The Improvement of the Cost-Effectiveness of Solar Power by Low Concentration Photovoltaics

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Introduction:

With the threat of climate change looming over our heads, many environmentally conscious homeowners are considering powering their homes with renewable energy. One option that has been proven, if not very popular, is solar photovoltaic panels mounted on rooftops. These are low-maintenance and long-lasting, and can eliminate electricity bills. Unfortunately, their cost severely limits their market penetration; a home system of 6.75 kW power output can cost almost $50,000, or $7.30 per Watt. Panels have to be made from large, pure quantities of silicon, so improving the amount of power any given area of panel can produce is crucial to lowering the cost. One option is with more advanced panel types, but the multiple layers are more expensive to produce. However, with the use of concentrators, the area can be decreased while the amount of light remains constant.

Some installations use concentrators to focus light to 500 times its normal intensity onto very small high-efficiency panels, but these require tracking devices to ensure power output over the course of the day. In general, the higher the concentration, the more that tracking is necessary, but tracking is bulky, heavy, costly, and unlikely to fit on a typical roof, so it's a non-option for nearly all residential applications. But what if these problems could be bypassed by using low concentration ratios, less than 2 times? Tracking would be unnecessary, so long as the concentration was low. Plus, the panel area would be halved, drastically reducing the costs of the system. This project investigates the effectiveness and feasibility of low-concentration systems in a residential application.

Objectives:

The goal of this project is to evaluate the effectiveness of low-concentration photovoltaic systems, using flat mirrors, compared with unconcentrated systems . If the systems can produce nearly the same amount of power with a significantly lower cost, then solar energy would become more available for everyone. The program used to test that would also be able to optimize the configuration of mirrors and panels for the maximum power production over the course of the year.

Overall approach:

In order to determine whether or not a low-concentration photovoltaic system has such a cost advantage over plain panels, I wrote a program to optimize the configuration of the system for any given location. With this, I can simulate the optimal low-concentration system, and compare it to an unconcentrated system.

The program works by producing a list of sun positions and sun intensities spanning the course of a year, which would be fixed for each location. Then, for each position, it simulates the power output, and then it uses those to integrate that into the total energy produced over the course of a year. Then, it optimizes the configuration of the panels and mirrors to maximize the energy output.

The photovoltaic system is described by four angles, the azimuth angle of the system, the zenith angle of the panel, and the angles between the panel's plane and each of the mirrors, and the dimensions of the panels and mirrors. The panel azimuth angle is defined by the angle between the azimuth, the panel's normal vector projected down onto the ground, and the vector pointing north along the ground, starting clockwise from north. The other angles and distances are shown in the Figures 1 and 2.

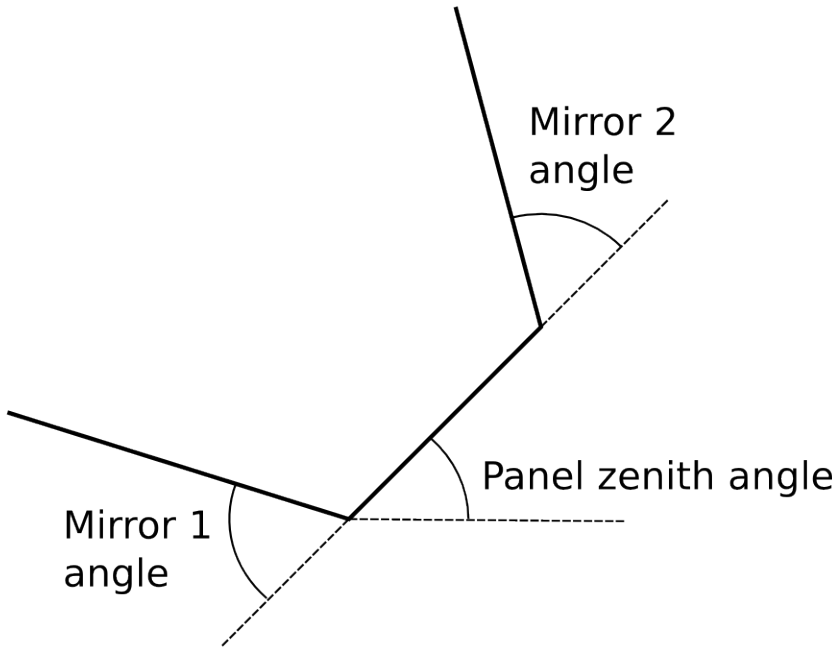

Fig. 1: A diagram of the mirrors and the angles that describe the system, as seen from the side.

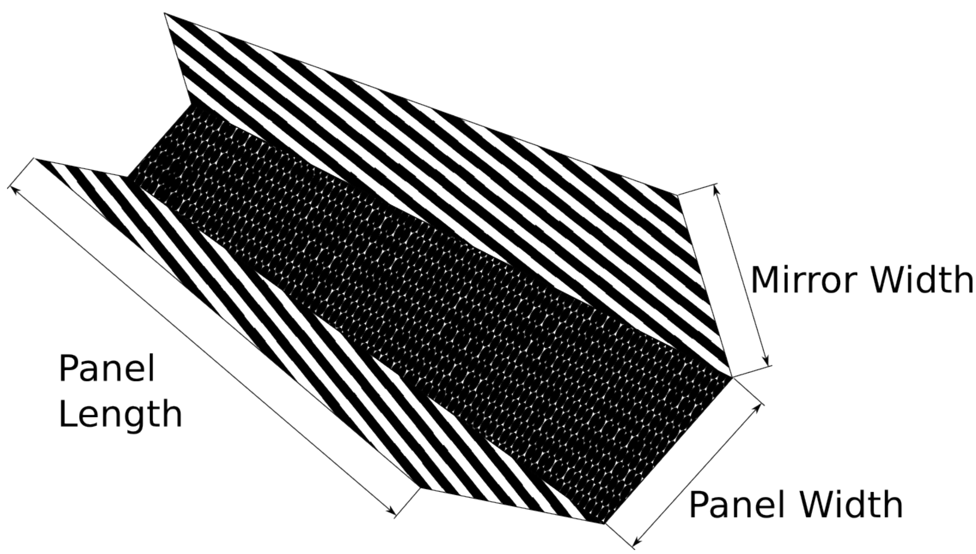

Fig. 2: A diagram of the mirror arrangements and the length measurements that describe the system.

Components:

The program is made up of the following components:

- Sun position calculator
- Vector class
- Parallelogram class
- Sun intensity calculator
- Power simulation
- Optimization routine
- Main routine

Task 1: Sun position calculator

To develop a routine that would could calculate the position of the sun at any given point in a year, I referred to the Javascript program found on the website of the National Oceanic and Atmospheric Administration [1]. I translated it into Python, leaving out functions that were not necessary, such as date-manipulation routines the atmospheric refraction routine, because refraction is only significant when the sun is near the horizon.

I tested this by comparing it to Figure 2.8 in the book Photovoltaic Systems Engineering, (Messenger, 2010) a chart giving a sample of sun positions over the course of a day on the equinox and the solstices for a location at 30 degrees north. However, I found that the NOAA routines, when translated into Python, failed to correctly calculate the solar azimuth angle in the afternoon.

The solar azimuth angle was calculated as a function of the solar zenith angle, and since the solar zenith angle decreases and then increases again over the course of a day, the solar azimuth angle would also increase and decrease again, giving incorrect sun positions once past solar noon. So, I decided that I would use my vector class to make solar azimuth a function of the hour angle. Since the hour angle is literally the angle that the sun is past solar noon, I used a rotation matrix to rotate the solar noon vector around the pole by the hour angle.

The results of testing the revised program showed that the error was less than 4 degrees, and that can be attributed to the use of the equation of time in the program. A table of testing results can be found in the appendix.

Task 2: Vector class

Another step was to write a simple class for 3-dimensional vectors. It implements addition, subtraction, scalar multiplication and division, cross products, dot products, projection, multiplication by a matrix, and a function that casts a “shadow” into the x-y plane from the tip of another vector, in the direction of a second vector.

The purpose of this class is to perform the vector calculations which are used in the sun position calculator and power output calculator.

I tested the class using a variety of problems that I could verify with hand-calculation.

Task 3: Parallelogram class

The third step was to create a class that handles parallelograms. It is restricted solely to parallelograms where one side, stored as a vector, lies along the x-axis and the other side, stored as a second vector, lies in the x-y plane. The functions I implement calculate the area of the parallelogram, and the area of the intersection between two parallelograms that share the side along the x-axis.

The purpose of this class was to calculate the area of shadows and light on the solar panel for the power output simulation.

I tested the functions using hand-calculable test cases that I made that cover all of the possible situations.

Task 4: Sun intensity calculator

This portion includes functions that give the intensity of the sun with respect to time of year and position in the sky. There are three major functions: 'airMass', 'occlusion', and 'weatherFactor'.

'airMass' takes into account the scattering of light by the atmosphere, assuming that the lower the sun is in the sky, the more atmosphere would be there to block it. The function for this came from the book Photovoltaics Systems Engineering. (Messenger, 2010)

'occlusion' takes input from a file storing the elevation angle of the horizon at ten degree intervals all around, and returns whether the sun would not be blocked or not based on the position of the sun.

'weatherFactor' takes input from a file that stores the average percent of sky that's uncovered. That data can be acquired from the National Renewable Energy Laboratory's Typical Meteorological Year data sets. For my purposes, I used the TMY2 dataset, writing a program that averaged the daytime cloud cover for each month. The function returns the proportion of light expected to show through the clouds at any one time.

Task 5: Power simulation

The next step was to develop a simulation for the power output of the photovoltaic system. This involved using all three previous steps, using the position of the sun to determine the reflections from and unshadowed areas left by the two mirrors on the solar panel, and calculating the power output. It takes the dimensions of the panels and the sun position, checks for the amount of shadowing on the panel, and then calculates the area of the panel hit by reflected light. These areas are each multiplied by the cosine of the angle of incidence of the panel. The resulting function would take in a year's worth of sun positions, and output the total energy generated over that year.

This is the precursor to the final step, the optimization, because there needs to be a function in order to find a maximum.

Task 6: Optimization routine

The final component in the program was a method for maximizing the performance of the system. For this, I chose the Nelder-Mead optimization method. This method uses a collection of simulated points numbered one more than the number of independent dimensions. In my case, optimizing 3 angles, the simplex has 4 points. The method works by replacing the worst point with one of a series of test points, generated by methods such as reflecting it over the centroid of the other points. This makes calculating gradients unnecessary, which is expensive for a complicated calculation.

When the simplex has become small enough that the best and worst points are very close in value, the function must have leveled off enough to be a maximum.

Each time the routine generates a new point, it runs the power simulation routines to determine its value.

To test this, I implemented the Himmelblau function as a drop-in replacement for the power simulation function. The Himmelblau function, $f(x, y) = (x^2 + y - 11)^2 + (x + y^2 - 7)^2$, is designed for testing optimization routines and has a local maximum at $x = -0.270844$ and $y = -0.923038$, which my routine found correctly.

Task 7: Main routine

The final part of the program is the part that runs all of the separate portions together. It takes its input from a configuration file that lets the user change the parameters of the system, including the panel specifications and numbers, the size of the mirrors, and the orientation of the roof the panels would be mounted on. It first runs the sun position calculator for every interval period over the course of a year, and stores all the sun positions in a list, along with the calculated power multiplier factor for that particular sun position. Then, depending upon the options selected, it can optimize some or all of the parameters, or simply run a simulation of the given parameters without optimizing them.

Testing

The critical question, of course, is how much less panel area might be necessary with concentration. So, I set up three test cases, where I optimized the output of a row of panels both with and without mirrors. The three locations are Metuchen, NJ, Claremont, CA, and Caribou, ME, chosen for the range of latitudes and weather conditions they span.

For this testing, I used the weather from the nearest location for which data was available in the NREL's TMY2 dataset. For Metuchen, NJ, I used Newark, NJ's weather data. For Claremont, CA, I used Long Beach, CA's weather. Caribou has its own dataset.

In addition, I assumed that the ground was clear all around. These measurements are site-specific, and include things like trees. For example, a tree directly south of the panels which would cover the wintertime sunlight would make the optimal panel zenith angle to be smaller, aiming the concentrators at the path the sun takes during the summer.

The other parameters that were used were that each of the 30 panels had a length (horizontal dimension) of 1.559 meters, were 0.798 meters wide, and produced 225 watts in factory standard testing conditions, or STC. STC is testing at an irradiance of 1000 Watts per square meter, 1.5 air masses, and a cell temperature of 25 degrees C. In addition, the mirrors were 1 meter wide.

Table 1 has the results of the testing. Each location has two rows. The top row with the *N/A*'s is the results of optimizing a plain system with only panels and no mirrors, and the second row is the optimized system with mirrors and the same panel area. The improvement is the percent difference between the concentrated system and the normal system.

Location	Latitude	Longitude	Panel zenith angle	Lower mirror angle	Upper mirror angle	Yearly energy output	Improve-ment
Units:	Degrees	Degrees	Degrees	Degrees	Degrees	MWh	%
Caribou, ME	46.87 N	68.02 W	38.57	N/A	N/A	7.30	N/A
			39.57	68.04	66.52	11.47	57
Metuchen, NJ	40.54 N	74.36 W	34.51	N/A	N/A	9.53	N/A
			35.52	68.04	67.15	14.81	55
Claremont, CA	34.11 N	117.72 W	29.15	N/A	N/A	13.53	N/A
			30.16	68.72	67.32	20.71	53

Table 1: Test conditions and results. The bottom of each pair of rows is with mirrors.

The next test I did was to determine the sensitivity of the system's power output to changes in the angles. For ease of viewing, as well as reducing the number of test simulations that had to be run, I set both mirror angles to be the same, and varied two dimensions: the two mirror angles together, and the zenith angle of the panels. All of the other parameters were the same as those used in Metuchen, NJ, with one-meter mirrors. The results are shown in Figure 3, with the numerical values available in the appendix.

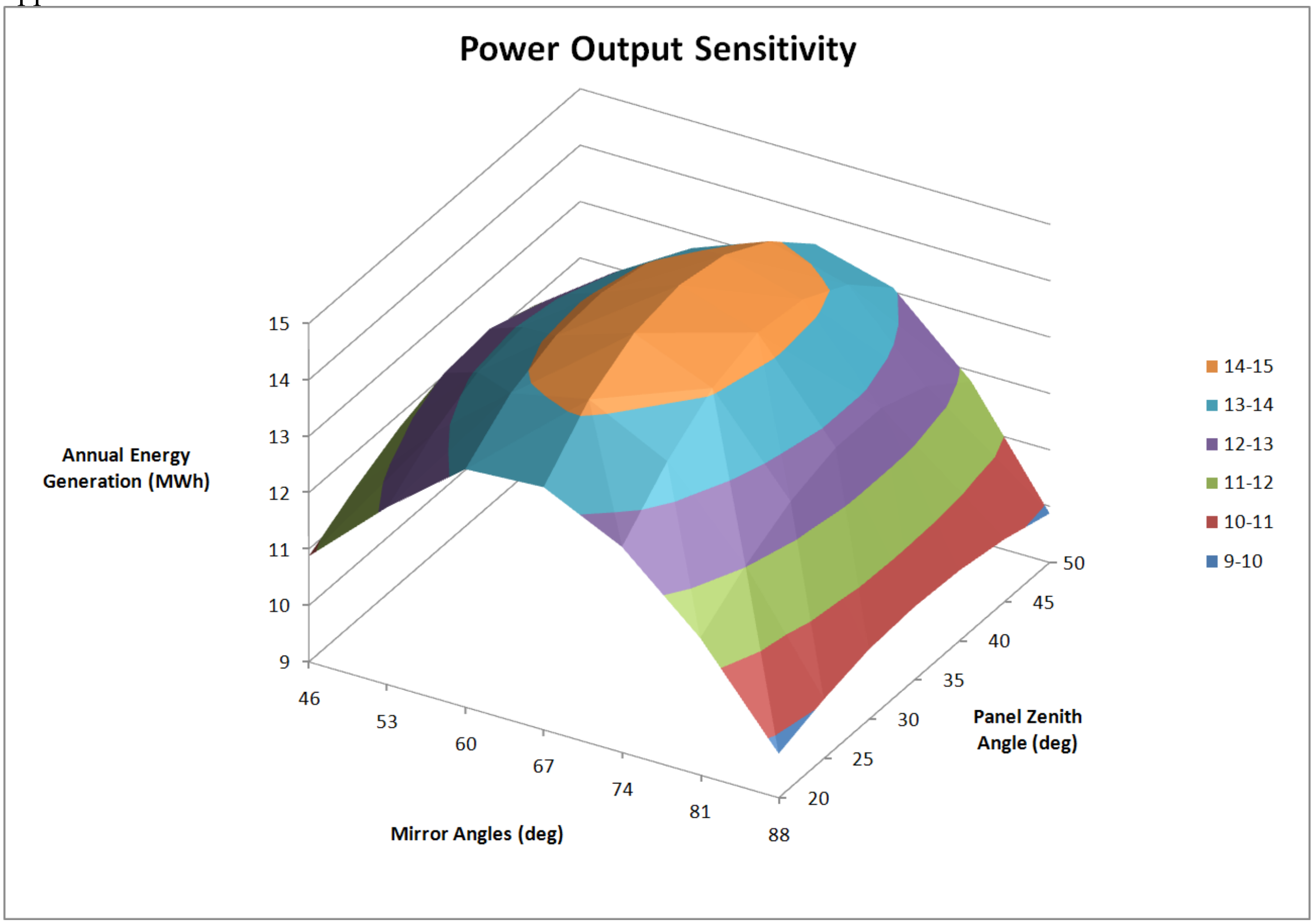

Fig. 3: Power output of the photovoltaic system with respect to the angles.

Discussion

The results are promising. At each of the locations, the addition of mirrors added over 50% to the yearly energy output. This would allow a large reduction in the cost of solar energy, simply by reducing the number of panels for a given power output.

The sensitivity testing showed that a 7 degree deviation in the mirror angles from their optimal decreases the power output at most 3.65%, and a 5 degree deviation in the panel zenith from optimum decreases the power output 1.01%. Changing both by the aforementioned amounts decreased the power output by at most 4.93%. This indicates that the system is relatively insensitive to errors in the positioning of the mirrors and panels.

However, there are a few cost trade-offs involved. A household can't simply get more power by adding mirrors. For the mirrors to be installed, the rows of panels must be placed farther apart, meaning that a given roof area can't fit as many panels. Secondly, the structure supporting the mirror assembly would be considerably larger than a solar installation with panels laying flat against the roof, further increasing the costs.

There are also physical concerns with the design. The supports have to be able to withstand strong dynamic loading from wind and precipitation. They should also not overload the roof when being forced by weather conditions, especially older roofs which may have deteriorated and lost strength. Also, the trough-like design of the mirrors is likely to retain snow in conditions where snow on plain panels would have slid off, reducing the power generation in snowy climates.

The simulation could be improved in many different ways. For one, the program models solar cells as having a linear response to the intensity of sunlight. In fact, for silicon solar cells, the more sunlight, past approximately one solar intensity, the less efficient they become. That would be easy enough to implement in the program, except for the fact that using the average solar intensities from cloud cover would overestimate the power production. That would require using the full hourly data available in the TMY2 dataset, which models the *typical meteorological year*, where the cloud cover fluctuates from full to none, replacing the solar intensity functions. Leaving this out causes overestimation of the benefits of concentration, because the increased intensity of light would reduce the efficiency, in addition to raising the temperature of the cells, another contribution to inefficiency.

Another improvement would be to take into account diffuse light, which my program disregards. Diffuse light ignores the concentration ratio, depending mostly on panel area and orientation, and it is generally far less strong than direct sunlight, so the effect would be small, but leaving it out causes overestimation of the improvement from the mirrors.

Lastly, the angle response of the panels, which I approximated as a cosine, would probably be less than cosine, because the glass covering a panel would become more reflective the more glancing the angle. Since the light reflected off of the mirrors comes in at a shallower angle than the direct light, the benefit of the mirrors would be reduced.

There are also improvements to the testing conditions I set up. One would be to try to have different weather conditions at each latitude. I covered arid, moderate, and wet climates, and a low, middle, and high latitudes, but I should have tried mixing the weather conditions, having all the weather conditions for each latitude.

Also, I could have tried seeing the effect of putting a “tree” south of the panel system, using the horizon map. That would likely cause the optimal zenith angle to decrease, but I haven't tested that.

Conclusion

In conclusion, the cost saving potential of low concentration photovoltaics is very promising, but the reduction in cost of the panels is offset partly by the cost of reflectors and by the structure needed to support them.

The test for angle sensitivity showed that the power output is more sensitive to the mirror angles than the panel zenith angle, so when they are constructed, the structure should have a priority on keeping the mirrors stiff and at a specific angle to the panels.

Further research, however, is necessary, such as setting up an experiment physically testing the power output of a low concentration photovoltaic system compared with an equivalently sized non-concentrated system.

Appendix

Sun position testing results

hour	Azimuth angle	Calc'd azimuth	Zenith angle	Calc'd zenith
30 degrees north:				
06/21/01				
5	64	62	90	91
6	68	69	79	79
7	74	76	66	66
8	81	82	55	54
9	89	88	41	41
10	100	96	28	28
11	116	112	16	15
12	180	177	8	7
1	244	247	16	15
2	260	263	28	27
3	271	272	41	40
4	279	278	55	53
5	286	284	66	66
6	292	290	79	78
7	296	297	90	90
09/21/01				
8	108	106	64	62
11	153	154	33	32
12/21/01				
8	124	126	82	78
11	163	164	58	55
30 degrees south				
12/21/01				
5	116	117	90	90
6	112	110	79	78
7	106	104	66	66
8	99	98	55	53
9	91	91	41	40
10	80	83	28	27
11	64	66	16	14
12	0	356	8	7
1	296	292	16	15
2	280	276	28	28
3	269	268	41	41
4	261	262	55	54
5	254	256	66	67
6	248	249	79	79
7	244	242	90	91
09/21/01				
8	72	72	64	64
11	27	25	33	34
06/21/01				
8	56	54	82	79
11	17	17	58	55

Rotation matrix used for calculating the azimuth angle of the sun:

Where lat is the latitude, $decl$ is the declination of the sun and hA is the hour angle:
The southern polar axis vector is $\langle 0, -\cos(lat), -\sin(lat)\rangle$.
The solar noon vector is $\langle 0, \sin(decl-lat), \cos(decl-lat)\rangle$.
The rotation matrix is:

$$\begin{bmatrix} \cos(hA) & \sin(lat)\cdot\sin(hA) & -\cos(lat)\cdot\sin(hA) \\ -\sin(lat)\cdot\sin(hA) & \cos^2(lat)+(1-\cos^2(lat))\cdot\cos(hA) & \cos(lat)\cdot\sin(lat)\cdot(1-\cos(hA)) \\ \sin(lat)\cdot\sin(hA) & \cos(lat)\cdot\sin(lat)\cdot(1-\cos(hA)) & \sin^2(lat)+(1-\sin^2(lat))\cdot\cos(hA) \end{bmatrix}$$

Data table for angle sensitivity test:

		Mirror Angles						
		46	53	60	67	74	81	88
Panel zenith angle	20	10.87	12.14	13.22	13.30	12.65	11.43	9.78
	25	11.36	12.75	13.87	14.16	13.47	12.02	10.05
	30	11.76	13.15	14.20	14.65	14.07	12.46	10.24
	35	12.04	13.26	14.26	14.80	14.36	12.72	10.30
	40	12.13	13.15	14.09	14.65	14.26	12.72	10.25
	45	11.85	12.83	13.67	14.19	13.83	12.41	10.11
	50	11.35	12.32	13.04	13.45	13.07	11.81	9.87

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Citations:

Messenger, Roger A., and Jerry Ventre. Photovoltaic Systems Engineering. Boca Raton, FL: CRC/Taylor & Francis, 2010. 29-32. Print.

"Solar Calculation Details." GMD - Surface Radiation Research Branch. Web. 07 Aug. 2010. <http://www.srrb.noaa.gov/highlights/sunrise/calcdetails.html>.

http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/

Solar panels simulated: SunPower model number SPR-225-BLK; info from SunPower document #001-42188 Rev **