# Performance Evaluation of Photovoltaic System Designed for DC Refrigerator

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**Abstract:** ***Refrigeration is closely related to the demand for cooling commodities. Solar refrigeration is thought of as one of the best alternatives to address this issue and it may be accomplished by using one of the refrigeration systems like vapor compression, absorption or thermoelectric refrigeration system. Introducing solar refrigerators into the cold chain indicate that solar refrigerators can provide a more sustainable vaccine cold chain.The solar photovoltaic (PV) system generates both electrical and thermal energy from solar radiation. Therefore an energy and exergy analysis of the system was carried out. Energy analysis was concerned only with the quantity of energy use and efficiency of energy processes. Exergy is the maximum work potential which can be obtained from energy. The experimental data were used for the calculation of the energy and exergy efficiencies of the PV systems. The average photovoltaic efficiency was found to be 8.4 and 8.2% for no load and full load conditions while exergy efficiency was 11.4 and 11.2%, respectively for May month. Photovoltaic efficiency and exergy efficiency were calculated for March and April month also. Hence it is concluded that there was no impact of load on the performance of photovoltaic panel. It was observed that the PV module temperature had a great effect on the exergy efficiency, could be improved by maintaining module temperature close to ambient and that could be achieved by removing the heat from PV module surface. It was concluded that the exergy losses increased with increasing module temperature.***

**Keywords**: Solar photovoltaic, vapor compression refrigeration, thermoelectric refrigerator, exergy efficiency, photovoltaic efficiency

## 1. Introduction

Due to the growing concern and awareness of environmental issues among the scientific community, power generation from renewable energy sources, particularly solar energy has become significantly important for the last few decades. Solar energy due to its intermittent nature is not available for a long time during the day. Its durability varies from country to country and place to place. Solar energy reaching to the surface of the earth can be utilized directly in two ways viz. directly converting the solar radiation to the electricity for useful purposes by the means of solar photovoltaic (SPV) modules or by heating the medium source for low temperature heating applications. Photovoltaic module is not only an expensive but also an essential component of any PV system and therefore its thermal assessment based on the exergy analysis is very important.

The energy efficiency of a solar panel, the ratio of the power output to the energy originally delivered to the solar panel, conventionally is used to measure solar PV efficiency. Energy analysis is based primarily on the first law of thermodynamics, as compared with exergy analysis which is based on the second law. Energy analysis is concerned only with the quantity of energy use and efficiency of energy processes.

Energy analysis thus ignores reductions of energy potential, which could be used productively in other physical and/or chemical process. Energy analysis can provide sound management guidance in those applications in which usage effectiveness depends solely on energy quantities.

Exergy analysis is used to find out the energy utilization efficiency of an energy conversion system. Exergy analysis yields useful results because it deals with irreversibility minimization or maximum exergy delivery. The exergy analysis has been increasingly applied over the last several decades largely because of its advantages over energy analysis. To perform energy and exergy analyses of the solar PV, the quantities of input and output of energy and exergy must be evaluated.

## 2. Literature Reviewed

Some researchers conducted experiments on the performance analysis of photovoltaic driven vapour compressor refrigeration system. Kattakayam *et al.* (1996) studied the electrical characteristics of a 100W AC operated domestic refrigerator using R-12 powered by a field of SPV panels, a battery bank and an inverter. A minimum current region was observed in the mains voltage range of 180– 190 V and at the inverter voltage range of 210–230 V. Charters and Oo (2003) suggested its use in developing countries for essential purposes such as vaccine serum storage at medical clinics in remote regions. Eltawil and Samuel (2007) stated that refrigerated storage was believed to be best method for storing the fruits and vegetables in fresh form, which were not available in rural or remote locations where grid electricity was almost not available. Fatehmulla *et al.* (2011) designed and developed low power refrigeration system using PV modules, 2 modules each of 36 solar cells. Yilanci *et al.* (2011) studied the energy an analysis of a refrigerator, powered by a photovoltaic investigated to obtain efficient operation conditions based on experimental data. Sobamowo *et al.* (2012) designed and developed photovoltaic-powered dc vapour compression refrigeration system for developing countries such as Nigeria and showed that its applicability to different climatic regions in Africa and could be used for perishable food storage, improvement in the health services and living conditions in remote and rural areas which were unable to access electricity from the grid.

## 3. Material and Methods

In this experimental study, the comparative energetic and exergetic analysis of solar photovoltaic (SPV) modules has been carried out for a March, April and May month under the different climatic conditions.

### Experimental System

A SPV refrigeration system consisted of DC vapour compression refrigerator of 25 liter capacity. Considering the power requirement of its continuous operation, two 80 W SPV panels were used to convert solar energy into electrical energy. The panels were arranged in parallel. The purpose of this arrangement was to have sufficient potential difference across the 12 V battery for properly charging of battery. The panels were kept on fixed masonry structure at 35° (tilt angle) from horizontal, facing south direction. A battery was used so that it could give high starting current required to start the motor of compressor. It consisted of one 12 V – 150 Ah sealed lead batteries connected in parallel. Panels were connected to the battery via charge controller which avoided the battery from deep discharge. Battery supplied DC current to refrigerator as it operated on DC current.

### Energy efficiency of the solar panel Photovoltaic efficiency

The efficiency of the solar panels defined as the ratio of the electrical power produced to the incident radiation and varies in between 10 to 15% at maximum power conditions for the PV array. If the PV refrigeration system is to operate at high efficiency, it is essential that the voltage imposed on the PV array be close to the voltage that provides maximum power. Photovoltaic efficiency of solar panel was determined at no load and full load condition by using following formula.

$$\eta_{pv} = \frac{P_{max}}{S \times A_{pv}}$$

Where, $\eta_{pv}$ = Efficiency of photovoltaic system

$P_{max}$ = Maximum power from photovoltaic system (W)

S = Solar irradiance (W/m$^2$)

$A_{pv}$ = Area of the photovoltaic system (m$^2$)

### Exergy analysis

Exergy is defined as the maximum amount of work that can be done by a system. Unlike energy, exergy is not subject to a conservation law; exergy is consumed or destroyed, due to the irreversibility present in every real process.

### Photovoltaic exergy

The energy of a PV module depends on two major components--electrical and thermal. In SPV system electricity is generated by the PV effect, the PV cells are heated due to the thermal energy present in the solar radiation. The electricity (electrical energy), generated by a photovoltaic system, is also termed as electrical exergysince it is the available energy that can completely be utilized in useful purpose. Since the thermal energy available on the photovoltaic surface was not utilized for a useful purpose it is considered to be a heat loss to the ambient. Therefore, due to heat loss, it becomes exergy destruction. The exergy output of the photovoltaic system can be calculated as: (Sudhakar and Srivastava 2013)

$$Ex_{out} = V_m I_m - \left(1 - \frac{T_0}{T_{cell}}\right)\left[h_c \times A_{pv}(T_{cell} - T_o)\right]$$

Where$V_m$, $I_m$, $h_c$, $A$ ,$T_{cell}$and$T_o$are the maximum voltage and current of the photovoltaic system, convective heat transfer coefficient from the photovoltaic cell to ambient, area of the photovoltaic surface, cell temperature and ambient temperature (dead state temperature), respectively.

The convective heat transfer coefficient from the photovoltaic cell to ambient can be calculated by using correlation

$$h_c = 5.7 + 3.8 \times v$$

Where, v = Wind velocity (m)

The module or cell temperature is used to predict the energy production of the photovoltaic module. Cell temperature is a function of ambient temperature, wind speed and total irradiance. The cell temperature can be determined by the following relationship:

$$T_{cell} = 0.943T_a + 0.028\,Irradiance - 1.528Windspeed + 4.3$$

Exergy input of the photovoltaic system, which is the exergy of solar energy, can be calculated approximately as below

$$Ex_{in} = Ex_{solar} = A_{pv} \times S \times \left[1 - \frac{4}{3}\left(\frac{T_o}{T_{SUN}}\right) + \frac{1}{3}\left(\frac{T_o}{T_{SUN}}\right)^4\right]$$

Where, $T_{SUN}$ = Temperature of the Sun taken as 5760 °K

Exergy efficiency of the photovoltaic system is defined as the ratio of total output exergy (recovered) to total input exergy (supplied). It can be expressed as

$$\psi_{PV} = \frac{Ex_{out}}{Ex_{in}}$$

### Stastical analysis

Multiple regression analysis is used to investigate the relationships between a dependent variable (photovoltaic efficiency, exergy efficiency and power output) and a set of independent variables (solar radiation, ambient temperature). Multiple regression equations were used to predict the photovoltaic efficiency, exergy efficiency and power output from photovoltaic system.

## 4. Result and Discussion

### Performance evaluation of photovoltaic system at no load

The performance of the photovoltaic system was evaluated in terms of photovoltaic energy and exergy efficiencies during no load testing. Solar intensity was measured hourly and the open circuit voltage and short circuit current was measured during the off cycle of the refrigeration system.

The hourly variation of conversion efficiency ($\eta_{mod}$) is illustrated in figures 3.1,3.2 and 3.3. It is clear from the figure that the efficiency was relatively higher during the early and late hours of the day as compared to midday which was due to thermal effects. It was found that, the conversion efficiency is inversely proportional to the module temperature. The photovoltaic efficiency was found in the range of 7.48 to 10.14%.The average efficiency of the photovoltaic system was observed 8.46% for May month. The average photovoltaic efficiency was 9.93 and 8.5 % for March and April months, respectively.

The exergy efficiency of the photovoltaic system is the ratio of the exergy out to the exergy in. figures shows the value of the overall irradiance incident on the inclined plane of the photovoltaic modules and the solar exergy for a cloudless day. At maximum solar radiation, difference between exergy in and out was found more. The exergy in was maximum due to more temperature which is due to more solar radiation. Increased PV array temperature determines the sensible decrease of this efficiency. In order to have maximum exergy efficiency, PV array temperature should be kept near the ambient temperature or in other words, PV array temperature should be controlled (Srinivas and Jayaraj 2013). Exergy efficiency was found to be 8.26% at 13h due to increase in cell temperature ( 56.11°C) with maximum solar intensity of 911.90W/$m^2$ .Exergy efficiency was determined to be 19.15% at 17h due to less cell temperature (35.9°C). Averageexergy efficiency was found to be 11.41%. Average exergy efficiency for March and April month were 13.02 and 12.18%.

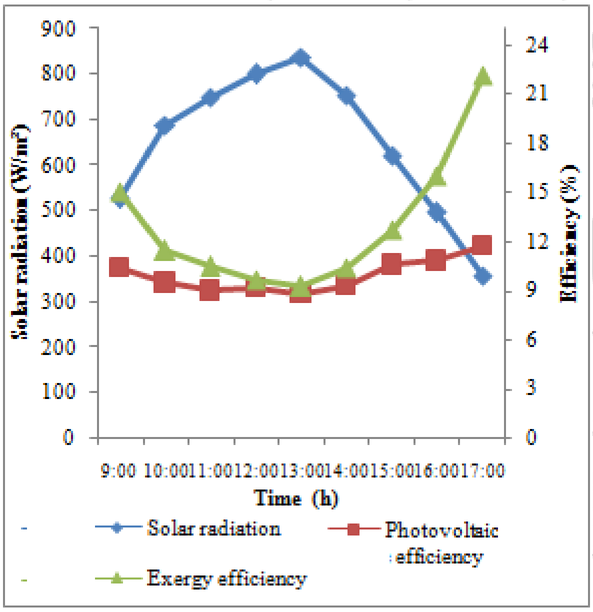


**Figure 1:** Variation of photovoltaic efficiency, exergy efficiency and solar radiation with time (March)

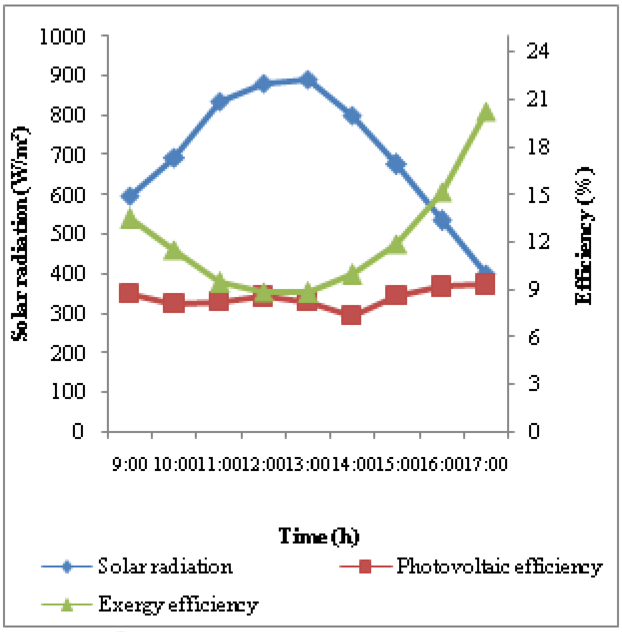


**Figure 2:** Variation of photovoltaic efficiency, exergy efficiency and solar radiation with time (April)

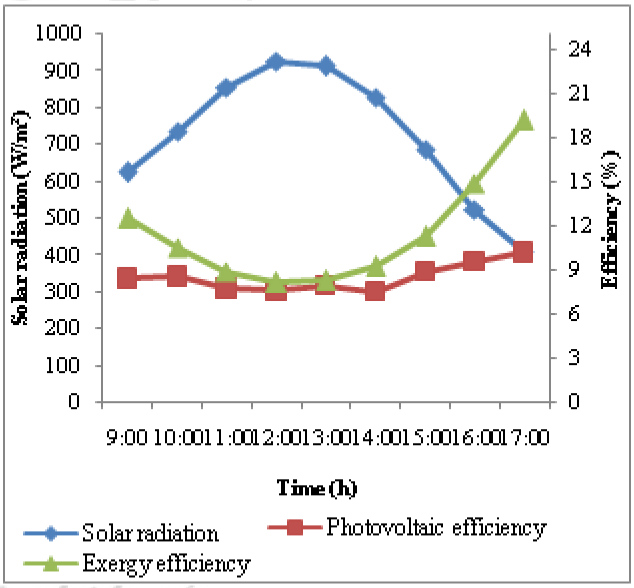


**Figure 3:** Variation of photovoltaic efficiency, exergy efficiency and solar radiation with time (May)

Multiple regression equations were obtained and used to predict the photovoltaic efficiency, exergy efficiency and power output with load. Following multiple regression equation used to predict the module efficiency of May month:

$\eta_{pv}$= 9.5555 – 0.0052SR + 0.0640$T_0$ $R^2$ = 0.89
Where, SR – Solar radiation $T_0$ – ambient temperature

Thus 89% total variation in efficiency could be accounted by linear function involving solar radiation and ambient temperature. It was observed that photovoltaic was significant at 1% level of significance.

Analysis of data indicated that insolation and ambient temperature wasfound 1% affected the exergy efficiency.

The correlation between exergy efficiency and ambient conditions can be expressed as follows.
$\psi_{PV}$ =20.3278 – 0.0206SR + 0.1420$T_0$ $R^2$ = 0.95

The correlation between power outputs by photovoltaic system under no load can be expressed as follows:
$P_{output}$= 18.7411 +0.0752SR +0.3131$T_0$ $R^2$ = 0.94

Analysis of data indicated that insolation was found highly significant (5%) affects the SPV power output. A variation of 94% in power output was observed which could be used in predicting power output at varying solar radiation and ambient temperature

Several multiple regression equations were obtained for March and April month also. Following are the multiple regression equations used to predict photovoltaic efficiency, exergyefficiency and power output for March month.
$\eta_{pv}$= 9.67 -0.008 SR +0.1645 $T_o$ $R^2$ = 0.95
$\psi_{PV}$ = 20.63 – 0.029SR +0.3442$T_o$$R^2$ = 0.95
$P_{output}$= 10.74 + 0.0854SR +0.744$T_o$ $R^2$ = 0.96

Following are the multiple regression euation were used to predict photovoltaic efficiency,exergy efficiency and power output of April month.
$\eta_{pv}$ = 9.33 – 0.0027SR +0.0298$T_0$ $R^2$ = 0.73
$\psi_{PV}$ = 15.54 -0.024SR +0.3649$T_0$$R^2$ = 0.95
$P_{output}$= 20.54 +0.103SR -0.2086$T_0$ $R^2$ =0.94
From this it was concluded that there is variation in photovoltaic efficiency, exergy efficiency and power output. Solar radiation and ambient temperature significantly affect the both efficiencies and power output.

**Performance evaluation of photovoltaic system at full load**

From figure 3.6 it is observed that photovoltaic efficiency found (8.24%) highest in early morning and 10.02% in afternoon at 17.00 h with corresponding solar radiation of 627.00 and 424.80W/$m^2$, respectively. Thus it was affected by solar radiation and module temperature. The average photovoltaic efficiency was found to be 8.2% for May month. The average photovoltaic efficiency for March and April month were 9.74 and 8.36 %, respectively.

The performance of photovoltaic system was evaluated at full load condition by adopting the same procedure as adopted in no load condition. From figures it can be easily seen that the exergy-in of sun was maximum of about 1258.22 W indicated the great potential of sun to emit power and it increased with increase in solar radiation. It was analyzed and shown in the figure that the photovoltaic exergy-out found 99.58 W found below the maximum power extract from the photovoltaic system due to the high cell temperature produced heat energy and this heat energy being lost by the system. The exergy efficiency was found to be 18.31% at cell temperature 37.74$^0$C at solar radiation of 424.80W/$m^2$. At 13.00h the exergy efficiency found minimum (7.9%)at cell temperature of 56.97$^0$Cand solar radiation 943W/$m^2$ for May month. The average exergy efficiency was found to be 13.02, 12.18 and 11.11% for March, April and May month, respectively.

Figure showed the exergy of the radiation incident on the inclined plane, i.e., the maximum electrical power obtainable from the radiation, and the power supplied by the photovoltaic modules. The actual power extracted from the photovoltaic modules over the course of the day was much less than could be extracted. The figure showed the influence of the battery charge controller on the efficiency of the photovoltaic modules. On sunny days, when there was a high radiation exergy, the battery quickly reached its maximum charge, and the controller switched to floating charge mode and cut the current flow to the battery.

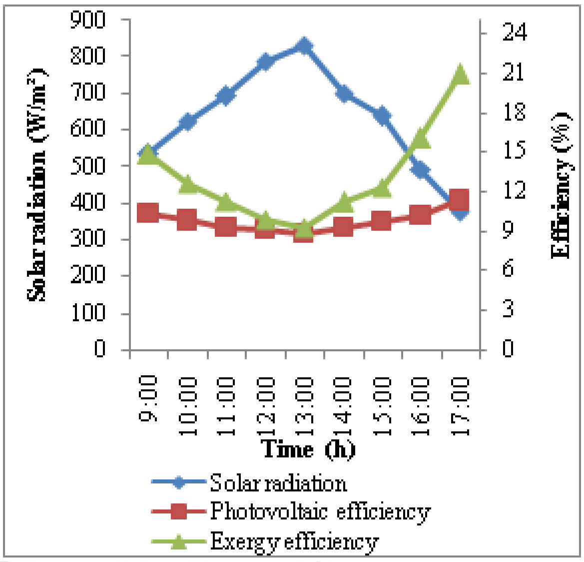


**Figure 4:** Variation of photovoltaic efficiency, exergy efficiency and solar radiation with time (March)

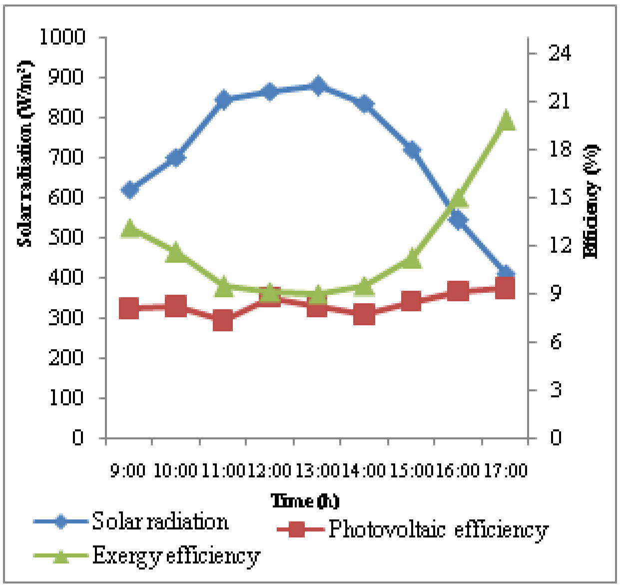


**Figure 5:** Variation of photovoltaic efficiency, exergy efficiency and solar radiation with time (April)

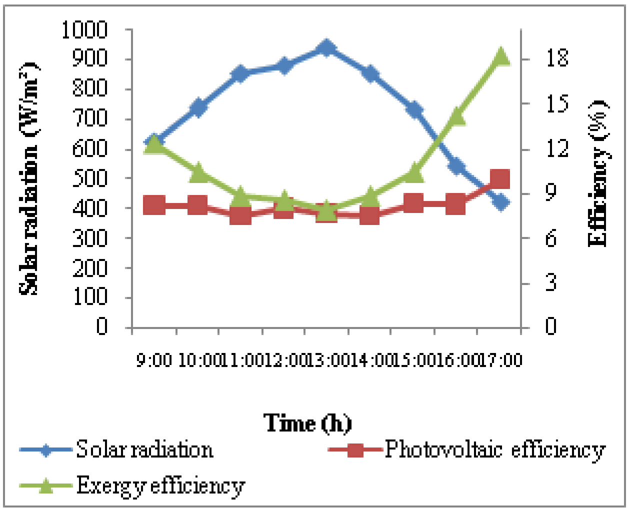


**Figure 6:** Variation of photovoltaic efficiency, exergy efficiency and solar radiation with time (May)

Multiple regression equations were obtained and used to predict the module efficiency, exergy efficiency and power output with load for May month. The regression equation for photovoltaic efficiency is as follows:

$\eta_{pv}$= 4.8542 – 0.0057SR + 0.1772$T_0$ $R^2$ = 0.87

Where, SR – Solar radiation $T_0$ – ambient temperature

Photovoltaic efficiency was found significant at 5 % level of significance. Thus combined linear effect of solar radiation and ambient temperature contribute significantly to variation in efficiency. The correlation between exergy efficiency of photovoltaic system and ambient conditions in case of full load condition can be expressed as follows:

$\psi_{PV}$ = 24.7071 – 0.0193SR + 0.0151$T_0$$R^2$ = 0.95

Above equation revealed that 95 % variation in efficiency and significant at 1 % level of significance and solar radiation affected the exergy efficiency. The multiple regression equation for power output of photovoltaic system is as given below:

$P_{output}$ = 36.2403 + 0.0930SR – 0.4488$T_0$ $R^2$ = 0.96

Analysis of data indicated that power output was significant at 1% level of significance and solar intensity and ambient temperature was highly significant and affected the SPV power output. Following are the multiple regression equations used to predict photovoltaic efficiency,exergy efficiency and power output for March month at full load condition.

$\eta_{pv}$ = 14.76 – 0.004SR – 0.064$T_0$ $R^2$ = 0.96

$\psi_{PV}$= 25.06 – 0.026SR + 0.13 $T_0$ $R^2$ = 0.94 $P_{output}$ = 45.42 + 0.105SR -0.7438$T_0$$R^2$ =0.99

From this it was concluded that solar radiation and ambient temperature significantly affect and used to predict photovoltaic efficiency, exergy efficiency and power output.

Several multiple regression equations were obtained for April month also which are as follows:

$\eta_{pv}$ = 2.7984 -0.0063 SR +0.4102$T_0$$R^2$ = 0.84 $R^2$ = 0.84

$\psi_{PV}$ = 8.81- 0.0265SR +05799$T_0$$R^2$ =0.97 $R^2$ = 0.97

$P_{output}$= 77.62 -0.070SR +2.937$T_0$$R^2$ =0.93 $R^2$ = 0.93

## 5. Conclusions

Performance of photovoltaic system at no load and full load condition were carried out to assess its technical viability. This study indicated the necessity and usefulness of energetic and exergetic techniques to evaluate the performance of the SPV refrigerator. The average photovoltaic conversion efficiency and exergy efficiency found nearer to 8.5% and 11% respectively in both no load and full load condition for May month. This indicates that the full load condition does not affect the PV system. The photovoltaic and exergy efficiency was found less due to the module temperature hence exergy were destroyed highly in PV

## 6. Future Scope

In the vapor compression cycle the compressor is the major power consuming device. The compressor of the vapor compression cycle requires large quantities of power for its operation and it increases as the size of the refrigeration system increases. In case of the vapor compression refrigeration system, the compressor can be run by electric power supply only; no other types of energy can be utilized in these systems. These days the electric power has become very expensive, hence the running cost of the vapor compression refrigeration system is very high. The Sun's Heat and Light energy can be effectively utilized to convert incident solar radiation into electric current hence solar energy systems are becoming more and more popular by the day. Majority of people believe that solar energy systems such as "solar panels" are going to be the source for future energy requirements. It is thus a renewable energy source and does not cause any kind of pollution to the ground or air or water bodies. Hence, Solar Energy Is both CLEAN and GREEN Energy!

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