Development of a Novel High Efficiency Photo-Thermovoltaic Concentrator Solar Cell

Rounok Joardar

1. INTRODUCTION

In recent times the need for generating energy from non-conventional sources and the importance of conserving and reusing energy has become quite apparent. This is not only because of the rising cost of conventional sources but also because of their harmful effects on our environment. Photovoltaic (PV) solar cells appear to be a good option for generating clean energy. Although the efficiencies of PV solar cells have improved a lot in the past two decades [1], for solar technology to compete successfully against fossil fuels it is more important to drive down the cost per watt (CPW) of electricity generated. CPW is a direct function of the solar power generating system cost, and inversely related to the efficiency of the cells used. It is therefore important to keep the system cost low and increase cell efficiency. Unfortunately, these two variables are not independent of each other. Higher efficiency cells are generally more expensive, and thus do not necessarily lead to a decrease in CPW.

A novel hybrid photo-thermovoltaic approach to improving concentrator solar cell performance is reported here. Most scientific reports on solar cell improvements focus only on efficiency improvements. This study attempts to consider both conversion efficiency and economics while developing a new approach to solar power generation.

1.1 Existing Technology and the Hybrid Solar Cell Approach

The efficiency of PV solar cells is limited by their inability to utilize the entire solar spectrum. Even the best commercially available PV cells are unable to use about 60% of the total available solar energy. This unused energy is mostly wasted as heat. What limits the efficiency of photovoltaic (PV) solar cells? PV solar cells operate by transferring some of the energy in sunlight to the electrons in the cell material. If these electrons gain sufficient energy they can "jump" from the valence band to the conduction band. While electrons in the valence band are not mobile, those that reach the conduction band are free to flow, i.e. generate an electric current. The "bandgap" between the valence and conduction bands has no intermediate stages that electrons can use to get to the conduction band from the valence band. Thus, there is a minimum amount of energy the electrons in a PV cell need to gain to be able to make the jump. The nature of sunlight is such that not all of the available energy can cause electrons to jump from the valence band to conduction band. Light is composed of particles called photons which behave like waves. The energy of a photon with a wavelength λ is given by:

$$E = \frac{h.c}{q.\lambda} \tag{1}$$

where E is the energy in units of eV, h is Planck's constant, c is the speed of light, and q is the charge of an electron. From (1) it can be seen that shorter wavelengths have higher energy. Sunlight is made up of photons with a continuous series of wavelengths from infrared to ultraviolet. Only those photons in sunlight with wavelengths that are short enough to cause electrons to jump from the valence to conduction band can be absorbed and converted to electricity. For example, in silicon solar cells, 1.1 eV of energy is required to cause this jump. From (1) it can be seen that only the photons with wavelengths shorter than about 1100 nm are effective in silicon solar cells. The remainder of the solar energy is simply turned into heat and goes unused. By using a stack of cells made from materials with varying bandgaps it is possible to increase the power output. The best commercially available examples of this approach are from Spectrolab [2] who have been able to manufacture cells with almost 40% efficiency. Still, this means about 60% of the solar energy is unused. The central idea of this project is to capture the unused heat from a solar cell and attempt to convert it to electricity.

Recently, a class of solid state devices known as thermoelectric generators (TEGs) has become commonly available [3]. TEGs are based on the Seebeck effect which states that a voltage is generated between two ends of a conductor whose ends are held at different temperatures. Modern TEGs based on this effect use tightly arranged pellets of material such as bismuth telluride to generate a practical amount of power from a temperature difference as low as 20ºC. The ratio of the electric energy produced by a TEG is proportional to the heat energy that goes into it is its efficiency. TEG efficiency depends on a special "figure of merit" labeled as Z_T of the material it is made from. Z_T is given as [4]

$$Z_T = \frac{\sigma \times S^2 \times T}{\kappa + \left(\sigma \times S^2 \times T\right)}, \tag{2}$$

where σ is the electrical conductivity of the thermocouple, S is the Seebeck coefficient, T is the average temperature of the TEG material, and κ is its thermal conductivity. For conventional alloys the highest Z_T obtained is about 1 using bismuth antimony telluride alloys. Advanced superlattice materials can have Z_T as high as 3.5 [5]. The exact dependence of a TEG's efficiency on Z_T is given by the following equation [6]:

$$\eta = \left[\frac{T_H - T_C}{T_H}\right]\left(\frac{\sqrt{Z_T + 1} - 1}{\sqrt{Z_T + 1} + {T_C}/{T_H}}\right), \tag{3}$$

where T_H is the hot side temperature and T_C is the cold side temperature in Kelvin.

It is conceivable that TEGs can be utilized to convert some of the unused energy from PV solar cells into additional electricity. Fig. 1 shows a concept view of such a hybrid solar cell. TEG modules are available in sizes that are slightly larger than typical concentrator PV solar cells making them suitable as a base for the PV cell in a mechanical arrangement as shown in Fig. 1. TEGs have been widely applied to waste heat recovery in automobiles [7]. Theoretical work has also been reported on the use of TEGs for solar power generation [8, 9]. However, there seems to be no practical implementations of such systems.

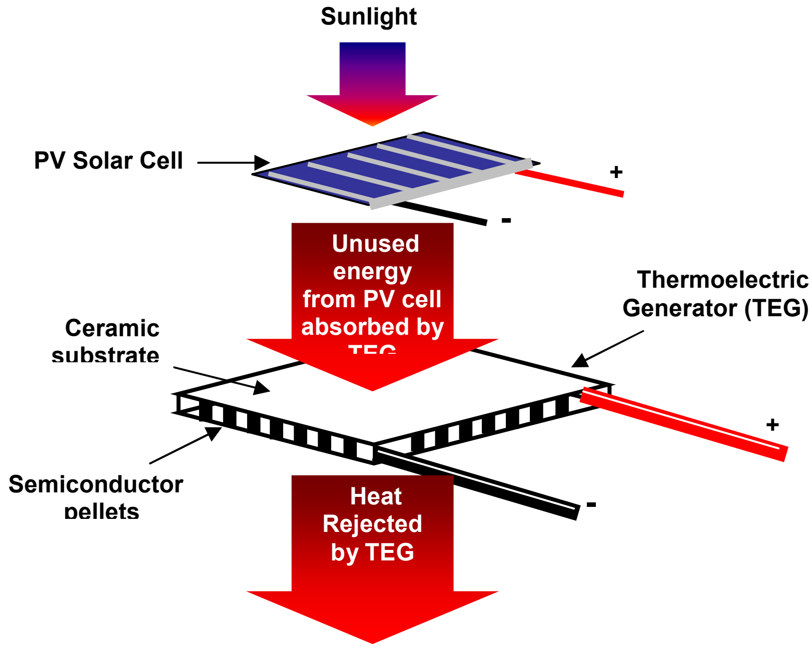


Fig. 1 Simplified diagram of solid state TEG. Placed under a PV solar cell, this combination will generate more power than the PV solar cell alone.

1.2 Project Objective

Based on the information presented so far, the problem statement for this project is summarized as follows: develop and demonstrate a working hybrid photo-thermovoltaic cell which (a) produces at least 5% more power, and (b) has at least a 5% lower cost per watt than its photovoltaic solar cell alone under identical light conditions. The 5% numbers have no particular significance. They represent modest improvements in efficiency and cost. The real intent of this project is to investigate the electrical and cost performance of hybrid thermoelectric solar cells.

1.3 Theoretical Analysis of Cascaded TEGs

Using (3) and based on an approximate Z_T value of 1 for bismuth telluride based TEGs, as well as other specifications provided by manufacturers, the maximum TEG efficiency that can be expected using a structure similar to Fig. 1 was estimated to be between 1% and 2%. This is possibly too low to meet the power improvement objective of this project. This thermal efficiency can be improved by using multiple TEGs stacked on top of each other as shown in Fig. 2. Some of the heat energy entering the first TEG's hot (top) surface is converted to electric energy. The rest is rejected out of its cold (bottom) surface and re-used by the second TEG to generate additional electricity. By stacking multiple TEGs in this way the total output electric energy and efficiency can be increased. This approach of using TEGs is called "cascading" [10]. Using simple algebraic analysis it can be shown that a cascade of n TEGs each with efficiency η_{TEG} will have, ideally, an efficiency η_{TOT} given by:

$$\eta_{TOT} = \eta_{TEG} \times \left\{1-(1-\eta)^n\right\} . \tag{4}$$

For low values of η_{TEG} the total efficiency increases linearly with the number of TEGs cascaded. It should be remembered that the hybrid cell cost increases linearly with each TEG added to it.

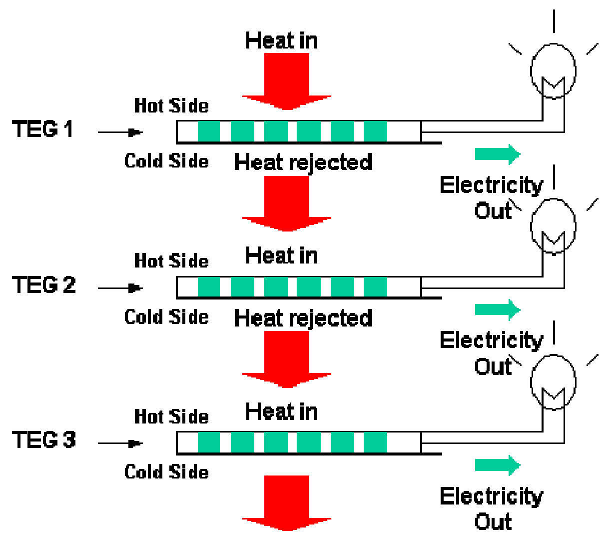


Fig. 2 Diagram showing cascaded arrangement of TEGs used to increase total electric output.

1.4 Theoretical Analysis of Cost per Watt (CPW)

The cost per watt of power generated from a solar cell is expressed simply as:

$$CPW = \frac{C_{system}}{P_{system}} , \tag{5}$$

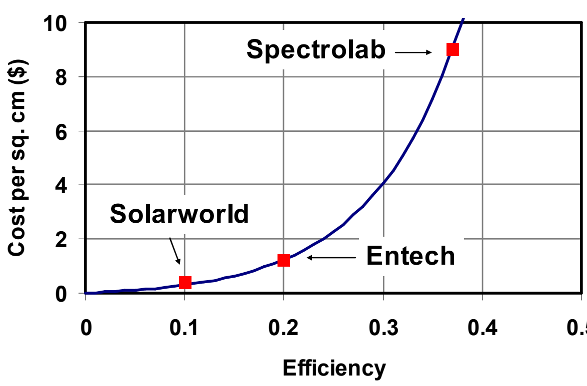
where C_{system} is the total system cost, and P_{system} is the power output of the system. C_{system} is comprised of a peripheral part C_{peri} and the cost of the solar cell itself. The total cost of parts which do not produce energy, e.g. the lens, cooling unit, tracker, is the peripheral cost. The cell cost is a function of its efficiency, the higher the efficiency, the higher the cost. From a survey of existing market rates, this dependency can be expressed as:

$$C_{cell} = C_0 (e^{\eta/\eta_0} - 1), \tag{6}$$

where C_0 and η_0 are fitting constants. The solid line in Fig. 3(a) shows how well equation (6) compares with actual data (shown by the three red dots). The nearly perfect match was obtained using the values $C_0 = 0.15$ and $\eta_0 = 0.09$. Using (6) in (5), CPW can be expressed as:

$$CPW = \frac{C_{peri} + C_0 (e^{\eta/\eta 0} - 1)}{\eta P_{solar}}, \tag{7}$$

where P_{solar} is the incoming solar power. Fig. 3(b) is a plot of CPW versus cell efficiency based on (7) for two different arbitrarily chosen values of C_{peri}. CPW decreases initially as efficiency increases but reaches a minimum beyond which it is counter-productive to pursue efficiency increases. Secondly, CPW decreases if peripheral costs are decreased, irrespective of the cell efficiency. Thus it will be important to reduce peripheral costs associated with hybrid solar cells..



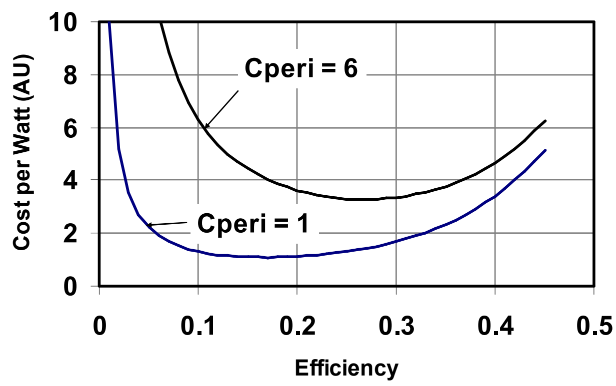


Fig. 3 (a) Solar cell cost versus efficiency based on retail information. (b) Cost per watt versus efficiency based on theoretical calculations.

1.5 Variables and Hypothesis

The independent variables of this project are the number of TEGs cascaded in the hybrid cell, and the different arrangements used to reduce CPW. The dependent variables are the output power, conversion efficiency, and the CPW for each hybrid configuration. The incoming solar intensity is constant in all experiments.

Based on the equations presented so far and a set of simplifying assumptions, a model was set up using Microsoft Excel to (a) estimate the power output from hybrid solar cells and (b) the associated cost per watt. The incoming solar power was assumed to be 100 mW/cm^2 times a user defined concentration factor. The PV power output was simply its efficiency times the incoming solar power. The remaining solar power was assumed to fully couple to the TEGs without any loss. Based on the thermal conductivity of the TEGs as specified by the manufacturer the temperature gradient across the TEGs was computed next. The TEG efficiency and power output were then calculated using equation (3) assuming a Z_T of 1. The total power output was simply the sum of PV and the TEG outputs. The system cost was estimated by adding the cost of the lens used to concentrate sunlight, the cooling system, TEGs, and PV cell. From this a CPW value was estimated. Setting this up allowed "what if" situations to be explored quickly. Fig. 4 is a screen capture of the spreadsheet. It became obvious immediately that to meet the project's CPW objective the number of TEGs used would have to be kept to a minimum due to their high cost. Yet, to meet the 5% higher power output objective, the number of TEGs used would need to be increased. A compromise could be reached by lowering peripheral costs, most of which was due to the cooling system. Based on this, the hypothesis was that the project goals of simultaneously increasing power output and lowering CPW could only be met by limiting the number of TEGs to two and designing a system that would not require active cooling.

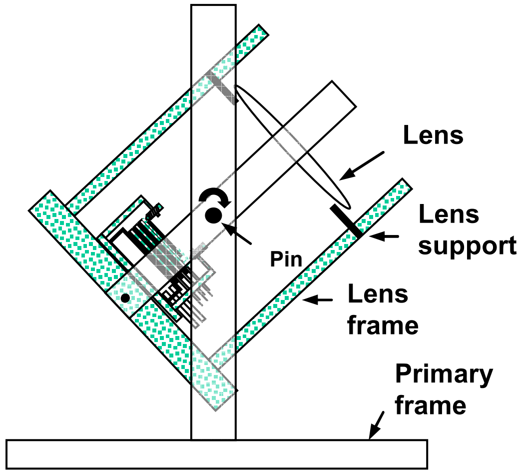
Item	VALUE	Units	Formula
TEG Make	**HZ-2**		
k	0.024	W/cm/K	
A	8.41	cm^2	
x	0.508	cm	
Rth	**2.51684503**	K/W	k * x / A
Solar Pin	0.09	W/cm^2	Direct normal
Solar concentration	*100*	Suns	INPUT
Spot radius	*0.9*	cm	INPUT
Spot area	2.5434	cm^2	pi * spot radius * spot radius
Total Solar Power	22.8906	W	Pin * Spot size * Concentration
PV efficiency	*10*	%	INPUT
PV Power Out	**2.28906**	W	Total Solar Power * Efficiency
Solar Power Unused	20.60154	W	Total Solar Power - PV Power Out
# of TEG modules	*3*		INPUT
Total Rth	7.55053508	K/W	Rth * # of TEG modules
Total ΔT	155.55265	K	Total Rth * # of TEG modules
ΔT per module	51.8508835	K	Total ΔT / # of TEG modules
TEG efficiency	*2*	%	INPUT
Stack efficiency	5.8808	%	(1 - (1 - TEG eff) ^ # of TEGs)
TV output	**1.21153536**	W	Solar Power Unused * Stack efficiency
Total Output	**3.50059536**	W	PV Output + TV Output
Composite Efficiency	**15.29272**	%	Total Output / Total Solar Power
Efficiency boost	**5.29272**	%	

Fig. 4 Partial screen capture of spreadsheet used to model hybrid solar cell performance.

2. EXPERIMENTAL SET-UP AND PROCEDURES

2.1 Design and Construction

A solar concentrator was first designed and built to hold the various hybrid solar cells and concentrating lens in place. Fig. 5(a) shows the design drawing and Fig. 5(b) a photograph of the actual structure. The concentrator had two-axis movement to allow tracking of the sun. Tracking was done manually. A water cooled heat sink was installed at the base for temperature control. The details of each hybrid cell used are described later in the next section with the results. This way the reasons for the changes made from one design to the next are easier to explain. The list of construction materials used in this project is as follows. 1) silicon PV solar cells (about 2 cm x 2 cm in size), rated about 10% efficient; 2) TEG modules; 3) Fresnel lens (22 cm sq.); 4) heat sink; 5) two small pumps for the heat sinks; 6) miscellaneous hardware items (e.g. wood pieces, screws, wires, etc.); (7) thermal conductive paste.



(a)

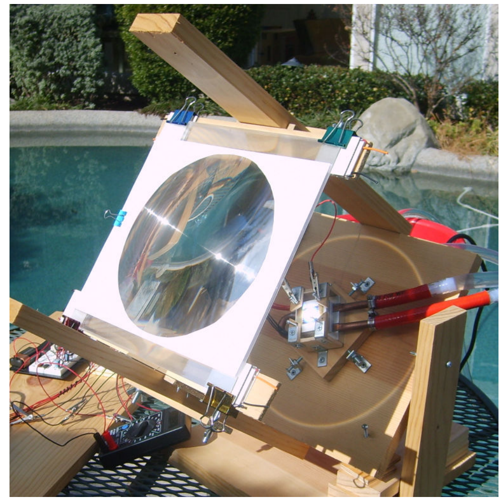

(b)

Fig. 5. (a) Design drawing and (b) photograph of solar concentrator used in this project.

2.1 Electrical Measurement Procedures

The electric power generated by a PV solar cell or a TEG depends on the resistance of the load attached to it. For a certain load the power generated is a maximum. Generally the peak power point occurs when the external load resistance is equal to the internal resistance of the TEG or PV cell. This peak power value is used in the project and can be determined using a "Load Test". Details of the how to do the load test are described here.

a) Set up the circuit as shown in Fig. 6. Connect ammeter and voltmeter outputs to data recorder channel 2 and channel 1. b) Vary the load by slowly adjusting the variable resistor. c) Record the ammeter and voltmeter reading for each setting of the variable resistor. d) For each setting of the load compute the load resistance by taking the ratio of the voltmeter and ammeter readings and the load power by taking their product. For speed and convenience the ammeter and voltmeter outputs were fed into a computer based data logger. Apparatus for electrical measurements: ammeter, voltmeter, variable load resistor, data logger.

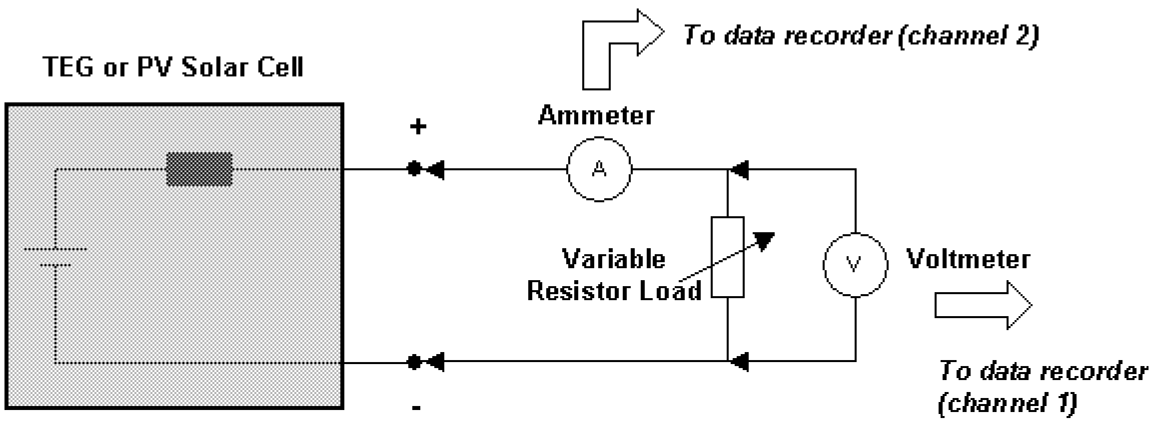


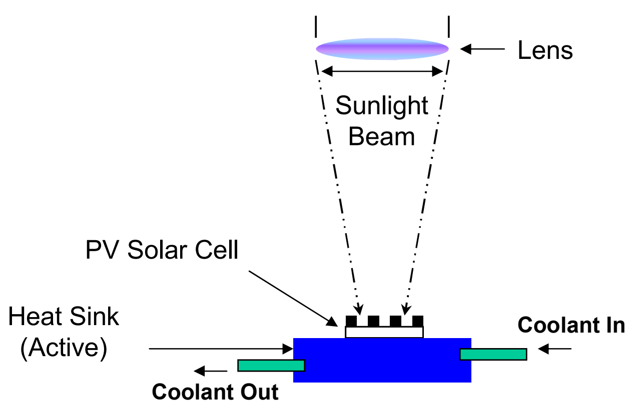
Fig. 6 Circuit diagram for load test of PV solar cell and TEGs.

3. EXPERIMENTAL RESULTS

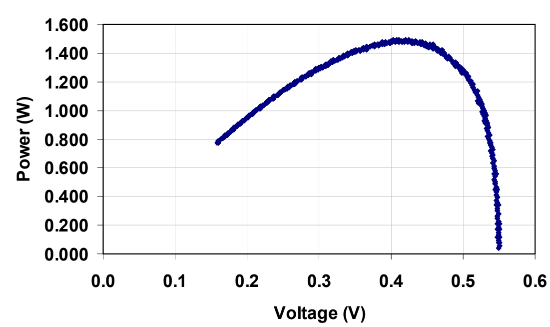
3.1 Measurements on Hybrid Solar Cells under Concentrated Sunlight

In this section a series of experimental results are presented. A brief analysis of the data from each experiment is given so that the thinking behind the next experiment is clear.

Experiment #1 The first experiment was conducted with a photovoltaic solar cell alone under concentrated sunlight in order to set a point of reference for cost and performance. The set-up used for this experiment is shown in Fig. 7(a). The load curve is shown in Fig. 7(b).



(a)



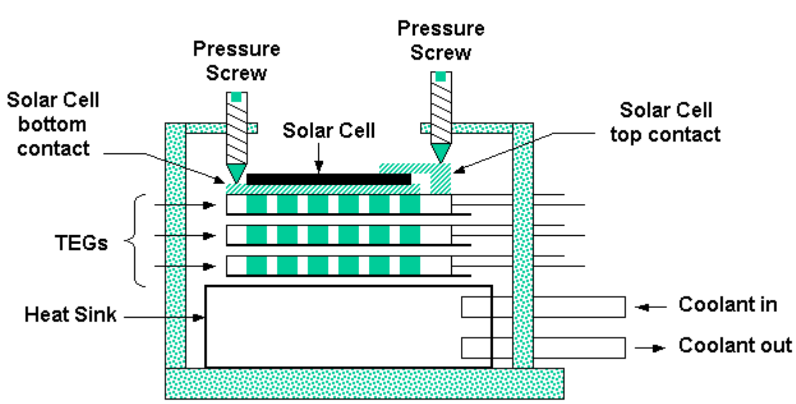
(b)

Fig. 7. (a) Pictorial view of experimental set-up used for Experiment 1. (b) Resulting load curve of solar cell.

The maximum power obtained was about 1.5 Watts. The total construction cost was \$9.40, mainly from the lens and cooling unit, resulting in a CPW of \$6.27. *This means the hybrid designs of this project will need to produce at least **1.575 W** of power at a CPW of **\$5.96** or less.*

Experiment #2 The second experiment was conducted with a cascaded hybrid solar cell design. The cell was built by stacking a number of TEGs and placing a PV cell on top of the stack. These were held tightly in place using four screws applying pressure from top as shown in Fig. 6. Thermal paste was used between the TEGs and foam board insulation was placed on all four sides of the cell stack to reduce heat leakage from the sides. Although Fig. 6 shows 3 TEGs cascaded, this experiment was repeated with cascades of 1 TEG, 3 TEGs, and 5 TEGs. Results from only the cell with the 5 TEG cascade are described here to keep the report short. Results form other cascade sizes are summarized later in the report.

The PV and thermoelectric load curves for a 5 TEG cascade hybrid cell are shown in Fig. 9. Data from only one TEG is shown as all 5 TEGs behave in almost identical manner. The maximum power produced by each of the TEGs was about 0.28 Watts resulting in a total of 1.4 Watts from the TEGs. The PV cell generated a peak power of 0.75 Watts. This resulted in a total electric power of 2.15 Watts, much higher than what was produced in the previous experiment. The total construction cost of this set-up was $29.40, mainly from the TEG's. Thus the cost per watt of this arrangement worked out to $13.67. This hybrid cell produced a lot more power than the PV cell could by itself, but the CPW was prohibitively high. Until the cost of TEGs goes down a better way to balance power output and cost will be needed.



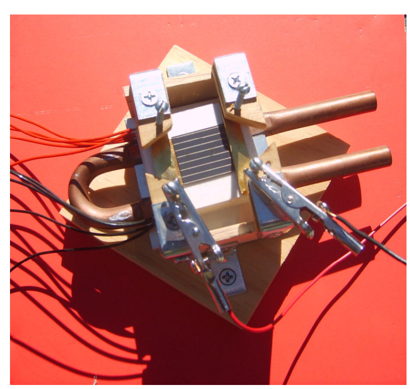
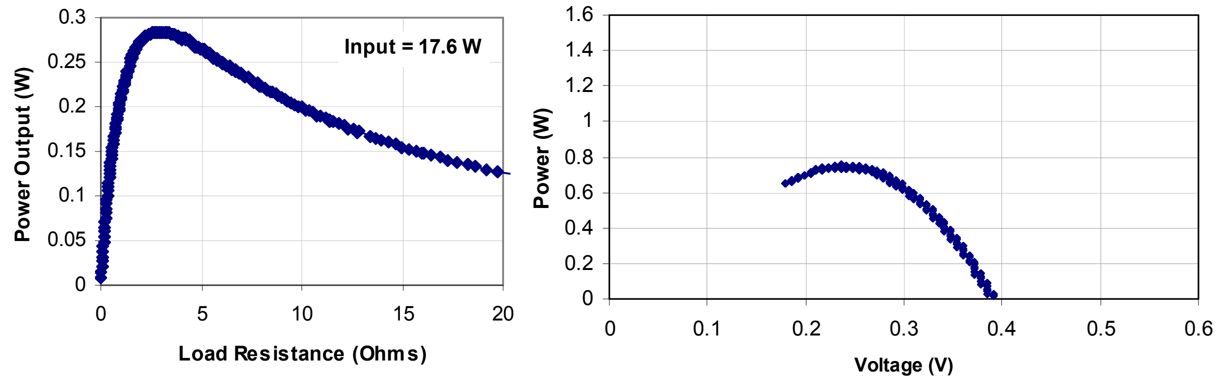


Fig. 8 Design drawing and photographic view of cascaded hybrid solar cell used in Experiment 2.

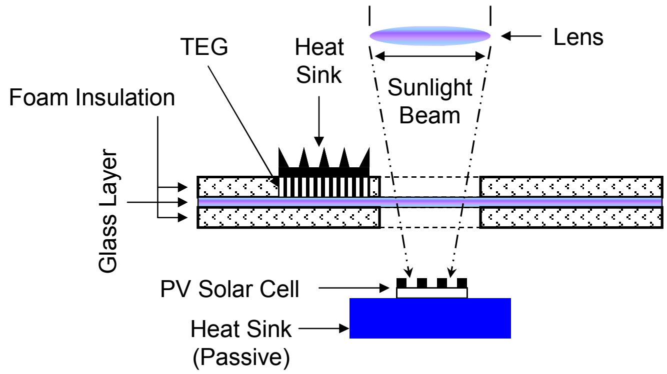


(a) (b)

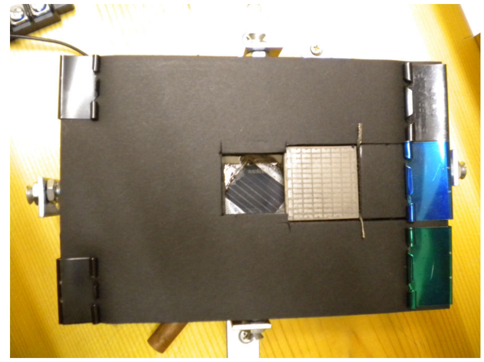
Fig. 9 Load curves of (a) one of the TEGs and (b) PV cell of the cascaded hybrid cell used in Experiment 2.

Another important observation from this experiment is that the PV power output in the cascaded hybrid cell dropped by half in comparison to Experiment 1 where the PV cell was used by itself. This drop in PV power output is because of the higher temperature at the top of the TEG stack.

Experiment #3 This experiment used a cost optimized hybrid solar cell structure. It was seen from the previous experiment that to reduce CPW fewer TEGs should be used and PV cell temperature should not be allowed to rise too much. It was also found theoretically that reducing peripheral costs help reduce CPW (Section 1.4). A big part of peripheral costs is the active heat sink. If a passive heat sink can be used then CPW should improve. All of this can be achieved if the long wavelength part of sunlight can be separated and directed to the TEGs before it reaches the PV cell. Using this idea a heat absorbing glass cover layer, about 5 mm thick, was used on top of the PV cell. When concentrated sunlight falls on this glass layer, the longer wavelengths heat up the glass. The shorter wavelengths pass through to the PV cell. TEGs in contact with the glass layer convert the heat to electricity. To prevent heat loss, the glass heat absorber is covered in foam insulation. Because the heat is absorbed by the glass before it reaches the PV cell, active cooling is not required, saving cost. The design drawing and a photographic view of this hybrid cell is shown in Fig. 10. The PV and thermoelectric load curves for this cell are shown in Fig. 11.



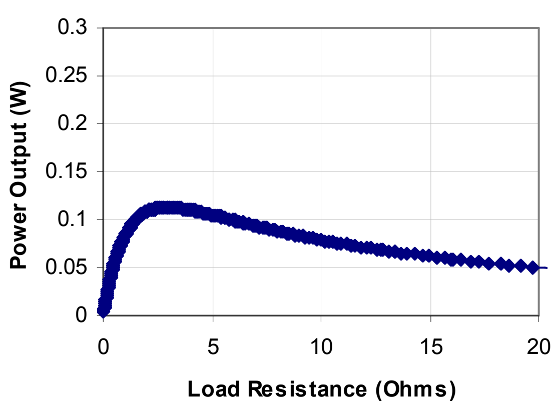
(a)



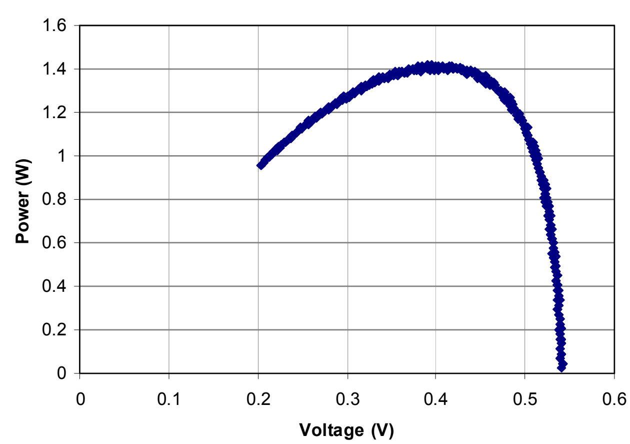
(b)

Fig. 10 (a) Design drawing and (b) photograph view of hybrid cell design used in Experiment 3.

From the data of Fig. 11 it is found that the maximum power produced by the TEG in this cell is about 0.11 Watts. In addition, the PV cell generated a peak power of 1.42 Watts, resulting in a total of 1.53 Watts, about the same as generated by the PV cell by itself (Expt. 1). The total power output was lower than in the previous experiment but so was the cost. The total construction cost of this set-up was $7.00, resulting in a CPW of $4.58. This was about 27% lower than the CPW found in Experiment 1, meeting the CPW objective of this project. However, the power output objective was not met. The PV cell produced more output than in Experiment 2 indicating it was cooler even though no active heat sink was used. Using a passive heat sink and only one TEG helped lower the CPW.



(a)



(b)

Fig. 11 Load curve of (a) TEGs and (b) PV cell used in Experiment 3.

Experiment #4 The previous experiment allowed the project's CPW target to be reached but not the power output target because the TEG produced too little power. One way to improve this situation would be to cascade a second identical TEG. This would probably double the TEG power output but the system cost would also go up leading to a situation where the power target would be met but not the CPW target. As a compromise it was decided to use a half size TEG in cascade with the first one. It would produce less power than the first TEG but would also cost less. Fig. 12 shows a diagram of the resulting structure.

Load curves measured on this hybrid solar cell are not shown to keep this report short. The changes made in this cell resulted in an improvement in electrical performance, increasing the TEG output to 0.16 Watts. This resulted in a total power output of 1.58 Watts, which barely met the target of 1.575 Watts. The cost of this set up was $9.00, resulting in a final cost per watt of $5.8. This also met the target of $5.96 per watt or less.

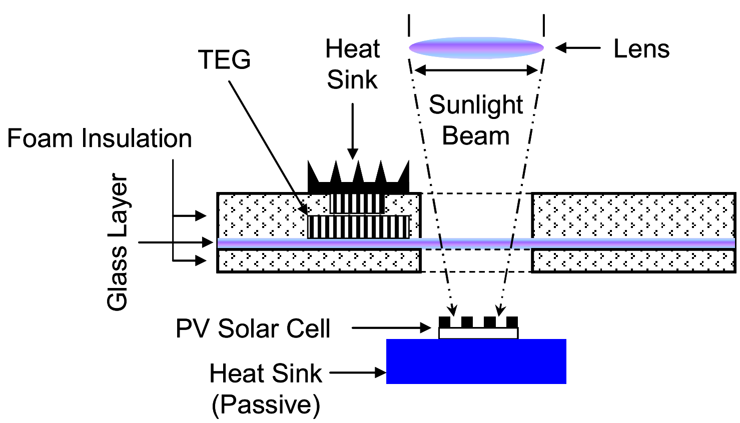


Fig. 12 Diagram of experimental set-up used for Experiment 4. Two cascaded TEGs are used.

Experiment #5 In this experiment a beam splitter was used to separate the long and short wavelengths of the incident sunlight as proposed in [9]. Depending on its characteristics a beam splitter allows a band of wavelengths to pass through it while reflecting the remainder of the spectrum. The available beam splitter had a cut-off wavelength around 700 nm. Fig. 13 shows the reflection and transmission characteristics of this filter as provided by the manufactirer.

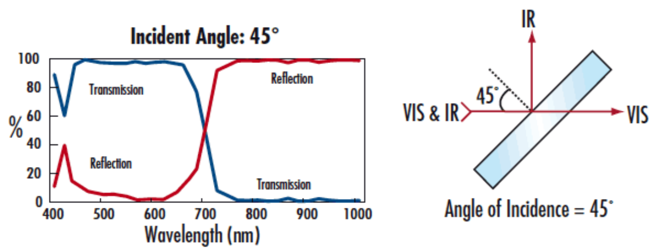


Fig. 13 Optical characteristics of beam splitter used in Experiment 5. Graphs from specifications provided by manufacturer

Fig. 14 shows the set up used in the beam splitter based hybrid cell approach. The shorter wavelengths pass through the splitter and are focused on the PV cell. The longer wavelengths are reflected and made to focus on a TEG. As a result the PV cell gets the useful part of the spectrum and stays cooler while the TEG receives the longer wavelengths and heats up.

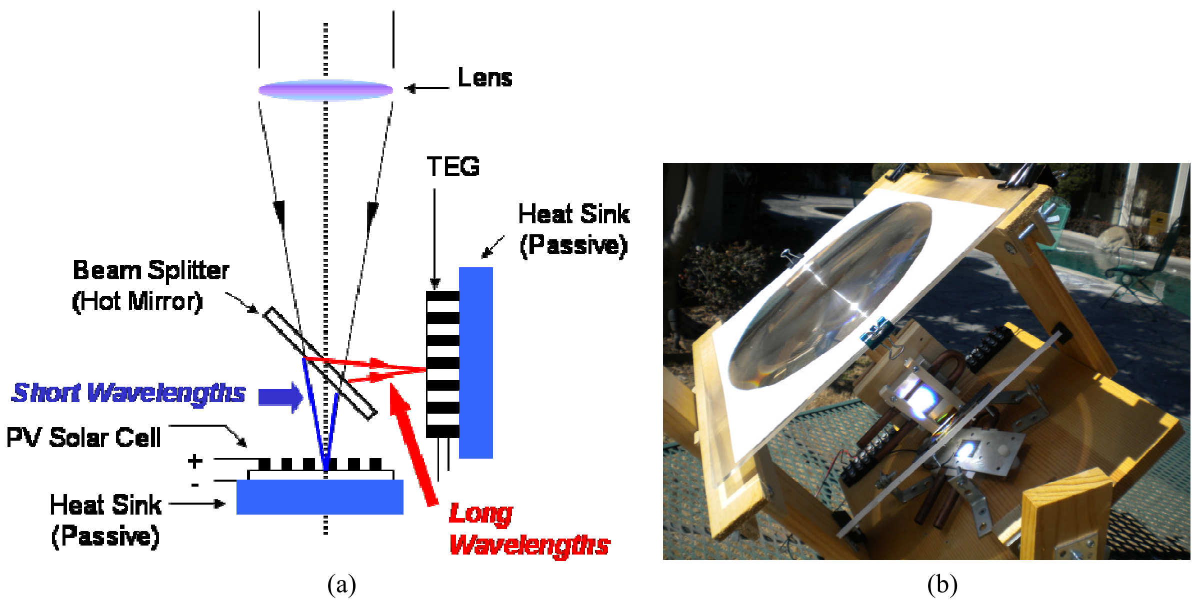


Fig. 14 (a) Design drawing and (b) photograph view of beam splitter based hybrid cell design used in Experiment 5. Note two bright spots in the photo.

It was found that the PV power output dropped in this experiment. That is because the beam splitter filtered out too much of the useful spectrum. On the other hand the power output from the TEG was higher than in previous experiments using the heat absorber approach. A total of 1.07 Watts of peak power was generated in this case. The total cost of the system was $11.40, most of the increase due to the beam splitter. Thus the cost per watt in this design is $10.65.

3.2 *Statistical Data*

Statistical data was taken to study the variability of the results arising from the probability of some error in the readings. Since the main focus in this work was the TEG, statistical data on the peak power generated by a TEG was taken. 50 measurements of open-circuit voltage and short circuit current of a TEG were taken under about 100x solar concentration. The peak power point was calculated from the 50 data sets. The standard deviation was found to be about 5 mW.

4. DISCUSSION

4.1 *Analysis of Experimental Data*

Table 1. Summary of results obtained from different hybrid solar cell designs.

Expt.	Measurement Summary				
	Description	**Number of TEGs Used**	**Peak Power Thermal (W)**	**Peak Power PV (W)**	**CPW ($/W)**
1	PV only with active cooling	0	-	1.5	6.27
2	PV + cascaded TEGs with active cooling	1	0.3	1.3	8.38
	PV + cascaded TEGs with active cooling	3	0.84	1.03	11.44
	PV + cascaded TEGs with active cooling	5	1.4	0.75	13.67
3	PV + TEG with heat absorber and passive cooling	1	0.11	1.42	4.40
4	PV + TEG with heat absorber and passive cooling	2	0.16	1.42	4.28
5	PV + TEG with beam splitter and passive cooling	1	0.2	0.87	10.65

Table 1 is a summary of the results obtained from the different experiments. The results show that by combining TEGs with PV cells in a concentrator system it was possible to get significantly larger power output. By optimizing the hybrid setup in a way that allowed the removal of the active coolant system it was possible to meet the project goals (Experiment 4).

One of the main topics of interest in this project was related to the cascading of TEGs to improve their overall thermal conversion efficiency. The theoretical dependence of the overall efficiency of a cascade of TEGs as a function of number TEGs obtained using equation (4) is plotted in Fig. 15 for different values of individual TEG efficiency. Data obtained data from Experiment 2 are also included in this graph. The output powers are converted to efficiency using an estimated solar input power of 17.6 Watts. The measured data (dots) closely follows the theoretical results (lines), implying an operating efficiency of 1% to 2% for each individual TEG.

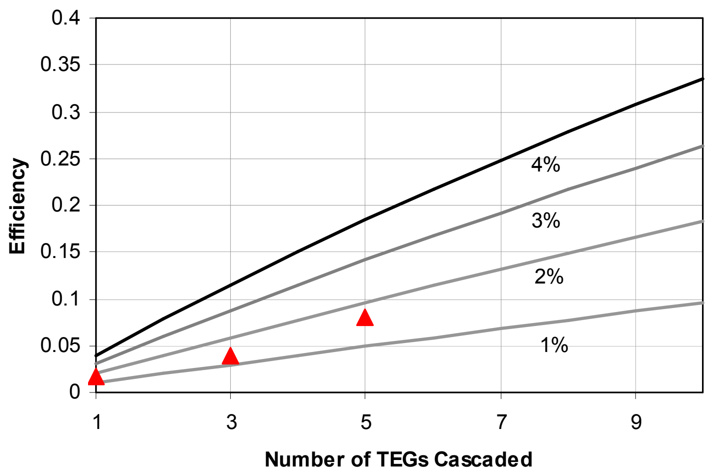


Fig. 15 Comparison of theoretical and experimentally measured efficiency of cascaded TEGs.

While the results shown here indicate that the extra cost of each TEG added to a cascaded hybrid cell in relation to the amount of power it generates is not favorable, this may change over time as improved manufacturing processes allow costs to come down.

Results from the beam-splitter experiment were not positive because the cut-off wavelength for the transmitted beam was a bit too low at about 700 nm. It is known that Si PV cells can use wavelengths up to about 1000 nm quite efficiently. As a result the PV cell output in this experiment decreased significantly. This outcome was not totally unexpected but unfortunately a beam splitter with a higher cut-off wavelength was not available.

4.2 Future Work

Balancing the cost and cell efficiency in TEG based hybrid solar cells is extremely difficult because present day TEG efficiencies are too low and they are too expensive for the amount of energy they generate. One possible way around this is to use higher levels of solar concentration, i.e. a bigger lens. This will result in higher temperature differences across the

TEGs and thus more power output. In theory the power output of a TEG increases quadratically as the temperature difference across it. This will be investigated in future.

While advanced materials with high Z_T values are being developed in various laboratories these solutions will probably be quite expensive at the beginning for commercial use [11]. In the mean time, one idea to consider is the following. If a PV cell is operated with a temperature gradient across it, it will theoretically produce more power than an identically illuminated cell with same temperature on both sides. This idea is basically about combining the Seebeck and photovoltaic effects into one device. This has been discussed theoretically but there seems to be no reports of actual implementations [12]. With this approach it may be possible to improve the performance of today's PV cells with some small changes in their designs

5. SUMMARY AND CONCLUSIONS

In summary, the following conclusions can be made from this study. (1) Concentrator solar cell electrical performance can be improved by addition of TEGs. (2) While the addition of TEGs improves cell efficiency the cost per watt of electricity increases quickly since TEGs are currently expensive and have low efficiency. These opposing trends need to be carefully balanced while designing a hybrid system. (3) Cascading TEGs is an effective way to improve the efficiency of thermal energy conversion. Experimentally obtained results matched well with theory. (4) Reducing peripheral costs in a solar energy system provides an effective way to reduce CPW. It was found that replacing active cooling with a passive heat sink greatly helps reduce CPW. However, cost analysis results from this study may not directly work in another system. Cost analysis must be done separately for each system. This work shows a way to do so.

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