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Practical Case Study

AN OFF-GRID WIND ENERGY SYSTEM POWERING A RESIDENCE IN GAZA

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Abstract: Coastal and mountain areas enjoy high wind speeds in comparison to other areas and this makes them adequate for exploiting wind energy in various applications efficiently. Harnessing wind energy to power electric appliances starts by converting the energy coming from the wind to electricity. Wind turbine systems change the kinetic energy of the wind into electricity. Where the wind energy turns blades coupled mechanically to an electric generator which, in turn, produces electric energy. Building wind turbine systems for domestic applications is one avenue of the various applications. The process of structuring a wind-energy system begins with the design and selection of the equipment ratings. This process depends on a number of factors such as site location, wind speed, and load requirements. The equipment ratings must be carefully selected to ensure a proper and economical operation of the system. In this paper, this paper demonstrates the procedures employed in building and selecting the equipment of an off-grid wind-energy system based on the Watt-Hours demand as a basic design factor. As a case-study, an off-grid wind-energy system for a medium-energy-consumption residence in Gaza city will be presented.

Keywords: Off-grid, wind-turbine, days-of-autonomy, availability factor, system sizing, load profile, and balance-of- system

INTRODUCTION

A wind energy system transforms the kinetic energy of the wind into mechanical or electrical energy that can be harnessed for practical use. Wind electric turbines generate electricity for homes and businesses and in some countries for sale to utilities [1]. Wind speed is a crucial element in projecting turbine performance, and a site's wind speed is measured through wind resource assessment prior to a wind system's construction. As a rule, an annual average wind speed equal or greater than four meters per second (4 $m.s^{-1}$) or 15 $km.h^{-1}$ is required for small wind electric turbines [3]. The power available in the wind is proportional to the cube of its speed, which means that doubling the wind speed theoretically increases the available power by a factor of eight. Wind energy is one of the cleanest, most environmentally friendly energy sources in the world. It is renewable and the supply will never run out, reduces demand for oil and natural gas, and cuts the electric energy bill [2]. Availability factor or just "availability" is another merit of wind turbines. It is a measure of the reliability of a wind turbine and it refers to the percentage of time that wind turbine is ready to generate, that is, not out of service for maintenance or repairs. Modern wind turbines have an availability of more than 98% and higher than most other types of systems.

The wind speed varies with time of the day, season, and weather conditions. Different geographical regions experience different weather patterns, so the site where we live is a major factor that affects the wind-energy system design from many sides; the orientation of the wind turbine, the availability factor where the wind turbine blades rotate and turn the electric generator and the average annual wind speed.

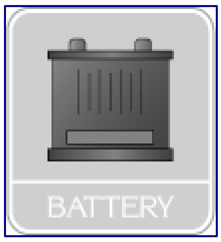
SYSTEM DESCRIPTION

Components

A Wind-energy system is composed of a variety of equipment in addition to the wind turbine, a Balance-of-System, that wired together to form the entire fully functional system capable of supplying electric power and these components are as follows:

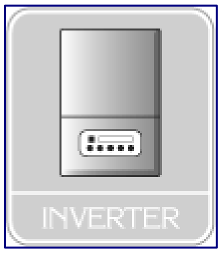
1. Wind turbine represents the fundamental power conversion unit. It transforms the kinetic energy of the wind into mechanical energy that turns an electric generator to produce electric energy. Wind turbines are available at different powers ratings varying between low to medium level to meet the needs for almost all kinds of applications. They are also available at both types of voltages, ac and dc voltages, at levels varying between 12 and 48-Vdc and between 110 and 240-Vac for domestic applications [4]. Wind turbines vary in their shapes and dimensions and designed to produce rated power at a certain wind speed. However a wind turbine produces less power at lower wind speeds and no power at a certain cut-in wind speed. It also produces more power at higher wind speeds and stopped at a certain maximum speed to prevent any damage of the gearbox. Wind turbines are usually supported on the top of turbine towers that have to be at least 6 meters above any surrounding objects within a radius of 150 meters [3].

2. A storage medium, battery bank, which is involved in the system to make the energy available at low wind speeds or at days-of-autonomy, sometimes called no-wind-days, when the wind speed is less than the cut-in speed or not high enough to turn the turbine blades. The standard batteries that are used in wind-energy system are lead-acid batteries because of their high performance, long life time and cost effectiveness. It is recommended though to buy high quality batteries because you get what you pay for. Good deep-cycle batteries can be expected to last 15 years [2], and sometimes more while cheap batteries can give you trouble in half that time.

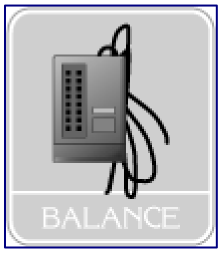


3. A voltage regulator or charge controller is an essential part of nearly all power systems that charge batteries, whether the power source is wind turbine or utility grid. Its purpose is to keep your batteries properly fed and safe for the long term. The basic functions of a controller are quite simple. Charge controllers block reverse current and prevent battery from getting overcharged. Some controllers also prevent battery from getting underdischarged, protect from electrical overload, and/or display battery status and the flow of power [9]. Wind generators are active electricity producers. If the wind is blowing, they will produce current whether the battery bank needs the charge or not. In order to prevent damage to the wind turbine, all of the electricity it produces must be used in some way. Built-in load diversion regulator is usually included with the wind turbine and if not external arrangement must be used.

4. An inverter is a device that changes a low dc-voltage into usable 230V ac voltage. It is one of the wind energy system's main elements, because the wind turbines generate power that is stored it in low dc-voltage batteries. Inverters differ by the output wave format, output power and installation type. It is also called power conditioner because it changes the form of the electric power. There are two types of output wave format: modified sine-wave (MSW) and pure sine-wave. The MSW inverters are economical and efficient, while the sine wave inverters are usually more sophisticated, with high-end performance and can operate virtually any type of load [10]. There are also two types of inverters for installation: off-grid installation and grid-connected installation.



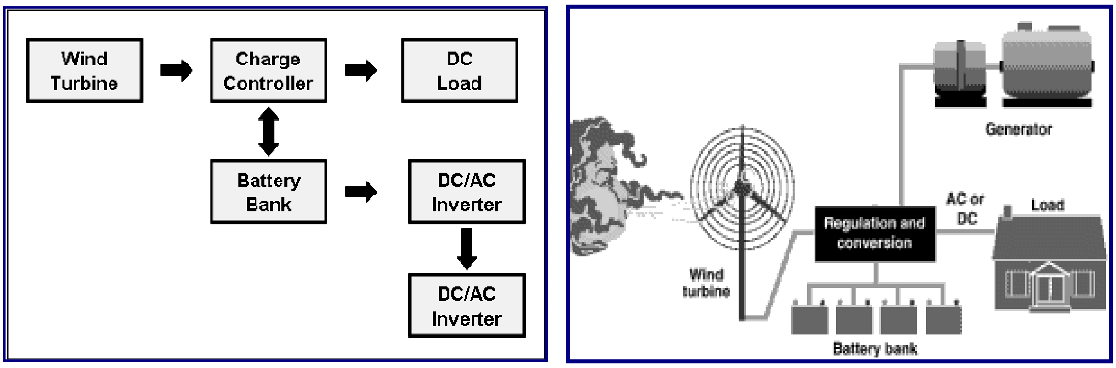
5. Balance-of-system such as protection devices that keep the system components safe during their operation such as lightning-protection that includes devices to protect the sensitive electronic components from the high voltage transients, and ground faults. Additional devices that used to ensure proper operation such as monitoring, metering, and disconnect devices. Wiring is also an important component. It is the mean through which the components of a wind-energy system are connected together. You will need to use correct wire sizes to ensure low loss of energy and to prevent overheating and possible damage or even fire. Selecting the correct size and type of wire will enhance the performance and reliability of your wind system. The size of the wire must be large enough to carry the maximum current expected without undue voltage losses because the wire resistance causes a drop in the voltage from the source to the load [5].



6. AC and DC loads which are the appliances such as lights and radios, and the equipments such as fridges, water pumps, washing machines and microwaves which consume the relatively high power generated by the wind turbine.

Configuration

The wind-energy systems are classified according to how the system components are connected to other power sources such as off-grid or stand-alone (SA) and utility-interactive (UI) or on-grid systems. In an off-grid system depicted in Figure 1, the system is designed to operate independent of the electric utility grid with a backup generator used during maintenance and in case of malfunction. The system is generally designed and sized to supply certain dc- and/or ac-electrical loads. A bank of batteries is used to store the energy in a form of dc power that is produced by the wind turbine to be used at times when the wind is slow and the blades are not rotating. The dc output of the batteries can be used immediately to run certain low dc-voltage loads such as lighting bulbs or refrigerators or it can be converted by an inverter to ac-voltage to run ac-loads that constitute most appliances. However, in utility grid connection or sometimes called utility-interactive or on-grid systems, power is brought in from of the utility grid to supplement the system output when needed, and sold back to the utility when the wind turbine output exceeds the power demand. The capital cost of a SA system is still high due the high price of the equipment used.



(a) (b)

Fig.1: Off-grid System Components (a) Block Diagram (b) Schematic Diagram

SYSTEM SIZING

System sizing is the process of evaluating the adequate voltage and current ratings for each component of the wind-energy system to meet the electric demand at the facility and at the same time calculating the total price of the entire system from the design phase to the fully functional system including, shipment, and labor.

Factors Affecting System Sizing

- The average power demand in Watt-hour per day that can be obtained by itemizing all appliances and their hours of use each day which is referred to as the application load profile.
- Geographical location that dictates the average wind speed, wind turbine orientation, the factor of availability, and number of days of autonomy (no-windy-days).
- Home design, which plays a major rule in maximizing the amount of the generated power by considering the following points: keeping a free wind passage to the wind turbine from any barrier such as trees, windows should be designed to face the south to keep the house as warm as possible, and insulation can be used to minimize the amount of heat losses.
- Using energy-efficient equipments such as compact fluorescent lamps (CFL) for illumination to reduce energy requirements. Moreover, hot water and cooking should not be parts of the residence wind-energy system. Natural gas for instance can be used for cooking and a separate thermal solar energy system can be employed to obtain the hot water directly to avoid the need for changing any part of the wind energy into electricity then using it to obtain hot water.
- The use of low-voltage DC powered electric appliances, nowadays available in the market, is also an important factor in minimizing the system cost. This will reduce significantly the power

rating of the inverter that is used to change the DC power of the batteries into AC power adequate for the ordinary appliances.

- Frequency of switching which determines how often major rotationary loads are switched on and off such as refrigerators and water pumps. Such loads draw high currents every time they start and these loads must be accounted for.

Sizing of the Inverter

Before sizing the inverter, the expected power requirements of the equipment that may operate simultaneously must be determined. The obtained number is multiplied by a factor of safety to obtain the ac average power output of the inverter. This value would be the inverter power rating and then can be used along with a value for the power factor to calculate the ac load current that is delivered to the appliances.

Sizing of the Battery Bank

The amount of rough energy storage required is equal to the multiplication of the total energy demand and the number of days-of-autonomy Erough=E×D. For safety, the result obtained is divided by the maximum allowable level of discharge (MDOD):

$$E_{safe} = \frac{\text{total energy demand}}{\text{maximum depth of discharge}} = \frac{E_{rough}}{MDOD} \qquad (1)$$

At this moment, we need to make a decision regarding the rated voltage of each battery Vb to be used in the battery bank. The capacity of the battery bank needed in ampere-hours can be evaluated by dividing the safe energy storage required by the DC voltage of one of the batteries selected:

$$C = \frac{\text{energy storage}}{\text{voltage of one battery}} = \frac{E_{safe}}{V_b} \qquad (2)$$

According to the number obtained for the capacity of the battery bank, another decision has to be made regarding the capacity C_b of each of the batteries of that bank. The battery bank is composed of batteries that are connected in series and in parallel according to the selected battery voltage rating and the system requirements. The total number of batteries is obtained by dividing the capacity C of the battery bank in ampere-hours by the capacity of one of the battery C_b selected in ampere-hours:

$$N_{batteries} = \frac{\text{capacity of battery bank}}{\text{capacity of one battery}} = \frac{C}{C_b} \qquad (3)$$

The connection of the battery bank can be then easily figured out. The number of batteries in series equals the DC voltage of the system divided by the voltage rating of one of the batteries selected:

$$N_s = \frac{\text{system dc voltage}}{\text{voltage of one battery}} = \frac{V_{DC}}{V_b} \qquad (4)$$

Then number of parallel paths N_p is obtained by dividing the total number of batteries by the number of batteries connected in series:

$$N_p = \frac{\text{total number of batteries}}{\text{number of batteries in series}} = \frac{N_{battaries}}{N_s} \quad (5)$$

Once the sizing of the battery bank is made available, we proceed to the next system component.

Sizing of the Voltage Regulator

According to its function it controls the flow of current from the wind turbine to the battery bank. A good voltage regulator must be able to withstand the maximum current produced by the wind turbine as well as the maximum load current [11]. Sizing of the voltage regulator can be obtained by multiplying the maximum current of the turbine by a safety factor F_{safe}:

$$I = \text{maximum turbine current} \times \text{safety factor} = I_{\max} \times F_{\text{safe}} \quad (6)$$

The factor of safety is employed to make sure that the regulator handles maximum current produced by the turbine that could exceed the tabulated value in case of unexpected wind speed. And to handle a load current more than that planned due to addition of equipment, for instance. In most modern wind turbines, a charge controller is included and there is no need for additional regulation. Also, the regulation must handle the load diversion control.

Sizing of the Wind Turbine

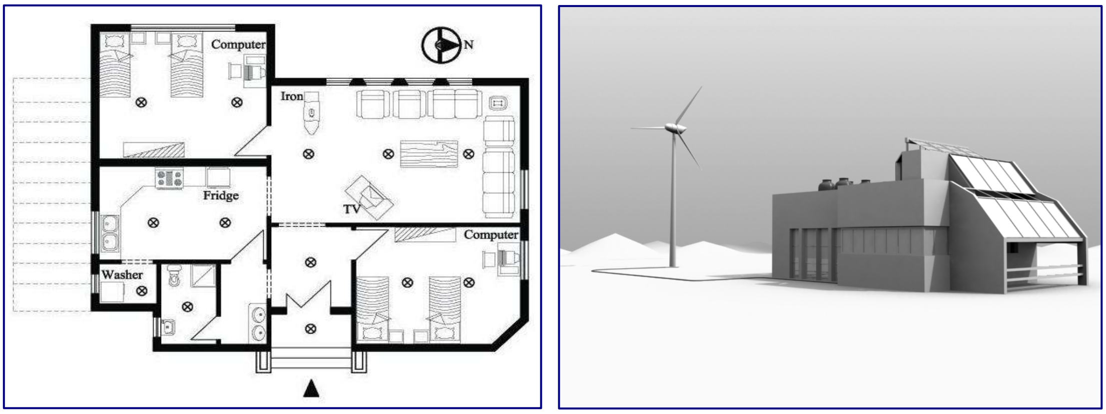
The wind turbine sizing depends mainly on the site location that dictates the average wind speed, the turbine orientation, and the average energy consumption of the application. The average wind speed is obtained from the record of the meteorological station in the site location whereas the average energy consumption is determined through itemizing the appliances of the application and the number of hours of their operation. With these two figures in mind, an investigation of the wind turbines available in the market should help in finding the adequate wind turbine for the application.

CASE STUDY: A RESIDENCE IN GAZA

The direct costal location of the Gaza Strip on the Mediterranean Sea at 31.3^{o} latitude and 34.3^{o} longitude makes it enjoy a reasonable wind patterns during the whole year as far as small wind-energy systems are concerned. This makes it a good candidate for exploiting wind energy for various applications. In the following we will apply the mathematical formulas discussed above on a coastal residence with medium-energy-consumption. The direct coastal location on the Gaza beach ensures passage-free wind and so the wind turbine harnesses most of the wind energy because of the absence of any obstacles. The average annual wind speed recorded in Gaza is 20.23 km.h^{-1} (5.62 m^{-1}), and the highest wind speed recorded is 60 km.h^{-1} in winter [6]. With such wind speeds it is feasible to construct a wind-energy system in this geographical location. The number of days-of-autonomy, where the wind speed will be less than the speed limit required for the turbine blades to rotate and turn with them the electric generator, is approximated to 6-days in July according to the wind speed records of Gaza [7,8].

The Suggested Residence

The area of the suggested coastal residence depicted in Figure 2 is about 100 m^2 with free-wind-passage and assuming that all environmental design factors are taken into account.



(a) (b)

Fig. 2: Suggested Residence (a) Top View (b) Isometric View

As a first step, the electrical appliances available at the residence are itemized with their power ratings and time of operation to obtain the average energy demand in Watt-hours per day as listed in Table 1.

Table 1: Residence Appliances and Daily Energy Consumption

Appliance	Power (Watt)	Hours used/day	Energy (Wh/day)
Compact Fluorescent Lamps	15 × 11	4	660
TV and Recorder	125	6	750
Refrigerator	200	8	1600
Computer with Accessories	125	4	500
Iron	1000	4/7	571
Washing Machine	245	3/7	105
Total Daily Average Energy Consumption			4186 approximated 4500

This approximated figure obtained would be used as the total daily average energy consumption, then the process of determining the equipment sizes and ratings starts with the inverter and this process goes back to the wind turbine and ending with system wiring and a cost estimate.

Sizing of the Inverter

The inverter must deliver energy of 4.5 $kWh.day^{-1}$ in a sinusoidal form at 220 V and 50 Hz frequency. If we choose the system DC voltage of 24 V, then the picture is clear. We are looking for an inverter that takes a 24-Vdc from the battery bank and transforms it to 220-Vac at a frequency of 50-Hz. The average power of the appliances that may run at the same time is given by P= (10×11+125+200+1000) =1435 W and the appliances with large surge currents that include motors are 245×3=735 W. To allow the system growth, we add 25% of the previous two values to get total power as follows:

$$P_{Total} = (\text{power of appliances running simultaneously} + \text{power of large surge current appliances}) \times 1.25$$

$$P_{Total} = (1435 + 735) \times 1.25 = 2712 \quad \text{W} \tag{7}$$

The inverter needed must be capable of handling 2712-W at 220-Vac. Latronics inverter, LS-3024, 3000-W, 24-Vdc, 220-Vac, true sine wave, with a half-hour rating of 3700-W and surge power of 9000-W for 5 seconds is a good choice. The listed price for this inverter is $2900 [10].

Sizing of the Battery Bank

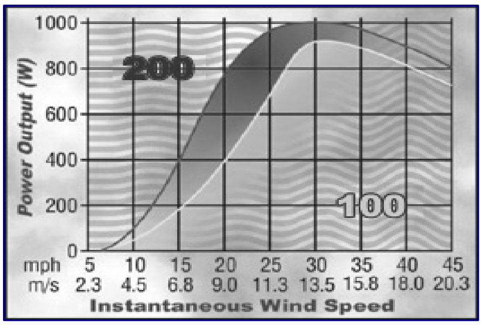
The amount of energy storage required is, E_{rough}=4.5×6 = 27 kWh, where the number 6 represents the number of days-of-autonomy (no-wind days in the location). For safety, we divide the previous value by allowable level of discharge, MDOD (75%)

$$E_{safe} = \frac{\text{required energy storage}}{\text{maximum depth of discharge}} = \frac{27}{0.75} = 36 \quad \text{KWh} \tag{8}$$

The capacity of the battery bank in ampere-hours assuming a battery voltage of 12 V has been selected, C =36000/12=3000 Ah, and according to the selected battery (UB-8D AGM -250 AH, 12V-DC and a price of $475) [12], the number of batteries needed is, $N_{batteries}$ =3000/250=12 batteries. With system DC-voltage of 24 V, six parallel branches are established according to the equation N_p=12/2=6. Each branch contains 2 series batteries. The storage batteries price amounts to $5700.

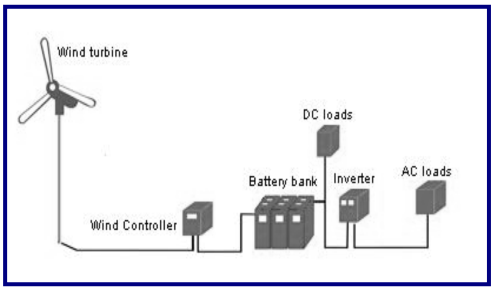
Sizing of the Wind Turbine

The manufacturers produce wind turbines with different sizes and ratings. Technical specifications are also provided that help select the sizes and ratings of theses turbines. The selected residence in our case study consumes and an average energy of 4.5 kWh.day^{-1} which is about 150 kWh.month^{-1}. The Whisper wind turbines series are produced in ranges vary between 900-5000 W for a dc voltage rating of 24. The Whisper 200 wind turbine is designed to operate in a site with medium to high wind speed averages of 3.6 m.s^{-1} and greater with an estimate of 25-30 years of service. A Whisper 200 wind turbine rated 1000-W with the characteristics shown meets the energy requirements of a home with 200-kWh consumption per month [4]. This makes the Whisper 200, 1000-W wind turbine adequate for our residence. With the minimum average wind speed recorded in October (4.89 m.s^{-1}), the generated power of this turbine would be 5.4 kWh.day^{-1} according to the characteristics shown. The Whisper 200 wind turbine comes with a charge controllers and load diversion and this eliminates the need for any additional charge regulation or load diversion techniques. The wind turbine orientation should be directed toward the south-west to capture maximum available wind energy where the wind blows most of the time from that direction. The listed price for the selected turbine is $3750 [4].



Sizing of the System Wiring

Selecting the correct size and type of wire will enhance the performance and reliability of a wind-energy system. The graph depicted shows the wiring diagram of a stand-alone wind-energy system. The dc-wires between the turbine and the batteries through the voltage regulator must withstand the maximum current produced by the turbine generator. This current is given by the maximum output power of the wind turbine divided by the operating dc voltage of the system; i.e. I_m=1200/24=50 A. For this current, the optimum wire size would be #5 copper wires (AWG) [13], while the ac-wire from the inverter to the electric panel of the residence must withstand the maximum current produced by the inverter output. This current is given by the following formula for a rated ac-voltage of 220V, I_m=3000/(220×pf)=17.04-A at 0.8 power factor. For this ac current, an optimum wire type would be #10 copper wires (AWG) [13]. In both ac- and dc-wiring the voltage drop is taken not to exceed the 4% value.



System Components Summary

The equipments used to construct the stand-alone wind-energy system for our suggested residence are summarized with some details and specifications in Table 2. We should mention that these equipments are not the only ones available in the market and there are many manufacturers who provide such equipments.

Table 2: Summary of the System Components

Item	Model	Component Rating			Size	Unit Price US$	Weight Lb/kg	Warranty Year	Photo
		W or Ah	A	V	inch or meter				
Turbine	Whisper WHI-200	1000 W	~	24	Rotor Dia. 2.7 m	3750	39.46kg	5	
Tower	W-Guyed Tower Kit	-	-	-	Height 9 m	448	130	5	
Batteries	UP Group UB-8D AGM	250 Ah	~	12	20.5 x 10.5 x 10	475	167	1.0	
Inverter	Latronics LS - 3024	3000 W	~	24/220	14.6 x 15.2 x 7.0	2900	24 kg	3.0	
Regulator		Whisper controller and load diversion technique are Included with the Turbine							
Wires	#05 AWG	Diameter= 4.62 mm, Area= 16.8 mm^2							
	#10 AWG	Diameter= 2.59 mm, Area= 5.27 mm^2							

This means there would be differences in equipment ratings and prices. However, equipment ratings, quality, and prices are the factors used to select these equipments in order to reach an optimum performance.

COST ESTIMATE OF THE SYSTEM

The cost of the equipment employed in the system sums up to $12798. Additional cost for design, labor, wiring, metering, monitoring, disconnect devices, and shipment has to be added.

An estimate for this additional cost could mounts to $5000. This will make the estimate for the total cost of the entire system reach the amount of $17798. An optional digital display that reads kWh production, battery voltage, maximum amperes, maximum voltage, and actual amperes in addition to anemometer that is directly connected to the tower to measure and display average and maximum wind speeds are also available [14]. In case such optional equipments are used their cost has to be added to the total system budget.

CONCLUSION

The location of the Gaza Strip directly on the Mediterranean Sea with an average annual wind speed of 20.23 $km.h^{-1}$ (5.62 $m.s^{-1}$) makes it a good candidate to harness wind energy. The Gaza Strip is an electric energy dependent region with about 60% of its need imported from neighboring countries. In many occasions, fuel supplies and electric energy has been cut-off leaving about 1.5 million inhabitants in the dark. Also some areas in the Gaza Strip are still beyond utility grid reach especially those along the east border line. A completely independent energy system harnessing the wind energy is an optional solution to such problems. In this study, the factors that affect the design and sizing of every piece of equipment in the system have been presented to get an optimum design for an off-grid wind energy system to ensure reliability, quality, and economy. Also, the procedures followed to design, size, and build such wind energy system are presented. The purpose of this system is to power all appliances at a residence with medium energy consumption in area with a free wind passage whether it is a coastal or an isolated residence. The study provided also a cost estimate for the system including design, shipment, and labor.

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