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Development of Dual Axis Heliostat and Testing its Effect on Solar Collector

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Abstract

This paper aims to provide an over view of a new innovative heliostat design which is fabricated especially for solar roof collectors. The design is based upon an inexpensive duel axis reflector assembly which has the ability to track the sun and reflect its image on a target placed horizontally on the ground. The proposed design gives the maximum solar power together with optical parameters. One more advantage of the designed heliostat is the ability of updating to perform two extra tasks in addition to sun reflection. The effect of the designed heliostat has been tested on evacuated solar roof collector. The designed heliostat costs 0.10 percent from the price of a single solar roof collector from the evacuated type and increases the exposure of the solar roof collectors to solar radiation by about seventy percent.

1. Introduction

Nowadays there is a renewed interest in the use of renewable energies, particularly solar energy, driven by the need of reducing the high environmental impact results of using fossil fuel and the fact that in a near future there will be a lack of this kind of fuels. However, there aretwo main drawbacks of solar energy systems: (i) the resulting energy costs are not yet competitive, and (ii) solar energy is not always available when needed.

Considerable research efforts are being devoted to develop efficient ways to collect, convert, store and utilize solar energy at reasonable costs.Solar plants have all the characteristics needed to use advanced control strategies able to cope with changing dynamics, non-linearity and uncertainties. The use of efficient control strategies resulting in better responses would increase the number of operational hours of solar plants and thus reduce the cost per kWh produced [1].The main solar energy plants and the control problems involved are described in [2].

Solar radiation is concentrated by reflection or refraction through mirrors or lenses. The mirrors can be plane, called heliostats, or parabolic. Heliostat is a device consists of an assembly which revolves slowly occupying a tracking mechanism so as to converge sunlight at a fixed focus. The concentrated sunlight at the focus provides better solar energy concentration usage. Heliostats have been used to concentrate solar energy for many years. Heliostats have a potential of being the lowest cost solution to all the power one needs. Among the challenges to be overcome are energy losses and sun tracking.An assembly based on a dual axis heliostat mirror which tracks the sun and concentrates the solar energy at point where thermoelectric generators are installed to produce electrical power is described in [3].

In [4]a method for closed loop control of a heliostat is developed and tested. A significant reduction of tracking error by smooth continuous tracking was achieved. The design and construction of a heliostat controlled by sun-tracking photo-sensors is discussed in [5]. The sensor,two photo-cells,was placed side by side on the bottom of the small box. Sun-tracking was achieved by rotating the heliostat equipped with the sensor, while maintaining the two photo-cells under illumination by the sun through a slit in the box.In [6] the principle and Sun-tracking methods are reviewed and discussed.It was found that the most efficient and popular sun-tracking device is in the form of polar-axisand azimuth/elevation types.

This paper focuses on the solar roof collectors used in the SUNWATER project and aims to find a way to minimize the number of solar roof collectors used in order to reduce the total cost of the system. Basically, cost reduction can be achieved by using less number of solar roof collectors while subjecting it to an extra amount of the solar radiation using reflectors. To ensure reflecting the maximum amount of solar radiation on solar roof collectors, the reflectors should be able to track the sun and reflect its radiation during day period using a tracking system.

2. System Description

The proposed heliostat design is manufactured and installed at a solar thermal based water desalination unit(WDU). A schematic of the WDU is shown in Fig. 1. This unit was funded by the EU and the Ministry of Higher Education and Scientific Research in Egypt (RDI) and has been installed in the faculty of engineering, Helwan University [7].

2.1 Water Desalination Unit

The water desalination unit is a combined system consists of two main subsystems and a meteorological station. The first subsystem is the solar energy harvesting and storing. It involves evacuated solar collectors array, a non-uniform losses stratified fluid storage tank and counter flow heat exchanger. The second subsystem is a state of the art water desalination unit (WDU). The meteorological station is used for automatic monitoring of the weather conditions: humidity, temperature, wind speed and direction, and the amount of solar radiation in the place at which the water desalination unit is installed [8]-[9].The WDU involves 16 solar roof evacuated tube collectors. Each solar collector generates power ranges from (0.5 to 3) KWP.

2.2 Heliostats and Sun Motion

Heliostats are used for many applications such as natural day lighting for residential to save electrical energy and concentrating solar energy onto the heat source of a power plant.Over the full day, 10.6 kilowatt-hours of energy has fallen on every square meter of surface area [10].This show the needs of heliostats as a meanof reflecting an extra amount of solar radiation on the desired medium to increase its thermal energy which is used for heating special fluids to be used in different applications.

The rotation of heliostat around two axes changes two angles which needed to track the sun motion. This is because while the sun marshes through the sky from the east to the west it change in the position and altitude. The sun position can be identified by two angles: the elevation angle (β) and the azimuth angle ($\emptyset_s$). Both angles can be determined using the following equations [11]:

$$\sin\beta = \cos L \cdot \cos\delta \cdot \cos H + \sin L \cdot \sin\delta \quad (1)$$

$$\sin \emptyset_s = (\cos\delta \cdot \sin H)/(\cos\beta) \quad (2)$$

$$\delta = 23.45 * \sin\left(\frac{360}{365} + (284 + dayofyear)\right) \quad (3)$$

$$H = 15(t_s - 12) \quad (4)$$

where:
β: Elevation angle.
L: The latitude.
H: Solar Hour.

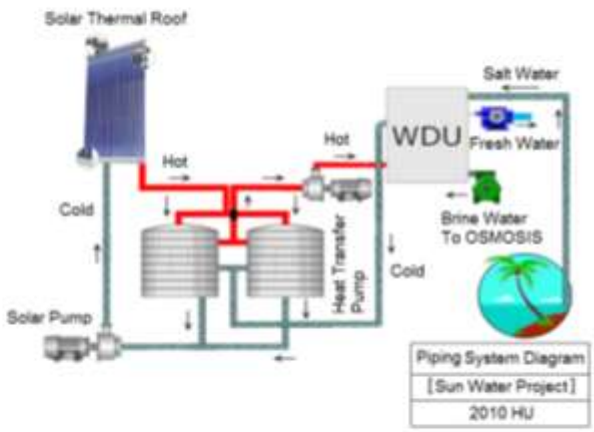

Fig. 1. Schematic of water desalination unit

δ: Declination angle.
H: Solar Hour.
t_s: Hour.

2.3 Heliostat for Evacuated Tube Collectors

USA energy information administration has classified the solar thermal as low, medium and high temperature collectors [12]. High-temperature solar thermal applications can be seen in the solar thermal power plant which uses heliostats to concentrate sunlight on a predetermined medium and heat up certain fluids to be used in power production or water desalination. Low and medium are flat and evacuated solar roof collectors and usually used to heat swimming pools also for residential and commercial uses.Solar roof collectors does not depend on heliostats in its operation, and virtually it's rarely to reach the temperatures that it was designed to operate under it.The research idea is to get advantage of the heliostats idea and apply it on solar roof collectors to boost its efficiency.

A new heliostat design has been invented specially for this research.The invented mechanism has the ability to reflect sun light on objects supported on the ground and its total cost is relatively low compared with evacuated solar roof collector used in the SUNWATER Project. The invented mechanism of heliostat is designed to reflect sun light on two solar roof collectors at the same time asshown in Fig. 2.It consists of two main parts: a lower frame which is used to support the mechanism on the ground and an upper frame which involves two inner pedestals that holds the reflecting surface. Thin stainless sheets, 406 bright, are selected as a reflecting surface.Each Pedestal rotates around fixed joint in order to track the sun azimuth angle.The upper frame which holds the two pedestals moves up and down to track the sun elevation angle.

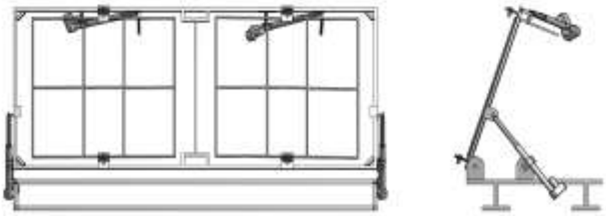

Fig. 2. A schematic of the developed heliostat

The mechanical and electronic components of heliostat are designed and fabricated tacking into consideration the cost factor. A low cost satellite dish actuator which has high fractional horse power and high gear ratio is used. It provides slow, accurate and powerful tracking motion. The energy used is very low where each motor withdraws 100 watt. The motors also involve reed magnet switch which is used to detect the motor position. In addition low cost electronic circuits are built to control the motor motion.

The designed heliostat can be supported close to the solar roof collectors in order to save space. The Sun elevation angle can be tracked and reflected on the desired position by the motion of the upper frame through changes in angle θ_H, Fig. 3. The heliostat has to be positioned by the controller so that the normal to its surface bisects the angle between the sun incident and reflected ray on the desired target.The assembly has the ability tocalculate elevation angles ranges from 35^o to 115^o which are adequate to track the sun elevation angle. An equation has been deducted from the motion of the heliostat while tracking the sun elevation angle.

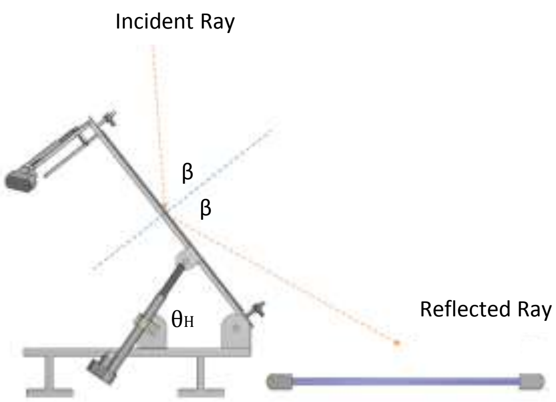

Fig. 3. Heliostat elevation angle tracking and reflecting

The assembly alsocalculates azimuth angles ranges from 45^o to 314^o. The sun azimuth angle can be tracked by the rotation of the inner Pedestal of the upper frame to the left or right as shown in Fig 4. The inner pedestal starts at point 1 while the sun rising.At noon time the inner pedestal reaches point 2 and finally reaches point 3 while the sunset.

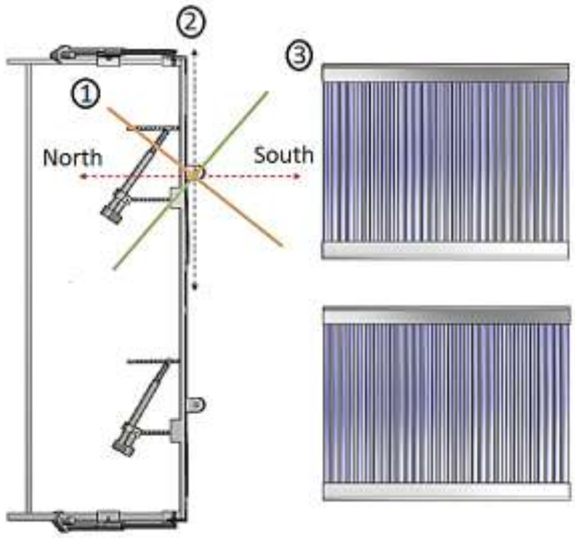

Fig. 4. Heliostat azimuth angle tracking and reflection

The assembly alsocalculates azimuth angles ranges from 45^o to 314^o. The sun azimuth angle can be tracked by the rotation of the inner Pedestal of the upper frame to the left or right as shown in Fig 4. The inner pedestal starts at point 1 while the sun rising.At noon time the inner pedestal reaches point 2 and finally reaches point 3 while the sunset.

Both estimated heliostat anglesareusedby the controller to follow the sun elevation and azimuth angles and reflect sun radiation on the central point of the evacuated tube collectors.

Fig. 5 shows a photograph of the designed heliostat supported in front of the evacuated tube collectors where the heliostat reflects sun radiation on the first two sets of solar roof collectors.

3. Implementation

3.1 Motor Modeling and Identification

The dynamic behavior of the DC motor used in the assembly is typically considered linear where identification and estimation of a linearized model is used to identify the best structure of the final linear model. Using the experimental setup for studying the DCmotor characteristics, a random angle signal is applied to excite the system.Each motor is subjected to an input excitation and the response is observed. The input is a control voltage signal which represents certain angle and the output is the change in the motor speed to reach the desired angle. Matlab identification toolbox [13] is used to deduce the acceptable model order that fits the measured data with the simulated results. Using the input/output recorded signals, the following motor transfer function isidentified:

$$G(s) = \frac{0.003749\ Z^{-5}}{1-0.9052\ Z^{-1}-0.09478\ Z^{-2}} \quad (5)$$

Proportional integral (PI) controller is applied to the motors used to drive the heliostat. Simulink is used to test the model transfer function and the selected values of the proportional and integral terms of the controller. Fig. 6 shows the Simulink model of the system.Using simulation, the best values of the controller parameters K_p and K_i, are 6 and 1e-6 respectively.

Fig. 5. Evacuated tube collectors under exposure of heliostat

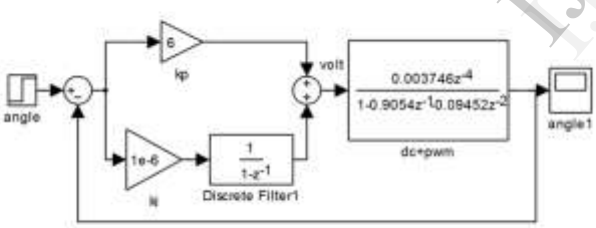

Fig. 6. Matlab Simulink closed loop transfer function block diagram

3.2 Tracking Algorithm

The designed heliostat is a sensorless tracking heliostat which uses astronomical calculations to determine the position of the sun. Further, sensors are used to reduce the error and to calibrate the system. The sun elevation and azimuth angles are measured instantaneously over time and according to these angles the heliostat corresponding angles are computed. The heliostat angles areused to point the heliostat reflecting surface accurately to reflect the sun image on the required position.

LabVIEWis chosen as the programming language and NI-USB-6008[14] is used as data acquisition/interface card.A program is designed to estimate the sun elevation and azimuth angles according to equations (1)-(4) instantaneously and compute the corresponding heliostat angles required to reflect the sun radiation. Fig. 7 shows the GUI of designed program to illustrate the controller behavior during operation. The program also has the ability to predict the amount of solar radiation at any day and plot the predicted values for the sun and heliostat angles.

4. Results

4.1 Heliostat Controller Accuracy

The recorded data of Sun angles and heliostat corresponding angles are used to test the tracking performance and error variation. The heliostat controlled motion is tested for three continuous days, 12 hours a day and the values of each sun angle and its corresponding heliostat angle are plotted. The heliostat controller accuracy represents the accuracy of the heliostat in tracking the sun azimuth and elevation angles.

Fig. 8 shows the recorded data of the sun azimuth angle and heliostat corresponding azimuth Angle. X-axis represents the time in hours and Y-axis represents the angle in degrees.

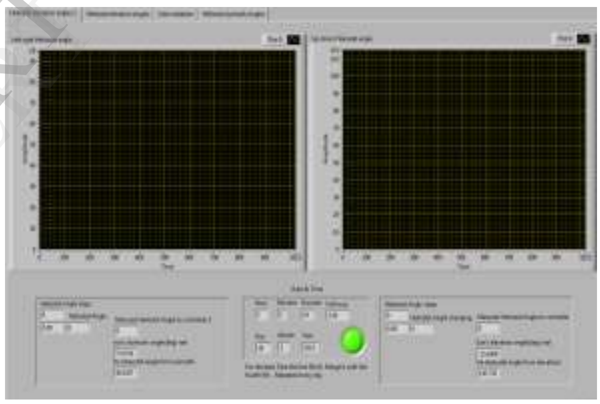

Fig. 7. GUI of Labview program

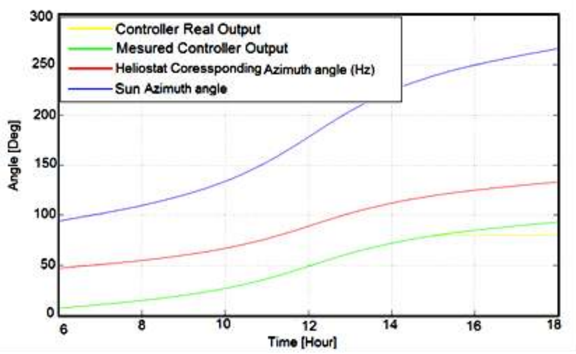

Fig. 8. Measured azimuth angles

Four different curves are displayed in the figure. The blue curve represents the recorded azimuth angles for the sun during the time from 6:00am to 6:00 pm. The results show that at 6:00 am, when the sun shines, the sun azimuth angle is at its lowest value and this value increases as the time increases according to the definition of azimuth angle. The red curve represents the heliostat recorded values correspond to azimuth angles required to set the surface of reflector to reflect sun light on evacuated tube collectors. The red curve is the control signal to the motor. This signal has to be subtracted from heliostat starting angle which is 45° in this case. The green curve represents the shifted red curve and the yellow curve represents the change in azimuth angle measured from the heliostat motors by the reed magnetic switch.

The error between the actual and the heliostat real angle, measured by the magnetic reed switch, is displayed in Fig. 9. The results show that the controller allows the mechanism to track the change in sun angle with error less than 0.1%.

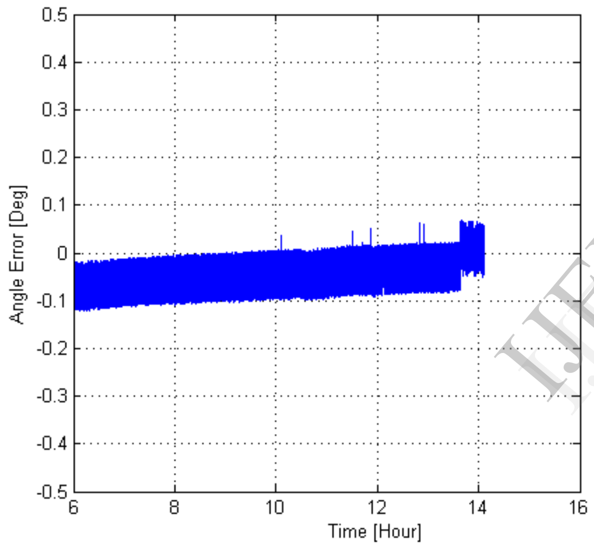

Fig. 9. Error between heliostat and real azimuth angle

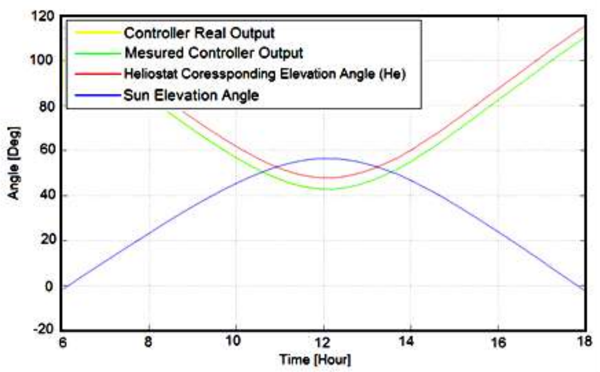

Fig. 10. Real elevation angles

The controller accuracy in tracking the sun elevation angle is investigated and the results are shown in Fig. 10. X-axis represents the time in hours and Y-axis represents the angle in degrees. The results show that the sun elevation angle, blue curve, is at its lowest value both at 6:00 AM, when the sun shines, and at 6:00 PM when the sun sets. The red curve represents the corresponding heliostat elevation angles required to set the surface of reflector to reflect sun light on evacuated tube collectors. The red curve is the control signal to the motors which is to be subtracted from heliostat starting angle, i.e. 35° in this case. The green curve represents the shifted red curve and the yellow curve represents the change in azimuth angle measured from the heliostat motors by the reed switch.

Figure 11 shows the error between the control signal and the heliostat elevation angle measured by the reed switch. The controller allows the mechanism to track the change in sun angle with error less than 0.1%.The controller generates plots for the predicted heliostat and sun azimuth and elevation angles as well as the amount of exposure of solar radiation.

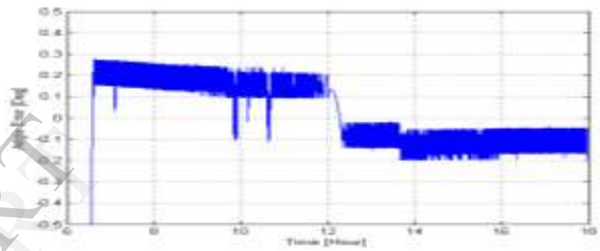

Fig. 11. Error between heliostat and real elevation angle

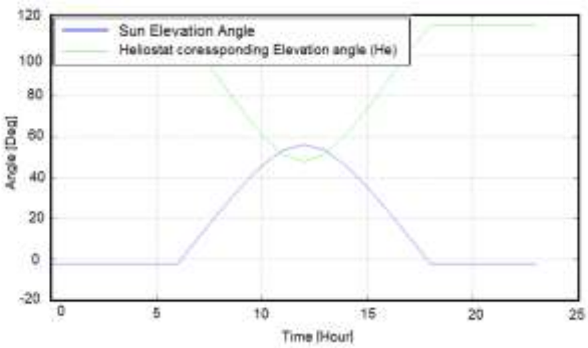

Fig. 12. Predicted elevation angles

Fig. 12 shows a plot of the predicted sun elevation angles during the day and the heliostat corresponding elevation angles reqiured to reflect the sun radiation on the desired spot. The change in sun elevation angles represented by the green curve and the change in heliostat corresponding elevation angles is represented by the blue curve. The figure shows the change in sun angles for twelve hours starting from 6:00AM to 6:00PM.Solar Radiation

The solar radiation sensor is installed in the center of the evacuated tube collectors, i.e. the center of reflected sun image during the noon time. The data is recorded for 30 minutes at the winter period on the first of March. Fig. 13 shows the difference between the solar radiation using heliostat and without heliostat. The results show that the maximum solar radiation without using heliostat (blue) was about 800 W.h./m^2. When using the heliostat the maximum solar radiation (red) is increased to about 1350 W.h/m^2. Thus an increase of about 70% is achieved through the use of the proposed heliostat design. This amount, however, depends on the reflectivity coefficient of the reflectors.

4.2 Layout of Solar roof collectors

When applying the proposed idea, the system lay out is as shown in Figure 14. The heliostat increases the solar radiation incident on the two evacuated tube collectors. The heliostat area (5 m^2) for each side will add about 7KWP to the evacuated tube collectors array.

If the proposed idea is applied on the whole solar collectors grid, the system lay out will be as shown in Figure 15. The grid will use only 8 units instead of 16 units.

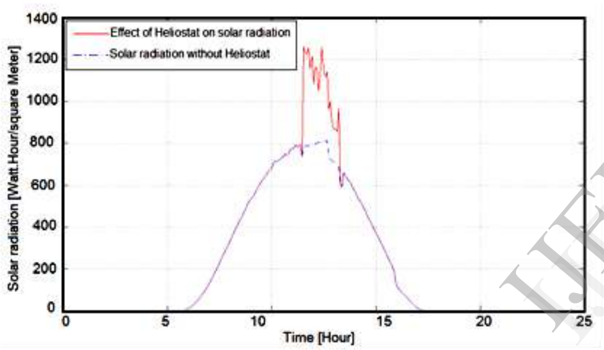

Fig. 13. Solar radiation measured by global solar irradiance pyrometers

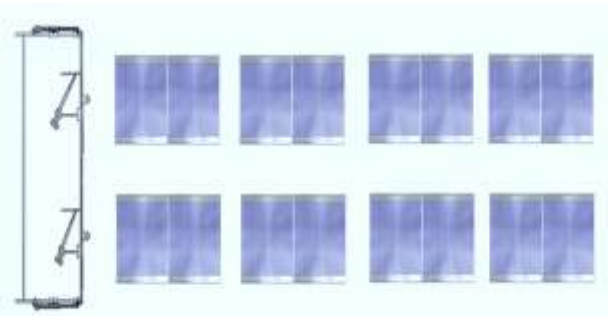

Fig. 14. Solar roof collectors when using one heliostat

Each solar roof collector will produce energy of the range 0.85 KWP to 5.1 KWP. Thus a reduction in the total cost by about 50% could be achieved using the proposed heliostats system.

Fig. 15. Solar roof collectors when using four heliostats

5. Conclusion

In this paper a dual axis heliostat is designed and its effect on solar roof collectors is investigated. The system is implemented on the solar roof collectors used in SUNWATER EU-funded project, managed by the Helwan University in Cairo, Egypt. The proposed system minimizes the number of solar roof collectors used in the project to reduce the project total cost.

Results show that an increase in the efficiency of the solar roof collectors due to subjecting it to an extra amount of the solar radiation could be achieved. An extra amount of solar radiation, about 700 KW/m2, can be gained. This leads to an increase in the efficiency of solar collectors by about 70%.

6. Acknowledgment

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