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Practical Case Study

A STAND-ALONE PHOTOVOLTAIC SYSTEM, CASE STUDY: A RESIDENCE IN GAZA

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Abstract: Harnessing the solar energy to power electric appliances starts by converting the energy coming from the sun to electricity. Photovoltaic is the direct conversion of the solar energy into electricity. Photovoltaic systems can be used to exploit the solar energy in almost all kinds of applications. Exploiting of solar energy for domestic use is one avenue where the energy emitted from the sun is converted into electricity to power most if not all the appliances available at our homes and residences. Building a photovoltaic system is the process of designing, selecting and calculating the ratings of the equipments employed in the system. This process depends on a variety of factors such as geographical location, solar irradiation, and load requirements. In this paper, I introduce the procedures employed in building and selecting the equipments of a stand-alone photovoltaic system based on the Watt-Hour demand. As a case study, a residence in Gaza with medium energy consumption is selected.

Keywords: Photovoltaic, stand-alone, solar irradiance, balance-of-system, system sizing, load profile, days of autonomy

INTRODUCTION

The sun provides the energy to sustain life in our solar system. In one hour, the earth receives enough energy from the sun to meet its energy needs for nearly a year [1]. Photovoltaic is the direct conversion of sunlight to electricity. It is an attractive alternative to conventional sources of electricity for many reasons: it is safe, silent, and non-polluting, renewable, highly-modular in that their capacity can be increased incrementally to match with gradual load growth, and reliable with minimal failure rates and projected service lifetimes of 20 to 30 years [5]. It requires no special training to operate; it contains no moving parts, it is extremely reliable and virtually maintenance free; and it can be installed almost anywhere. A photovoltaic system is a complete set of interconnected components for converting sunlight into electricity by photovoltaic process including array, balance-of-system, and load. Over the last three decades, steady advances in technology and manufacturing have brought the price of photovoltaic modules down significantly to about $4-$5 per peak watt [6]. The intensity of the sunlight that reaches the earth varies with time of the day, season, location, and the weather conditions. The total energy on a daily or annual basis is called irradiation and indicates the strength of the sunshine. Irradiation is expressed in $Wh.m^{-2}$ per day or for instance $kWh.m^{-2}$ per day. Different geographical regions experience different weather patterns, so the site where we live is a major factor that affects the photovoltaic system design from many sides; the orientation of the panels, finding the number of days of autonomy where the sun does not shine in the skies, and choosing the best tilt-angle of the solar panels. Photovoltaic panels collect more energy if they are installed on a tracker that follows the movement of the sun; however, it is an expensive process. For this reason they usually have a fixed position with an angle called tilt angle β. This angle varies according to seasonal variations. For instance, in summer, the solar panel must be more horizontal, while in winter, it is placed at a steeper angle.

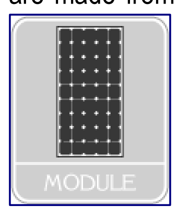
In this paper, the various components of a photovoltaic system and factors affecting its design for the purpose of domestic exploitation will be presented. Then a residence model with medium energy requirements in Gaza will be taken as a practical case study. The design procedures of the photovoltaic system will be provided in a step-by-step manner, and finally a cost estimate for the whole photovoltaic system will be given.

SYSTEM DESCRIPTION

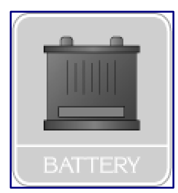
Components

Photovoltaic system is composed of a variety of equipment in addition to the photovoltaic array, a Balance-of-System that wired together to form the entire fully functional system capable of supplying electric power and these components are:

1. Photovoltaic cells represent the fundamental power conversion units. They are made from semiconductor and convert sunlight to electricity. An individual photovoltaic cell is usually quite small, typically producing 1 or 2 watts of power. To increase the power output of photovoltaic cells, they are connected together to form larger units called modules. Modules, in turn, are connected in parallel and series to form larger units called panels and arrays to produce electric power that meets almost any electric need [3, 4].



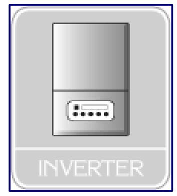
2. A storage medium, battery bank, which is involved in the system to make the energy available at night or at days of autonomy (sometimes called no-sun-days or dark days), when the sun is not providing enough radiation. The standard batteries that are used in solar system are lead-acid batteries because 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 for 5 to 15 years [4], and sometimes more. While cheap batteries can give you trouble in half that time.



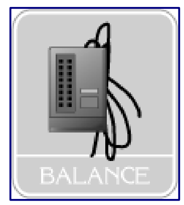
3. A voltage regulator or charge controller is an essential part of nearly all power systems that charge batteries, whether the power source is photovoltaic, or utility grid. Its purpose is to keep your batteries properly fed and safe for the long term. The basic functions of a controller are quite simple. Charge controllers block reverse current and prevent battery from

getting overcharged. Some controllers also prevent battery overdischarge, protect from electrical overload, and/or display battery status and the flow of power.

4. An inverter is a device that changes a low dc-voltage into usable ac- voltage. It is one of the solar energy system's main elements, as the solar panels generate dc-voltage. Inverters are different 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. There are also two types of inverters for installation, stand-alone installation and grid-connected installation.



5. Balance-of-system such as protection devices that keep the system components safe during their operation including, blocking-diodes that protect the components from getting damaged by the flow back of electricity from the battery at night. Bypass diodes that are connected across several cells to limit the power dissipated in shaded cells by providing a low resistance path for the module current. And 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 the mean through which the components of a solar 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 photovoltaic system. The size of the wire must be large enough to carry the maximum current expected without undue voltage losses. All wires have certain amount of resistance to the flow of current. This resistance causes a drop in the voltage from the source to the load. Voltage drops cause inefficiencies, especially in low voltage systems.

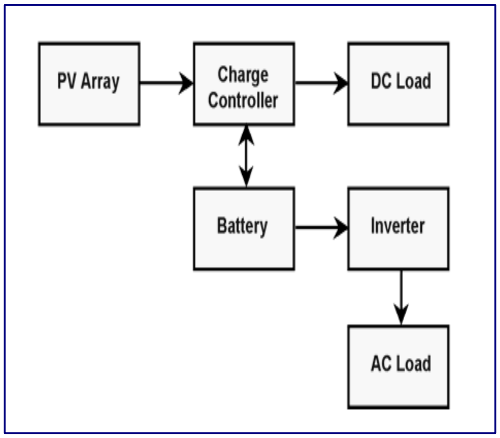


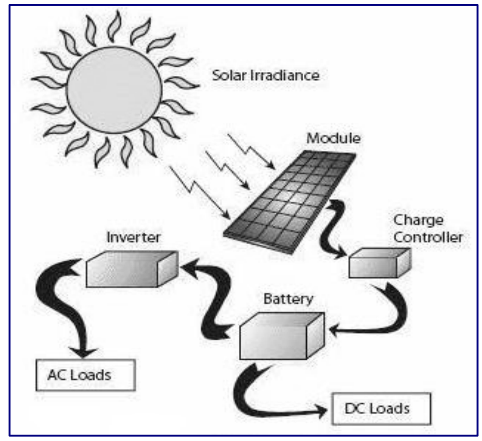
6. AC and DC loads which are the appliances (such as lights and radios), and the components (such as fridges, water pumps, washing machines and microwaves) which consume the power generated by the photovoltaic array.

Configuration

The photovoltaic systems are classified according to how the system components are connected to other power sources such as stand-alone (SA) and utility-interactive (UI) systems. In a stand-alone system depicted in Figure 1, the system is designed to operate independent of the electric utility grid, and is generally designed and sized to supply certain dc- and/or ac-electrical loads [14]. A bank of batteries is used to store the energy in a form of dc power that is produced by the photovoltaic modules to be used at night or in the no-sun days. 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 systems, power is brought in from the grid to supplement the system output when needed, and sold back to the utility when the photovoltaic modules' output exceeds the power demand. The capital cost of a SA system is still high due the high price of the equipment used. For these reasons the SA applications have been limited to remote locations that are beyond the utility grid reach [15].





(a) (b)

Fig. 1: stand-alone photovoltaic System (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 photovoltaic 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 load profile.
- Geographical location that dictates the tilt angel, panel orientation, and the average sun hours per day.
- Home design, which plays a major rule in maximizing the amount of the generated power by considering the following points: keeping the southern area free from any barrier that prevents the sun-ray from reaching the panels, 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 [17].
- 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 photovoltaic 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 a part of the solar energy into electricity via the photovoltaic system and then using it to obtain hot water [11].
- The use of low-voltage DC powered electric appliances, nowadays available in the market, is also an important factor in minimizing the photovoltaic 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 [16].
- 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 Solar Array

Before sizing the array, the total daily energy in Watt-hours (E), the average sun hour per day $T_{\min}$, and the dc-voltage of the system (V_{DC}) must be determined. Once these factors are made available we move to the sizing process. To avoid undersizing, losses must be considered by dividing the total power demand in Wh.day^{-1} by the product of efficiencies of all components in the system to get the required energy E_r.

$$E_r = \frac{\text{daily average energy consuption}}{\text{product of component's efficiencies}} = \frac{E}{\eta_{\text{overall}}}$$

To obtain the peak power, the previous result is divided by the average sun hours per day for the geographical location $T_{\min}$.

$$P_p = \frac{\text{daily energy requirement}}{\text{minimum peak sun-hours per day}} = \frac{E_r}{T_{\min}}$$

The total current needed can be calculated by dividing the peak power by the DC- voltage of the system.

$$I_{DC} = \frac{\text{peak power}}{\text{system DC voltage}} = \frac{P_p}{V_{DC}}$$

Modules must be connected in series and parallel according to the need to meet the desired voltage and current in accordance with: first the number of series modules which equals the DC voltage of the system divided by the rated voltage of each module V_r.

$$N_s = \frac{\text{system DC voltage}}{\text{module rated voltage}} = \frac{V_{DC}}{V_r}$$

Second, the number of parallel modules which equals the whole modules current divided by the rated current of one module I_r.

$$N_p = \frac{\text{whole module current}}{\text{rated current of one module}} = \frac{I_{DC}}{I_r}$$

Finally, the total number of modules Nm equals the series modules multiplied by the parallel ones:

$$N_m = \text{number of series modules} \times \text{number of parallel modules} = N_s \times N_p$$

Sizing of the Battery Bank

The amount of rough energy storage required is equal to the multiplication of the total power demand and the number of autonomy days $E_{\text{rough}}=E\times D$. For safety, the result obtained is divided by the maximum allowable level of discharge (MDOD):

$$E_{safe} = \frac{\text{energy storage required}}{\text{maximum depth of discharge}} = \frac{E_{rough}}{MDOD}$$

At this moment, we need to make a decision regarding the rated voltage of each battery V_b 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:

$$C = \frac{\text{safe energy storage required}}{\text{battery voltage}} = \frac{E_{safe}}{V_b}$$

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:

$$N_{batteries} = \frac{\text{capacity of the battery bank}}{\text{capacity of one battery}} = \frac{C}{C_b}$$

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:

$$N_s = \frac{\text{the system DC voltage}}{\text{battery voltage}} = \frac{V_{DC}}{V_b}$$

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

$$N_p = \frac{\text{the total number of batteries}}{\text{number of batteries in series}} = \frac{N_{battaries}}{N_s}$$

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. A good voltage regulator must be able to withstand the maximum current produced by the array as well as the maximum load current. Sizing of the voltage regulator can be obtained by multiplying the short circuit current of the modules connected in parallel by a safety factor F_{safe}. The result gives the rated current of the voltage regulator I:

$$I = \text{parallel modules short circuit current} \times \text{safety factor} = N_p \times I_{sc} \times \mathrm{F}_{\text{safe}}$$

The factor of safety is employed to make sure that the regulator handles maximum current produced by the array that could exceed the tabulated value. And to handle a load current more than that planned due to addition of equipment, for instance. In other words, this safety factor allows the system to expand slightly.

Sizing of the Inverter

When sizing the inverter, the actual power drawn from the appliances that will run at the same time must be determined as a first step. Secondly, we must consider the starting current of large motors by multiplying their power by a factor of 3. Also to allow the system to expand, we multiply the sum of the two previous values by 1.25 as a safety factor.

CASE STUDY: A RESIDENCE IN GAZA

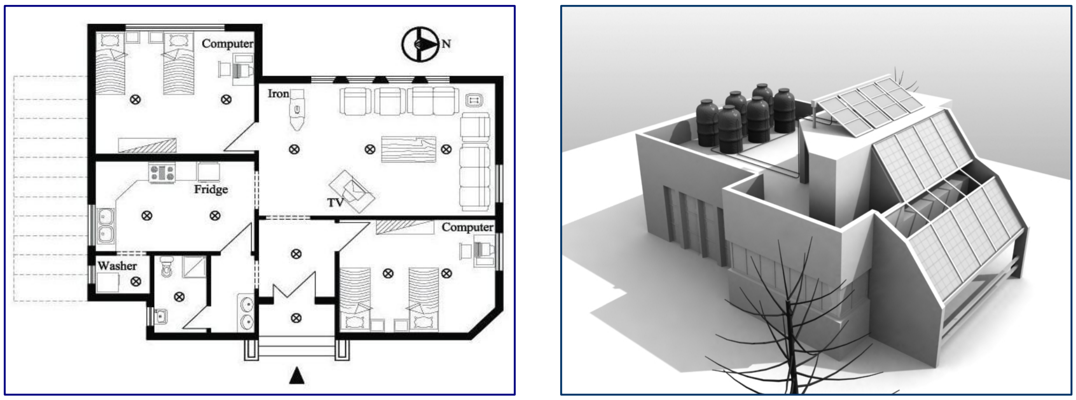
The geographical location of the Gaza Strip makes it one of the relatively sun-rich regions in the globe. It is located in the northern hemisphere area of the earth at 31.3° latitude and 34.3° longitude with an annual incident solar irradiance of about 2000 kWh.m^{-2} [7]. This implies that the solar panel must be mounted facing the south to capture a maximum amount of solar energy, and the number of days of autonomy, where the system will operate without receiving an input charge from the sun is approximated to 4-days according to the record [7,8] and to the equation below:

$$D = -0.48T_{\min} + 4.58$$

Where T_{min} is the minimum peak sun-hours per day and equals 3.84 for the Gaza strip location. The most important factors that will be affected by the site location are panel orientation and the tilt angle. For the Gaza Strip area, the optimum tilt angle that captures the maximum amount of solar radiation over the whole year is given as 35^o [7].

The Suggested Residence

The residence shown in Figure 2 is 100 m^2 with an inclined roof facing the south with a tilt angle of 35^o to install the photovoltaic panels directly to capture the maximum amount of solar radiation.



(a) (b)

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

The roof is also graded as shown to make sure that the panels are always subjected to solar radiation without hindrance. A separate thermal solar system on the top of the roof as shown is also used to obtain hot water. This will reduce the size and cost of the photovoltaic system.

4.2 Residence Appliances

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

Table 1: Residence Appliances and Daily Energy Consumption

Appliance	Power (Watt)	Hours used day^{-1}	Energy (Wh day^{-1})
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 Average Energy Consumption			4186 approximated to 4500

Then this figure obtained as the total average energy consumption is used to determine the equipment sizes and ratings starting with the solar array and ending with system wiring and cost estimate as explained below.

Sizing of the Solar Array

To avoid undersizing we begin by dividing the total average energy demand per day by the efficiencies of the system components to obtain the daily energy requirement from the solar array:

$$E_{array} = \frac{\text{daily average energy consuption}}{\text{product of component efficiencies}} = \frac{4500}{0.9 \times 0.9 \times 0.9} = 6.173 \quad \text{KWh.Day}^{-1}$$

Then the peak power is:

$$P_p = \frac{\text{daily energy requirement}}{\text{minimum peak sun-hours per day}} = \frac{6173}{3.84} = 1608 \;\; \text{W}$$

The total current needed for a DC-voltage of 24 is, I =1608/24=67 A, and according to the selected panel (Mitsubishi - MF180UD4, 180-W, 24-V, 7.45-A, and a price of $810) [10]. The number of series panels, N_s=24/24=1 and the number of parallel panels, N_p=67/7.45=8.9 approximated to 9 which means that the number of panels needed is (1×9) = 9 with a total cost of $7290.

Sizing of the Battery Bank

The amount of energy storage required is, E_{rough}= 4500×4 = 18 kWh, where the number 4 represents the number of days of autonomy or the no-sun days [11]. For safety, we divide the previous value by allowable level of discharge, MDOD (75%)

$$E_{safe} = \frac{\text{required energy storage}}{\text{maximum depth of discharge (MDOD)}} = \frac{18000}{0.75} = 24 \;\; \text{KWh}$$

The capacity of the battery bank in ampere-hours required assuming we select a battery voltage of 12 V is: C =24000/12=2000 Ah, and according to the selected battery (UB-8D AGM -250 AH, 12V-DC and a price of $475) [9], the number of batteries needed is, $N_{batteries}$ =2000/250=8 batteries. With DC-voltage of 24 V, four parallel branches are established according to the equation N_p=8/2=4. Each branch contains 2 series batteries. The storage batteries price amounts to $3800.

Sizing of the Voltage Regulator

The total current required, I = 9×8.03×1.25=90.34 A, where the current I_{sc} for each of the selected modules equals 8.03-A and a safety factor of 1.25 is used. The number of regulators required is, N =90.34/60=1.5 approximated to 2. According to selected regulator (Xantrex C-60, 24-V, 60-A, and a price of $165) [10], we need two regulators connected in parallel with a total cost of $330.

Sizing of the Inverter

The power of appliances that may run at the same time is given by the following formula:

$$P= (10\times11+125+200+1000) =1435 \text{ W}$$

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

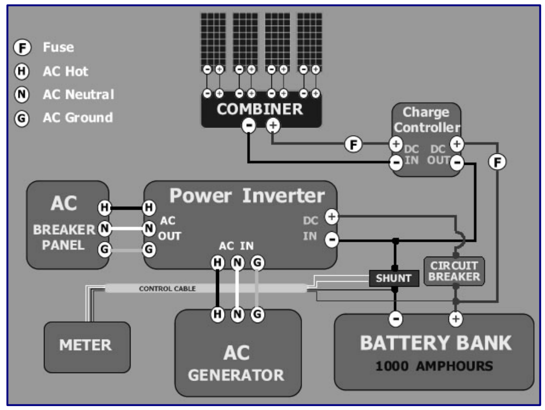
$$P_{Total} = (\text{power of appliances running simultaneously + power of large surge current appliances}) \times 1.25$$

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

The inverter needed must be able to handle about 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 [11].

Sizing of the System Wiring

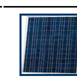
Selecting the correct size and type of wire will enhance the performance and reliability of a photovoltaic system. The graph depicted shows the wiring diagram of a stand-alone photovoltaic system with a standby generator. The dc-wires between the photovoltaic modules and batteries through the voltage regulator must withstand the maximum current produced by these modules. This current is given by I_m=9×8.03×1.25=90.34 A. The optimum wire type for this current is #2 copper wires (AWG) [12], 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 a power factor of 0.8. An optimum wire type for this ac-current would be #10 copper wires (AWG) [12]. 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 photovoltaic system for the suggested remote residence described above are summarized with some details and specifications in Table 2. These are not the only equipments available in the market and there are many manufacturers who provide such equipments.

Table 2: Summary of the System Components

Component	Model	Component Rating			Size (inch)	Unit Price US$	Weight Lb/kg	Warranty Year	Photo
		W/Ah	A	V					
Panels	Mitsubishi MF180UD4	180 W	7.45	24	65.3×32.6×1.81	810	43	25	
Batteries	UPG Group UB-8D AGM	250 Ah	~	12	20.5 x 10.5 x 10	475	167	1.0	
Regulators	Xantrex C60	~	60	24	08 x 5.0 x 2.5	165	2.5	2.0	
Inverter	Latronics LS - 3024	3000 W	~	24/220	14.6 x 15.2 x 7.0	2900	24 kg	3.0	
Wires	#02 AWG #10 AWG	Diameter= 6.54304 mm, Area= 32.0 mm^2 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 $14320. Additional cost for design, labor, wiring, metering, monitoring, disconnect devices, and shipment has to be added. An estimate for this additional cost could mount to $4000. This will make the estimate for the total cost of the entire system reach the amount of $18320.

CONCLUSIONS

The geographical location of the Gaza Strip at 31.3° latitude and 34.3° longitude makes it a relatively sun-rich region with an annual solar irradiance of about 2000 $kWh.m^{-2}$. This implies that solar energy systems would be very efficient in this part of the world. Some areas in the Gaza Strip are still beyond utility grid reach especially those along the east border line. The study has presented the components required for the design of a stand-alone photovoltaic system that will power all electric appliances at a medium-energy-consumption residence in Gaza. The factors that affect the design and sizing of every piece of equipment used in the system have also been presented. Over- and under-sizing have also been avoided to ensure adequate, reliable, and economical system design. A cost estimate for the whole system including design, shipment, and labor is also provided. The same procedures could be employed and adapted to applications with larger energy consumptions and could also be employed for other geographical locations, however, the appropriate design parameters of these locations should be employed. The capital cost of such systems is relatively high and the payback periods are more than 10 years, however, the benefits and the environmental impact should not be underestimated.

The recommendation would be that, the governmental role has to be present and influential in encouraging people to turn to such alternative energy systems. This role should encourage and support renewable energy research and should provide technical assistant to potential users. Another way would be through facilitating the import of the equipment used to construct such systems, especially, the import of low dc-voltage appliances, that are still absent from the local market. New energy policies should be endorsed that allow tax exemption or at least minimal taxes on equipment used in photovoltaic systems. In addition, policies that allow utility-interactive systems are needed to enable the purchase of surplus solar energy from users.

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