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Sizing a Stand-alone Off-grid Wind Turbine-battery Power System for a Remote House in Catalca Istanbul Turkey

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Abstract- For remote houses with no connection to the grid, if the site is suitable for wind energy, an off-grid wind turbine-battery power system is a good alternative for supplying the energy need of the house. If the reliability of the power supply is crucial then sizing of the components, wind turbine and the battery bank, is very important. In the market there are many wind turbines with different ratings and power curves. For an off-grid turbine-battery power system, for every different chosen wind turbine the minimum required number of batteries in the battery bank would be different for reliable and continuous power supply to the house. It is the usual case in practice that either the battery bank is chosen as undersized such that the consumer suffers from no power from time to time or the battery bank is chosen as oversized without any calculation and this results in high initial costs for the consumer. In this study, for a remote house in Catalca Turkey, a stand-alone wind turbine-battery system will be sized using wind data of the site and consumption data of the house. Our results show that the minimum number of batteries needed in the battery bank for an uninterrupted electrical energy supply changes very much according to the chosen wind turbine and the minimum required number of batteries depends on the power curve of the chosen wind turbine rather than the rated power of the wind turbine.

Keywords Wind turbine-battery system, stand-alone off-grid system, optimum sizing of battery bank, wind energy, reliability

1. Introduction

With increasing number of installed wind turbines each year, wind energy is getting more public attention. Wind power generation increases in two directions worldwide; installation of larger and larger wind turbines in large-scale wind farms contributing to national power grids and installation of small to medium scale wind turbines for distributed or isolated power generation. The latter is sometimes called residential microgeneration. Residential microgeneration can either be on-grid with net metering in which the system is connected to the grid, buying and selling according to the demand of the residents and generation in the system or be off-grid in which the system is a stand-alone system isolated from the grid. If the resident is far away from the central electricity network and where there are limited conventional fuel resources but available renewable energy resources, a stand-alone off-grid system is the only choice for energy generation. In stand-alone off-grid systems, reliability of power supply is one of the main issues. In a wind turbine-battery off-grid system the wind turbine and the battery bank must be chosen carefully in order to provide continuous secure power supply to the end user. Therefore, in such systems sizing the wind turbine and the battery bank is very important otherwise there might be a chance that the system cannot supply the energy demand and the consumers might suffer from no power for a long time. With appropriate planning, systems selection and sizing, stand-alone off-grid systems can supply secure reliable and economic power to remote locations and distributed micro-grids.

Stand-alone wind-battery systems are described briefly in [1][2][3] in terms of methodology in system design, selection and sizing. Continuity and reliability of electricity supply from wind energy are the most important criteria for feeding isolated sites. Economics (initial cost) is also a very important criterion for the owner of the system. In order to meet the continuity and reliability criteria with improperly selected system one can end up with high ownership costs [4][5][6][7][8]. In a stand-alone power system, if more than one power source is considered, i.e. wind-solar-battery hybrid system, an optimization methodology should be followed in order to size each component [9][10][11][12][13]. A brief review on different optimization methodologies in such systems is given in [14]. For a stand-alone wind turbine-battery system, choosing optimal configuration is a subject of many studies in the literature [15][16][17][18]. In stand-alone power systems with only one power source, such as a wind turbine-battery system, sizing each component requires choosing the power source, i.e. the wind turbine in our case, and calculating the minimum required number of batteries in the battery bank that would supply uninterrupted continuous power. In the market, there are many different brand small wind turbines to use in residential power generation in remote areas. Different wind turbines generate different amount of power at any given wind speed. Therefore the minimum number of batteries in the battery bank that would guarantee reliable uninterrupted continuous power supply would be different for any chosen wind turbine since the power curve and power ratings are different for any wind turbine.

In this study, we will size a wind turbine-battery system for a remote house in Catalca, Istanbul, Turkey. With today's design and manufacturing technology most of the small wind turbines have a life expectancy about 25 years. We will consider many different small wind turbines with rated powers varying between 1 kW to 10 kW and calculate how many batteries are needed in the battery bank for each different wind turbine that will supply the household continuously without any power shortage for 25 years. We note that, off course the life of today’s batteries are much less than 25 years and it is necessary to replace the batteries from time to time, however the number of batteries in the system will remain the same through the years and therefore the system should be designed accordingly. The number of batteries needed for a continuous supply is a crucial information during the design and purchase of the system. The calculations will be done using actual 10-minute averaged wind data on the supply side and 10-minute averaged data on the consumption side. For the consumer such a study is important for two reasons. The first reason is that the system with a chosen wind turbine and the battery bank with enough number of batteries calculated using actual data will guarantee that the system can supply the house continuously. The second reason is that the consumer can have the chance to compare each different system with different wind turbine and the corresponding calculated number of batteries needed in the battery bank in terms of the cost. Therefore, after calculating the minimum number of batteries required in the battery bank for each different chosen wind turbine, normally each wind turbine-battery system should be compared with each other in terms of cost. In order to do this the cost of each system should be obtained. However, the price of wind turbines can change from country to country. Also the price of the batteries can change a lot according to the brand and also according to the battery Ah rating. Moreover, the prices vary in time. The usual case is the price of wind turbines and also the price of batteries decrease in time. Another important fact is that the price of each component can vary in the market according to negotiation. Since it is hard to set a universal price for each system and also since the prices are most likely to change in time, we will not compare each different system with each other in terms of cost in this study. Thus, we will only suggest different systems with a different wind turbine and with corresponding number of batteries that will ensure reliable continuous power supply to the house and leave the comparison of each system in terms of cost out of the scope.

2. Methodology and Calculations

2.1. Catalca Site Information and Wind Measurement Mast

This study is done for a remote house in Catalca. Catalca is located in West of Istanbul city in Turkey. The location is shown on the map in Figure 1. Catalca is known to be a good site for wind energy and in Catalca there are many wind farms with megawatt scale wind turbines. The wind data used in this study comes from a 80 meter lattice tower mast located close to the house. The mast has 2 wind speed anemometers located at 80m and at 40m heights, a wind direction vane at 80m, a relative humidity sensor, a temperature sensor, a barometric pressure sensor and an Ammonit data logger. The data logger logs 10-minute averaged data coming from the sensors, the lowest and the highest data and also the standard deviation of the data within every 10-minute. In this study the data we used belongs to 2012 whole year.

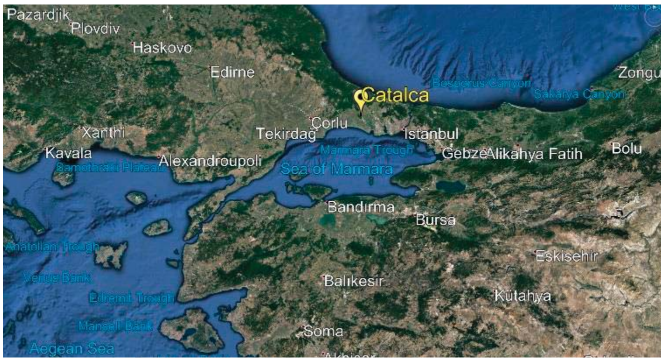


Fig. 1. Location of Catalca on the Map

2.2. Wind calculations

In the considered off-grid system in Catalca, the small wind turbine is planned to have a 12m tube tower. The power law equation is used to calculate the wind speed at 12m height using the measured wind data from the mast at 80m and 40m heights as the following

$$v = v_{ref}\left(\frac{h}{h_{ref}}\right)^{\alpha} \tag{1}$$

where v_{ref} is the reference wind speed measured at h_{ref} height and h is the height where we would like to calculate the wind speed and α is the wind shear exponent. In our calculations h=12m, h_{ref}=80m and v_{ref} is the measured wind speed at 80m height. From the power law equation (1), the wind shear exponent is calculated as

$$\alpha = \frac{\log\left(\frac{v_2}{v_1}\right)}{\log\left(\frac{h_2}{h_1}\right)} \tag{2}$$

where in our calculations v_2 and v_1 are the measured wind speeds at h_2=80m and h_1=40m respectively.

In order to size the system and also to do a wind resource assessment for the site, we need to calculate the density of the air. The air density is a function of the barometric air pressure, the air temperature and also the relative humidity in the air. In order to calculate the density of moist air we first calculate the saturation vapor pressure at a given temperature using the following equation suggested by Herman Wobus, a mathematician who worked at the navy weather research facility Norfolk Virginia

$$P_{sat} = \frac{6.1078}{p^8} \tag{3}$$

where P_{sat} is the saturated vapour pressure in [mBar] and p is an approximating 9th order polynomial defined as the following

$$p = c_0 + T(c_1 + T(c_2 + T(c_3 + T(c_4 + T(c_5 + T(c_6 + T(c_7 + T(c_8 + T.c_9)))))))) \tag{4}$$

where T is the air temperature in Celcius degrees [°C] and the coefficients of the polynomial are

$$\begin{aligned} c_0 &= 0.99999683 \\ c_1 &= -0.90826951 \times 10^{-2} \\ c_2 &= 0.78736169 \times 10^{-4} \\ c_3 &= -0.61117958 \times 10^{-6} \\ c_4 &= 0.43884187 \times 10^{-8} \\ c_5 &= -0.29883885 \times 10^{-10} \\ c_6 &= 0.21874425 \times 10^{-12} \\ c_7 &= -0.17892321 \times 10^{-14} \\ c_8 &= 0.11112018 \times 10^{-16} \\ c_9 &= -0.30994571 \times 10^{-19} \end{aligned} \tag{5}$$

With these coefficients, the 9th order polynomial suggested by Herman Wobus fit the saturation vapor pressure values listed in table 94 on pp. 351-353 of the Smithsonian Meteorological tables (6th edition by Robert J. List) and this approximation is valid for a temperature range of -50 °C < T < 100 °C. The actual vapor pressure (P_v) is calculated as the following

$$P_v = \emptyset \, P_{sat} \tag{6}$$

where $\emptyset$ is relative humidity from the sensor. Then the dry air pressure (P_d) is calculated as the following

$$P_d = P - P_v \tag{7}$$

where P is total pressure from the barometric pressure sensor. Finally, the density of the air is calculated as the following

$$\rho = \frac{P_d}{R_d \, T} + \frac{P_v}{R_v \, T} \tag{8}$$

where T is in Kelvin [K] and the specific gas constants for dry air and for water vapor are

$$\begin{aligned} R_d &= 287.058 \quad [\mathrm{J/(kgK)}] \\ R_v &= 461.495 \quad [\mathrm{J/(kgK)}] \end{aligned} \tag{9}$$

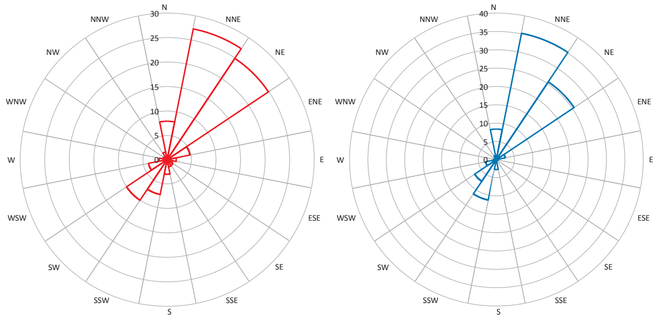
Table 1. Joint Wind Speed/Direction Frequency Distribution Table

[m/s]	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	TOTAL
calm	0	0.01	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0.03
1	0.08	0.07	0.06	0.06	0.06	0.04	0.05	0.06	0.06	0.11	0.06	0.07	0.06	0.05	0.05	0.05	0.98
2	0.19	0.31	0.31	0.18	0.1	0.11	0.28	0.24	0.19	0.21	0.25	0.25	0.11	0.06	0.06	0.07	2.92
3	0.29	0.61	0.45	0.35	0.37	0.28	0.69	0.68	0.31	0.46	0.63	0.56	0.41	0.17	0.1	0.07	6.42
4	0.53	0.83	0.73	0.51	0.45	0.2	0.17	0.21	0.38	0.59	1.14	0.53	0.34	0.2	0.16	0.15	7.11
5	0.67	1.58	1.12	0.49	0.35	0.19	0.06	0.11	0.38	0.83	1.1	0.4	0.22	0.14	0.09	0.15	7.87
6	0.67	2.29	1.74	0.53	0.19	0.11	0.03	0.05	0.27	0.73	1.28	0.41	0.15	0.05	0.09	0.13	8.73
7	0.76	2.32	2.12	0.73	0.12	0.09	0.01	0.02	0.18	0.57	1.41	0.32	0.1	0.06	0.07	0.18	9.07
8	0.81	2.56	2.3	0.59	0.07	0.05	0.03	0.02	0.23	0.59	0.98	0.24	0.08	0.04	0.05	0.17	8.82
9	0.88	2.74	2.86	0.43	0.02	0.03	0.01	0.03	0.18	0.49	0.71	0.24	0.04	0.03	0.02	0.19	8.89
10	0.73	3.08	3.26	0.3	0.02	0.01	0.01	0.02	0.14	0.24	0.56	0.17	0.02	0.01	0	0.17	8.73
11	0.57	2.71	3.59	0.29	0.01	0	0	0.01	0.15	0.28	0.58	0.16	0.02	0	0	0.09	8.46
12	0.45	2.56	2.87	0.15	0.01	0	0	0.01	0.09	0.29	0.46	0.12	0.01	0.01	0.01	0.07	7.12
13	0.39	1.76	1.7	0.04	0	0.01	0.01	0.02	0.04	0.23	0.25	0.11	0.01	0	0	0.05	4.62
14	0.35	1.05	0.97	0.03	0.03	0.01	0.01	0	0.11	0.19	0.2	0.12	0.01	0	0.01	0.02	3.12
15	0.23	0.84	0.47	0.03	0.04	0.02	0.02	0.01	0.09	0.21	0.1	0.03	0.01	0	0.01	0.01	2.11
16	0.12	0.63	0.24	0.02	0.02	0.02	0.01	0.01	0.1	0.24	0.1	0.03	0	0.01	0	0	1.57
17	0.07	0.5	0.13	0.01	0	0.01	0	0	0.06	0.28	0.07	0.01	0	0.01	0	0	1.18
18	0.03	0.39	0.04	0.01	0	0	0	0	0.03	0.28	0.04	0.02	0.01	0.01	0	0	0.87
19	0.02	0.32	0.01	0	0	0	0	0	0.01	0.23	0.05	0.02	0	0.01	0	0	0.68
20	0.02	0.15	0.01	0	0	0	0	0	0.02	0.13	0.02	0.02	0	0	0	0	0.38
21	0.01	0.06	0	0	0	0	0	0	0	0.07	0.02	0.02	0	0.01	0	0.01	0.19
22	0.01	0.01	0	0	0	0	0	0	0.01	0.03	0	0.01	0.01	0	0	0	0.08
23	0	0	0	0	0	0	0	0	0	0.02	0	0.01	0.02	0	0	0	0.05
24	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0.01
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	7.89	27.39	25	4.78	1.86	1.15	1.39	1.51	3.01	7.3	10.03	3.89	1.63	0.85	0.74	1.58	100

2.3. Wind Statistics in Catalca

In Catalca at 80m height the average wind speed is 8.45 m/s and the average wind power density is calculated as 538.42 W/m2 which suggests that this site is very suitable for wind energy. Table 1 shows the frequency distribution of the wind speed at 80m classified in 16 sectors for wind direction.

Figure 2 shows the wind direction rose and energy rose. Wind direction rose shows the percent of the total time of the wind in 16 sectors and energy rose shows the percent of total wind energy in [Wh/m2] in each 16 sectors. As seen in the wind direction rose and also in the frequency distribution table, Table 1, in Catalca the wind comes from NNE and NE directions most percent of the time. Wind direction itself only is not a good indicative for wind energy potential therefore we should plot the energy rose also. Looking at the wind energy rose we can see that the wind coming from NNE and NE directions constitutes most of the energy [Wh/m2] with approximately 60.9% of the total wind energy. This states that in Catalca not only most of the time the wind comes almost from the same directions but also these are the strong winds that has the most energy.



a) Wind direction rose **b)** Wind energy rose

Fig. 2. Wind Direction/Energy Rose

2.4. Off-Grid System

Figure 3 shows the off-grid wind-battery system schematically. In a typical off-grid system there is a small wind turbine, a charge controller, a dump load, a battery bank with required number of batteries and an off-grid inverter. A small wind turbine produces an electricity with variable frequency AC with variable voltage potential depending on the rotational speed of the rotor. While most of the small wind turbines have a three-phase AC output, there are some wind turbines having single-phase AC output also depending on the armature winding. In between the wind turbine and the battery bank there is a charge controller which converts the AC to DC and charges the batteries. The charge controllers might have different charging strategy, while some have PWM charge control system some others might have MPPT function with adjustable power curves. Some charge controllers might have only buck converter while some might have buck and boost converter. In the market different charge controllers have different efficiency in charging the batteries. In our calculations we assume that the charge controller has an efficiency of 95%. Since the wind turbines should always operate under an electrical load, when the batteries are fully charged the charge controller will divert the generated energy to a dump load to dissipate the energy in order to protect the batteries from overcharging and also to protect the wind turbine from over speeding. When there is a demand in the house, the DC in the battery bank should be inverted to AC. In our case the AC should be 220 V and 50 Hz which are the grid voltage and frequency in Turkey. For this purpose, in a typical off-grid system there will be an inverter in between the battery bank and the house as shown in the figure. We note that the inverter will also have an efficiency. In our calculations we assumed the efficiency of the inverter is 90% which is an average efficiency in the market.

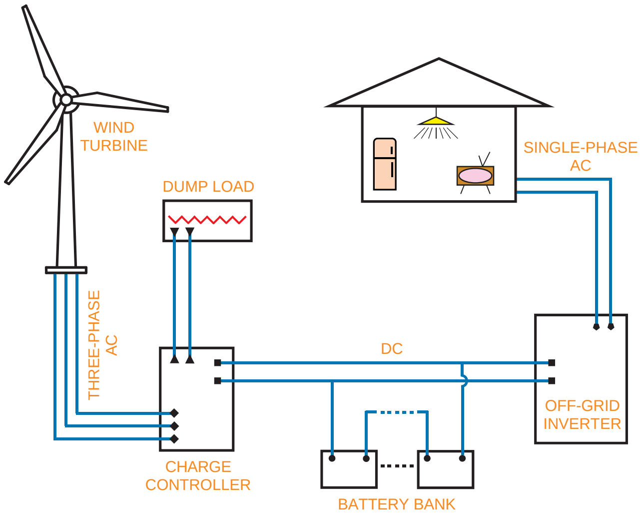


Fig. 3. Schematics of stand-alone off-grid wind turbine-battery system

2.5. Battery Bank

Batteries store charge in the form of chemical energy and then converts it into electrical energy. The most common measure of battery capacity is Ah (Ampere Hour). For batteries Ah rate refers to the battery's storage capacity and it shows the number of hours for which a fully charged battery can provide a current equal to the discharge rate until a cut-off voltage in the battery. This capacity decreases as the rate of discharge increases approximately according to Peukert's law.

In this study we will consider 100 Ah batteries in our calculations. We note that if 50 Ah batteries were considered then the number of batteries calculated in this study would be doubled. We also note that in the market the price of a 100 Ah battery is not exactly twice the price of a 50 Ah battery. Depending on the Ah rating of the battery and also depending on the brand of the battery the price would differ a lot in the market.

2.6. Power Consumption of the house

In order to be able to size the battery bank we need the power consumption data of the house in Catalca. For this site we have 10-minute averaged wind speed data for the whole year as shown in Figure 4. The wind speed data will be used to calculate the power generated by the wind turbine. However, we do not have continuous yearly data for the consumption of the house. Looking at the daily electric

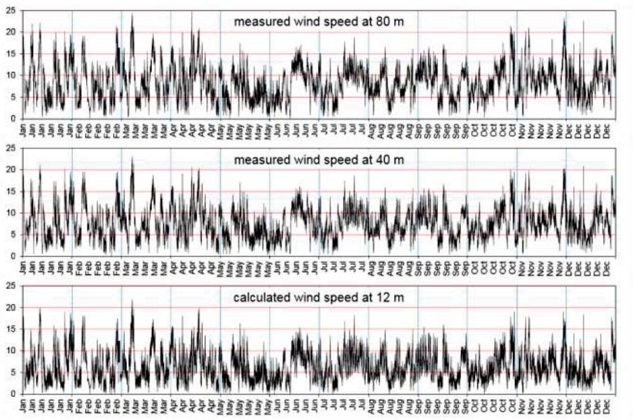
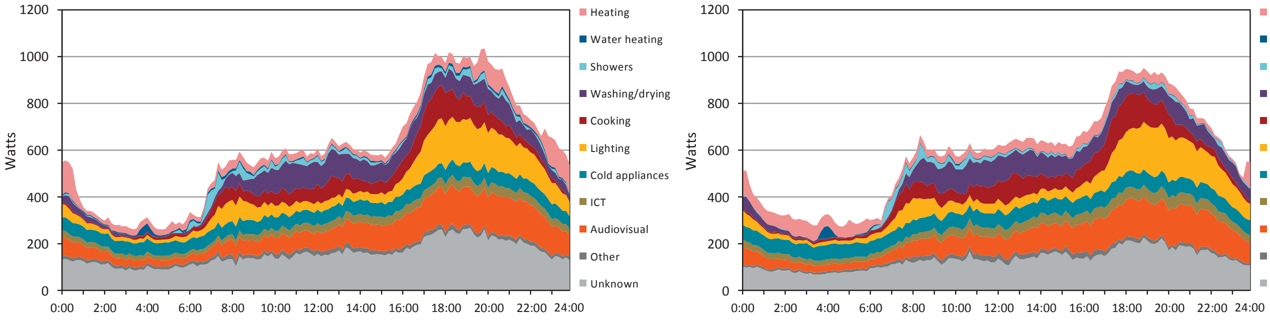


Fig. 4. Measured and calculated wind speeds at 80m, 40m and 12m heights

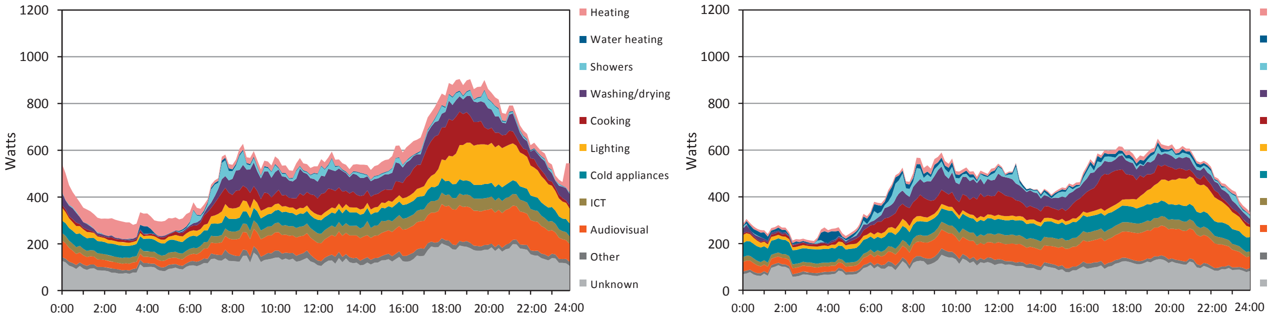
metering, we can say that the consumption increases in the evenings compared to the consumption in day time since all the household is at home, and also the consumption decreases after midnight since everybody is sleeping. The consumption varies with the seasons also. For example, consumption increases in winter and decreases in summer. From the electric bills, the house consumes an average of 310 W electric power.

In 2010 in the United Kingdom, the Department of Energy and Climate Change (DECC), the Department for Environment, Food and Rural Affairs (Defra) and the Energy Saving Trust jointly commissioned the Household Electricity Survey (HES) in a project to understand residential energy usage in UK. In this Household Electricity Study, a total of 251 house across England was undertaken to monitor the electrical power demand and energy consumption over the period May 2010 to July 2011. During this period, the consumption of these houses are logged. The daily average electricity consumption data in 10-minutes interval for each 12 months obtained in this study are open to public in UK government's web site [19]. The average daily consumption obtained in the Household Electricity Survey (HES) in different months in a year is given in Figure 5.

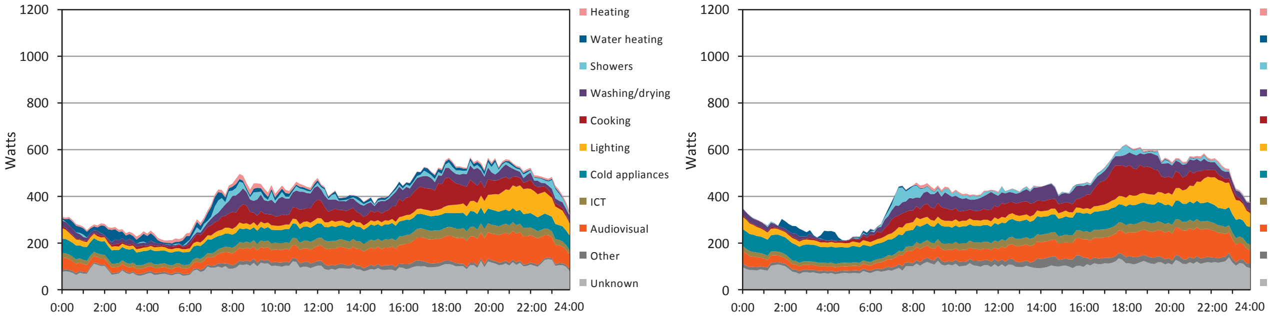
When we examine these HES data we see that the average power consumption is 517.6 W. When we scale these data with 0.6 the average consumption of HES almost matches with the consumption of our house in Catalca (≈ 310 W). Also when we compare some of our measured instantaneous



a) January **b)** February

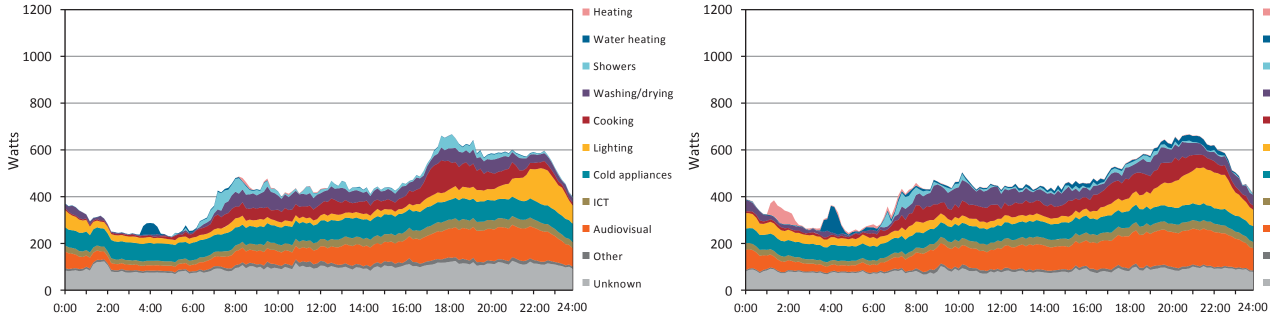


c) March **d)** April

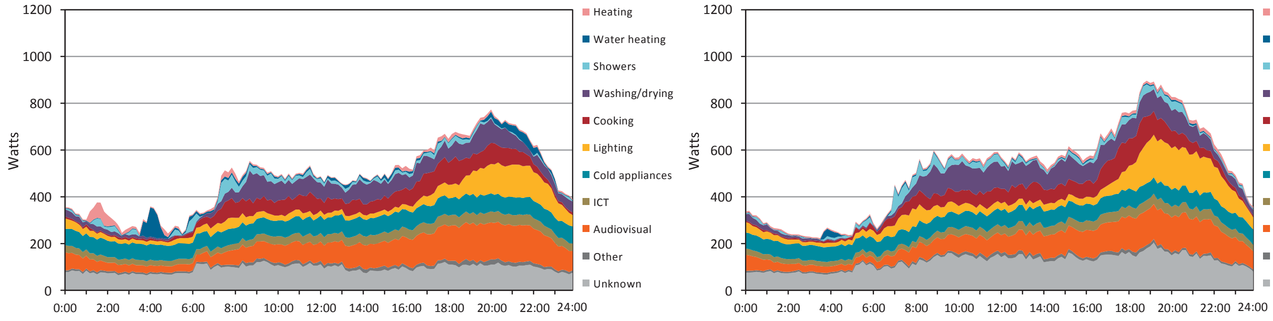


e) May **f)** June

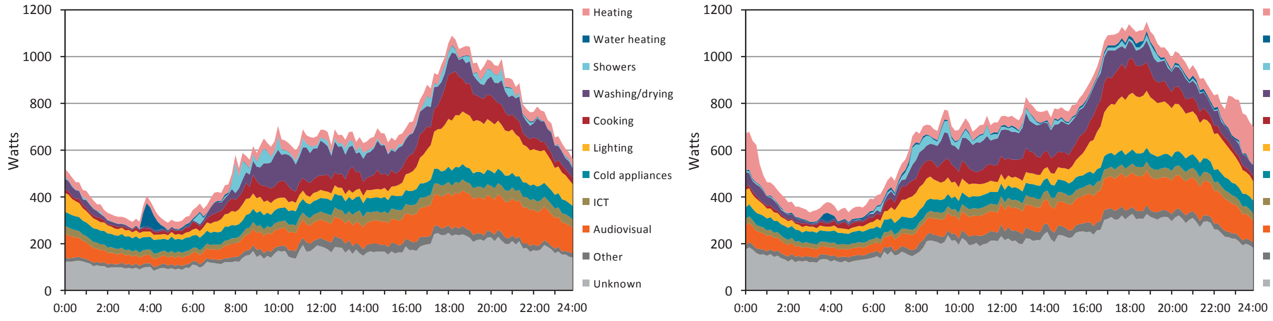
Fig. 5. Average daily consumption of the Household Electricity Survey



g) July **h)** August



i) September **j)** October



k) November **l)** December

Fig. 5. Average daily consumption of the Household Electricity Survey (continued)

consumption data from the house taken at some random days and nights at some random hours in different months of the year with the HES data, we see that our measured instantaneous consumption data have 0.6 ratio at any time in the year with the published HES data with an error less than ≤ ±5%. Since the energy consumption of our house in Catalca matches very well with the published HES data with a 0.6 ratio within a small percent error, we decided to use these published data as representative of the electrical consumption of our house.

2.7. Calculations

The Figure 6 shows the algorithm followed in calculating the number of batteries for a chosen wind turbine. First, a wind turbine is chosen and therefore the corresponding power curve is used in calculation of the power generated by the wind turbine. At the beginning the calculations are started with 1 battery. We have wind data for every 10-minutes and also we have the consumption of the house for the same 10-minutes. Using the equations given in Section 2.2 the density of the air is calculated considering the air pressure, temperature and humidity. Also the wind speed is calculated at 12m heights which is the hub height of the selected wind turbine. We note that it is the usual case that the power curves of the wind turbines are given as normalized to the sea level air density which is 1.225 kg/m3. Since the calculated air density is different at every 10-minutes, the power curve of the wind turbine is corrected at every 10-minutes according to this calculated air density. From this corrected power curve using the calculated wind speed at 12m height, the power generated by the wind turbine is calculated in this 10-minutes and then the charge controller efficiency is applied to the calculated generated power. For the same 10-minutes the power consumption is known and the generation is compared with the consumption. If the consumption is less than the generation the excess energy will charge the batteries. We note that when the batteries are full in order to protect batteries the excess energy is diverted to the dump load by the charge controller. On the other hand, if consumption is greater than the generation the amount of the difference is discharged from the battery in order to supply the house, thus the energy stored in the battery is decreased. In the case when the batteries need to supply energy to the house inverter efficiency is applied. At any time if the batteries become empty this means that the amount of batteries is not enough for a self-sufficient system

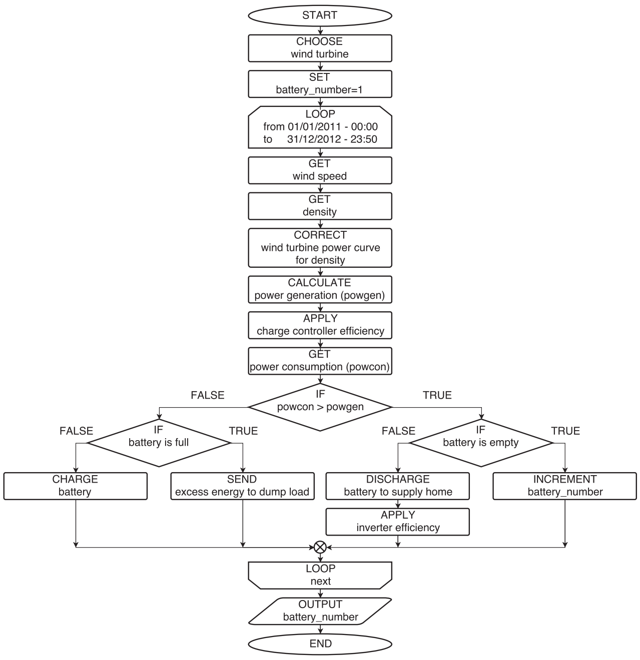


Fig. 6. Flowchart of the calculation algorithm

therefore another battery is added to the system and therefore the number of batteries in the battery bank is increased by 1. These calculations are carried out for 25 years. In this 25 years the wind speed data and the consumption data is assumed to repeat each year. Within this 25 years of calculation if the energy in the battery bank never goes to zero the minimum number of batteries that would supply continuous energy to the house is obtained. The same calculations are then repeated for a different wind turbine and the minimum number of batteries needed for that particular wind turbine for 25 years of continuous supply is obtained.

Table 2. Wind turbines used in our calculations

Wind Turbine Model Name	Manufacturer's Rated Power
Swift [24]	1 kW @ 11 m/s
Sumec PWB01.2.1 [25]	1 kW @ 10 m/s
Pika T701 [26]	1.5 kW @ 11 m/s
Sumec PWB02.2.1 [27]	2 kW @ 10 m/s
Skystream 3.7 [28]	2.1 kW @ 11 m/s
Kestrel e400nb [29]	2.5 kW @ 11 m/s
Sumec PWA03.2.1 [30]	3 kW @ 11 m/s
Windera S [31]	3.2 kW @ 11 m/s
Fortis Montana [32]	3.3 kW @ 11 m/s
Windspot 3.5 [33]	3.5 kW @ 12 m/s
Sumec PWA05.2.1 [34]	5 kW @ 11 m/s
Kingspan KW6 [35]	5.2 kW @ 11 m/s
Excel 6 [36]	5.5 kW @ 11 m/s
Virdy CS-8 [37]	8 kW @ 10 m/s
Excel 10 [38]	8.9 kW @ 11 m/s
LA10 [39]	9.6 kW @ 11 m/s
CF10 [40]	10 kW @ 11 m/s
Osiris 10 [41]	10 kW @ 9 m/s
Xzeres 442SR [42]	10.4 kW @ 11 m/s
GW 133-11 [43]	10.7 kW @ 11 m/s

2.8. Wind Turbines

In this study 20 different small wind turbines with different rated powers are used. In choosing the wind turbines we have decided that we use the horizontal axis wind turbines that are tested and have certification given by a third-party authority only. The list of wind turbines that have received the Small Wind Certification Council (USA) approval can be found on the organization's website [20]. The wind turbines that have received MCS (UK) accreditation are listed on the Microgeneration Certificate Scheme website [21]. The list of the wind turbines that are tested by Intertek, a total quality assurance provider, can be found on the company's website [22]. The small wind turbines tested at National Renewable Energy Laboratory (NREL) National Wind Technology Center (NWTC) as part of the U.S. Department of Energy's (DOE's) Independent Testing project can be found in NREL's web site [23]. Among the available certified wind turbines, we only consider the horizontal axis wind turbines that has rated powers ranging between 1-10 kW. Table 2 lists the wind turbines used in this study.

3. Results

In Table 2 the listed wind turbines used in this study are sorted according to their manufacturer's rated power. As it is seen in Table 2, manufacturers rate their wind turbine at different wind speeds and this makes it difficult to compare different wind turbines with each other. American Wind Energy Association (AWEA) defines the "AWEA Rated Power" as the wind turbine's power output at 11 m/s (24.6 mph) per the power curve from IEC 61400-12-1 standard. From now on, for the considered wind turbines in this study the AWEA Rated Power will be used instead of the manufacturer's rated power. Following the calculation algorithm given in Section 2.7, for each wind turbine listed in Table 2 the minimum number of batteries needed in the battery bank that would guarantee uninterrupted continuous power supply for 25 years is obtained. Table 3 shows the calculated minimum battery numbers for each wind turbine to be used in our off-grid wind-battery system sorted according to AWEA Rated Power.

Examining the results in Table 3, the Swift wind turbine [24] has the maximum number of batteries with 25155 batteries and the Osiris 10 wind turbine [41] has the minimum number of batteries with 14 batteries. The difference between this maximum and the minimum number is huge. The Swift wind turbine [24] has a unique different design. For an off-grid system most of the consumers would think that as the rated power of the wind turbine increases the needed minimum number of batteries in the battery bank would decrease. However as seen in Table 3 this not the usual case. In this table it can be seen that some smaller rated power wind turbines require less number of batteries than some greater rated power wind turbines. For example, while 7.6 kW Virdy CS-8 wind turbine [37] requires 43 number of batteries, a much smaller 3 kW Sumec PWA03.2.1 wind turbine [30] requires 31 number of batteries which is quite less. While 3.2 kW Windspot 3.5 wind turbine [33] and 7.6 kW Virdy CS-8 wind turbine [37] requires almost the same number of batteries

Table 3. Calculated minimum number of batteries required in the battery bank

Wind Turbine Model Name	Number of batteries	AWEA Rated Power (@ 11 m/s)
Swift [24]	25155	0.9 kW
Sumec PWB01.2.1 [25]	79	1.2 kW
Pika T701 [26]	114	1.5 kW
Sumec PWB02.2.1 [27]	36	1.7 kW
Skystream 3.7 [28]	71	2.1 kW
Kestrel e400nb [29]	65	2.5 kW
Sumec PWA03.2.1 [30]	31	3 kW
Windera S [31]	35	3.2 kW
Windspot 3.5 [33]	45	3.2 kW
Fortis Montana [32]	33	3.3 kW
Sumec PWA05.2.1 [34]	27	5 kW
Kingspan KW6 [35]	32	5.2 kW
Excel 6 [36]	23	5.5 kW
Virdy CS-8 [37]	43	7.6 kW
Excel 10 [38]	21	8.9 kW
LA10 [39]	23	9.6 kW
Osiris 10 [41]	14	9.8 kW
CF10 [40]	19	10 kW
Xzeres 442SR [42]	22	10.4 kW
GW 133-11 [43]	18	10.7 kW

(45 and 43 respectively), 5 kW Sumec PWA05.2.1 wind turbine [34] requires 27 batteries. Another example, 10.4 kW Xzeres 442SR wind turbine [42] requires 22 batteries on the other hand almost at half power, 5.5 kW Excel 6 wind turbine [36] requires 23 batteries. The number of batteries in the Table 3 clearly shows that the minimum number of batteries needed is not directly related with the rated power of the wind turbine. At first this sounds contradictory, however the explanation to this lies in the power curves of the wind turbines.

We group the considered wind turbines according to their rated powers; rated power < 3 kW, 3 kw ≤ rated power < 5 kW, 5 kw ≤ rated power < 8 kW and 8 kw ≤ rated power and examine these 4 group of wind turbines separately.

The power curves of the wind turbines with rated power < 3 kW are given in Figure 7. In Table 3 the Swift wind turbine [24] requires 25155 batteries. At first this number seems too big for a 0.9 kW wind turbine however looking at its power curve in Figure 7 we can see that below 5 m/s wind speeds the Swift wind turbine [24] does not give any power and at 10 m/s wind speed the power it can deliver is 650 W. We note that according to Table 1 in Catalca almost 70% of the time the wind has a speed ≤ 10 m/s. This means that the Swift wind turbine [24] delivers less than 650 W 70% of the time which is not enough to compensate the consumption of the house. We also calculate the minimum number of battery that is necessary when there is no wind turbine and the battery bank is the only source to supply energy to the house for 25 years and we find that 56828 number of batteries are needed to run the house on batteries only without any wind turbine. Comparing this many batteries (56828 batteries) with the minimum number of batteries needed along with the Swift wind turbine [24] (25155 batteries), we can say that the Swift wind turbine [24] can only decrease the number of batteries needed by half roughly.

In Table 3 in rated power < 3 kW wind turbine group, we can see that Sumec PWB02.2.1 wind turbine [27] requires the minimum number of batteries with 36 batteries. If we look at Figure 7 we can see that Sumec PWB02.2.1 wind turbine [27] can deliver the largest power at any wind speeds up to 11 m/s. In this group even though Skystream 3.7 wind turbine [28] delivers the most power above 11 m/s, since the frequency of the wind above 11 m/s speed is quite low, the Sumec PWB02.2.1 wind turbine [27] has the smallest number of batteries. This suggests that for a wind turbine the power

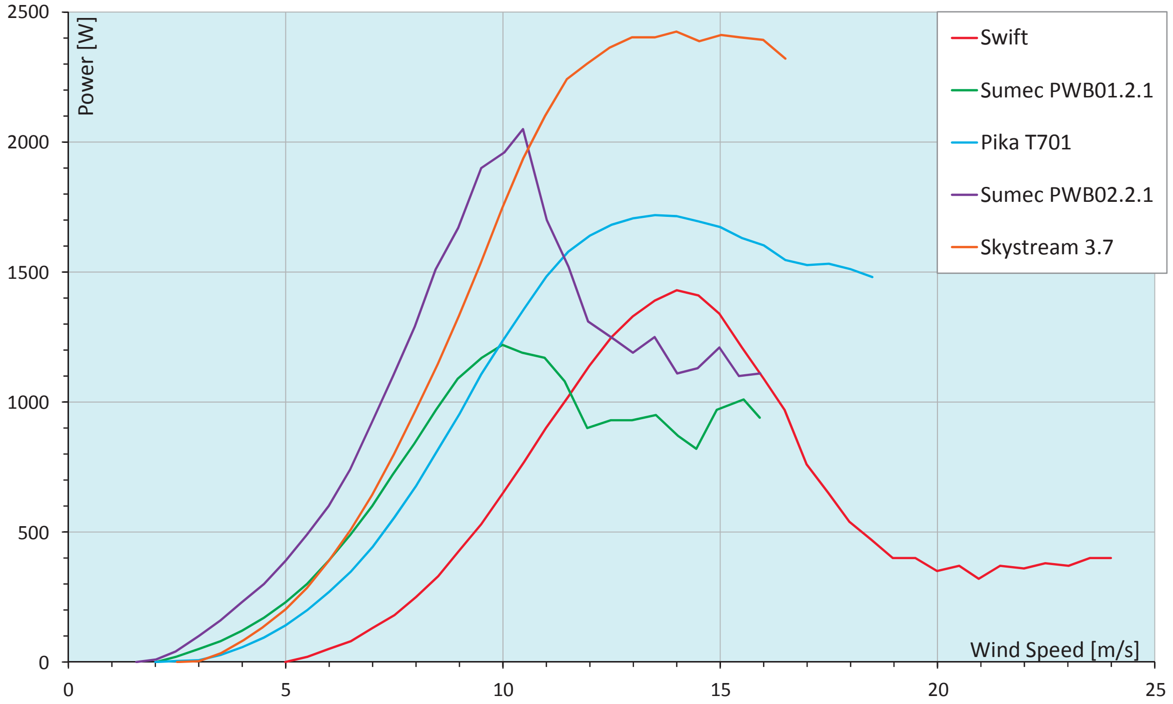


Fig. 7. Wind Turbine Power Curves (rated power < 3 kW)

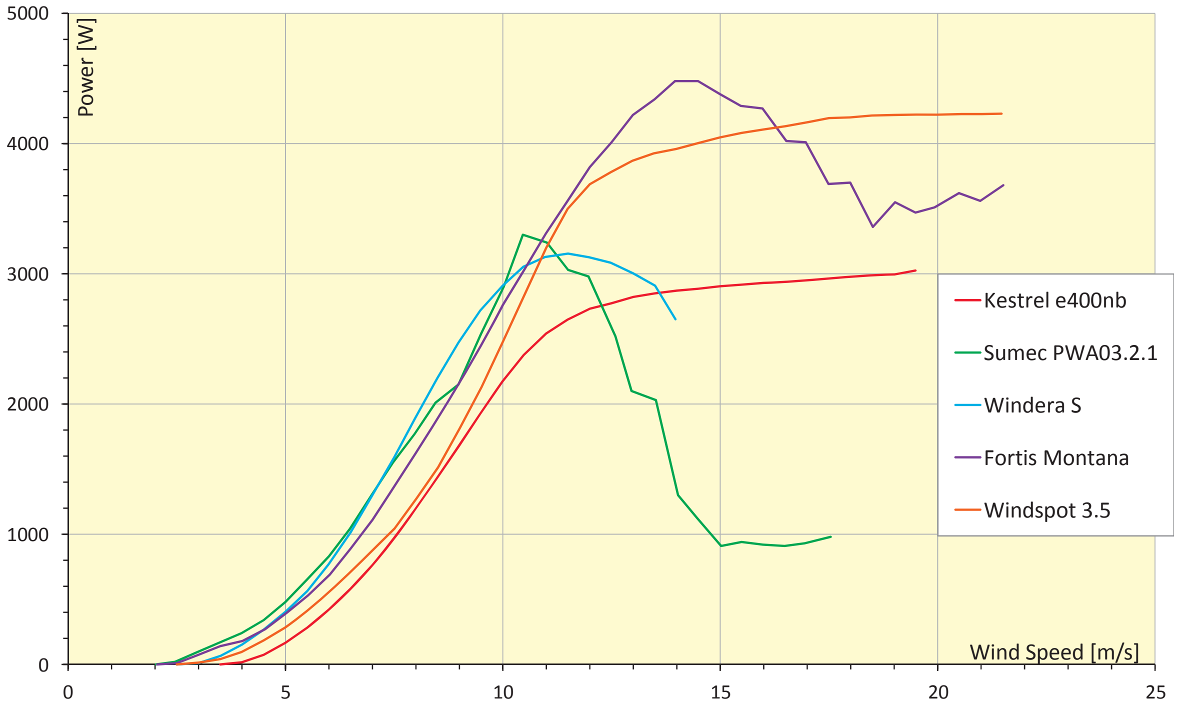


Fig. 8. Wind Turbine Power Curves (3 kw ≤ rated power < 5 kW)

generated at low wind speeds is far more important than the power generated at high wind speeds. For a wind turbine's power curve, it is better if it shifts to left and also up in order to deliver more power at low wind speeds.

In Table 3 looking at 3 kw ≤ rated power < 5 kW wind turbine group, we see that Sumec PWA03.2.1 wind turbine [30] requires the smallest number of batteries then followed by Fortis Montana wind turbine [32] and then Windera S wind turbine [31]. Looking at Figure 8 we can see that up to 7 m/s wind speeds Sumec PWA03.2.1 wind turbine [30] delivers the most power compared to others while above 7 m/s Windera S wind turbine [31] starts to deliver more power and also above 11 m/s Fortis Montana wind turbine [32] delivers the most power. As the same with the previous group, Sumec PWA03.2.1 wind turbine [30] that delivers the most power at low speeds requires the least number of batteries. Comparing the wind turbines with second and third least number of batteries in this group, we see that up to 4 m/s wind speed Fortis Montana wind turbine [32] delivers more power compared to Windera S wind turbine [31] however after 4 m/s wind speed Windera S wind turbine [31] delivers more power

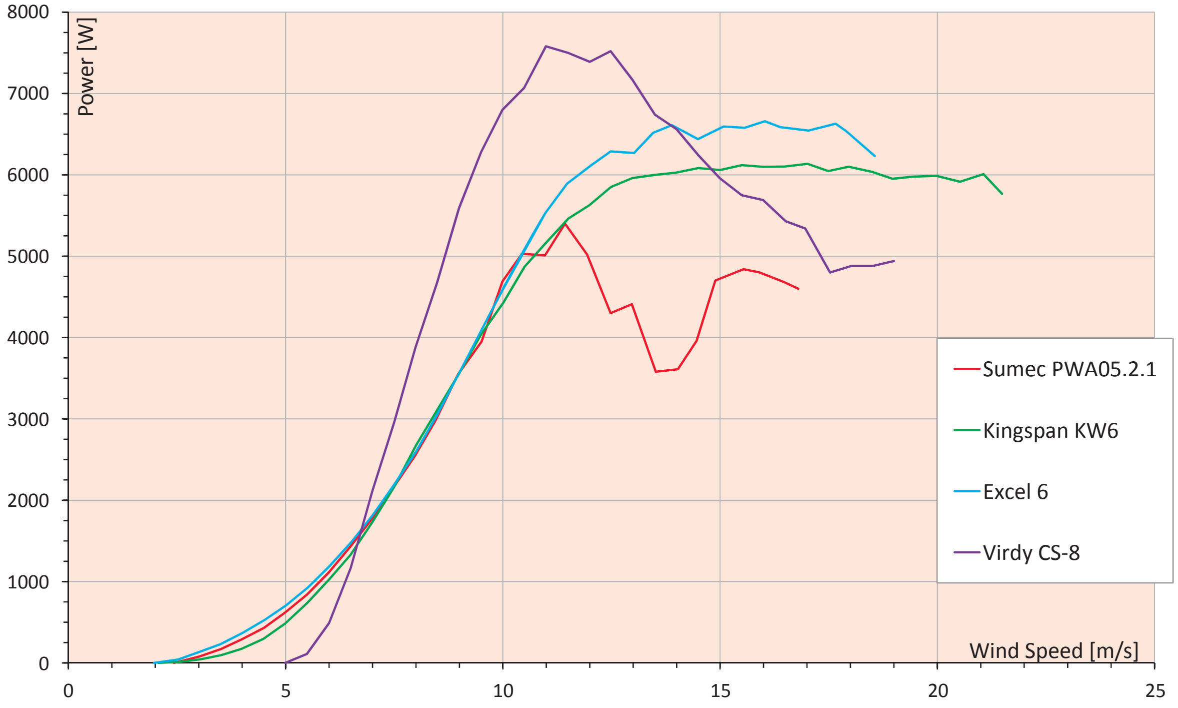


Fig. 9. Wind Turbine Power Curves (5 kw ≤ AWEA rated power < 8 kW)

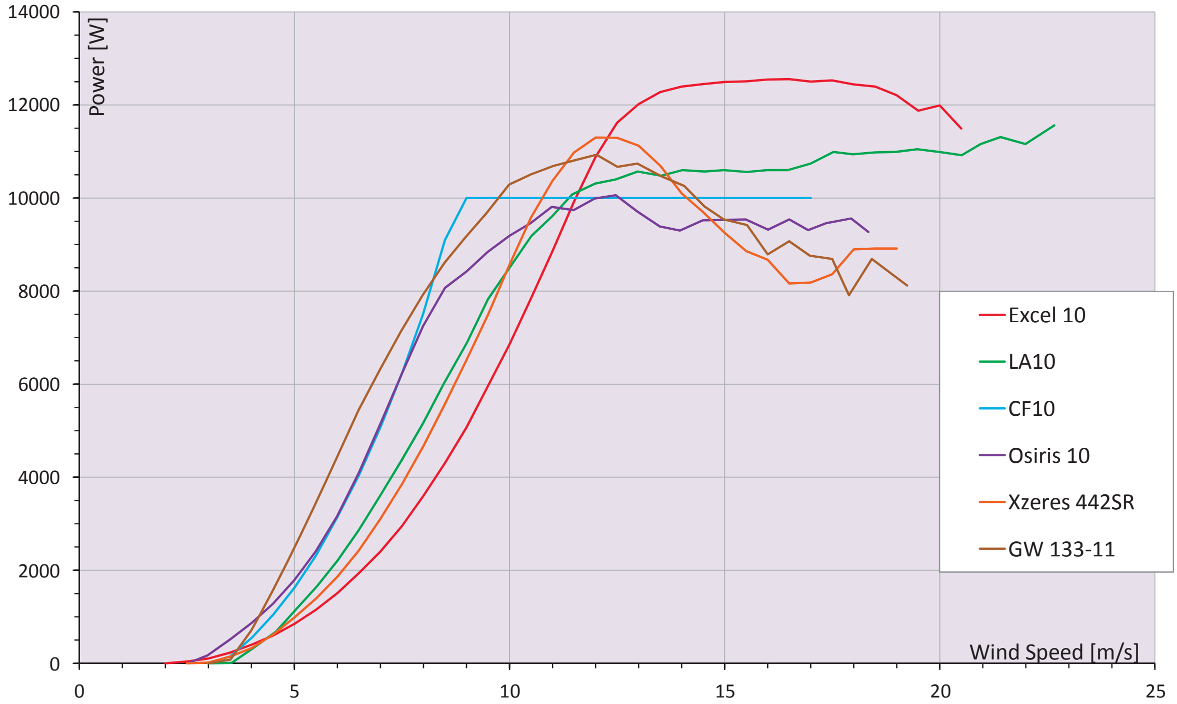


Fig. 10. Wind Turbine Power Curves (8 kw ≤ rated power)

than Fortis Montana wind turbine [32]. Looking at Table 3 Fortis Montana wind turbine [32] requires 33 batteries however Windera S wind turbine [31] requires 35 batteries. This suggests that even though the power generated at wind speeds less than 4 m/s are quite low since the frequency of the wind at these speeds is high, it cumulatively makes a difference.

In Table 3 looking at the 5 kw ≤ rated power < 8 kW wind turbine group, we see that Excel 6 wind turbine [36] requires the lowest number of batteries. In Figure 9 among this group of wind turbines Excel 6 wind turbine [38] delivers the most power at wind speeds less than 7 m/s.

In Table 3 looking at 8 kw ≤ rated power wind turbine group, we see that the Osiris 10 wind turbine [41] requires the minimum number of batteries with 14 batteries. In this group for example the LA10 wind turbine [39] requires 23 batteries which is almost 65% more than that of Osiris 10 wind turbine [41]. Following Osiris 10 wind turbine [41], GW 133-11 wind turbine [43] is the second with 18 number of batteries. In Figure 10 we can see that the Osiris 10 wind turbine [41] delivers the most power up to 4 m/s and above 4 m/s GW 133-11 wind turbine [43] delivers the most power up to 8 m/s wind speed. Although above 4 m/s the Osiris 10 wind turbine [41] is not the wind turbine that delivers the most power, due to the power delivered below 4 m/s, the Osiris 10 wind turbine [41] requires the lowest number of batteries.

We note that in this last group (8 kw ≤ rated power) the wind turbine rated powers are rather big compared to previous groups of wind turbines and most of the time since the wind turbine power generation is much greater than the consumption of the house, most of the power generated by the turbines must be directed to the dump loads. Table 4 lists the total energy generated by the wind turbines in 25 years and also the energy dissipated in the dump loads. We note that the total electrical consumption of the house for 25 years is 68193.5 kWh. In our calculations we consider that the batteries are fully charged in the beginning. At the end of 25 years if the batteries are not in fully charged state, this would mean that the amount of energy from the fully charged state is used in the house. In Table 4, how much energy is used from the batteries from the fully charged state at the end of 25 years is also listed. In Table 4 we can clearly see that the Swift wind turbine [24] can only generate 38029.7 kWh electrical energy which corresponds to almost half of the demand of 68193.5 kWh. During this 25 years at very rare times the Swift wind turbine [24] can able to fully charge the battery bank and when this happens the further excess amount of energy is diverted to the dump loads to dissipate. Almost all of the energy generated by the Swift wind turbine [24] in 25 years is consumed in the house while only 9.4 kWh of energy diverted to the dump load in 25 years, as listed in Table 4. Since the energy generated by the Swift wind turbine [24] is not enough, the rest of the energy required to supply the house actually comes from the initially fully loaded 25155 batteries. In Table 4 we can see that all the wind turbines except that the Swift wind turbine [24] can generate more energy than the consumption as a total. We note that the wind turbines in Table 4 are also sorted according to AWEA rated power as it is done the same in Table 3. One interesting thing in Table 4 is that except some of the wind turbines (Sumec PWB02.2.1 [27], Windspot 3.5 [33], Xzeres 442SR [42]) the total energy generation by the wind turbines increases as the AWEA rated power increases downwards in the list. This is something expected, as the AWEA rated power of the wind turbine gets bigger, the wind turbine can generate more energy cumulatively at the end of 25 years. One usually think that the number of batteries would decrease as the AWEA rated power of the wind turbine increases. However, as shown in this study, the required number of batteries does not decrease in an order as the AWEA rated power of the wind turbine increases. The minimum required number of batteries in a wind turbine-

Table 4. Wind turbine energy generation and energy sent to dump load

Wind Turbine Model Name	Wind Turbine Generation [kWh]	Energy Sent to Dump Load [kWh]	Net Energy Used from Battery Bank [kWh]
Swift [24]	38029.7	9.4	30173.1
Sumec PWB01.2.1 [25]	75938.0	7810.1	65.5
Pika T701 [26]	76290.2	8193.6	96.8
Sumec PWB02.2.1 [27]	117411.1	49217.7	0
Skystream 3.7 [28]	108596.8	40403.4	0
Kestrel e400nb [29]	128037.4	59843.9	0
Sumec PWA03.2.1 [30]	168143.1	99949.6	0
Windera S [31]	177723.3	109529.8	0
Windspot 3.5 [33]	158985.4	90792.0	0
Fortis Montana [32]	183758.7	115565.3	0
Sumec PWA05.2.1 [34]	267241.2	199047.8	0
Kingspan KW6 [35]	278718.7	210525.3	0
Excel 6 [36]	300934.4	232741.0	0
Virdy CS-8 [37]	345614.5	277421.0	0
Excel 10 [38]	461125.7	392932.3	0
LA10 [39]	531733.5	463540.1	0
Osiris 10 [41]	636675.3	568481.8	0
CF10 [40]	655160.0	586966.6	0
Xzeres 442SR [42]	511808.4	443614.9	0
GW 133-11 [43]	719767.6	651574.1	0

battery system depends completely on the power curve of the wind turbine, especially the behaviour of the power curve at low wind speeds. The key point is that, ideally it is best if the wind turbine generates electric power enough to supply the demand when the wind speed is less while the battery is not full. Otherwise if the wind speed is high and the wind turbine generates power more than necessary or consumption and meanwhile if the batteries are full, the excess power will be useless and diverted to the dump load. In Table 4 except the three wind turbines, we can see that the net energy used from the battery are all zero at the end of 25 years. This basically means that at the end of 25 years the batteries are in fully charged state. For these wind turbines since both at the beginning and at the end of 25 years the batteries are in fully charged state, during the 25 years the net energy used from the battery is zero.

In Table 4 we can see that, for example, when GW 133-11 wind turbine [43] is used the total amount of energy dissipated in the dump load is almost 10 times of the total consumption of the house. This probably states that GW 133-11 wind turbine [43] is oversized for the needs of this house and almost 90% of the generated energy by the wind turbine is not used but dissipated. However, practically for the consumer the best system among the calculated wind turbine-battery system would be the one with the lowest cost since all of the systems with the calculated number of batteries in the battery bank would guarantee continuous energy supply to the house. After such a study for the consumer the next step would be to negotiate and obtain the final total cost of each wind turbine and the corresponding battery bank and then decide on the wind turbine-battery system.

4. Conclusions

For a remote house in Catalca Istanbul which is isolated from the grid lines that uses a wind turbine-battery system, we have calculated the minimum required number of batteries in the battery bank for different chosen wind turbines that will ensure uninterrupted continuous supply to the house. In our calculations we have considered only the wind turbines that have certifications with rated powers ranging from 1 kW to 10 kW. In our calculations we have used actual wind measurement data and actual consumption data collected with 10-minutes averages through one year. We find that the required minimum number of batteries are different for each wind turbines and this number does not change linearly with wind turbine ratings. Our calculations show that the shape of the power curve of the wind turbine affects the minimum number of batteries more rather than the maximum power or rating power of the wind turbine. Especially the power that the wind turbine generates at low wind speeds affects the number of batteries the most.

In designing an off-grid wind turbine-battery system if continuity of electricity without interruption is crucial such a study should be done. Only considering the rated power of a wind turbine alone and from this trying to guess the required number of batteries in the battery bank, which is very common in real practical applications, might either result in a high initial investment cost due to oversized battery bank or worse might result in no available power from time to time due to undersized battery bank.

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