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# TECHNICAL PERFORMANCE AND FINANCIAL ANALYSIS OF A SMALL GRID-CONNECTED PV SYSTEM IN EGYPT

**E. T. El Shenawy*, Aiat Hegazy and M. Abdellatef**

National Research Centre, Solar Energy Department, El Behouth St., 12622, Dokki, Giza, Egypt.

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***Corresponding Author**
**Dr. E. T. El Shenawy**
National Research Centre, Solar Energy Department, El Behouth St., 12622, Dokki, Giza, Egypt.

## ABSTRACT

Photovoltaic (PV) is one of the important technologies which can efficiently use the solar energy in generating electricity and can be considered the most promising solution for the electric energy shortage in the future. PV systems can supply electricity either for isolated loads (stand-alone) or directly coupled to the electric networks (grid-connected). The present paper demonstrates the technical performance and financial analysis of a 2-kW grid-connected PV system installed in Cairo, Egypt. It gives the details of system components, installation and operation. The paper also illustrates the measured input and output parameters of the system for one year of operation such as solar irradiation, surface temperatures of the PV modules and produced electrical energy. A financial analysis based on payback period is carried out for evaluating the feasibility of these systems in Egyptian climates. The results showed that the annual average daily electrical energy produced by the system is 9.85 kWh/day, where the total annual generated one is about 3.37 MWh/year. The financial analysis showed that the payback period of the grid-connected PV system is about 8.2 years, which indicates the great benefits from these systems during the long lifetime.

**KEYWORDS:** Solar energy; Photovoltaic system; Grid-connected installation; Photovoltaic financial analysis.

## 1. INTRODUCTION

The energy problems especially in the electricity sector have been raised over the world due to the continuous increase in the world population and the promising development programs.

Also, the pollution associated to the expending of the conventional energy sources encouraging the dependence on the alternative energy for electricity supply such as PV energy (Jiaming, 2019). In addition to the clean nature of the PV energy, the high reliability, low maintenance efforts, modularity and modern technologies increase the use of these energies over the world (El Shenawy et al., 2017).

Electricity generation from the PV plants has grown over the past decades. From 1990, the solar PV increased by small portion per year and the total installation reached to 3.4 GW in 2004 (Enas et al., 2016). In 2008, the PV market was increased to 16 GW and reached 22.9 GW at the end of 2009 (Hao and Yunhe, 2011). At the end of 2013, the installed global capacity was 139 GW and the total power generated was 106.4 TWh (Yonghong et al., 2016). In 2015, China and India added the largest PV plants in the world by 15.2 GW and 2 GW, respectively from the total 50 GW added over the world. The total cumulative installation of the PV systems reached 227 GW by the end of 2015 (Renu and Sonali, 2017). The installed PV power was increased by about 97 GW, by the end of 2017. Recently, the boosted capacity is growing up by the end of 2018 to about 104 GW (Allouhi et al., 2019). In Egypt, due to the huge consumption of electricity resulting from high population rate and development plans, the current energy strategy has been aiming to share about 20% of its energy from solar (PV) and wind energies at the end of 2020. In the way of incorporating the PV energy, Egypt started to build 20 grid connected PV power plants of 50 MW each in the region of Aswan. Two of them were tied to the electricity grid and entered the service while the other will be completely finished at the end of 2020.

Various silicon PV technologies have been used over the world since 1960s which can be classified according to the efficiency and material to crystalline, thin film and multijunction PV technologies. The crystalline PV cells can be monocrystalline or polycrystalline cells with efficiencies ranged between 18-22%. 95% of the annual production of the PV cells from crystalline type, while a small percentage of the total share is thin film. The concentrated PV cells are special type of the PV technologies that use light concentration technique. This type can be used in some areas where there are small solar irradiation levels and low ambient temperatures (Allouhi et al., 2017). Recently, the most of development in the PV technologies studies tend to increase the overall efficiency of the PV cells and use new materials to decrease the production costs (Chandrakant et al., 2018).

The great advantageous of the PV systems help in incorporating this technology in different applications which can be classified into two main categories such as stand-alone and grid-connected systems. In the stan-alone PV systems, the generated electricity can be used directly for supplying loads at site. These systems consist of PV modules as the generator, batteries for storage capabilities, suitable inverters and charge controllers. The system costs are higher since the batteries should be replaced periodically for two or three times during the lifetime of the system depending on the utilization. The off-grid PV systems can be used in remote loads, street lighting, water pumping and other applications in rural areas (Kaundinya et al., 2009). The other important application for the PV systems is used to generate electricity and connect it to the electric grid as gird-connected systems. It can be used for investment in the electricity sector or reducing the electricity bill in different installations. Most of these systems do not use the batteries, so their capital costs are less than that of the stand-alone ones (Kazem et al., 2017). The PV panels, inverters and electric energy meters are the main components of the grid-connected PV systems (Shafiqur et al., 2017).

The grid-connected PV systems can be classified into three types according to the installed PV power as follows; i) residential systems or small PV plants which are used for private or residential applications with small power up to 5 kW, ii) commercial systems or medium PV plants of power up to 250 kW which are used for office and industrial buildings and iii) PV power plants for centralized power generation up to 50 MW or more (Castro et al., 2005). Different studies were carried out to analyze the performance of the small grid-connected PV systems for different power scales. (Ratan and Srinjoy, 2016) studied the performance of a small grid-connected power plant of 1 kW installed in Kolkata. They concluded that the power delivered to the grid was about 814 W for irradiation level of 1000 $W/m^2$ and the system efficiency differs according to the solar intensity and ranges between 12%-18%. The performance of the same grid connected power plant of 1 kW that installed in Algeria was analyzed by (Missoum et al., 2014). The study showed that installing 1 kW can save average electrical energy of 4 kWh/day. In Serbia, (Dragana et al., 2015) studied the performance of a 2 kW roof top grid connected PV plant under different real climatic conditions. A comparison study was carried out between the measured and the calculated data resulting from 3.2 kW grid connected PV power system installed in South Africa, which showed a good agreement between the obtained results (Okello et al., 2015). The operation of household 5 kW grid connected PV plant was studied by (Hartner et al., 2017) for more than 5 years in Austria.

For medium and centralized power size, performance and economic calculations were carried out based on practical measurements for 20 kW grid connected PV plant in India (Kumar et al., 2014). The same analysis was carried out using HOMER software for a 20 kW grid connected PV system in Greece in terms of electrical energy and cost of energy by (Fantidis et al. 2013). The capacity factor, final yield and performance ratio were used to simulate and evaluate the performance of 171 kW grid connected PV plant in Crete Island (Kymakis et al., 2009). The technical and economic performance of the centralized grid connected power plants also was studied for 3 MW (Padmavathi and Arul, 2013) and 5 MW (Sundaram and Babu, 2016) PV plants in India for two years 2011-2012. The results indicated that the measured results are close to that of the predicted using RETscreen program and the average annual generated energy was about 1.37 MWh per kW. In India also, the simulated results using PV-GIS program were compared to that obtained from the real measurements for the 10 MW PV grid connected plant installed at Ramagundam by (Kumar and Sudhakar, 2015). (Cheikh et al., 2016) studied the performance of the first bigger 15 MW grid connected PV plant in Mauritania to supply a small percentage up to 10% of the required electric energy of Nouakchott. The biggest centralized PV power plant of 750 MW coupled with the electric network of Pakistan was introduced and analyzed by (Zafar et al., 2016).

The present paper introduces technical and financial analysis of the small grid connected PV power plant of 2 kW installed for research purposes at Solar Energy Department, NRC, Cairo, Egypt. The study shows the plant installation and orientation according to the geographic location. Using the measured data from the plant for about one year, the performance can be analyzed to evaluate the plant output. The financial analysis in terms of payback period is carried out using the actual prices of the plant components in addition to installation, maintenance and operation costs taking into consideration the current price of electricity and the expected increase in Egypt.

## 2. Input solar radiation

The performance of any solar system is mainly affected by the amount of input solar radiation incident on its surface, which in turn is a function of system location and orientation. Cairo is a capital of Egypt located at the northern hemisphere and lies at longitude of $31.24^{o}$ East of zero meridian line and latitude of $30.04^{o}$ North of equator. The weather data related to the monthly average ambient temperature and wind speed through the year are shown in Figure 1. It is evident that, the ambient temperature reaches more than 30

$^{o}$C in summer (May, June, July, August and September) and decreases than 20 $^{o}$C in winter (January, February and December). Generally, July is the warmest month, while January is the coolest one. The mean monthly wind speed ranges between 3.3 – 4.3 m/s. The rainy season is in winter and the maximum rainy months are December and January which are more than 5 rainy days per month.

Solar radiation in terms of sunshine hours as monthly average in Cairo is plotted in Figure 2. From the figure, we can see that the mean sunshine hours increased from more than 200 hours in winter reaching to its maximum of more than 350 hours in summer giving annual sunshine hours in the range of 3300-3600 hours, which can be considered one of the largest annual sunshine rates in the world. This result, since Egypt lies in the world Sunbelt, that ensures large sunshine hours and high solar irradiation levels. The measured solar irradiation energy on a horizontal surface in kWh/m$^2$/day through the year in Cairo is plotted in Figure 3. The figure represents the daily solar energy incident on a horizontal surface in Cairo that reaches more than 4 kWh/m$^2$/day in winter compared to high levels in summer recording 10 kWh/m$^2$/day. This arises because the sunshine hours reach more than 11 and 8 hours for typical days in summer and winter, respectively. Also, the instantaneous irradiation level at noon on a horizontal surface reaches to 1000 W/m$^2$ in summer and about 800 W/m$^2$ in winter.

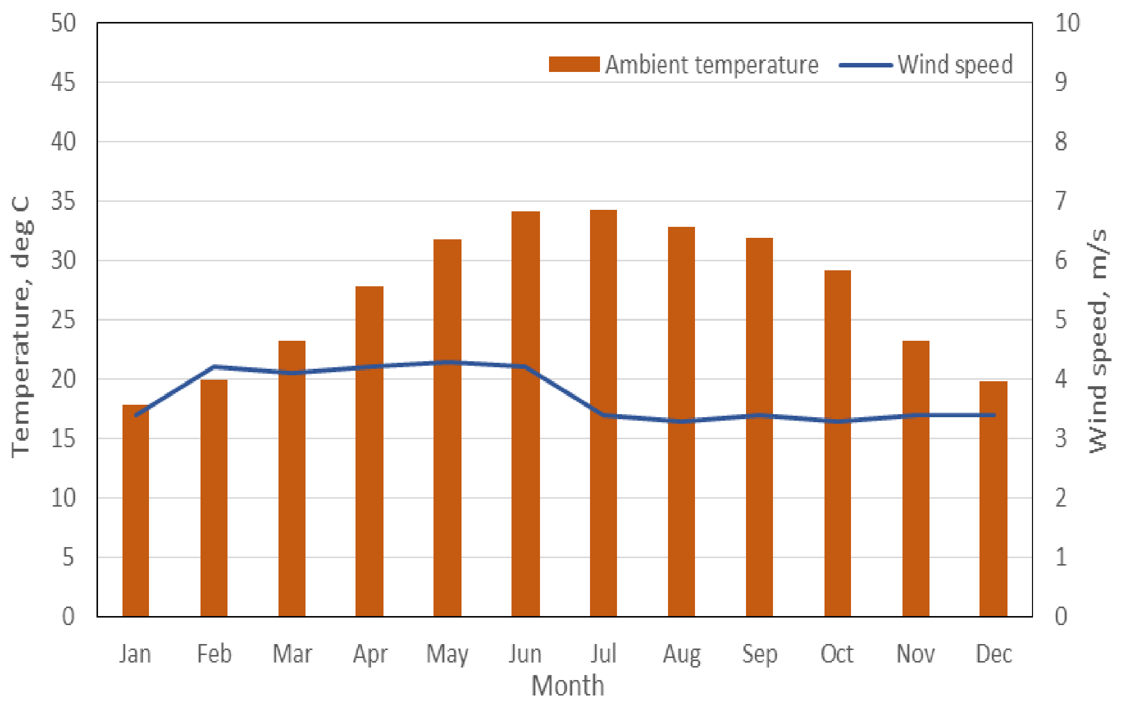


**Figure 1: Monthly mean ambient temperature and wind speed through the year in Cairo.**

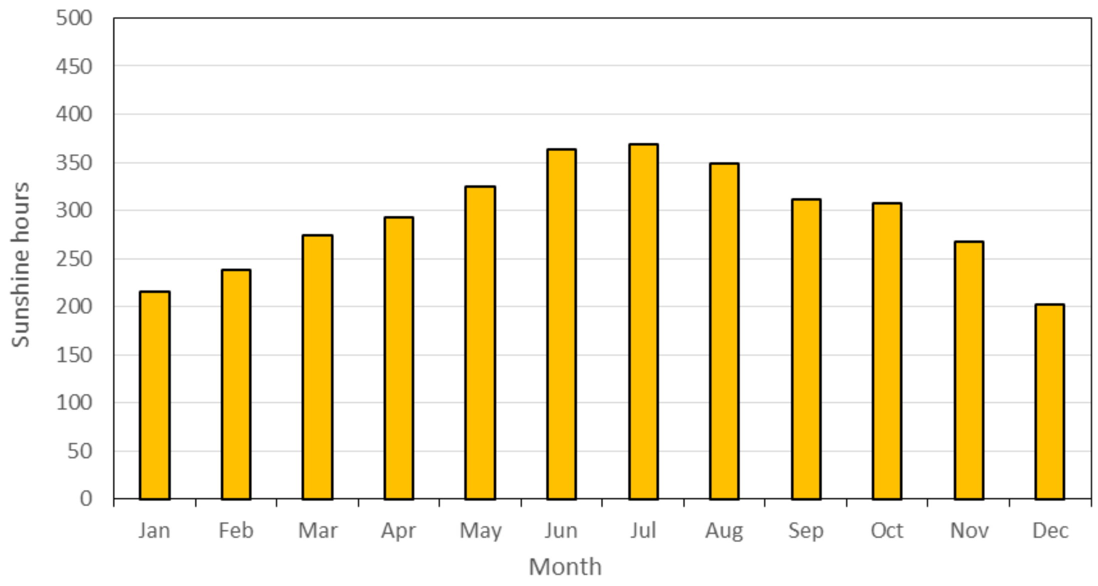


**Figure 2: Monthly average sunshine hours through the year in Cairo.**

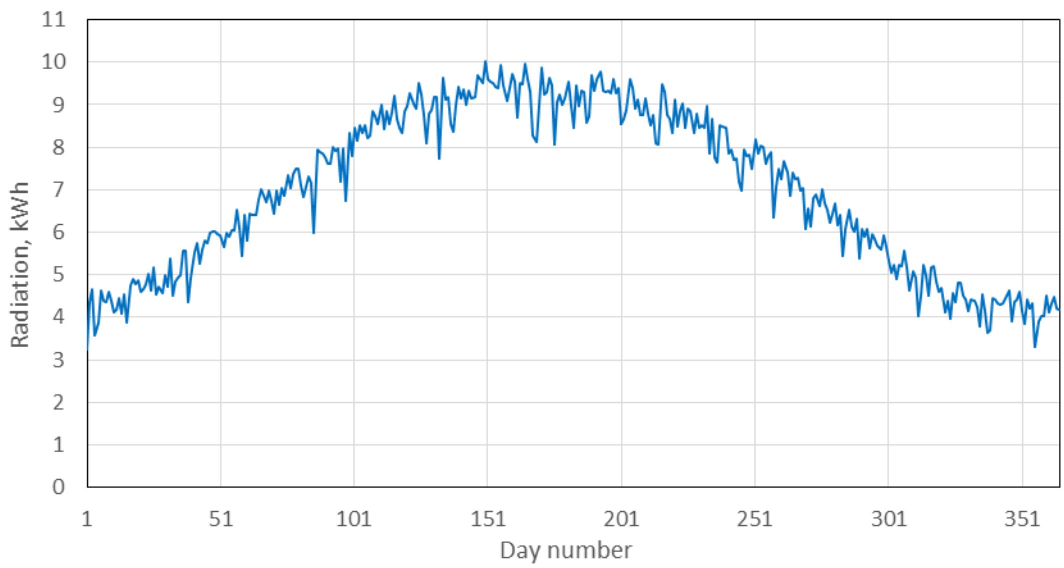


**Figure 3: Measured solar irradiation energy on a horizontal surface through the year in Cairo.**

As the amount of solar energy incident on any surface is affected by the geographic location, it is also affected by the system orientation in terms of facing (with respect to south or north) and tilting (with respect to horizontal) (Laib et al., 2018). In the northern hemisphere, the solar system must be facing south to capture the maximum solar irradiation. Deviation from south direction can reduce the amount of incident solar energy on the system depending on the location and degree of deviation (El Shenawy et al., 2017). Also, tilting the solar system by a certain angle over the horizontal surface (equals to the site latitude ± $2^o$) can collect more solar irradiation over the year than that of the horizontal one (Caroline et al., 2017).

Figure 4 shows the measured monthly average solar irradiation energy incident on an optimally tilted surface of $30^o$ in Cairo through the year. From the figure, it can be seen that the daily solar irradiation energy captured in winter increased for the tilted surface (Figure 4) than that of the horizontal one by about 20% (Figure 3) due to the high sun altitude angles in winter. In summer, the small tilt angle can capture more irradiation energy than the optimal tilted one. Generally, tilting the solar system by $28\text{-}30^o$ in Cairo (latitude of $30.04^o$) increases the total yearly solar energy captured by about 10% over that of the horizontal one and capture an average annual daily solar irradiation of 6.48 kWh/$m^2$/day.

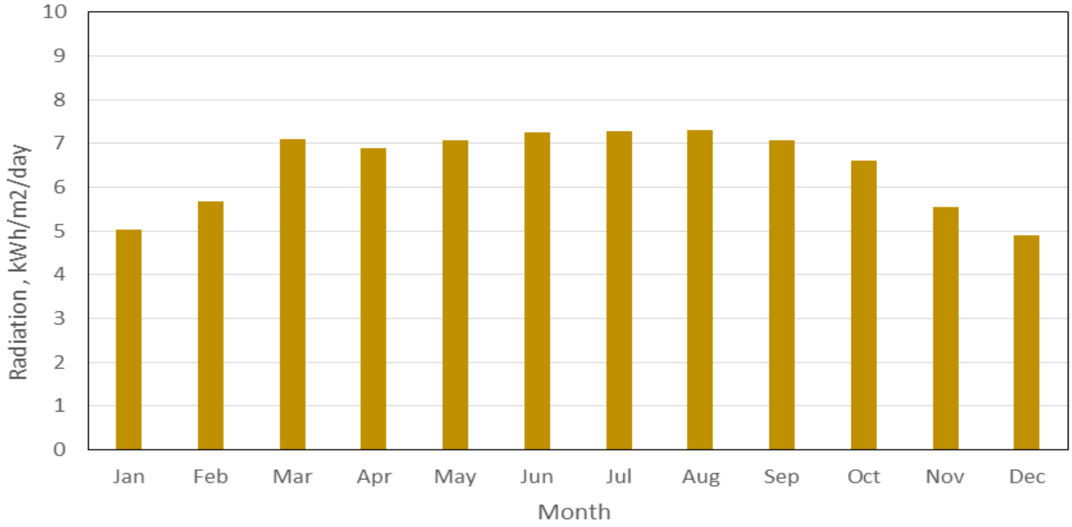


**Figure 4: Measured monthly mean solar irradiation energy on the optimal tilted surface in Cairo through the year.**

### 3. Grid connected PV system configuration

The grid connected PV power system of 2 kWp is installed in SED, NRC for research purposes. The system consists of 2 kW PV modules and on-grid inverter of 1900 W in addition to the energy meter with switching and control facilities. Figure 5 shows a schematic diagram of the grid connected PV system.

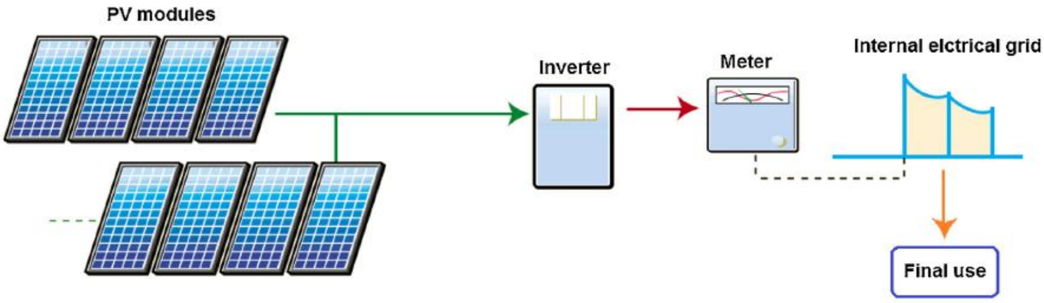


**Figure 5: A schematic diagram of the grid connected PV system.**

### 3.1. PV panels

The grid connected PV system consists of eight PV modules of 250 W each. The PV module consists of 60 polly-crystalline solar cells with efficiency up to 19%. The cells are connected electrically to form the required module power. The apparent efficiency of the PV module is 15% which is less than that of the single cell due to the electrical losses between cells in the module. Each PV module has its own ionized type frame of aluminum to withstand the extreme operating conditions expected for operation. The module front surface has covered with a white tempered glass with high resistance to avoid scratches. The back side of the module is made from EVA plastic for heavy loads. Table 1 gives the technical and mechanical specifications of the PV modules at standard test conditions (STC) and Figure 6 indicates the current-voltage and power-voltage characteristics of the PV module at STC. The modules are installed on a mechanical support made from ionized steel to withstand the weight of the PV modules and wind loads in all environmental conditions. The mechanical support of the PV modules is inclined by tilt angle of $30^o$ over the horizontal plane to capture the maximum solar energy through the year. Figure 7 shows the installed PV system in the test field of SED.

**Table 1: Technical and mechanical specifications of the PV modules at STC*.**

| Item | Specifications | |
|---|---|---|
| Rated power | 250 | W |
| Rated voltage | 30.5 | V |
| Rated current | 8.17 | A |
| Voltage at open circuit | 37.4 | V |
| Current at short circuit | 8.80 | A |
| $V_{OC}$ temperature coefficient | - 0.320 | %/$^o$K |
| $I_{SC}$ temperature coefficient | + 0.053 | %/$^o$K |
| System voltage | 1000 | V |
| Dimension | 166.7x99.7x0.47 | cm |
| Weight | 20.1 | kg |
| * (1000 W/$m^2$, 25 $^o$C and 1.5 AM) | | |

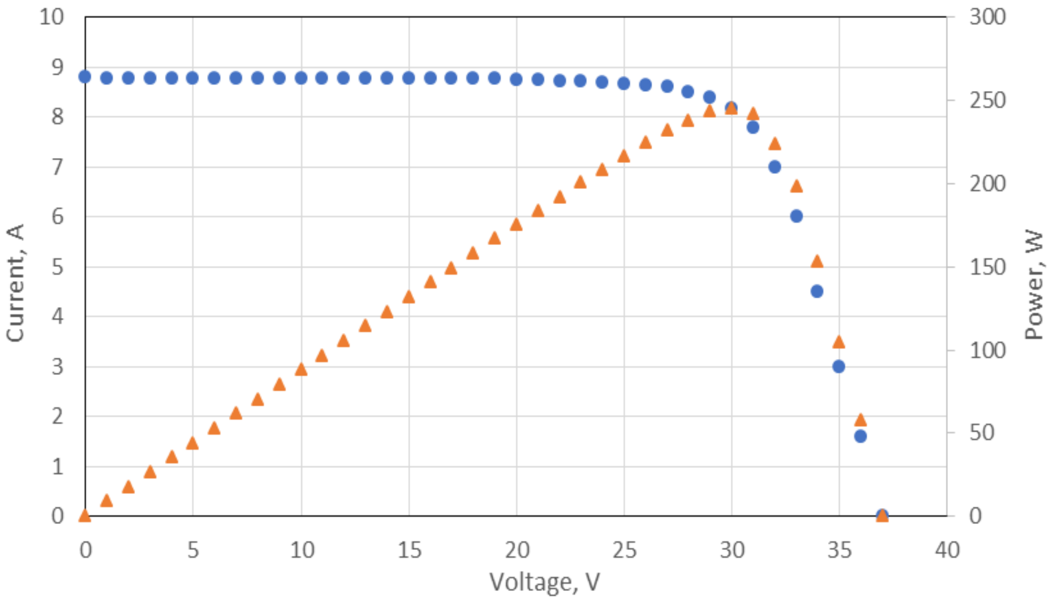


**Figure 6: Current-voltage and power-voltage characteristics of the PV module at STC.**

**Figure 7: The installed PV system in the test field of SED.**

### 3.2. Grid connected inverter

The inverter in the grid connected PV system is used mainly for converting the DC electrical signal produced by the PV module into AC signal to match the grid utility. Also, it makes the required synchronization between the grid signal and that of the generated from the PV system for ideal matching. An on-grid single phase inverter of 1900 W rated power is used in the system to make the required conversion of the generated power and ensure save coupling to the grid. Table 2 shows the inverter technical specifications. The inverter uses a galvanic isolation to isolate the PV modules from the utility power. It also uses a microcontroller based maximum power point tracker to continuously adjust the PV module voltages to ensure delivering the maximum power to the grid all the time. At night, the inverter keeps minimum consumption of electric energy due to keeping the components in sleep mode. The inverter has a protection capability against over load, over temperature, reverse polarity of the input and module disconnection.

**Table 2: Inverter technical specifications.**

| Item | Specifications | |
|---|---|---|
| DC input voltage | 80-400 | V |
| Rated DC input voltage | 300 | V |
| Disconnection voltage | 50 | V |
| Rated input current | 16 | A |
| Maximum input power | 2200 | W |
| DC connection | 2 | Lines |
| Rated AC output power | 1840 | W |
| Grid AC voltage | 190-265 | V |
| Grid type | L/N | |
| Grid frequency | 57.2-62 | Hz |
| Rated AC output current | 8 (at 230 V) | A |
| Power factor | > 0.95 | |
| MPPT Efficiency | 99% | |
| Inverter efficiency | 95% | |
| Ambient temperature | -25 to 60 | $^{o}$C |
| Dimension | 35.1x54.2x14 | cm |
| Display | LED display | |

According to the inverter input ranges in Table 2, the eight PV modules are connected in series forming one string that has open circuit voltage of 299.2 V and maximum operating current of 8.17 A. The energy meter is located in the system between the inverter and the grid network to measure the energy delivered to the grid from the PV system. Switching and protection facilities are used in the system to turn the system components on and off or for electrical protection, respectively.

## 4. RESULTS AND DISCUSSIONS

The PV system was installed and operated for more than one year ago and the important parameters were measured and stored using a data acquisition system which has the required sensors and transducers. The instantaneous solar radiation is measured at the surface of the PV modules using a Kipp-Zonen pyranometer that converts the instantaneous solar irradiation value to a small electrical signal which can be amplified and estimated. The PV module surface temperature is recorded using K-type thermocouple and amplification circuit. The DC and AC voltages and currents are determined using suitable voltage and current transducers embedded in the data acquisition system. The delivered AC energy to the utility grid is measured using a special energy meter recording the accumulation of electrical energy in kWh. The inverter software records all the generated electricity in daily and accumulation basis and also detects the fault signals in case of fault occurring.

Figure 8 elucidates the total monthly generated electrical energy in MWh over the year. It is clear that the system generates more than 0.3 MWh/month of electrical energy in summer months while the output decreases to about 0.2 MWh/month in winter. The total annual electrical energy delivered by the system is about 3.37 MWh/year, which is corresponding to 4.93 kWh/kWp. The monthly generated electrical energy with the daily solar irradiation levels is plotted in Figure 9. The figure illustrates that the generated electrical energy increases with the daily irradiation energy. When the daily irradiation falls under 5 kWh/m$^2$/day, the generated electrical energy is under 200 kWh/month, while it increases more than 300 kWh/month when the irradiation levels reach more than 7 kWh/m$^2$/day. Figure 10 dedicates the monthly mean daily system efficiency through the year. The apparent efficiency of the PV module is 15% as shown before, while the figure shows that the overall system efficiency is smaller due to some parameters such as dust, losses and higher ambient temperatures. The system efficiency is ranged from 11.5% in summer to 13.8% in winter due to the effect of the considerably higher surface temperatures of the PV modules in summer season. The surface temperature of the PV modules at noon in summer is higher than that of the winter by more than 25 $^o$C, due to the higher ambient temperatures and solar irradiation levels in summer. Figure 11 shows the surface temperatures of the PV modules in summer and winter.

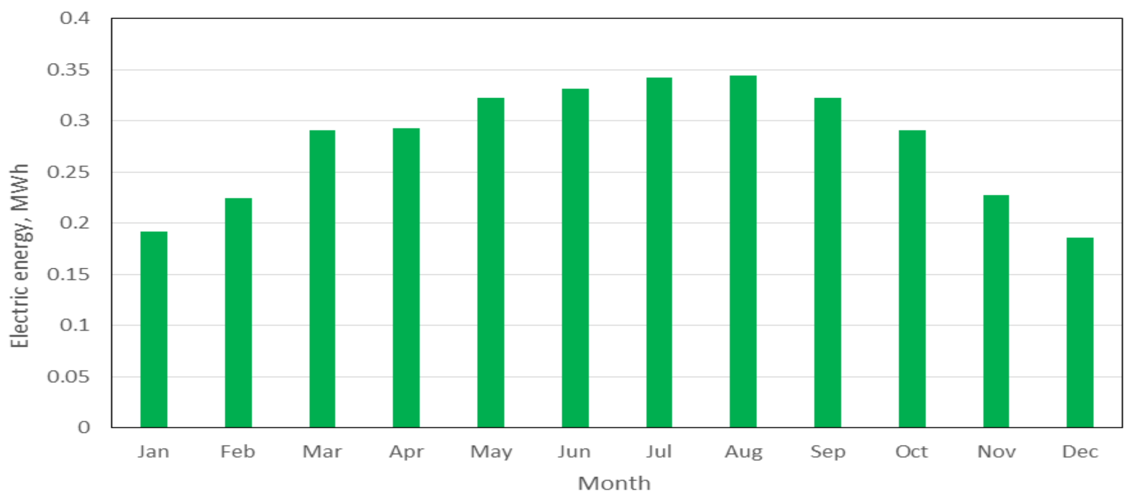


**Figure 8: Monthly generated electrical energy in MWh through the year.**

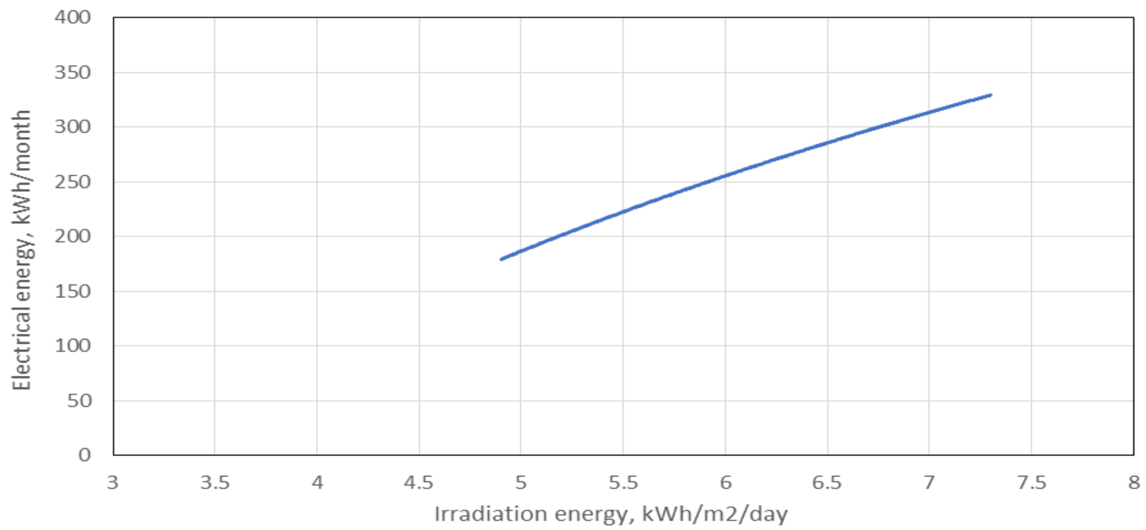


**Figure 9: Monthly generated electrical energy with the daily solar irradiation levels.**

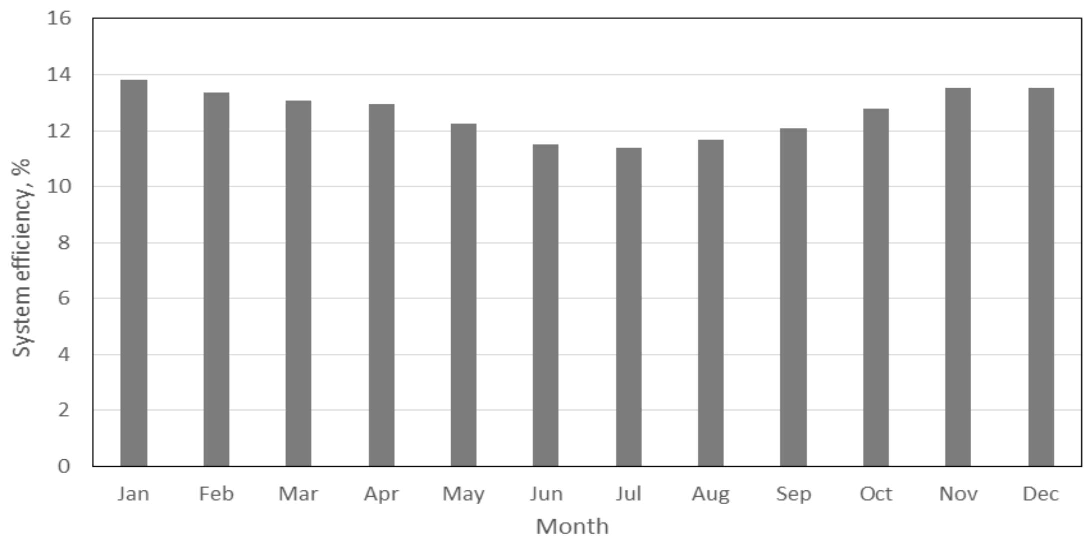


**Figure 10: Monthly mean daily system efficiency through the year.**

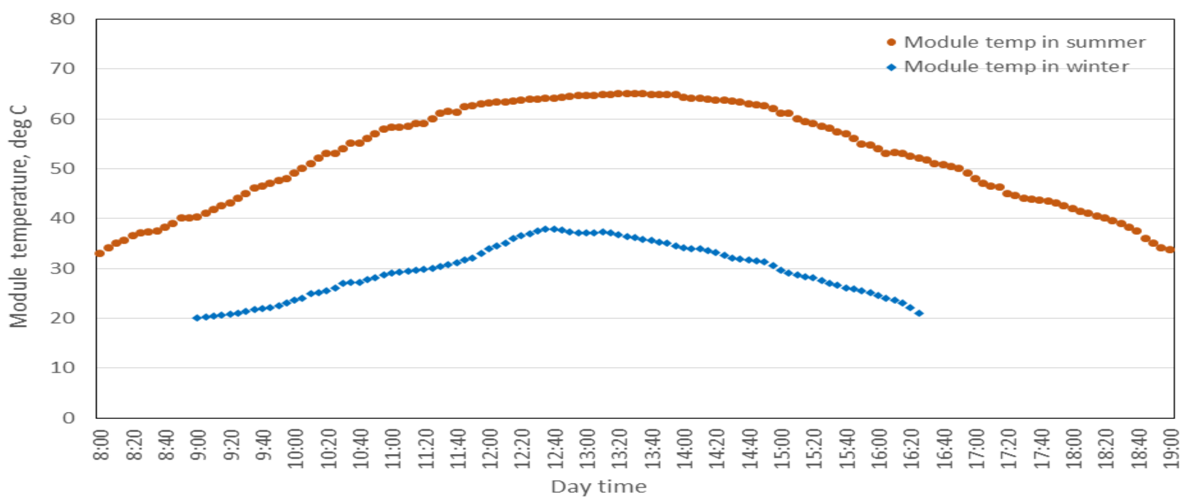


**Figure 11: PV module surface temperatures in summer and winter days.**

## 5. Financial analysis

The financial analysis helps the investors and decision makers to take the correct action about the investment in producing the electrical energy from PV power systems. To evaluate the benefits from installing such grid connected PV systems, different economic measures were used such as life cycle value, net present cost, internal rate of return, ratio of saving to investment and payback period (Kasra et al., 2018). The payback period is a simple way to evaluate the grid connected system which refers to the time in years needed to get back the total investment of the system, or the time required to start capturing benefits from the system after reaching the point of break even. To calculate the payback period, we sum the system total initial costs, including PV panel, inverter and other installation costs, to the annually required costs such as operating and maintenance cost (O&M) and compare the resulted sum with the annual income from the system to get the required period to equal the total system costs to its income. For acceptable systems, the payback period should be shorter than the total lifetime of the PV system. The payback period can be calculated using the following relation (Moien et al., 2018);

$$PBP = \frac{I_i}{[(\sum_{n=1}^{N}(R_n - I_n))/N]} \qquad (1)$$

$$R_n = E_{gn} \cdot C_{Eo}\left(\frac{1+r}{1+i}\right)^n \qquad (2)$$

$$I_n = I_o\left(\frac{1+i}{1+d}\right)^n \qquad (3)$$

Where: $I_i$ is the initial total investment of the system, $R_n$ is the income in time period n, $I_n$ is the investment in time period n, N is the life time of the system, $E_{gn}$ is the generated electricity in time period n in kWh, $C_{Eo}$ is the initial electricity price in c$/kWh, r is the annual increase of the electricity price, i is the inflation rate, $I_o$ initial annual investment and d is the discount rate.

The cost of the grid connected system includes the cost of the initial, installing and M&O. the initial costs are the costs of all components such as PV modules and the inverter, while the installing costs including that required for mechanical structure, cables, switching & protection facilities and metering. The O&M costs gather all costs needed for spare parts, cleaning of PV modules and other required maintenance. The system costs can be considered as follows;

- The PV cost is the main parameter affecting on total capital cost of the system. The PV system is purchased from the local market in Egypt with the price equals to 750 $/kWp (1500

$ per 2-kWp). It should be noted that the life time of the PV panels in the range of 25 years (as dedicated by the data sheet of the PV modules).

- The total purchasing cost of the single phase on-grid inverter is about 555 $. The inverter lifetime is about 13-15 years; accordingly, it should be replaced one time more over the lifetime of the system.
- Installation costs including the mechanical structure, wiring, switching, protection and the energy meter (net metering) can be taken as 8.5% of the PV cost (Kasra et al., 2018; Moien et al., 2018).
- Annual operating and maintenance (O&M) cost is taken as 2% of the PV cost (El Shenawy et al., 2017).
- Inflation and discount rates are taken as 4% and 8%, respectively (El Shenawy et al., 2017).
- Grid electricity price is detected according to the monthly consumption. Table 3 tabulates the electricity consumption price during the last three years in Egypt. It must be noted that the price is annually increased by different ratios according to the category of the monthly consumption. The energy meter used in the PV system is a net metering device, which makes the price of the generated kWh by the PV system is equal to the used one by the consumer, shown in Table 3.

**Table 3: Electricity prices in Egypt for household through 2017-2019.**

| **Energy consumed** | **Electricity price** | | | **Annual increase** | |
|---|---|---|---|---|---|
| | 2017 | 2018 | 2019 | 2018 | 2019 |
| kWh | c$/kWh | c$/kWh | c$/kWh | | |
| 0-50 | 0.61 | 0.72 | 1.22 | 18% | 69% |
| 51-100 | 1.06 | 1.22 | 1.67 | 16% | 36% |
| 0-200 | 1.17 | 1.5 | 2 | 29% | 33% |
| 201-350 | 2.33 | 3.06 | 3.89 | 31% | 27% |
| 351-650 | 3.06 | 4.17 | 5 | 36% | 20% |
| 651-1000 | 5.28 | 6.94 | 7.5 | 32% | 8% |
| 0- > 1000 | 5.83 | 7.5 | 8.06 | 29% | 7% |

According to the total initial cost of the grid connected system, annual O&M costs, the electricity price, inflation and discount rates taken above, Figure 12 illustrates the total income and the total system cost through the lifetime of the grid connected system. Obviously, the total system cost increase annually due to the O&M costs including the spare parts of inverter and other small accessories, while the annual income from exporting electricity to the grid as measured by the net-metering device increases annually according to the increase in the electricity price. The difference between the total income and the total cost through the lifetime of the grid connected system is plotted in Figure 13. It can be seen that the total cost of the grid connected system is less than that of the income from the system in the first years and this difference is annually decreased till the break-even point of the system in which the total system costs equal to the total income from the system. After that, the system starts to get benefits through the lifetime. Figures 12&13 show that the payback period is about 8.2 years, which can be considered small compared to other countries due the high solar irradiation levels in Egypt, which encourages the development planes to take into considerations these kind of systems for generating green electricity.

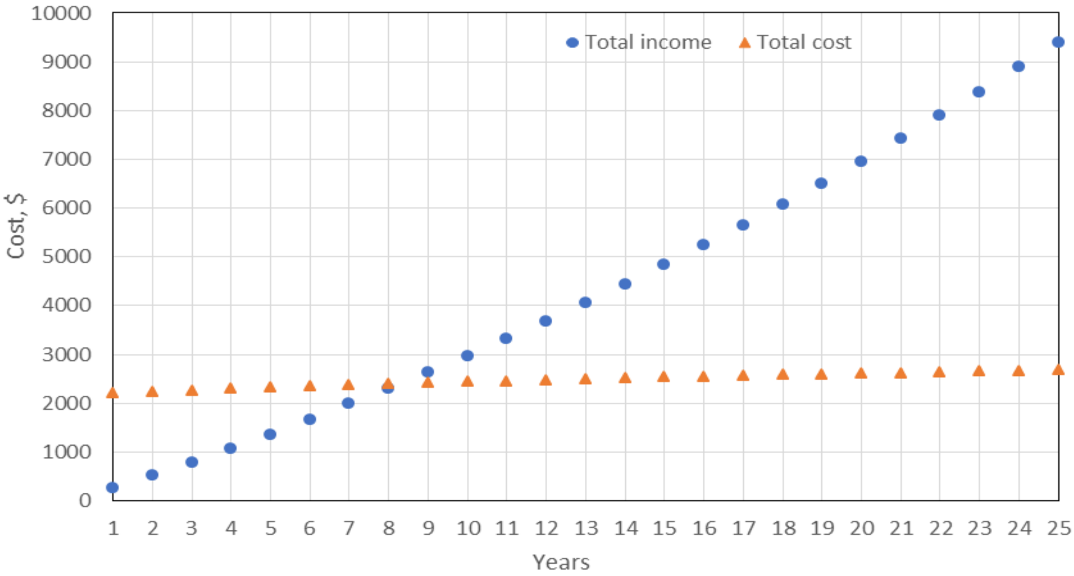


**Figure 12: Total income and total cost through the lifetime of the grid connected system.**

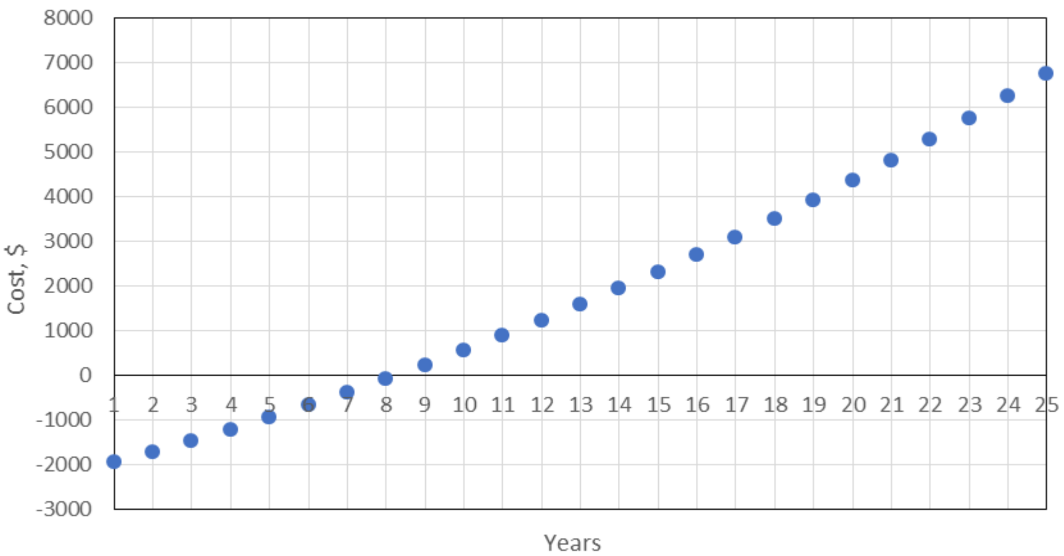


**Figure 13: Difference between the total income and the total cost through the lifetime of the system.**

## 6. CONCLUSIONS

The present paper described the technical performance and financial analysis of a 2 kW grid connected PV system installed in Cairo, Egypt. It gives the details of the site parameters in terms of ambient temperatures, sunshine hours, wind speed and solar irradiation levels on horizontal and optimal tilted surface. The grid connected system consisted of 8 PV modules of 250 W each, grid connected inverter of 1900 W, energy meter and other installation components such as wiring, switching and controlling. The PV modules are installed on a mechanical structure tilted by 30 deg on the horizontal surface. The annual average daily electric energy generated by the system was 9.85 kWh/day, while the annual generated energy was 3.37 MWh/year. The financial analysis using payback period method was carried out taking into account all initial and M&O costs of the system in addition to the electricity price showed that the system payback period was 8.2 years, while the life time of the system is 25 years.

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