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Design and Optimization of Stand-alone PV System for Egyptian Rural Communities

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Abstract

In recent years, supplying electricity has become necessary for the daily survival and further development of emerging communities. In Egypt, there are many rural areas living without electricity as they are located away from the electricity grid. In order to tackle this problem, intensive efforts are being made to bring electricity to these areas. Encouraging the use of alternative energy sources such as solar energy is promising; especially since Egypt has high irradiation levels. This paper presents the use of solar (photovoltaic) energy to supply the electrical energy for a household of about 50 m^2 in a rural area situated in Shalateen (Egypt). Design and installation of the stand-alone photovoltaic system according to the daily electrical load for the house and the irradiation data related to the location are detailed. The sizing of each system components (photovoltaic, mechanical structure, battery, inverter and charge controller) was studied. The paper also studies the economic analysis for the system in terms of life cycle cost and electricity unit cost. The unit cost of electricity using the installed PV system was $0.201/kWh. This encourages the use of this efficient system and clean energy in development plans at rural communities.

Keywords: Solar energy; Stand-alone PV system; Storage batteries; Design and installation; Economic analysis.

INTRODUCTION

Due to the shortage in the fossil fuels as well as the continuous increase in the fuel prices in recent years, there has been a demand to using nontraditional energy sources such as renewable energy [1]. Also, the need to minimize the global air pollution and to control the climate changes must encourage the dependence of renewable energy sources [2]. Solar energy can be considered one of the most important and reliable energy sources to cover the limited availability of the traditional energy sources [3]. Solar energy can be directly converted either into thermal energy via solar collectors or electrical energy via photovoltaic (PV) technology and is considered as an environmentally friendly source of electricity [4]. PV system is an interdisciplinary field, which involves a large variety of applications and can protect urban and rural areas from pollution while avoiding CO_2 emissions [5].

Egypt utilizes many renewable energy sources such as wind, solar and biomass energy, to fulfill its high energy demand. Due to high irradiation levels and maximum number of sunshine hours over the year, solar energy has been considered the main future source of energy in Egypt [6]. In Egypt there are many remote, rural and urban areas that have no access to the electric utility grid. Since these rural communities are small, centralized and spread far away from each other, supplying electricity via transmission lines will not be cost effective. Alternatively, fuel transportation to produce electricity via generators on site is also challenging due to the rough roads and long distances between these communities. Therefore, solar photovoltaic systems are well-suited technologies that have good reliability, less transmission and distribution losses in which on-site electricity can be produced.

In this paper we present the design and installation of the stand-alone PV system in remote Egypt, Shalateen (Red Sea Governorate, latitude of 23.13° North; longitude of 35.59° East; and 12 m elevation) for the electrification of 50 m^2 family house holding six individuals. All system components such as PV arrays, storage system, charge controller, DC-AC inverter were designed and chosen for optimal operation in accordance to the house daily required electrical energy, site parameters and meteorological data. The best orientation of the PV structure (tilt and facing) was also optimized, to receive the maximum allowable irradiation all year. We also present an economic analysis of the PV system over the life cycle of crystalline PV array in terms of life cycle cost and electricity unit cost, considering the prices of the components, installation cost, operation and maintenance (O&M) cost, inflation and discount rates.

Many investigations are carried out all over the world to study the design, operation, optimization and cost analysis of the stand-alone PV system for household electrification [7-9]. Ghassan Zubi et al. [10] introduced four basic off-grid PV systems for different electric load combinations such as lighting, cooking electric appliances and food conservation. A review of the PV systems in both on-grid and stand-alone applications for decentralized energy systems were carried out by Kuandinya et al. [11]. Chakrabartyand Islam [12] analyzed the technical viability and the system feasibility of stand-alone PV solar home systems in Bangladesh using several models. The study showed the different evaluation parameters such as life cycle and energy costs, cost effectiveness and financial indicators. The economic feasibility of depending on PV electricity for supplying remote and rural areas in Palestine was studied by Mahmoud and Ibrik [13]. They concluded that in rural areas where there are considerable levels of solar radiation, it is more economic to use the PV energy for remote villages than supplying the electric network or depending on the traditional fuel generators. Kolhe et al. [14] also analyzed the life cycle cost for different combinations of diesel and stand-alone PV systems for a school in India. They concluded that, as the cost of the off-grid PV systems decreases in the near future, it will be considered more suitable solution for energy shortage in remote areas. Roy and Kabir [15] compared two electrical energy sources (stand-alone PV and diesel) via cost analysis of the life cycle of both systems. Using the net present cost, the analysis was carried out for small and medium energy systems for rural communities in Bangladesh. Ghasemi et al. [16] performed the economic feasibility of using different configurations (PV-batteries-diesel systems) of stand-alone hybrid renewable energy systems for remote areas in isolated Iranian communities. The feasibility of using hybrid off-grid PV system with diesel in supplying electricity to a school in Malaysia was also carried out by Ajan et al. [17].

Oko et al. [18] introduced an economic analysis of the off-grid PV system in Nigeria based on geographical data and the required load energy. In Southern Iraq, Al-Karaghouli and Kazmerski [19] designed and simulated different variations of a PV system using battery storage and DC-AC inverter for a health clinic in a rural area. They compared the unit energy cost of the PV system with that of the diesel system, to highlight the great benefits of using the PV technology in electrification of rural areas in Iraq. According to their optimum PV configuration (6 kWp PV system with the corresponding storage batteries and inverter), the life cycle cost of electricity was $0.238/kWh, while this cost of diesel generator was four times higher. In comparison to the diesel generator, in terms of pollution, the use of specified PV system can protect the environment form 14.927 kg/year release of CO_2, 36.8 kg/year of CO, 329 kg/year of NO_x, 30 kg/year of SO_2 and other suspended particles. Nafeh [20] simulated an off-grid PV system for rural community in Sinai, Egypt. The system had a 1365 Wp PV panel with 6 storage batteries 250 A and 12 V each to supply a daily load of 5.5 kWh. The author concluded that the unit energy cost was $0.74/kWh. Kumar and Mandapati [21] illustrated a stand-alone PV system used for electrification of a conference hall with 9.5kWh/day energy demand in Bhopal, India. The unit energy cost was Indian RS28.99/kWh. In India also, Saxena et al. [22] presented a PV system driving a biscuit packaging machine of a load of 233.17 Ah/day. The system consisted of a total PV area of 172.23 m^2 with 315 storage batteries. The analysis showed that the system life cycle cost (over the life cycle of PV array) was Indian RS15.059/kWh. In Jordan, Bataineh and Dalalah [23] presented an optimal configuration for a stand-alone PV system using a computer program and life cycle cost analysis. They concluded that using the renewable energy sources in remote areas is cost effective over the long life of these systems, with a life cycle cost of $0.239/kWh. Soufi et al. [24] demonstrated a 4 kWp stand-alone PV system using 1200 Ah, 12 V storage system with 5 kW DC-AC inverter in Algeria to supply 5.5 kWh/day to livestock shelters. The cost of electricity was not concluded by the author, however the system's capital cost was US$ 9700. Bhuiyan and Ali [25] presented a small PV system of 282 Wp with 128 Ah battery to supply a limited residential load for only 4 hours per day at Dhaka. Nogueira et al. [26] presented a methodology for design and optimizing a renewable energy hybrid system consists of PV and wind turbines and a storage battery backup system for remote community in South Brazil. According to their analysis for different configurations, they concluded that the life cycle costs were R$0.922/kWh and R$0.785/kWh for PV and wind systems respectively. Khan et al. [27] presented a stand-alone PV system for very small load requirement in Bangladesh. The load was 2 fluorescent and 2 W LED lamps operated for only 3 hours during the night. The PV system was only 25 Wp PV module with 30 Ah, 12 V battery. The comparison of the energy cost of the oil lamp with the PV system showed that yearly cost was $64.1 and $37.82 for oil lamp and PV energy, respectively. Askari and Ameri [28] presented a comparison between different hybrid energy system configurations; PV, wind and hybrid PV-wind systems for 50 rural household with annual load energy of 24.4 MWh and the minimum cost of electricity was reported as $0.247/kWh, in Kerman, Iran. The feasibility of different configurations of renewable energy systems for electrification of a village in rural Madhya Pradesh, India (annual load of 15768 kWh) was carried out and analyzed by Sreeraj et al. [29]. The system consisted of 8 kWp PV modules with 7 kWp wind turbine with the required batteries. The cost of electricity of PV was $0.38/kWh, $0.24/kWh for wind and for PV-wind hybrid was $0.47/kWh. Abdul Ghafoor and Anjum [30] reported an economic analysis and design approach for an off-grid PV system to supply a household load (5.9 kWh/day) in rural area in Faisalabad, Pakistan. The PV system was 1928 Wp, 12.85 m^2 PV area, 9640.5 Wh battery capacity, 56.65 A charge controller rated current and 1020 W rated power DC-AC inverter. The life cycle cost, annual life cycle cost and cost of electricity of the PV system were PKR457,306, PKR31,963 per year and PKR14.8/kWh, respectively. They concluded that the unit cost of the grid electricity to these areas is much higher than their off-grid PV system installation.

The design of the stand-alone PV system for household electrification reported here, started with the exact assessment of the site metrological data such as daily and yearly solar irradiation levels, ambient temperatures and wind speed. A good knowledge of these parameters as well as the daily required electrical energy can ensure an accurate system design.

SITE METEOROLOGICAL DATA

Shalateen is the biggest town north of the Halayeb Triangle; it is located 520 kilometers south of Hurghada (Red Sea Governorate). Fig. 1 shows the map indicating Halayeb Triangle in Egypt. Since 1998, the Egyptian government implemented a development plan to build some settlements, including 500 new houses built in Shalateen and 250 in Aboramad and Halayeb. Approximately 8,000 people have settled there along the coast. However, there are some small spread communities in this area, which makes providing electricity through the grid system not feasible. The stand-alone PV system can help supplying electricity to these communities and improve their livelihood.

Figure 1: Map of Halayeb Triangle in Egypt [31].

As shown in Fig. 1, Shalateen lies in far south-east of Egypt, at latitude of 23.13° North and longitude of 35.59° East, with elevation of 12 over sea level. Table 1 shows the meteorological data of Shalateen city (monthly mean minimum and maximum daily temperature and monthly mean wind speed m/s over the year). The table shows that the selected site has considerably high temperatures especially in summer months. The minimum temperature in winter is 15-16 °C while the maximum is 39-40 °C in the summer. Annually, the wind speed is around 4 m/s. Such low rates decrease the system's structural and mechanical costs and minimize the movement of sand particles. This can help protect the glass cover of the PV modules from scratch.

Since PV systems directly convert solar radiation into electric energy via the photovoltaic effect, the output of the PV system increases with the solar radiation incidence on its surface. Egypt lies in Sunbelt region which ensures very high irradiation levels and maximum sunshine hours all the year [32]. Fig. 2 provides the monthly mean sunshine hours. The figure clearly indicates that this site has high sunshine hours all year long, reaching 365-370 h/month in the summer and 290-300 h/month in the winter and total sunshine hours >3870 h/year.

The PV system must be correctly oriented to receive the maximum radiation levels over the year. The effect of system inclination on the levels of irradiation received is shown in Fig. 3. Horizontal, optimum tilt (24 deg) and 45 deg tilted surfaces were compared. From the figure, it is clear that irradiation levels are higher in summer than in winter, and the annual average of daily radiation on a horizontal surface is 6.56 kWh/m^2/day. Titling the solar system over the horizontal one can raise the incident radiation according to the tilt angle. The system optimum tilt angle is 24 deg which is close to the site's latitude angle. Fig. 3 summarizes the annual average daily radiation on optimum tilted surface with 7.02 kWh/m^2/day. Alternatively, the 45 deg tilted surface provided 6.63 kWh/m^2/day. The monthly effect of tilting the solar system was studied. Fig. 4 displays irradiation fraction ratios of horizontal surface to optimum tilted one; while Fig. 5 displays the same ratios of surface titled by 45 deg to optimum tilted one, respectively.

Table 1: Monthly mean minimum and maximum daily temperature and wind speed in Shalateen city.

Month	Minimum temperature °C	Maximum temperature °C	Wind speed m/s
Jan	15.1	23.8	4.31
Feb	16.5	25.3	3.94
Mar	18.0	27.4	4.00
April	20.4	30.6	3.64
May	23.3	33.9	3.75
June	25.7	36.9	3.94
July	27.2	38.4	3.47
Aug	28.1	39.7	3.56
Sept	26.4	36.2	3.75
Oct	23.9	32.8	3.33
Nov	20.6	28.6	3.89
Dec	16.7	25.6	4.36

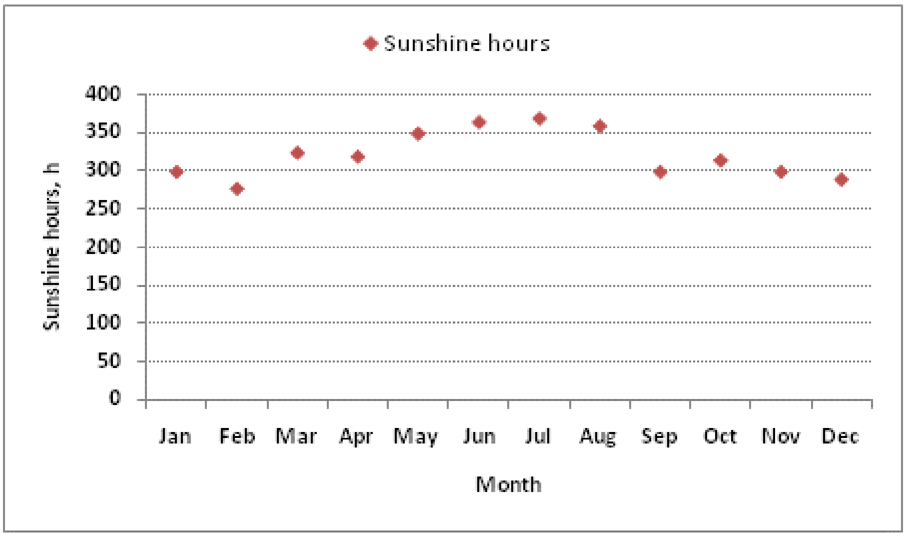

Figure 2: Monthly mean sunshine hours [33].

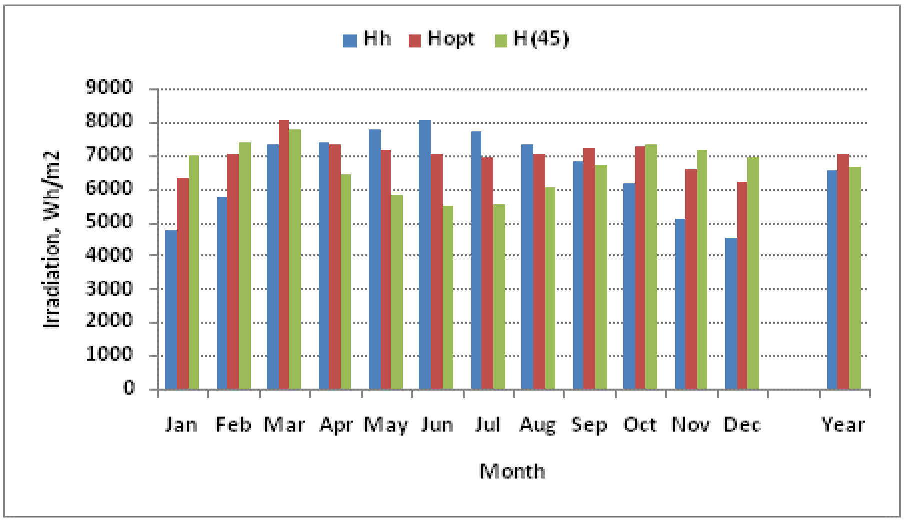

Figure 3: Irradiation on horizontal, optimum tilt and 45 deg. tilted surfaces [34].

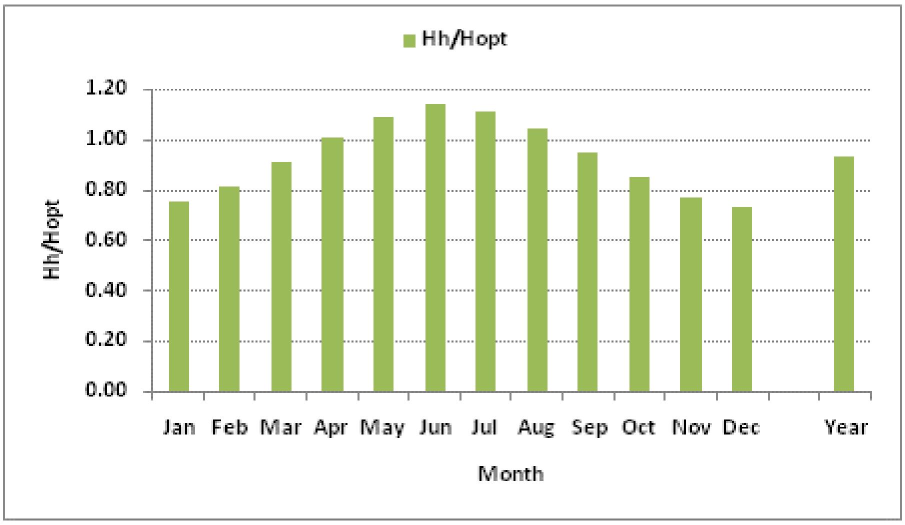

Figure 4: Irradiation fraction ratios of horizontal surface to optimum tilted one [34].

The optimum tilt angle of 24 deg. improves the system irradiation mainly in winter periods, since the site is located at latitude 23.13ºN. Accordingly, the radiation can be considered normal to the horizontal system at summer. Fig. 4 declared that the yearly radiation on horizontal surface is only 93% from that of optimally tilted one. While raising the system tilt angle to 45 deg is contributed to the radiation rise in winter periods and, eventually, a 6% decrease in the annual system radiation below that of the optimum tilted one (Fig. 5).

In Egypt, the PV solar system must be facing south towards the sun. The change of the system's azimuth angle (the angle between the normal to the system and the south direction) affects the irradiation levels in any solar system. Fig. 6 reveals instantaneous irradiation of sample days in July and December at optimum tilt angle for zero azimuth angles. It is evident from the figure that Shalateen has higher irradiation values in summer and winter with a longer duration of daylight in the summer.

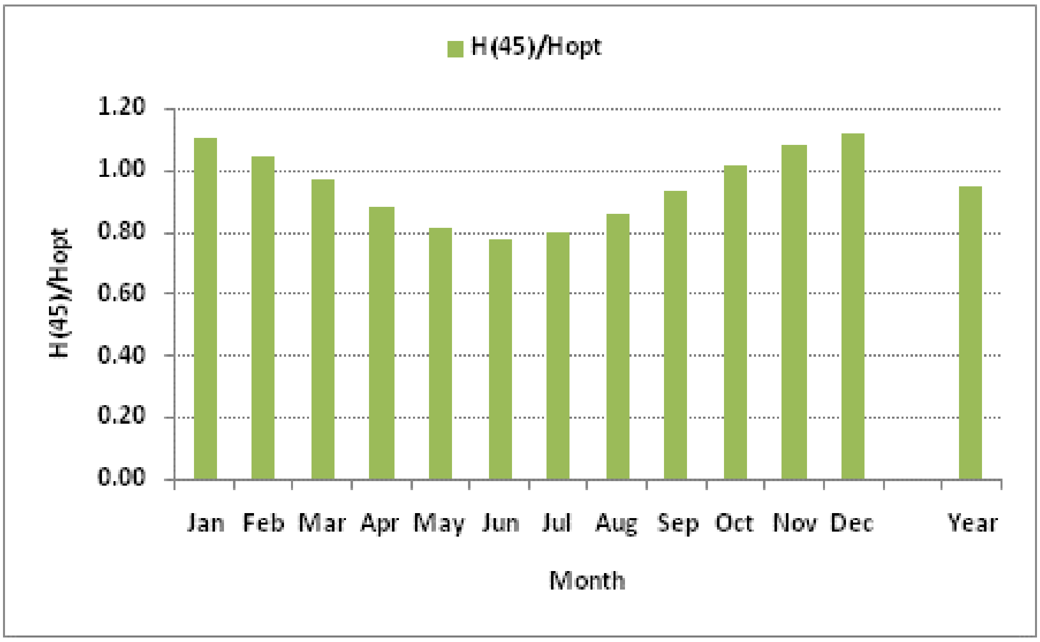

Figure 5: Irradiation fraction ratios of 45 deg tilted surface to optimum tilted one [34].

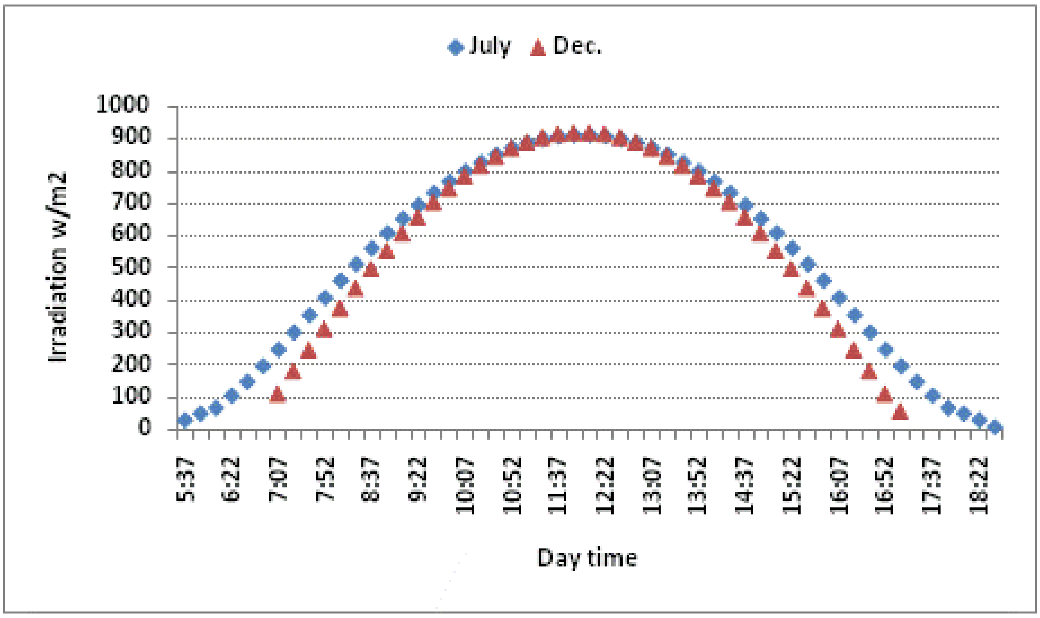

Figure 6: Instantaneous irradiation of sample days in July and December at optimum tilt angle [34].

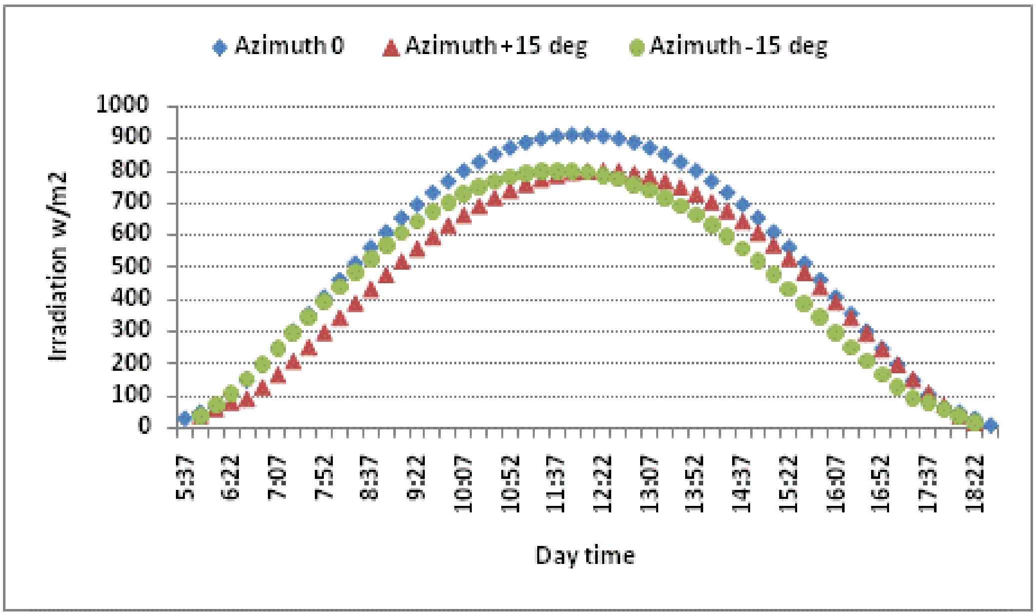

Figure 7: Instantaneous irradiation at different azimuth angles from a sample day in July [34].

Deviation of the solar system from the zero azimuth angle can directly affect the irradiation levels and hence the overall system performance. Fig. 7 displays the deviation effect for a change in the azimuth angle on the instantaneous system radiation (-15 deg E and +15 deg W). The system irradiation increases in the morning when the azimuth angle deviates -15 deg E and then significantly decreases in the afternoon. As shown, the reverse happens for +15 deg W. The variation of azimuth angle by ± 15 deg resulted in a 14% reduction in the daily system radiation during the summer.

From the above analysis, it can be concluded that Shalateen has high radiation levels with an annual average of 7kWh/m^2/day for 24 deg tilted facing south system. The annual sunshine hours reach 3873 hours/year, such irradiation values are promising for PV systems.

DAILY LOAD REQUIREMENTS

As all rural areas in Egypt, the selected family house in the present study is of low energy demand, homing 6 persons over 50 m^2. Table 2 shows the household's electrical devices and their corresponding power and operating time, while Fig. 8 shows the corresponding load curve of the typical day's consumption. The house load is very simple and consists of 6 LED lamps of 7 Watt each, a small refrigerator, a television, a washing machine and two electric fans, with total power of 542 W. We calculated 2.936 kWh/day as maximum total daily energy required. However, this value is expected to decrease in the winter months when the two electric fans are not operated.

Table 2: Electrical equipments of a family house.

Equipment	Quantity	Unit power W	Working time	Hours of operation in h	Energy required Wh
LED lamps	2	7	0 – 5	5	70
LED lamps	1	7	9 - 17	8	56
LED lamps	4	7	17 - 19	2	56
LED lamps	6	7	19 - 22	3	126
LED lamps	2	7	22 - 0	2	28
Refrigerator	1	100	0 - 24	24*	800
Fan	2	50	12 - 20	8	800
TV	1	100	14 - 20	6	600
Washing machine	1	200	11 - 13	2	400
Total					2936

*To estimate the number of hours that a refrigerator actually operates at its maximum wattage, divide the total time that the refrigerator is plugged in by three. Refrigerators, although turned "on" all the time, actually cycle on and off as needed to maintain interior temperatures [35].

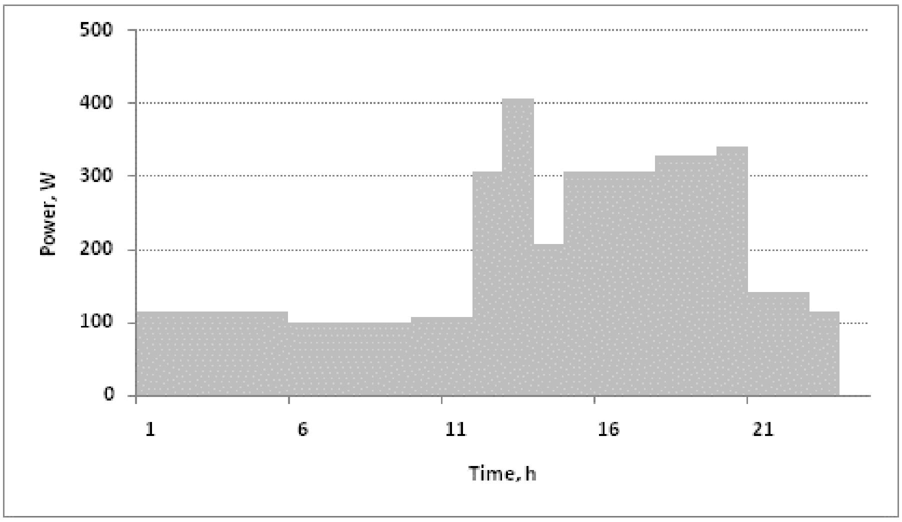

Figure 8: The load curve of a typical complete day's consumption for a rural house.

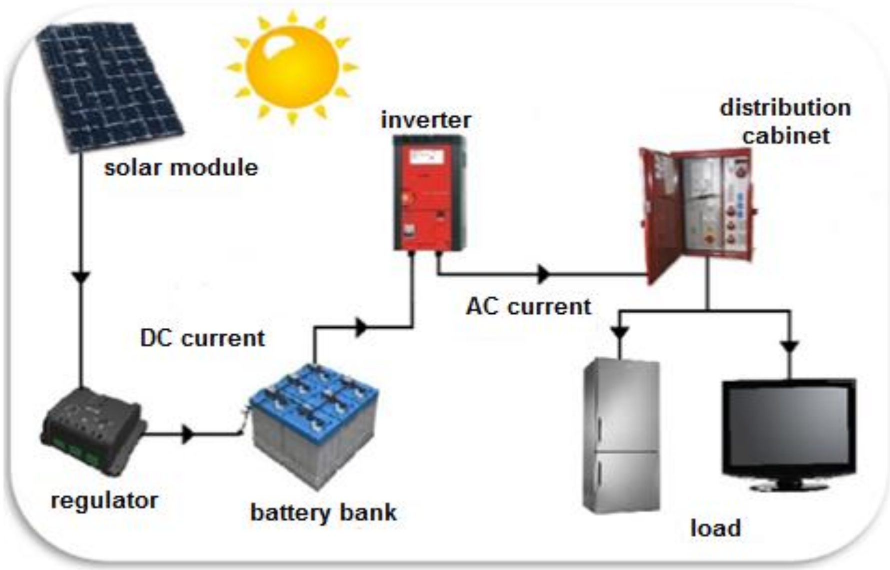

Figure 9: A schematic diagram of a stand-alone PV system [36].

SYSTEM DESIGN

The stand-alone PV system usually consists of the PV generator with the required mechanical structure, storage batteries, charge controller and DC-AC inverter, in addition to wiring cables to the required control and switching devices. Fig. 9 is a schematic diagram of a stand-alone PV system. The following subsections introduce the design and optimization of each component in the proposed system.

PV sizing

The PV power (P_{PV}) must be calculated to meet the required daily load energy (E_L) according to the household's necessities (table 2) and the total daily solar energy (H) in kW/m^2/day. Different system parameters should be considered in the design to satisfy the optimum system operation;

- The module efficiency (η_{PV}) is substantially low, due to internal series and shunt resistances of the PV module as well as recombination effects in the solar cells,
- Module temperature coefficient (T_C) must be considered as the PV module output is affected by its surface temperature. The temperature correction factor for silicon modules is about -0.5%/ºC, so T_C can be taken safely of 0.80 [5,37].
- The efficiencies of other system components such as charge controller efficiency (η_C), DC-AC inverter efficiency (η_{Inv}) and storage battery efficiency (η_B).

According to the above parameters, the total area of the required PV array (A_{PV}) can be calculated as follows [5,38];

$$A_{PV} = \frac{E_L}{H \times T_C \times \eta_{PV} \times \eta_{Inv} \times \eta_C \times \eta_B} \quad (1)$$

Using the standard solar irradiation (H_{SC}) as 1000 W/m^2, the PV array peak power can be calculated as follows [39, 13];

$$P_{PV} = A_{PV} \times H_{SC} \times \eta_{PV} \quad (2)$$

Equations (1&2) can be used to calculate the required peak power of the PV array. Since the daily required load energy is 2.936 kWh/day (table 2) and the average daily irradiation energy is 7.02 kWh/m^2/day (Fig. 3), the required PV area is 3.65 m^2 and PV peak power is 712 W. The setup included the module coded (Lorentz, LC185-24M) with a peak power of 185 W, a PV module consisting of 72 cells connected in series. Four PV modules (total power of 740 Wp) were used to cover the required electrical energy while taking into consideration 20% PV module efficiency; 91% inverter efficiency; 95% controller efficiency; 85% battery efficiency; and 80% temperature coefficient. Table 3 illustrates the technical and mechanical characteristics of the PV module; electrical performance and temperature and radiation dependence are shown in Figs. 10&11.

Table 3: Electrical and mechanical specifications of the PV module [40].

Parameter	Value	Unit
Module type	Lorentz	LC185-24M
Peak power	185	Wp
Short circuit current	5.5	A
Open circuit voltage	44.8	V
Maximum power	5.1	A
current	36.4	V
Maximum power	- 0.5	%/ºC
voltage		
Peak power temperature	1000	V
Coefficient	72	cells
Maximum system	1	cell
voltage	Monocrystallaine	
No. of cells	80.8 x 158 x 0.35	cm
No. of cells in parallel	15.4	kg
Cell technology		
Dimensions		
Weight		

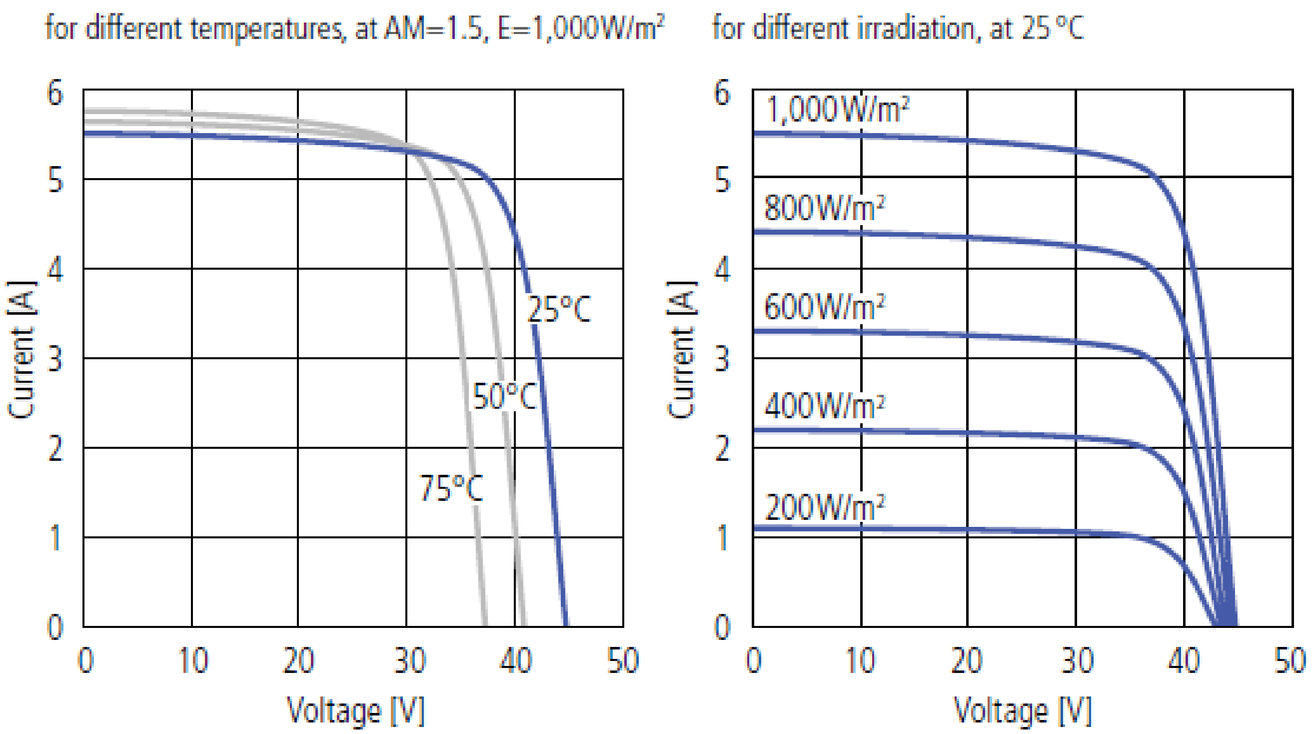

Figure 10: I-V curve of the PV module for different irradiation levels and different temperatures [40].

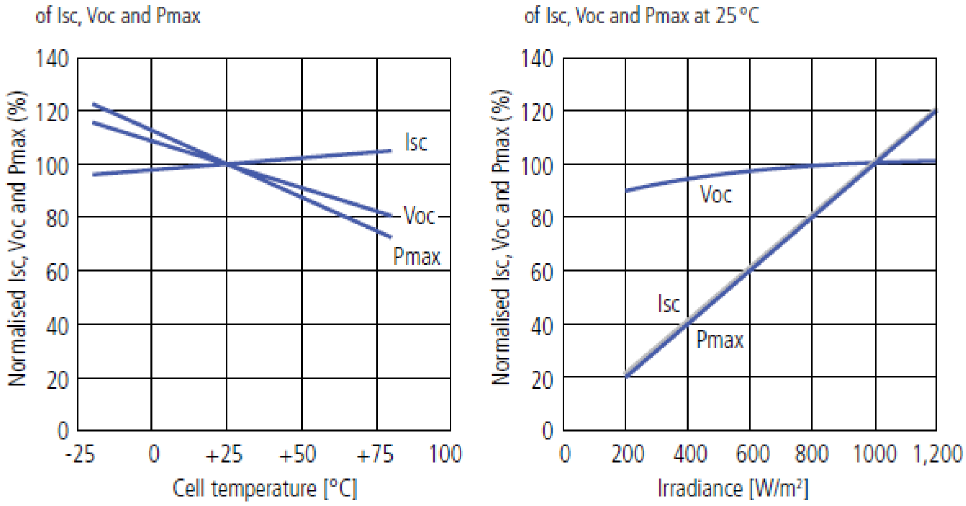

Figure 11: Effect of irradiation and temperature on the PV module parameters; I_{SC}, V_{OC}, P_{max} [40].

Sizing of the storage capacity

The role of battery in the stand-alone PV system is to store electric energy for night time supply or when there is no sunlight during the day. The capacity of the storage batteries (B_C) can be calculated according to the battery efficiency, inverter efficiency, depth of discharge (DOD) and the number of continuous cloudy days (N_C) to cover the total energy required. The depth of discharge is inversely proportional to the battery life; as the selected batteries have deep discharge capabilities, taking 80% DOD can result in 7-8 years lifetime of the selected batteries. As shown before, the installation site of the system has annual sunshine of more than 3873 hours. Therefore, with less continuous cloudy days per year, it is considerable N_C equals unity (ignoring a few days per year with loss of electricity for cost minimization considerations). The storage capacity in Wh can be calculated as follows [41];

$$B_C = \frac{E_L \times N_C}{DOD \times \eta_{Inv} \times \eta_B} \quad (3)$$

From equation (3), the calculated storage capacity is 4745 Wh. For 12V battery, the required battery capacity will be 395 Ah. The battery bank consists of 4 batteries (NSB 100 FT) of 100 Ah, 12 V each. The batteries have high deep cycle capability and operating temperature range from -40°C to 65°C.

To minimize the system losses, DC current must be kept as small as possible. Accordingly, it is better to select a 48 V as DC voltage bus. So, PV modules (table 3) can be connected in two parallel strings each string having two modules connected in series (with optimum charge current of 10.2 A, according to table 3). Also, the four storage batteries can be connected in parallel in one string to ensure 48 DC V.

Sizing of the charge controller

The charge controller in a stand-alone PV system is used to improve the life of the storage batteries. It protects the batteries from overcharge which can damage the batteries. Since the charge controller is used mainly in charging the batteries by the PV arrays, a 48V/20A charge controller was directly connected between the PV arrays and the batteries to withstand the maximum charging current of the PV system (10.2 A). Table 4 summarizes the technical specifications of the charge controller (Steca-Tarom 440). Its features include pulse width modulation (PWM) battery charging, automatic load reconnection, temperature compensation and manual load disconnection. In terms of protection and functionality, it has high and low input voltage disconnection; depth of discharge disconnection; reverse polarity connection (for PV arrays, battery and load); over temperature; over voltage; open circuit battery and reverse current at night. For monitoring purposes, the charge controller has two lines LCD showing the state of discharge, battery voltage, battery current, module current, load currents and the cumulative system Ah.

Table 4: Technical specification of the charge controller.

Parameter	Value	Unit
Type	Steca	Tarom 440
System voltage	48	V
Max. module input current	20	A
Max. self consumption	14	mA
End of charge voltage	54.8	V
Depth discharge protection	44.4	V
Ambient temperature allowed	-10 to +60	°C
Dimensions	18.8 x 12.8 x 4.9	cm
Weight	550	gm
Enclosure protection class	IP 22	

Sizing of the DC-AC inverter

The DC-AC inverter is used to feed the AC loads with the required electrical energy, so it must be set to at least 10-25 % higher than the maximum AC power of the load (table 2) [30,37]. Also, the inverter must guard against any power surge to protect any electric motors such as refrigerators and washing machines [42]. The selected inverter is 700 W (TS-700-248). This inverter is suitable for home appliances and is chosen to cover the starting currents of the AC loads. It provides true sine wave output, high surge power up to 150% load for 10 sec, front panel indicators. It has protection against; battery low, over temperature, over voltage, overload, reverse input polarity and output short circuit. Table 5 summarizes the technical specifications of the inverter.

Table 5: Technical specification of the DC-AC inverter.

Parameter	Value	Unit
Type	MW	TS-700-248
Output voltage	200-240	V AC
Output frequency	50 ± 0.1	Hz
Battery voltage	48	V DC
Input voltage range	42-60	V DC
Input current	19	A DC
Efficiency	91%	
Overload capability	105-115% load	for 180 sec.
	115-150% load	for 10 sec.
Dimension	7 x 18.4 x 29.5	cm

As shown above, the designed stand-alone PV system consists of four PV module connected in two parallel strings each has two modules in series to give an operating DC voltage of 48 V and short circuit current of 10.2 A at standard test conditions (1000 w/m^2 solar radiation, 25 ºC module temperature and air mass of 1.5). According to the required DC bus voltage of 48 V, the four batteries are connected in series as one string. The mechanical structure is designed to meet the weight of the PV modules and other loads of winds and storms. The mechanical structure is made of 4 cm steel rods tied and fixed by electrical welding and installing screws. The mechanical structure is coated with a special paint to withstand the different weather and environmental factors. The mechanical structure is adjusted to face south with the optimal tilt angle described above. This is to ensure maximum irradiation collection on the surface of the PV system over the entire year. Fig. 12 shows the installed PV system.

SYSTEM OPERATION

Fig. 13 shows the monthly average generated PV energy from the installed system based on the average daily solar radiation shown previously in fig. 3. The system can generate more than 3 kWh/day all year round, except two months in the winter (January and December). As stated earlier in table 2, the required daily load of 2.936 kWh/day can be reduced in winter to 2.136 kWh/day. The average monthly generated energy throughout the year (Fig. 13) is higher than the average monthly demand indicating appropriate selection, design and optimization of the installed system. Additionally, the total annual load energy demand of the house is 1072 kWh, while the generated energy from the PV system is approximately 1160 kWh.

Figure 12: Installed stand-alone PV system.

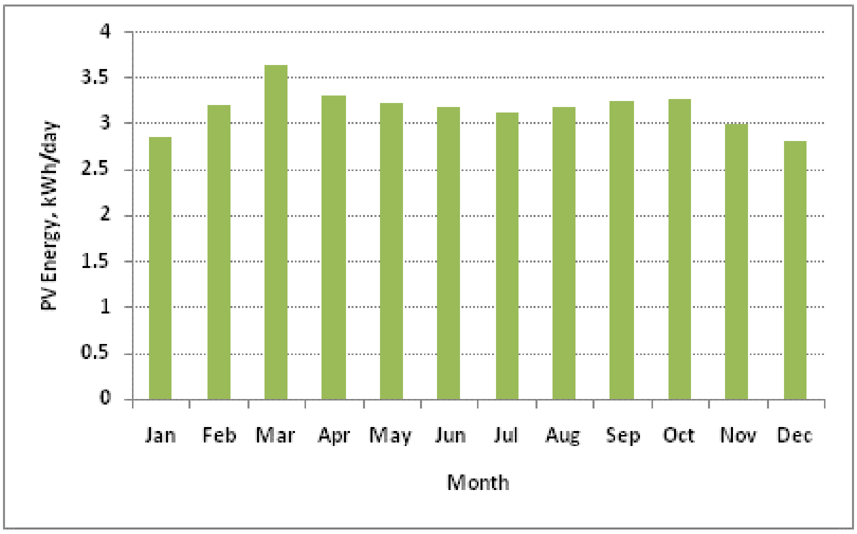

Figure 13: Average monthly generated energy from the PV system.

ECONOMIC ANALYSIS

The most valuable statistical evaluation tool for the economic behavior of energy systems is life cycle cost (LCC) analysis. In renewable energy systems, it covers all system life stages; capital cost and initialization stage, operation & maintenance stage and the replacement stage [15]. The initial capital cost of any system is the cost required for purchasing all system components, this includes PV arrays, storage system, charge controller, inverter and installation (including wiring and other auxiliaries). Operation and maintenance costs include annual periodic expenses for system management, regular maintenance and site supervision. For continuous operation and to ensure efficient system performance, some parts of the system must be replaced periodically. Storage batteries in any PV system need to be replaced every 5-10 years according to the battery type and the operating conditions.

In life cycle analysis, the analysis must be carried out according to the longest life component of all system parts. The optimum life cycle of the crystalline silicon modules used is around 20 years, whereas the life cycle of the storage batteries can run up to 7 years. Given a maximum life cycle of 20 years, the batteries will need to be replaced every 7 years. For future estimations, two important parameters must be considered; the inflation rate and the discount rate. Inflation rate represents the escalation trend in the costs over the all system life, while the discount rate represents the decrease in the components cost with future mass production.

The PV array costs (PV_C) \$882 while the storage batteries cost (B_C) \$556. The inverter (Inv_C) and charge controller (C_C) costs \$333 and \$222, respectively. For the PV arrays life cycle of 20 years and the 7years battery life, the installation cost (I_C) is 10% of the PV cost while the annual O&M cost (OM_C) is 2% of the PV initial cost. Given an inflation rate (i) of 4% and discount rate (d) of 8%, the system life cycle cost and the unit electrical cost can be estimated.

The annual O&M costs can be calculated depending on the system capital cost taking into consideration the inflation and discount rates, as follows;

$$OM_C = 2\%PV_C \times \left(\frac{1+i}{1+d}\right)\left[\frac{1-\left(\frac{1+i}{1+d}\right)^{20}}{1-\left(\frac{1+i}{1+d}\right)}\right] \quad (4)$$

Since the battery life is only considered 7 years, it must be replaced twice in the system's lifetime. The battery replacement costs are calculated for first time after 7 years and for second replacement after 14 years as follows [30];

$$B_{C1} = B_C\left[\frac{1+i}{1+d}\right]^7 ,$$

$$B_{C2} = B_C\left[\frac{1+i}{1+d}\right]^{14} \quad (5)$$

The system's life cycle cost can be calculated by adding the PV, battery, battery replacements, inverter, controller, installation, operation and maintenance costs [5].

$$LCC = PV_C + B_C + B_{C1} + B_{C2} + Inv_C + C_C + I_C + OM_C \quad (6)$$

The annual life cycle cost (ALCC) can be estimated as follows [30];

$$ALCC = LCC\left[\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^{20}}\right] \quad (7)$$

The unit electrical cost (UC) in \$/kWh can be estimated from the annual life cycle cost and the annual energy generated by the PV system [43];

$$UC = \frac{ALCC}{365 \times E_L} \quad (8)$$

According to the above methodology, table 6 summarizes the cost analysis of the PV system, while the cost percentages of the PV system components over the 20 years life cycle are shown in Fig. 14.

The sum of the PV and battery costs of the stand-alone PV system is 71.4% of the total system cost, while the battery costs are 42.7%. It must be noted that the unit cost of the installed system over 20 years of operation is \$0.201/kWh, which can be considered one of the smallest unit cost of PV system compared to others recently studied (\$0.407/kWh in Egypt 2002 [5], \$0.238/kWh in Iraq 2010 [19], \$0.433/kWh in India 2012 [21], \$0.239/kWh in Jordan 2012 [23], \$0.239/kWh in Iran 2011 [28], \$0.240/kWh in India 2010 [29]).

Table 6: Cost analysis results of the PV system.

Item	Value
PV cost	\$ 882
Battery cost (initial set)	\$ 556
First batteries replacement	\$ 427
Second batteries replacement	\$ 328
Inverter cost	\$ 333
Charge controller cost	\$ 222
Installation cost	\$ 88
O&M cost	\$ 243
LCC	\$ 3079
ALCC	\$ 215
UC	\$ 0.201/kWh

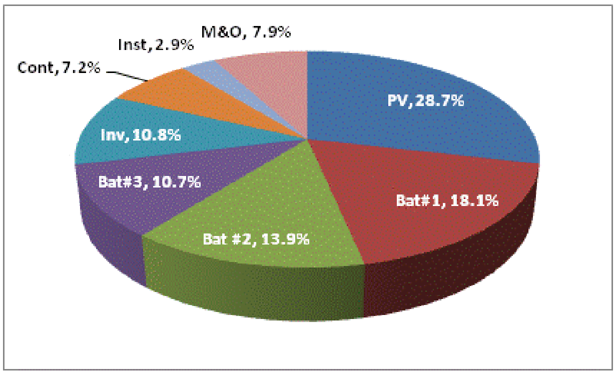

Figure 14: Cost percentages of the PV system components over its 20 years life cycle.

CONCLUSION

Utilization of solar energy is critical for development programs in locations which have high irradiation levels such as Shalateen (Egypt). According to the irradiation data captured by different system orientations and tilt angles, Shalateen has an annual average of 7kWh/m^2/day and annual sunshine hours of 3870 h. The reported PV system introduced a design, optimization and installation for a simple household electrification (2.936 kWh/day), situated in Shalateen, Egypt. The optimal system design for a single-household (6 persons) consisted of a) four PV modules with a total power of 740 W arranged in two parallel strings each has two modules in series to ensure an operating DC bus voltage of 48 V and maximum charging current of 10.2A, b) four storage batteries 12V and 100AH each; connected in series, c) DC-AC inverter of 700Wp rated and d) 20A charge controller. The mechanical structure was designed to be facing south and tilted to receive the maximum solar radiation all year round.

To assess the cost feasibility of a stand-alone PV system in such remote areas, economic analysis is essential. Considering 20 years lifetime of mono-crystalline PV arrays and seven years for batteries (deep discharge capability) with installation cost of 10% of the PV cost, annual operating & maintenance cost of 2%, in addition to inflation rate of 4% and discount rate of 8%, the system life cycle cost was \$3079 and the unit electrical cost was \$0.201/kWh. The obtained electricity unit cost is lower than most of recent studies around the world. This was partly due to high irradiation levels in Egypt as well as large sunshine hours in the selected area. The presented model can be used in assessment of the electricity life cycle and unit costs in any geographic site according to its input parameters.

Nomenclatures :

A_{PV}	PV area, m^2.
B_C	Battery capacity, Wh.
DOD	Depth of discharge.
E_L	Daily required electrical energy for the household, kWh/day.
H	Daily irradiation, Wh/m^2/day.
H_{SC}	Standard solar irradiation, 1000 W/m^2.
I_{SC}	PV module short circuit current, A.
N_C	Number of continuous cloudy days, day.
P_{max}	PV module peak power, W.
T_C	Temperature coefficient of the PV module.
V_{OC}	PV module open circuit voltage, V.
η_B	Battery efficiency.
η_C	Charge controller efficiency.
η_{inv}	Inverter efficiency.
η_{PV}	PV efficiency.

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