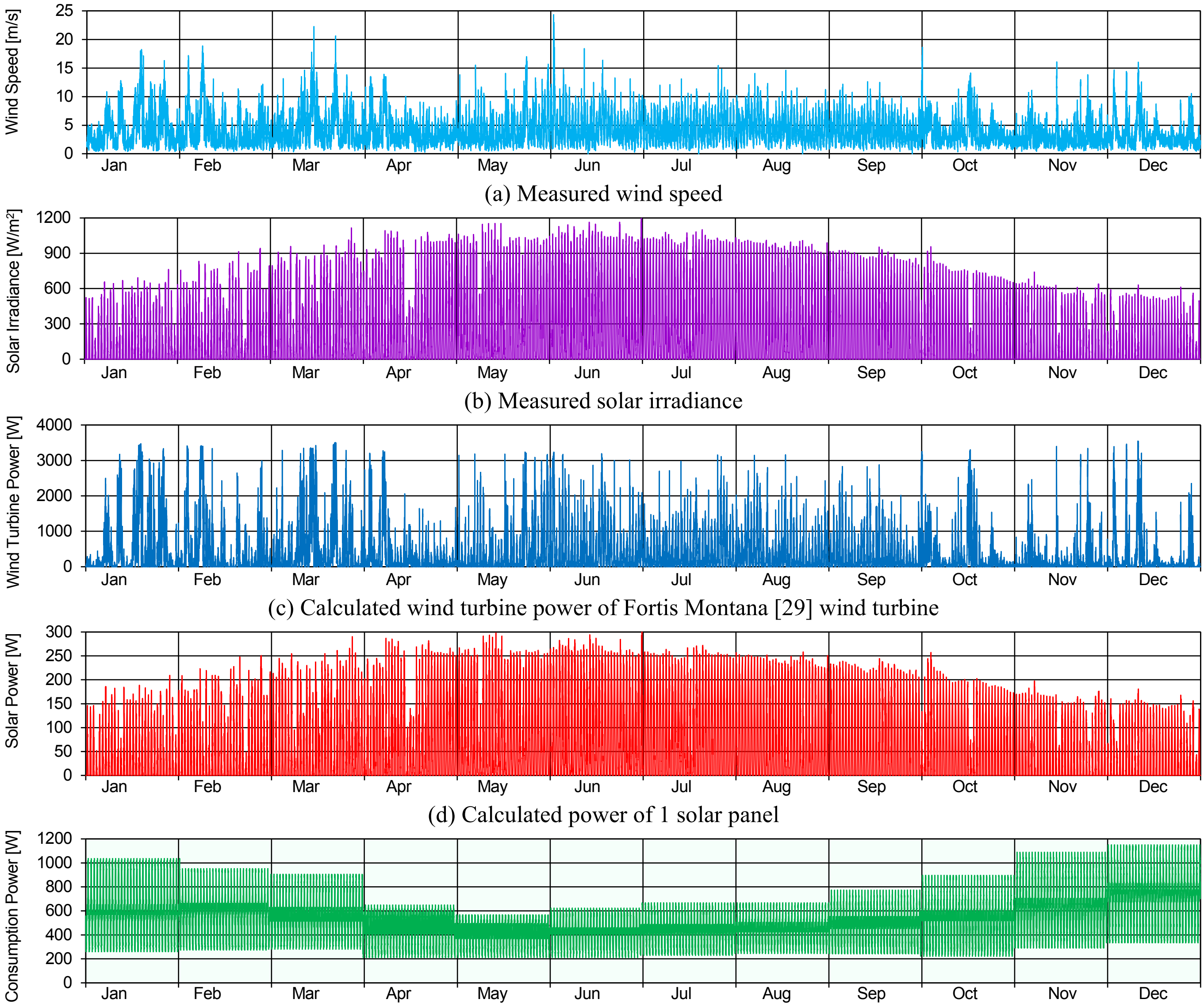
Fig. 7 shows the change in the ambient air temperature, solar panel cell temperature, solar irradiance and solar panel power generation in a particular "no cloudy" day both in winter and summer. As seen in the figure, in winter even when the air temperature is below 0 °C, the solar panel cell temperature can reach to ≈ 16 °C. Also, in summer the solar panel reaches to as high as ≈ 60 °C. This shows that during operation the solar panel cell temperature can reach to high values.



(a) Solar panel and air temperature in a winter day (b) Solar irradiance and solar panel power in a winter day

(c) Solar panel and air temperature in a summer day (d) Solar irradiance and solar panel power in a summer day

Fig. 7. Daily temperature, irradiance and solar power generation.



(a) Measured wind speed

(b) Measured solar irradiance

(c) Calculated wind turbine power of Fortis Montana [29] wind turbine

(d) Calculated power of 1 solar panel

(e) Power consumption of the house

Fig. 8. Measured and calculated yearly data.

Fig. 8 presents measured wind speed data, measured solar irradiance data, calculated wind turbine power generation for Fortis Montana [29] (3.3 kW) wind turbine model, calculated solar power generation of 1 photovoltaic solar panel and power consumption of the house. As seen in Fig. 8a, Afyon city is not a very good site for wind power. The average wind power density is calculated as 90.6 W/m2 and due to such low values Afyon site has wind power class of 1 according to [42]. However, with the solar irradiance levels seen in Fig. 8b, and with an average solar irradiance of 209.1 W/m2 Afyon has a very good solar power potential.

Table 3. Hybrid system configurations and minimum number of batteries needed in the system.

Number of solar panels (GCL-M3/60H)	No Wind Turbine	Air-X (0.148 kW)	Swift (0.9 kW)	Pika T701 (1.5 kW)	Skystream 3.7 (2.1 kW)	Fortis Montana (3.3 kW)	Kingspan KW6 (5.2 kW)	Excel 10 (8.9 kW)
10	840	794	662	480	368	241	150	112
11	723	688	574	404	319	199	133	99
12	633	599	497	334	272	163	119	86
13	554	527	427	277	229	131	106	73
14	486	459	359	233	192	102	93	62
15	419	392	293	193	161	89	80	52
16	353	326	239	162	132	76	67	42
17	292	266	196	133	103	63	56	33
18	239	220	158	105	77	53	46	30
19	197	178	127	80	58	43	37	26
20	159	140	99	56	48	35	29	23
21	120	102	74	44	41	29	25	20
22	82	71	49	37	34	25	22	20
23	53	46	38	32	29	22	20	20
24	36	34	33	29	27	21	20	20
25	33	33	32	28	26	20	20	19
26	32	31	30	27	25	19	20	19
27	30	30	29	25	23	19	19	19
28	29	29	28	24	22	19	19	19
29	28	27	26	23	20	19	19	19
30	26	26	25	21	19	19	19	18

Following the algorithm presented above, after many calculations we obtain the minimum number of batteries needed in different hybrid system that has different number of solar panels and different wind turbine model that can supply continuous power uninterruptedly for 20 years to the considered remote house. The calculated needed minimum number of batteries are tabulated in Table 3. In Table 3, the columns show different considered wind turbine models in the hybrid system. Since the wind energy potential of Afyon is not very good, we consider the possibility of not having a wind turbine in the power system also. Similarly, in Table 3, the rows show different number of solar panels in the hybrid system. Also, the intersection of the columns and rows show the minimum number of batteries needed in the corresponding hybrid system. Therefore, in Table 3 every cell together with the column and the row denotes a different possible hybrid system configuration for the considered remote house in Afyon. For example in a hybrid system configuration in order to supply the house, if Swift [26] wind turbine model (0.9 kW) and 15 solar panels are used together, then 293 batteries are needed in the power system for uninterrupted continuous power. Or else in a hybrid system configuration with Fortis Montana [29] wind turbine (3.3 kW) and 25 solar panels, minimum 20 batteries must be used in order to have continuous power all the time.

Prices of solar panels, wind turbines and also batteries vary from country to country such that for these hybrid system components setting a universal price will not be accurate. Besides any price information will be outdated quickly since the prices of these hybrid system components change most likely in time. Therefore, in the present study we do not consider the prices of different hybrid system configurations.

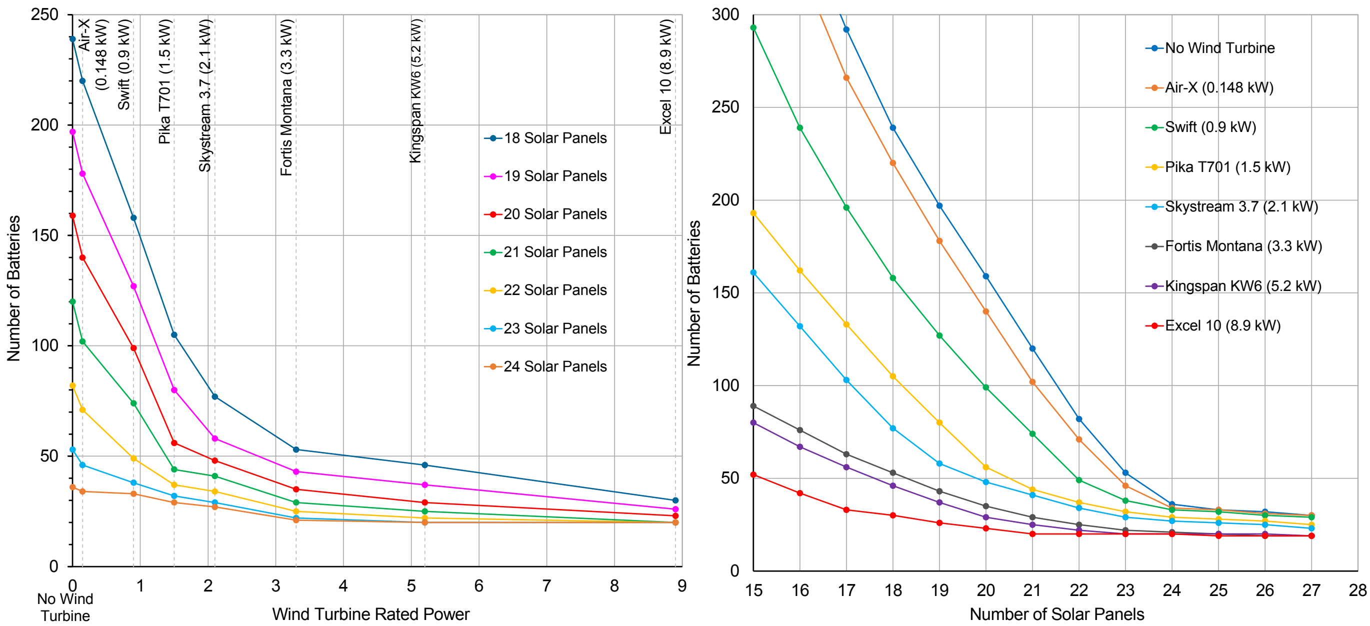
Table 4. Change in number of batteries when one solar panel is added to the system.

Number of solar panels (GCL-M3/60H)	No Wind Turbine	Air-X (0.148 kW)	Swift (0.9 kW)	Pika T701 (1.5 kW)	Skystream 3.7 (2.1 kW)	Fortis Montana (3.3 kW)	Kingspan KW6 (5.2 kW)	Excel 10 (8.9 kW)
10								
11	117	106	88	76	49	42	17	13
12	90	89	77	70	47	36	14	13
13	79	72	70	57	43	32	13	13
14	68	68	68	44	37	29	13	11
15	67	67	66	40	31	13	13	10
16	66	66	54	31	29	13	13	10
17	61	60	43	29	29	13	11	9
18	53	46	38	28	26	10	10	3
19	42	42	31	25	19	10	9	4
20	38	38	28	24	10	8	8	3
21	39	38	25	12	7	6	4	3
22	38	31	25	7	7	4	3	0
23	29	25	11	5	5	3	2	0
24	17	12	5	3	2	1	0	0
25	3	1	1	1	1	1	0	1
26	1	2	2	1	1	1	0	0
27	2	1	1	2	2	0	1	0
28	1	1	1	1	1	0	0	0
29	1	2	2	1	2	0	0	0
30	2	1	1	2	1	0	0	1

Examining the hybrid system configurations given in Table 3, for a particular chosen number of solar panels, if the rated power of the wind turbine increases, i.e. if we move towards right in a row in the table, we see that the required number of batteries decreases. This shows that in a hybrid system configuration with a chosen number of solar panels, if a higher rated power wind turbine is used then less number of batteries are needed. Also, in Table 3, for a particular chosen wind turbine model, as the number of solar panels increases, i.e. if we move towards down in a column in the table, the required minimum number of batteries decreases. This shows that in a hybrid system configuration with a chosen wind turbine model, if more solar panels are used in the system then less number of batteries are needed. Among so many hybrid system configurations given in Table 3, it is difficult to suggest a particular configuration for the considered remote house in Afyon. For this purpose, instead of looking at the required number of batteries for any hybrid system configuration as it is given in Table 3, we decided to look at the change in the number of batteries when the number of solar panels increase by 1 in a hybrid system configuration. For example, in Table 3 in the hybrid system configuration with Swift [26] wind turbine model and 14 solar panels, minimum 359 batteries are required. Also, in Table 3 in the hybrid system configuration with Swift [26] wind turbine model and 15 solar panels, minimum 293 batteries are required. Therefore in a hybrid system configuration with Swift [26] wind turbine model, when the number of solar panels increase by 1 from 14 to 15, the number of batteries decrease from 359 to 293. Thus, in this hybrid system configuration with 14 solar panels, adding 1 more solar panel to the system decreases the number of batteries by 66 since they are not needed anymore. Table 4 shows the amount of decrease in the number of batteries in a hybrid system configuration when the number of solar panels increase by 1.

In Table 4, in a system with a particular chosen wind turbine model, each time when another solar panel is added, i.e. if we move towards down in a column in the table, the number of batteries we can remove from the system decreases. In Table 4 some of the cells are highlighted with yellow color. Assuming that one GCL-M3/60H [34] solar panel price is approximately in the order of three 100 Ah gel batteries price, these yellow highlighted cells show that, for every chosen wind turbine after some many solar panels, adding another solar panel do not decrease the number of batteries significantly (decrease is ≤ 3) such that adding another solar panel to the system is almost useless in terms of cost. Therefore, any hybrid system configuration highlighted with yellow color is not suggested for the considered remote house. We highlight the same hybrid system configurations in Table 3 with yellow color also in order to mark them as "not suggested".

In Fig. 9 we plot the number of batteries as a function of wind turbine rated power and also as a function of number of solar panels. In Fig. 9a we see that as the wind turbine rated power increases above 2.1 kW and/or 3.3 kW, the decrease in the number of batteries changes significantly and the profiles show almost a flat behavior. This suggests that either Skystream 3.7 [28] (2.1 kW) or Fortis Montana [29] (3.3 kW) wind turbine is a good choice for the hybrid power system. In Fig. 9b looking at the profile for Fortis Montana [29] wind turbine, we see that above 21 and/or 22 solar panels the number of batteries do not change significantly and the profile becomes almost horizontal. This suggests that for a hybrid power system with Fortis Montana [29] wind turbine, 21 and/or 22 solar panels is a good choice and can be suggested. Similarly looking at the profile for Skystream 3.7 [28] wind turbine, we see that above 22 and/or 23 solar panels the change in the number of batteries is very small and the profile becomes almost flat. This suggests that for a hybrid power system with Skystream 3.7 [28] wind turbine, 22 and/or 23 solar panels is also a good choice and can be suggested. These suggested hybrid systems are highlighted with green color in Table 3. Also considering the fact that the wind energy potential of Afyon city is low, as an alternative, a power system with no wind turbine can also be suggested. This suggested hybrid system is also highlighted with green color in Table 3. For the considered remote off-grid house in Afyon, among many combinations of wind turbines, number of solar panels and number of batteries, 5 different hybrid system configurations highlighted with green color in Table 3 are suggested for reliable uninterrupted continuous power supply. These suggested hybrid systems for the considered zero-energy house in Afyon are also summarized in Table 5 separately.



(a) Battery number w.r.t. wind turbine rated power (b) Battery number w.r.t. solar panel number

Fig. 9. Change in minimum number of battery in the system.

Table 5. Suggested hybrid systems for the considered house.

System #1	Skystream 3.7 [28] wind turbine 22 photovoltaic panels 34 batteries
System #2	Skystream 3.7 [28] wind turbine 23 photovoltaic panels 29 batteries
System #3	Fortis Montana [29] wind turbine 21 photovoltaic panels 29 batteries
System #4	Fortis Montana [29] wind turbine 22 photovoltaic panels 25 batteries
System #5	no wind turbine 24 photovoltaic panels 36 batteries

4. Conclusions

In this study we examined the sizing of a stand-alone hybrid wind-solar-battery power system for a zero-energy house which does not have a grid connection in Afyon Turkey. As an essential requirement, this hybrid system is expected to supply sustainable continuous power to the house uninterruptedly. In our analysis we used actual 10-minute averaged measured wind and solar data for power production as well as actual 10-minute averaged measured power consumption data of the house.

Our analysis indicate that both the number of solar panels used in the system and also the chosen wind turbine for the system have a significant effect on the minimum battery number needed in the hybrid system for uninterrupted continuous power supply. Since Afyon city does not have a good wind power potential especially small rated wind turbines are not advised for the considered site since at low wind speeds they cannot generate significant power. On the other hand, high rated wind turbines are not advised also since their contribution does not decrease the number of solar panels and also the number of batteries significantly. For the considered house 5 different hybrid systems with different wind turbines, different number of solar panels and different number of batteries are suggested after a detailed analysis.

A study that considers long time averaged powers of generation and consumption may not guarantee uninterrupted continuous power at any instant. For hybrid systems in which without interruption the continuity of electricity is critical, an analysis that considers small time interval power generation or consumption data is essential. In the absence of such an analysis, the hybrid system will suffer from no power from time to time with undersized components or else the hybrid system suffers from high investment cost with oversized incompatible components.

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