Optimal Design & Development of a Photovoltaic Panel

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Question

How can the efficiency of a solar panel be increased by using solar concentrators?

Hypothesis

If solar concentrators are used to concentrate sunlight, then a solar panel with the solar concentrator would generate more power.

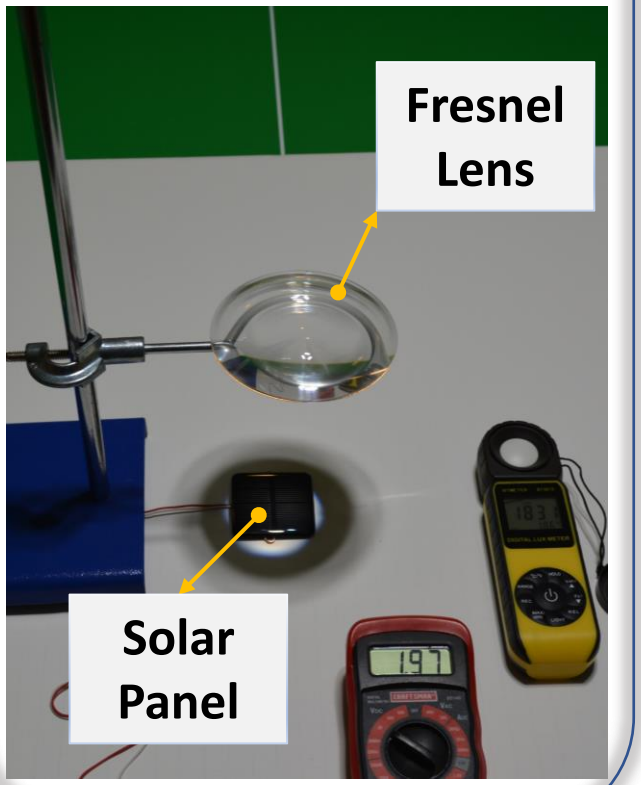
Experiment

<u>Independent variable</u>: Optical solar concentrators.
<u>Dependent variable</u>: Power generated by the solar panel.
<u>Control group</u>: Solar panel without optical concentrators.
<u>Controlled variables</u>: Light source, temperature, angle of incidence of the light, position of the solar panel with respect to the light source, size of the solar panel and type of solar panel.

Experiment – Effect of Solar Concentrators

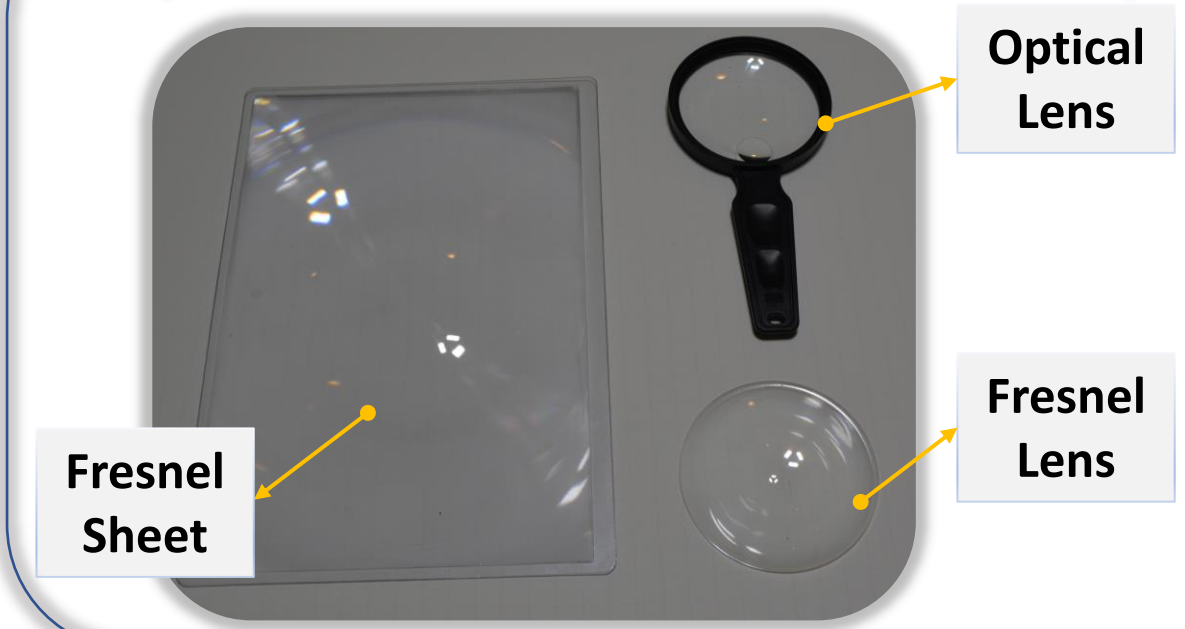
Test Setup

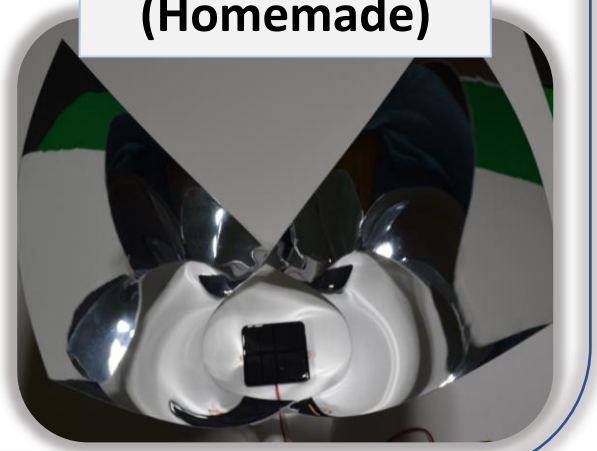
LED Light Source



A test bench was illuminated with an 8000 lumen LED light source. The solar panel was placed under different optical concentrators. The output current and voltage were measured from the panel using a multimeter. A light meter was used to measure illuminance.

Optical Concentrators used in the Experiment





Measurement

Instrument List

- Digital Multimeter
- Digital Illuminance meter
- Digital Thermometer
- Ruler

Measurement

Voltage and current output from the solar panel is converted to Output Power.

$$Output\ Power = Voltage\ \times Current$$

Output power is then normalized to the solar panel area of 50X50 mm^2.

Available or input power from the light source measured using illuminance meter is converted to Input Power per unit area using this formula [1]:

$$116\ lux = 1W/m^2$$

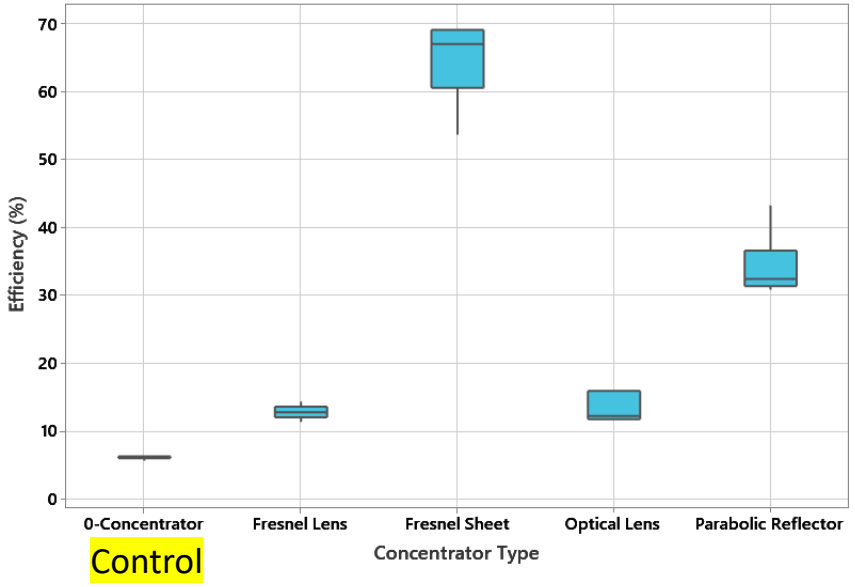
Efficiency of the Solar panel (η):

$$\eta = \frac{Output\ Power}{Input\ Power}$$

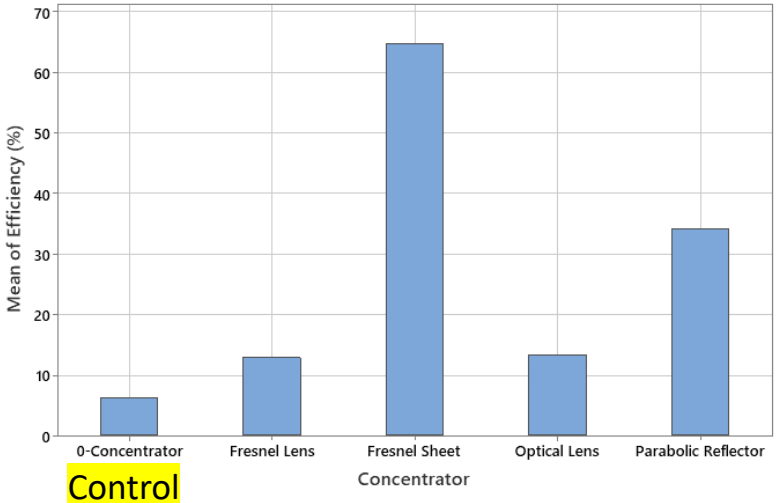
A total of 6 sets of tests were done to generate the data.

Data Processing – Effect of Concentrators

Box plot of Efficiency for Concentrators



Mean Efficiency for Concentrators



Statistical Data Analysis

A 2-Sample t hypothesis test was performed to compute the confidence interval between the control (no concentrator) and the concentrators. The example shown compares the efficiency of the control with that of the Fresnel lens.

Method

μ_1: population mean of Efficiency (%) when Concentrator = Control
μ_2: population mean of Efficiency (%) when Concentrator = Fresnel Lens
Difference: $\mu_1 - \mu_2$
Equal variances are not assumed for this analysis.

Descriptive Statistics: Efficiency (%)

Concentrator	N	Mean	StDev	SE Mean
Control	6	6.189	0.236	0.096
Fresnel Lens	6	12.88	1.01	0.41

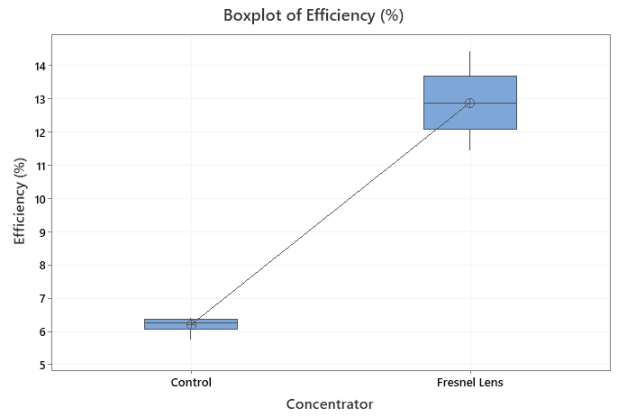
Estimation for Difference

Difference	95% CI for Difference
-6.689	(-7.777, -5.600)

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 \neq 0$

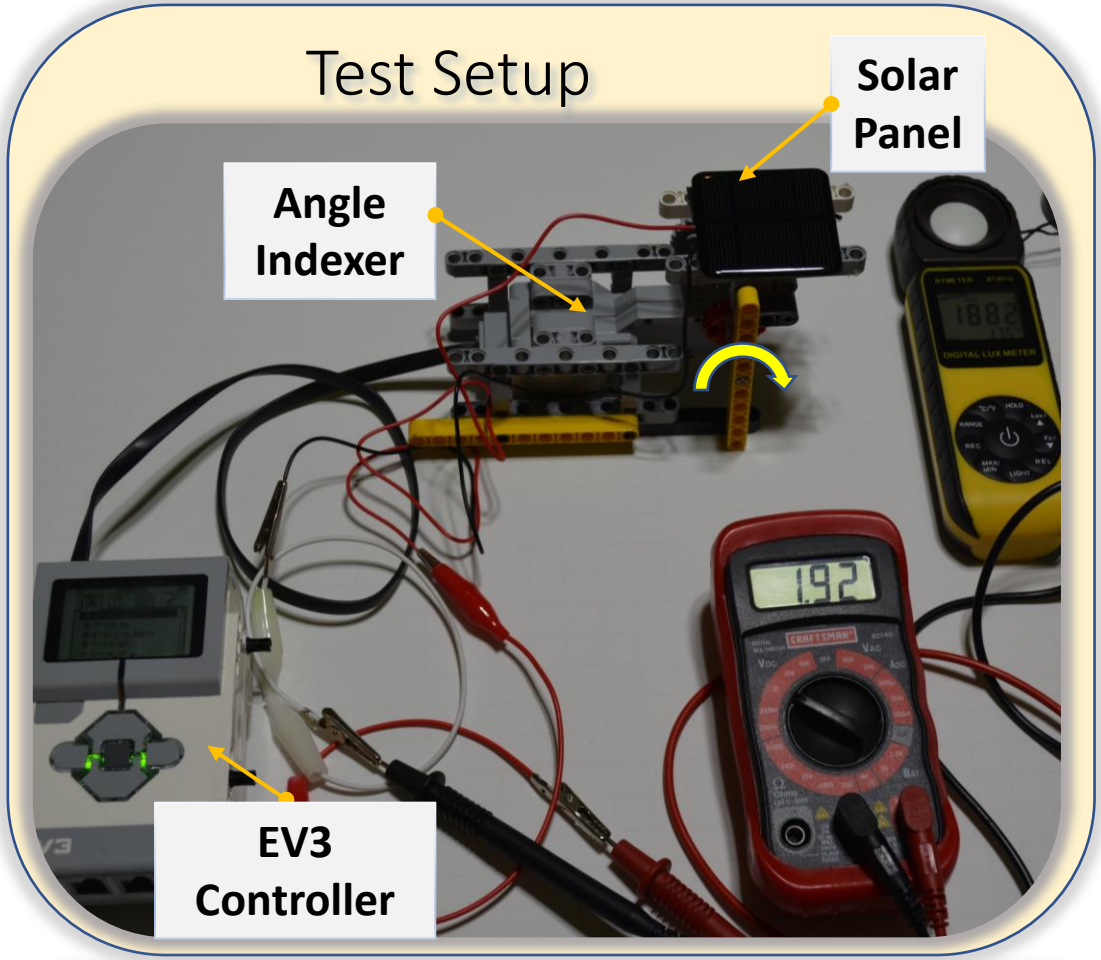
T-Value	DF	P-Value
-15.80	5	0.000

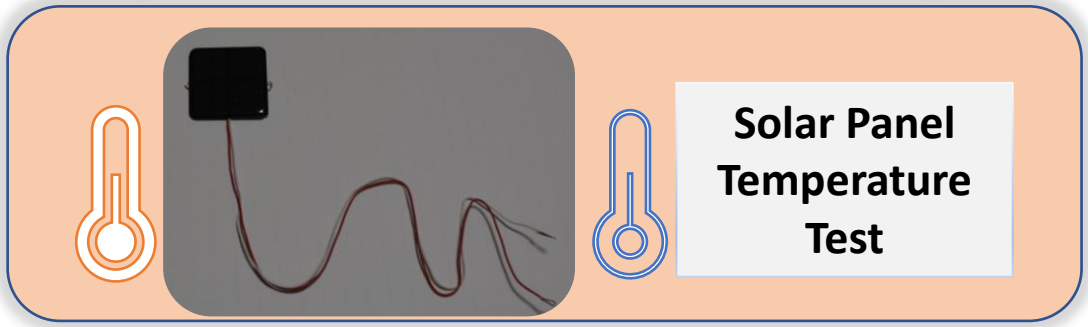


The 2-Sample t hypothesis test showed statical significance (p~0) for all the concentrators as compared to the control. An α of 0.05 was used.

The efficiency for the standalone solar panel is ~7%. Highest efficiency of 65% was achieved with the Fresnel sheet concentrator.

Experiment – Effect of Angle of Incidence & Temperature





Effect of Angle of Incidence

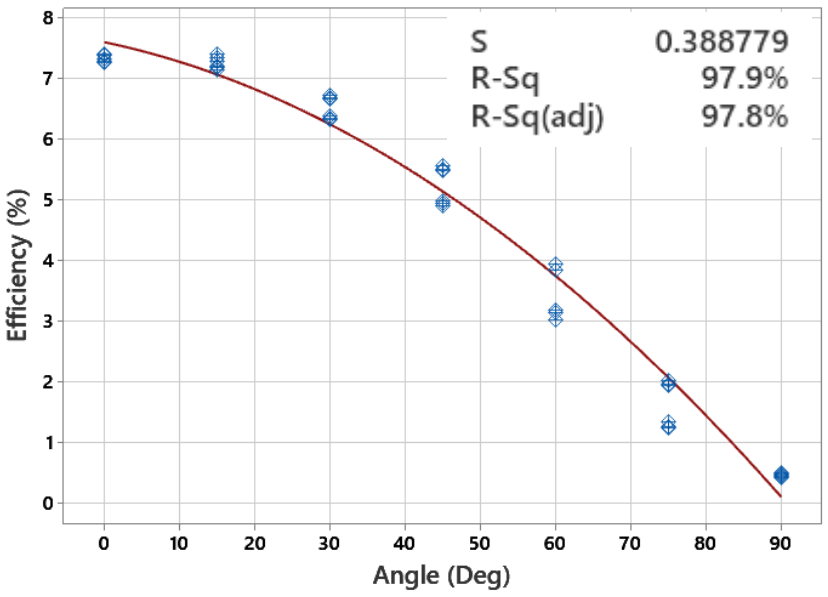
The Solar panel is mounted to a Lego mechanism which is activated to move in 15° angle increments. The output power from the solar panel is measured for each angular increment.

Effect of Temperature

The solar panel is kept in a low-temperature freezer, taken out after 3 hours, and placed on the test bench. The output power of the panel is measured for temperature changes.

Data Processing – Angle of Incidence & Temperature

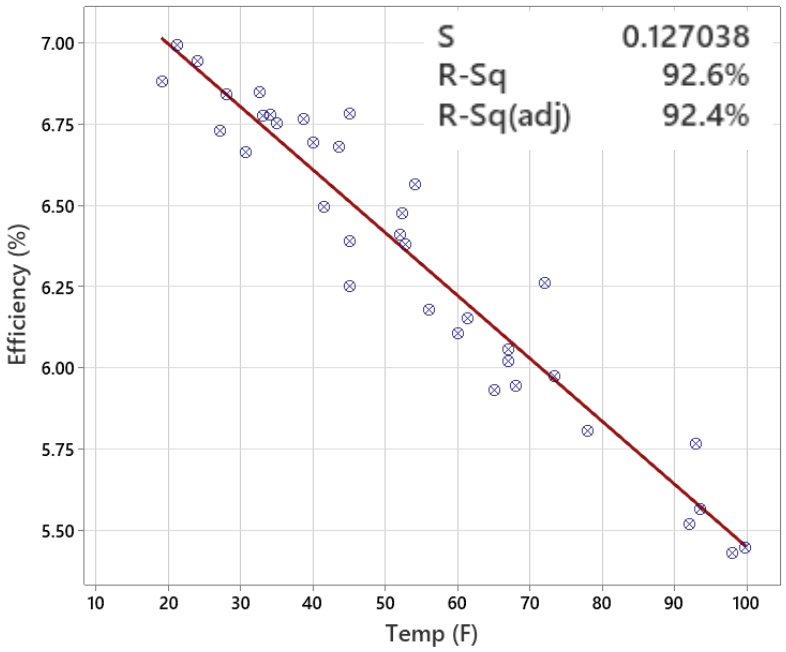
Efficiency vs Angle of Incidence



Efficiency (%) = 7.597 - 0.02599 Angle (Deg) - 0.000635 Angle (Deg)^2

Efficiency drops as the angle of incidence increases

Efficiency vs Temperature



Efficiency (%) = 7.382 - 0.01934 Temp (F)

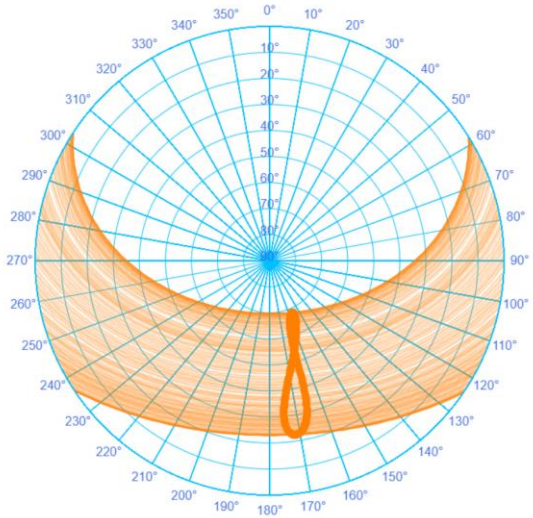
Efficiency drops as the temperature increases

A total of 6 sets of tests were done to generate the data. The measured values were converted to efficiency. Regression analysis was performed, and the regression equation was generated. Please see the attached analysis report for measured and calculated data values.

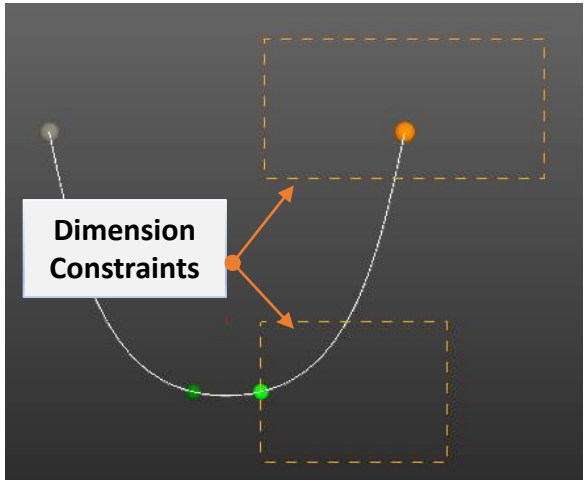
Optimization Process –Set Up

<u>Goal:</u> Generate an optimized solar concentrator system placed on top of the building in Canton, Michigan using Optical Simulation.

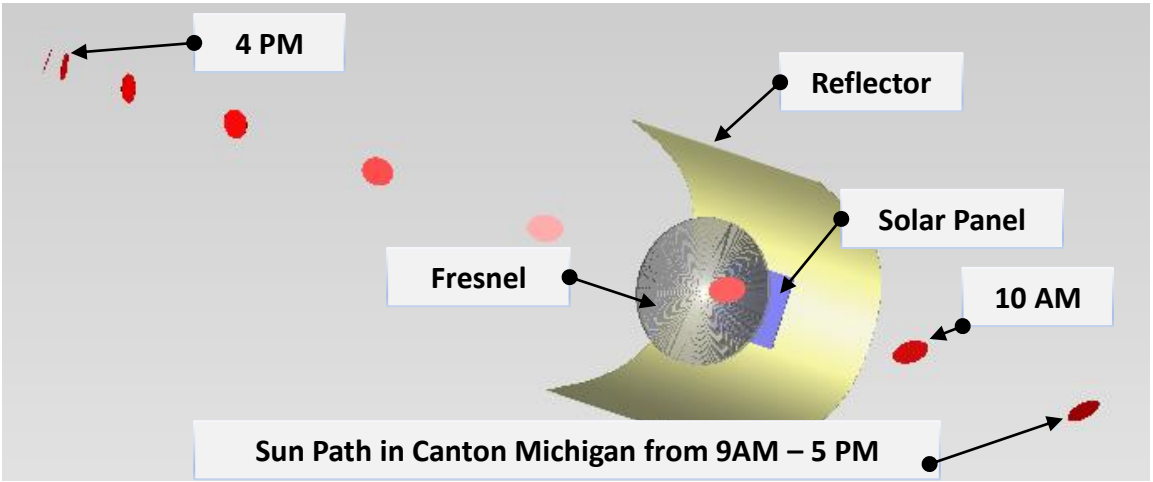
Sun Path Diagram for Canton, Michigan [2]



Reflector Shape Optimization



Model Setup

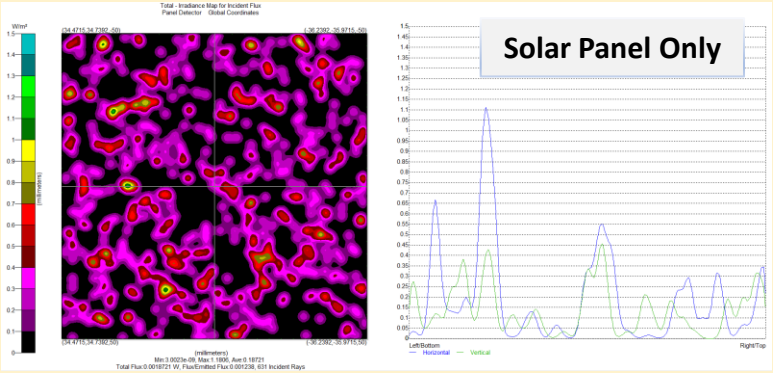


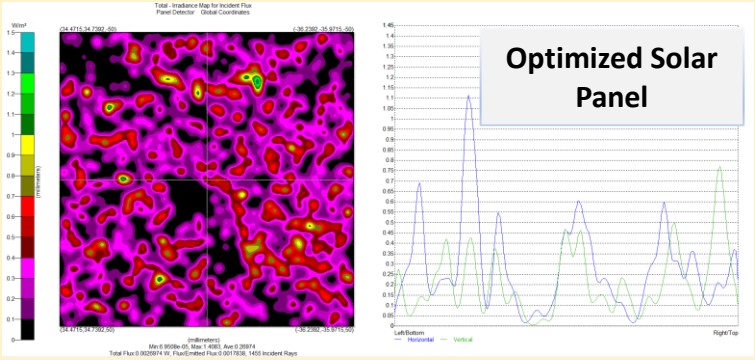
Based on the sun path data for Canton, Michigan on March 20th, 2022, a simulation model was set up to optimize the shape and angle of installation. The simulation automatically runs and optimizes for three different positions of the sun (10 AM, 12 PM & 2 PM). The optimization goal was to get uniformity of solar flux on the panel.

[2] *PV education*. (n.d.). Sun Position Calculator. Retrieved January 2, 2022, from https://www.pveducation.org/pvcdrom/properties-of-sunlight/sun-position-calculator

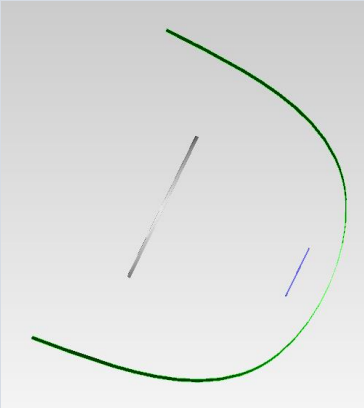
Optimization Process - Results

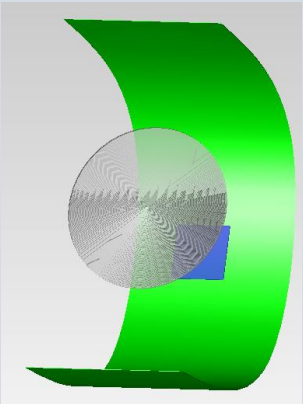
Total Incident Solar Flux Distribution for 10 AM Sun

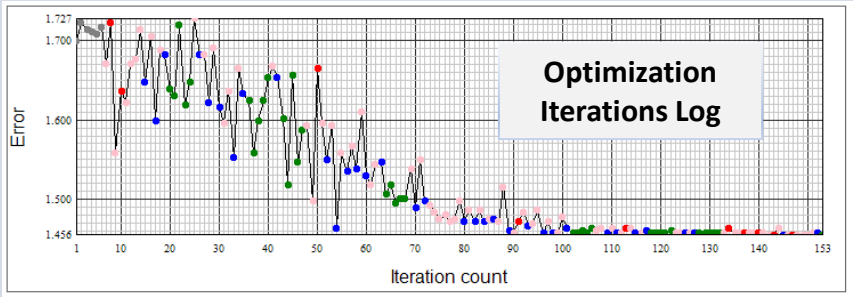




Different Views of the Optimized Solar Panel



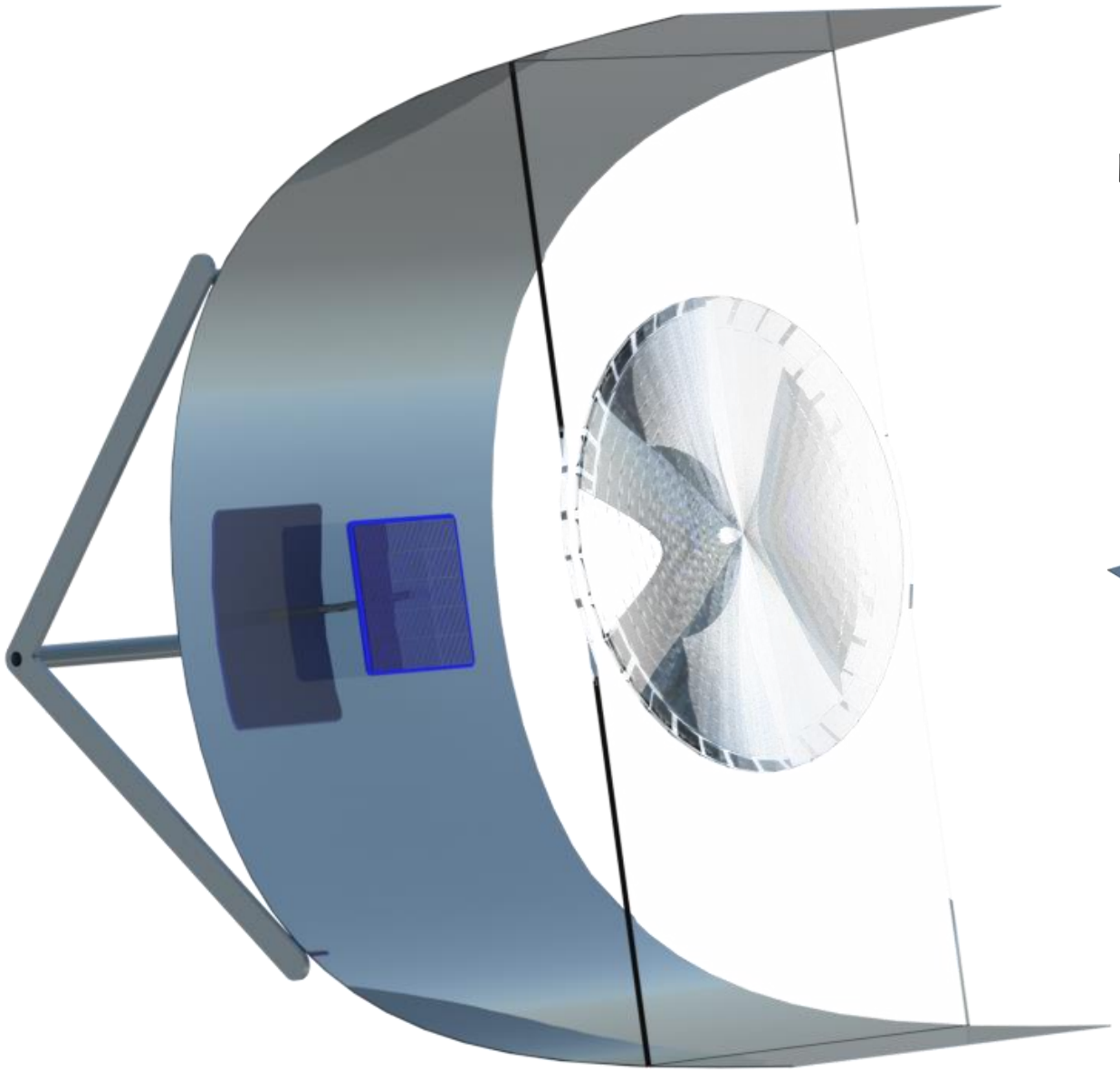


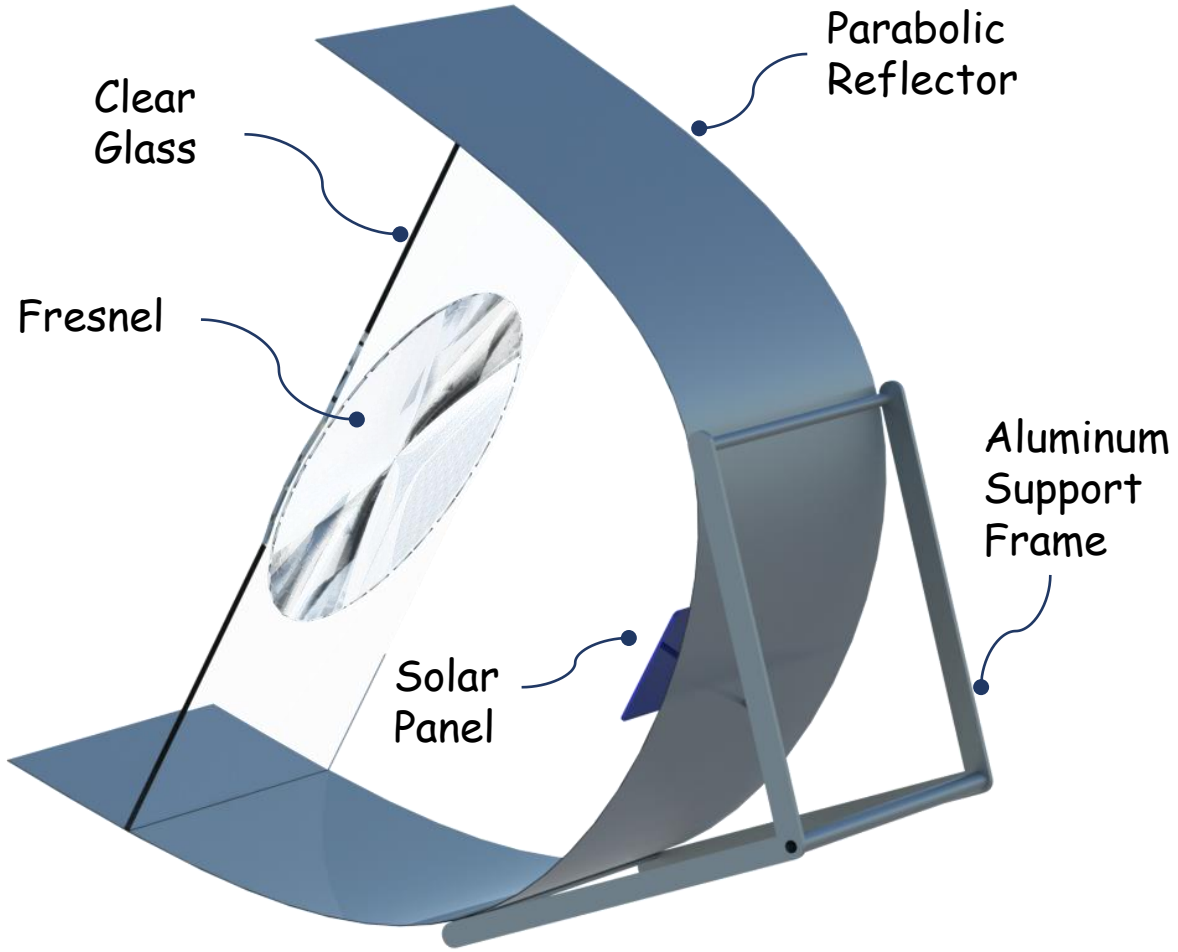


The final shape and angle of the reflector were achieved using optical simulation. This shape was imported into CAD software to finalize a design that could be fabricated.

Based on the sun location inputs, the optimizer simulation changes the shape of the parabolic reflector and angle automatically and produces the optimal shape.

Solar Panel Design





Design Features

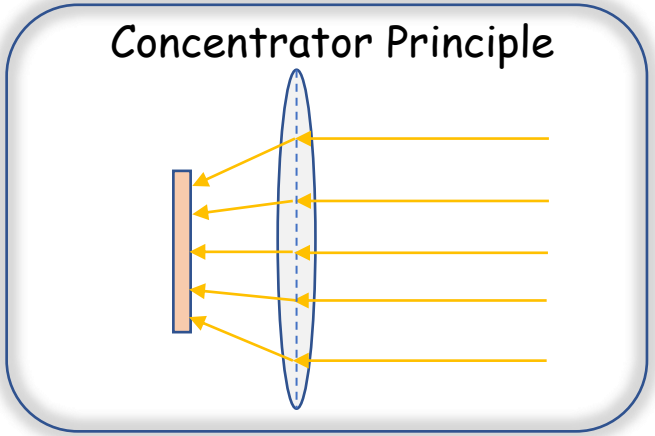
- **Low Cost**
- **Recyclable**
- **Low Weight**
- **Low Maintenance**

Summary

1. The solar concentrators increase the efficiency of the solar panel. The efficiency of the solar panel is 7%, with the Fresnel sheet concentrator, maximum efficiency of 65% was achieved in the experiment.
2. Considering the vector normal of the solar panel as 0°, Increasing the angle of incidence from 0°, reduces the solar output power. In the experiment, it was observed that the peak efficiency of 7% at 0° drops to 0% when the angle is 90°.
3. Increasing temperature reduces the solar power output. Efficiency drops by 2% when the temperature was increased from 20F to 100F.
4. Based on the above experimental data, an optimal solar panel reflector shape and angle of installation for a location in Canton, Michigan was generated using optical simulation.
5. The optimized shape was then used to design a solar panel prototype using CAD software that could be further fabricated.

Conclusion

- The results of this experiment support my hypothesis that the solar concentrators when used with a solar panel generate more power. This is because more light is captured by the larger area of the concentrators and focused on a narrower area as shown in the picture below.
- The cost of the solar generation systems could be reduced by using smaller solar panels with the concentrators.
- A potential drawback with the concentrators is that it also increases the temperature, increasing temperature reduces the output (as shown through the experiment) and deteriorates the panels. Potential solutions is to use magnifications between 3X-10X. Higher magnifications would need a cooling system [3].



Works Cited

[1] Michael, P., Johnston, D., & Moreno, W. (2020). A conversion guide: solar irradiance and lux illuminance. *Journal Of Measurements In Engineering*, *8*(4), 153-166. doi: 10.21595/jme.2020.21667

[2] *PV education*. (n.d.). Sun Position Calculator. Retrieved January 2, 2022, from https://www.pveducation.org/pvcdrom/properties-of-sunlight/sun-position-calculator

[3] *Introducing Concentrating Solar Power*. (n.d.). EME 812 Utility Solar Power and Concentration. Retrieved January 2, 2022, from https://www.e-education.psu.edu/eme812/node/646

[4] How Does Solar Work? (2022). Retrieved 12 January 2022, from https://www.energy.gov/eere/solar/how-does-solar-work.

[5] Mehrdad Khamooshi, Hana Salati, Fuat Egelioglu, Ali Hooshyar Faghiri, Judy Tarabishi, Saeed Babadi, "A Review of Solar Photovoltaic Concentrators", International Journal of Photoenergy, vol. 2014, Article ID 958521, 17 pages, 2014. https://doi.org/10.1155/2014/958521

[6] Geospatial Data Science Modeling. (2022). Retrieved 20 December 2022, from https://www.nrel.gov/gis/modeling.html