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Impact of the Location of a Solar Cell in Relationship to the Focal Length of a Fresnel Lens on Power Production

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Abstract The purpose of this study was to optimize the energy output of solar cells using a Fresnel lens. A Fresnel lens is a flat approximation of the standard convergent thin lens that is able to converge rays of light perpendicular to its surface onto a single point, its focal point, thus concentrating the light energy on a small spot size. To test how Fresnel lenses would impact the energy outputs of solar cells, eight lenses were placed above eight monocrystalline solar cells at heights equal to 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, and 1.8 times the lenses' focal lengths, with an additional solar cell with no lens serving as the control. These setups were tested outdoors for seven days, with the power outputs across 120Ω resistors measured by an Arduino-based data logging circuit. It was found that all experiment groups outperformed the control group in average energy production except for the 1.0F group with the solar cell at the focal length (F), which decreased the energy production by an average of 9.76%. The net increases ranged on average from 1.25% to 14.93% with the 0.8F group performing the best, generating 14.93% more energy than the control. The 1.0F group failed to improve the performance of the solar cell. Findings of the current study indicate that uses of Fresnel lenses with solar cells at optimized lens-solar cell distances could enhance cell output and therefore the practicality of the use of solar energy.

Keywords Solar energy, Solar panel, Photovoltaic cells, Fresnel lens, Focal length, Power production

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1. Introduction

Solar energy is a huge, albeit largely untapped source of electrical energy that can be harvested relatively cleanly. It is estimated for example that the peak insolation in New York State is approximately 500 Watts/m^2, and is even higher at lower latitudes, where the sunlight is more direct[1]. However, due to the Shockley-Queisser limit, the theoretical efficiency of even the most efficient monocrystalline silicon-based solar cells is approximately 29%. Current solar panels can only achieve about 18% practical efficiency[2]. The efficiency of silicon solar panels can be further decreased by high temperatures as greater temperatures lower the bandgap of the silicon, making the bandgap less optimized, as less energy from photons that move to the conduction band can be harvested[3]. In fact, it has been shown that the maximum efficiency of a solar panel, as a function of temperature, decreases at a linear rate set by the temperature coefficient[4]. Thus, it is rare that a solar panel can perform at its maximum efficiency because heat is a byproduct of solar radiation[5]. Furthermore, silicon solar panels are very expensive[6], as the silicon must be of high purity (>99.9%) for the solar panel to function properly. Even with tax breaks, a consumer investment in solar energy by installation of solar panels can require as much as 10 years to pay for itself[7].

Such high price and long break-even time are prohibitive for some homeowners and businesses, preventing a broader adoption of solar energy. Therefore, an inexpensive method of increasing the output of a typical silicon solar cell was investigated, thereby improving the power output-to-cost ratio of the solar cell and lessening the break-even time of such an investment.

There have been many previous attempts to increase the output of solar cells, and most of them utilized parabolic reflectors, mirrors, and Fresnel lenses for concentrating the solar radiation onto a single point on the solar panels. For example, Mlavsky and Winston[8] designed a solar concentrator that utilized the geometry of a mirror to focus light onto a solar panel positioned at the focal point. Al-Baali[9] reported a two-stage design consisting of a water circulation system and a reflecting mirror for improving the efficiency of solar panels. Dallakyan and Vardanyan[10] developed a cost effective mirror reflecting system to increase the solar energy output. Although some improvements were achieved in certain complicated concentrating systems, the overheating problem for solar panels prevented them from becoming practical[11]. In addition to improvements to existing silicon solar cells, organic polymer[12][13][14] and ceramic[15] solar cells are being developed. A recent breakthrough that could greatly

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boost the efficiency of solar cells utilized printed colloidal quantum dots as the photosensitive layers to respond to specific wavelengths of light[16].

The purpose of this investigation was to optimize the energy output of silicon-based solar cells using a Fresnel lens by positioning the lenses at different heights above the cells. Unlike the previous Fresnel lens solar concentrator system[8] that positioned the lens at its focal point (1.0F) (Figure 1a), our designs placed the solar cells off the focal point either below or above it (Figures 1b and 1c) to overcome the overheating issue of the solar cells.

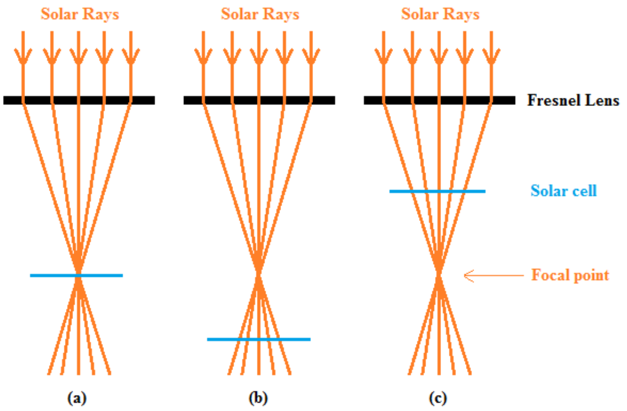

Figure 1. (a) Previous design, solar cell at the focal point (1.0F); (b) and (c) Our designs, solar cell at off the focal point, either below (>1.0F) or above (<1.0F) the focal point

A convergent Fresnel lens is an approximation of a typical convergent lens. It employs concentric rings of sloped ridges that replicate the surface curvature of an actual thin lens. This gives the light focusing ability, while being light and inexpensive, by removing the bulk of the material that would be in the inside of a traditional lens[17]. Like a thin convergent lens, it has the special property of focusing incoming rays of light that are perpendicular to its surface onto a single point, known as the focal point. With the special properties of the Fresnel lens, it was hypothesized that if the solar cell was positioned off the focal point of the Fresnel lens, then the energy outputs would be greater than the lens at the focal point or no lens was used, regardless of different silicon types for the solar cell. That was because there would not be much of an overheating issue while the rays were concentrated for higher energy density.

2. Materials and Methods

2.1. Materials

Monocrystalline silicon solar cells were purchased from Electronic Goldmine[18]. They are circular in shape with a diameter of 10.0 cm, producing a maximum of 0.5 V and 1.0 A, with an optimal power of 1 W. Fresnel lenses were obtained from 3D Lens[19], and are made of PVC, having a size of 218 mm × 156 mm × 0.4 mm (about 4 times area of solar cells) with a 0.3 mm groove pitch. The focal length (F) of the Fresnel lenses is 300 mm. Arduino Uno R3 microprocessor from Adafruit Industries[20] was used to build the data logging circuit. All other parts were obtained from RadioShack® and Home Depot®.

2.2. Experiment Designs

In order to test how the Fresnel lenses will impact the performance of solar cells, and optimize the energy outputs, an experiment setup shown in Figure 2 was designed.

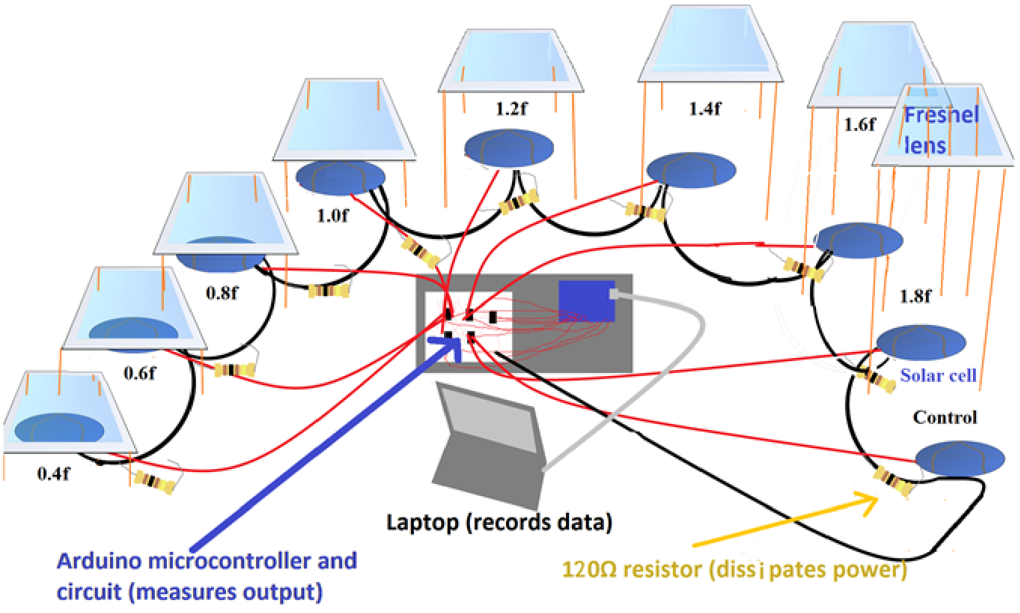

Figure 2. A schematic representation of the experiment setup (Above) and a picture of the experiment setup (Below)

Nine solar cells were mounted on cardboard backings and secured on an obstruction-free field in New York (~40° latitude). Eight rectangular Fresnel lenses with foam frames were each affixed at four corners onto dowels of diameters of 1 cm. The Fresnel lenses were each placed above the solar cell at varying heights. The heights of the Fresnel lenses were adjusted to make the distances between the Fresnel lenses and solar cells equal to 0.4F, 0.6F, 0.8F, 1.0F, 1.2F, 1.4F, 1.6F and 1.8F (120 mm, 180 mm, 240 mm, 300 mm, 360 mm, 420 mm, 480 mm and 540 mm, respectively). A solar cell without a Fresnel lens was used as the control. The setups were adequately separated from each other as to not have one Fresnel lens shadow or lens a different experimental group. All the negative poles of each solar cell were wired to form a common cathode. There were nine resistors added across the anodes and cathodes of each solar cell so that the power lost across the resistors could be later calculated. The resistors were 120Ω, with an error of ± 5%.

After the solar panels were set up, a custom Arduino Microprocessor-based data logging circuit (Figure 3) was constructed, which was designed to log voltage drop across each of the nine 120Ω-resistors attached between the cathodes and anodes of the solar cells at two minute intervals from the test period of 6:00 AM to 6:00 PM.

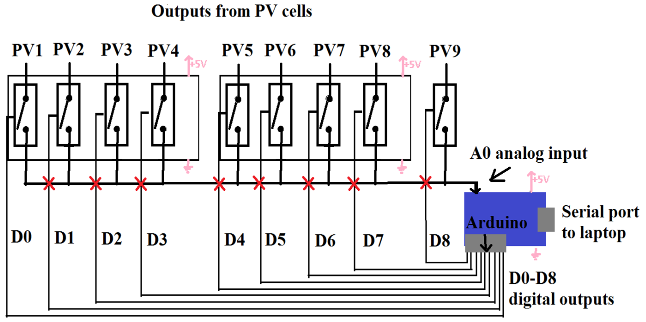

Figure 3. The specially designed Arduino Microprocessor-based data logging circuit measured the voltage drop across the 120Ω resistor of each of the 9 solar cell setups

The experiments were run outdoors for total seven days including under both sunny and cloudy weather.

3. Results and Discussion

The power dissipation of the resistor was calculated by equation 1:

$$P = \frac{V^2}{R} \tag{1}$$

Figure 4 shows the power dissipated by the 120Ω resistor over the time period between 6:00 AM and 6:00 PM on a typical cloudy day (02/15/2013).

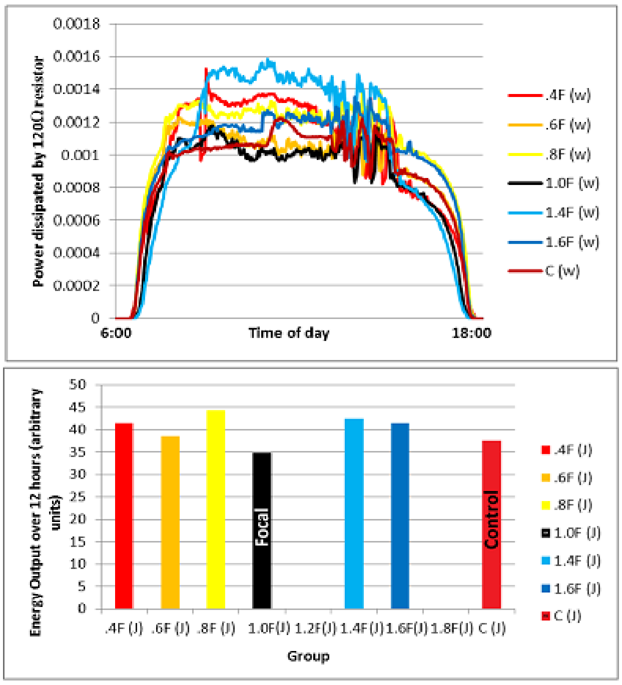

Figure 4. Power *vs.* Time graph for a cloudy day (Above). Total energy outputs over a period of 12 hours (Below). Note: Data missing for the 1.2F and 1.8F groups due to data logging error

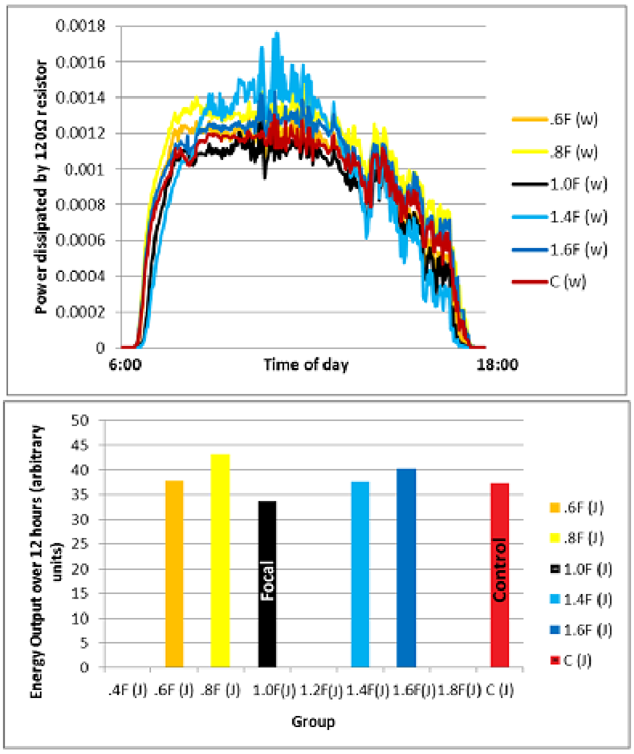

Figure 5. Power *vs.* Time graph for a sunny day (Above). Total energy outputs over a period of 12 hours (Below). Note: Data missing for the 0.4F, 1.2F, and 1.8F groups due to data logging error

To find out how much energy each solar cell produced during a 12 hours period, the power *vs.* time graph was integrated using the Riemann sum approximation since energy is the product of power and time. An arbitrary unit for the energy output was used for the sake of simplicity. It should be acceptable for the following reason: since an arbitrary resistance (i.e., 120Ω) was chosen for the load resistor, rather than an optimized resistance, the power dissipated was not optimized.

As shown in the bar graph (Figure 4), all experimental groups with Fresnel lenses except for the focal point (1.0F) group increased the energy outputs compared to the control. The 0.8F group performed the best with about a 17.77% increase in energy output compared to the control. On the contrary, on this cloudy day, the focal point (1.0F) group performed the worst and lowered the power output of the solar cell by 7.74%. To test if this trend was weather-dependent, experiments were run on sunny days. The results for a typical sunny day (02/19/2013) are shown in Figure 5.

Consistent with the cloudy day data, the 0.8F group produced the most energy or 15.49% more than that of the control group. The focal point (1.0F) again performed the worst by producing 9.56% less energy than the control.

These preliminary results suggested that the above-observed trend was not weather-dependent. To further confirm these results, five more experiments were carried out on both cloudy and sunny days. The results are summarized in Table 1.

It was clear that the 0.8F group outperformed all other experimental groups by increasing the energy output by an average of 14.93% compared to the control. The focal point (1.0F) group failed to increase the energy output, and on the contrary, lowered the energy production by an average of 9.76%. There were net increases in energy outputs in all other experimental groups in percentages varied from 1.25% to 9.53%. These results demonstrated the benefit of Fresnel lenses in helping improve the efficiency of solar cells when positioned correctly.

Table 1. Percent increases in total energy outputs for each of the groups relative to the control group in a 12 hours period for all seven testing days. ND: Data not available due to data logging equipment errors

Group		0.4F	0.6F	0.8F	1.0F	1.2F	1.4F	1.6F	1.8F
Day of Testing	Day 1, Cloudy 02/13/2013	11.00	3.28	15.03	-4.36	ND	10.99	9.66	ND
	Day 2, Cloudy 02/15/2013	10.23	2.36	17.77	-7.74	ND	13.05	10.27	ND
	Day 3, Sunny 02/16/2013	-2.64	-0.43	13.86	-8.95	ND	2.25	6.95	ND
	Day 4, Sunny 02/18/2013	1.08	2.66	10.19	-8.99	ND	2.91	6.63	ND
	Day 5, Raining 02/19/2013	ND	1.19	15.49	-9.56	ND	0.76	7.59	ND
	Day 6, Cloudy 03/04/2013	ND	5.98	15.27	-18.97	1.80	7.49	9.75	2.78
	Day 7, Cloudy 03/05/2013	ND	6.73	16.91	ND	0.70	11.25	9.96	16.28
Average		4.92	3.11	14.93	-9.76	1.25	6.96	8.69	9.53

A possible explanation for the low output of the 1.0F group is that the spot size of the sunlight on the solar cell was too small, as all the light converged onto one point that for most times, the light did not even reach the solar cell. In fact, this was evidenced by the observation of a burn mark on the cardboard beside the solar cell. Even when the light did reach the solar cell, when it was positioned at the focal point of the Fresnel lens, the light covered little area and caused higher temperatures that would lower the efficiency[11]. Conversely, although the light intensity on the solar cell in the 0.8F group was lower than that of the 1.0F group, but still greater than that of the control group, the spot size was much bigger, and the temperature factor took its toll on efficiency to a lesser extent. As a result, overall increase of energy output was achieved.

4. Conclusions

In general, positioning the solar cell at a height equal to 0.8 times of the focal length (0.8F) of the Fresnel lens optimized the energy production of the solar cell out of all the setups tested. In every test that was conducted, irrespective of the weather (sunny or cloudy), the energy output of the solar cell at 0.8F was greater than that of any one of the other setups. Furthermore, on average, that configuration improved the energy output by almost 15% compared to the control. The 0.8F distance between the Fresnel lens and solar cell well balanced concentration of the light intensity and minimization of the overheating issue. By contrast, the 1.0F group performed the worst, being the only experiment group that on average lowered the energy output of the solar cell by almost 10%. While being able to concentrate the light rays the most, the 1.0F distance made the sunlight spot too small and might have caused the massive heat problem, which lowered the energy outputs.

5. Applications

An inexpensive method of increasing solar panel energy production was designed and tested in this investigation, yielding almost 15% average increase in overall energy production in one of the tested prototypes. Such improvement has both implications in residential and commercial purposes. In residential houses, a 15% increase in energy production could decrease the break-even time of a solar investment by 15%, encouraging more people to adopt the solar energy. An increase in solar panel output could also benefit commercial applications by reducing the reliance of fossil fuels that cause great pollution and global warming. Not only is this invention inexpensive, but it is also scalable. Larger solar panels can be fitted with larger Fresnel lenses, and material costs can also be lowered by decreasing the focal length, eliminating the need for long supports that hold the Fresnel lens at a set distance from the solar panel.

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