



## **An Applied Comparison Study: Solar Energy vs. Thermoelectric Energy**

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## **Abstract**

Thermoelectric generators (TEG) are devices that convert temperature differences into usable electricity. TEGs are made from thermoelectric modules which are solid-state integrated circuits that employ three established thermoelectric effects known as the Peltier, Seebeck and Thomson effects. TEGs require heat as an energy source and can generate power as long as there is a heat source such as gas or oil flame, stove, camp fire, industrial machinery, and furnace. Solar modules which convert light energy into usable electricity need direct sunlight to generate maximum rated power. Usually solar tracking systems are used to receive direct sun light to increase the efficiency of the modules. This type of setup increases the cost of the photovoltaic systems. A team of students with a renewable energy projects background compared solar panels with TEGs. The comparison study dealt with efficiency, power generation capability and capacity, cost, size, potential consumer applications, and system installation complexity to generate power. The balance of the system included the number of the components that go into the system. For both devices, two separate laboratory environments were created to measure the power outputs and efficiencies. Both devices were tested at different locations due to operating environments were not similar. A solar PV module was tested under sun light whereas TEG module was tested inside an air conditioner condenser unit on same days. This paper documents test results of the comparison of two energy generating systems and lists potential applications.

## **Introduction**

Devices that scavenge energy from the ambient surrounding environment have become a popular topic for research. For some applications, energy scavenging eliminates the need for batteries or increase the time between battery replacements. One ambient energy source found in our environment is a temperature change (thermoelectric-Seebeck) effect. This form of ambient energy is found in buildings, machines, bridges, staircases, furnaces, indoor and outdoor temperature differences, and the human body. The use of TEGs based on thermoelectric effects (or Seebeck, Peltier, Thomson effect) is made possible by direct conversion of temperature differences to electrical power [1-6]. The Seebeck effect occurs when a temperature difference exists between two dissimilar electrical conductors or semiconductors, producing a voltage across two materials.

Thermal gradients in the environment are directly converted to electrical energy through the Seebeck (thermoelectric) effect as reported by Disalvo and Rowe [7-8]. Temperature changes between opposite segments of a conducting material result in heat flow and consequently charge flow since mobile, high-energy carriers diffuse from high to low concentration regions. Thermopiles consisting of n- and p-type materials electrically joined at the high-temperature junction are therefore constructed, allowing heat flow to carry the dominant charge carriers of each material to the low temperature end, establishing a voltage difference across the base electrodes in the process. The generated voltage and power is relative to the temperature differential and the Seebeck coefficient of the thermoelectric materials. Big thermal gradients are essential to produce practical voltage and power levels [9]. However, temperature differences greater than 10°C are rare in a micro-system, so consequently such systems generate low voltage

and power levels. Moreover, naturally occurring temperature variations can also provide a means by which energy can be scavenged from the environment with high temperature. Stordeur and Stark have demonstrated a thermoelectric micro-device which is capable of converting  $15 \mu\text{W}/\text{cm}^3$  from  $10^\circ\text{C}$  temperature gradients [10]. While this is promising and, with the improvement of thermoelectric generators, could eventually result in more than  $15 \mu\text{W}/\text{cm}^3$ , situations in which there is a static  $10^\circ\text{C}$  temperature difference within  $1 \text{cm}^3$  are very rare. This, however, assumes no losses in the conversion of power to electricity.

There are a variety of thermoelectric generators available in the market, and there are industrial applications of TEGs. The efficiency of thermocouples has been under research by both academic institutions and private sectors to increase output power of thermoelectric generators. According to the Bierschenk and Townsend, a compact, thermal energy harvester can power temperature and vibration sensors that monitor motors anywhere inside the plant, alerting managers of excessive motor wear and allowing them to perform preventative maintenance to avoid factory downtime. This task lessens the regular maintenance schedules and costly unnecessary repairs [14]. Basically, a solid-to-air miniature harvester consisting of a thermoelectric device positioned between an aluminum interface plate and small, finned natural convection heat sink sustains requirements. One of the latest designs of thermoelectric energy harvester was the TEG designed and introduced in the available technologies web site of Pacific Northwest National Laboratory [11]. This new thermoelectric generator is equipped for conversion of environmental (ambient) thermal energy into electric power for a variety of applications that necessitate low power source use. This thermoelectric energy harvester includes an assembly of very small and thin thermocouples in a unique configuration that can exploit very small ( $>2^\circ\text{C}$ ) temperature variations that occur naturally in the environment of the application such as ground to air, water to air, or skin to air interfaces. The body of the TEG consists of reliable and stable components that provide maintenance free, continuous power for the lifetime of the application claimed by the manufacturer. Depending on the temperature range, a TEG's electrical output can be changed from a few microwatts to hundreds of milliwatts and more by modifying the design. Applications of this energy harvesting design are diverse, including automotive performance monitoring, homeland and military security surveillance, biomedicine, and wilderness and agricultural management. It is also documented that the thermoelectric energy harvester may be appropriate for many other stand-alone, low-power applications depending on the nature of the application. In addition to PNNL's patent pending thermoelectric generator, Applied Digital Solutions Corporation has developed and presented a thermoelectric generator as a commercial product. This thermoelectric generator is capable of producing  $40\mu\text{W}$  of power from  $5^\circ\text{C}$  temperature variations using a device that is  $0.5 \text{cm}^2$  in area and a few millimeters thick [12]. This device generates about 1V output voltage, which can be enough for low power electronic applications. Moreover, the thermal-expansion actuated piezoelectric generator has also been proposed as a method to convert power from ambient temperature gradients to electricity by Thomas, Clark and Clark [13]. As an example, Figure 1 shows a picture of a Seebeck effect TEG [14].

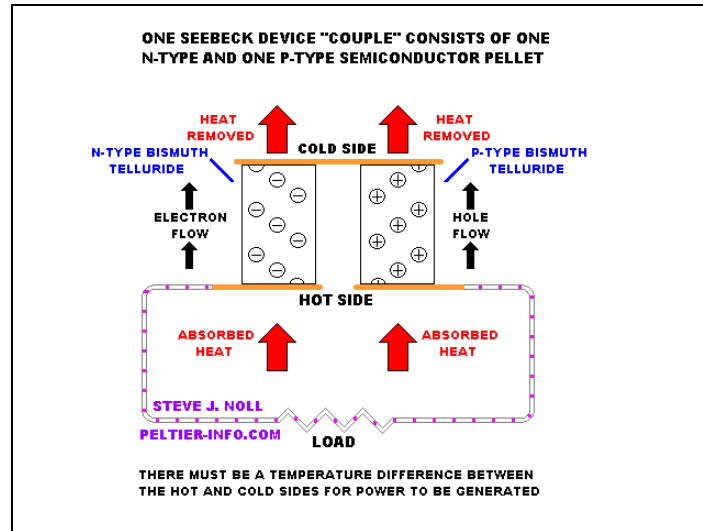


Figure 1. Seebeck Effect Thermoelectric Power Generator

When two modules are compared a question may raise about the environment. There are two dissimilar modules with dissimilar functions but is being tested in the same environment. For example, a solar PV module converts sunlight into electrical energy whereas a TEG uses a temperature difference across the TEG module and thermoelectric effect to generate electricity. The environments in these two cases are not similar. However, in this study, environment refers to the overall climatological environment in the area, particularly for one building. Therefore, it is fairly often the case that the HVAC unit is running at the same time the PV array is producing the most output so a rough comparison of the outputs of the two methods can be at least qualitatively performed (“qualitative” because we do not expect comparable outputs from PV versus TEG because our equipment is not sized for a direct comparison and therefore would require considerable extrapolation to achieve a true quantitative comparison). The purpose of the this study is not favor one to another but make comparison study to determine appropriate applications for each module. Main purpose is not to say that PV is better than TEG or vice versa.

### Thermoelectric Generator (TEG)

A TEG module was purchased from Custom Thermoelectric (\$99.75). The hot side of the module is rated to a maximum of 300 degrees Celsius (572 degrees Fahrenheit) continuous and cold side is rated to a maximum of 180 degree Celsius continues (356 degrees Fahrenheit). Both sides of the TEG have graphite foil pre-applied as a thermal interface material (TIM). Figure 2 shows power, voltage, resistance, and current plots based on temperature difference.

First graph in Figure 3 shows power output based on temperature differences on both sides of TEG unit. The tested temperature for cold side is from 25°C to 100°C and hot side temperature from 50°C to 300°C. The larger the temperature difference is the more output power is available from TEC unit. For example, TEG generates about 20W power having cold side 25°C and hot side 300°C which is about 275°C temperature differences.

Second graph in Figure 3 shows voltage output based on same temperature conditions for power output. The maximum voltage generated is 4 Volts at 275°C temperature difference between hot and cold plates. The ambient temperature should be considered when there is very low or hot ambient temperature is available.

TEG current output graph is similar to power and voltage graphs. The current increases with temperature differences. The TEG resistance graphs shows temperature and average resistance. Both temperatures (cold and hot side) are added and dividend by two to find out average temperature. When average temperature increases the resistance increases almost linearly.

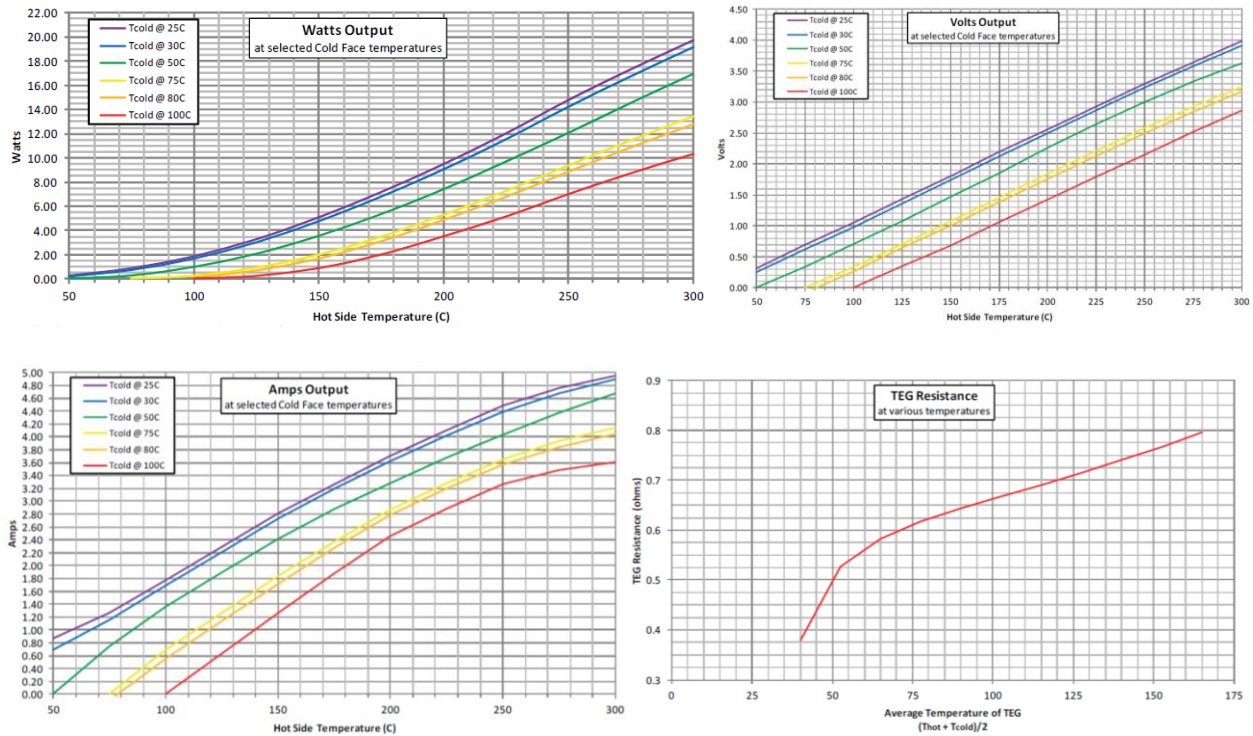


Figure 2. Power, voltage, resistance, and current plots of the TEG module [16]

Figure 3 shows dimensions of a single module. The weight of the module is 60grams. The AC resistance is .38 ohms @ 27°C [15-17].

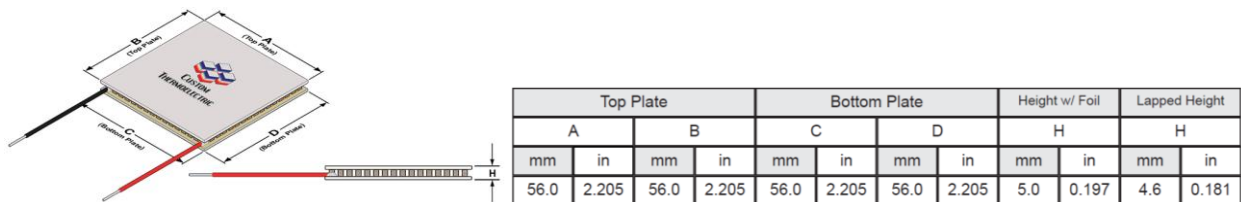


Figure 3. Dimensions of 1261G-7L31-24CX1 TEG module [17]

A TEG will deliver the maximum power output when the load resistance equals the TEG’s internal resistance. Charts can be used to determine the TEG’s resistance. In order to make a

calculation, the values of both the hot and cold side temperatures are added, and then divided by two to get the average temperature. If the load cannot be matched, then the load resistance must be kept higher than the TEG resistance rather than lower.

Figure 4 shows power specifications of the TEG power module. There are two columns. The first column shows a 100 degrees difference between hot and cold sides. The power generation is only about 3.54W. For the second main column, there is a 270 degree difference between hot and cold sides. The power generation for this difference is about 19.1Watts.






Specifications								Dimensions mm (inches)			
Part #	PDF	150°C Hot side 50°C Cold side			300°C Hot Side 30°C Cold side			Max T <sub>max</sub> (°C)	A	B	H
		P (watts)	I (Amps)	V (Volts)	P (watts)	I (Amps)	V (Volts)				
1261G-7L31-04CL <b>NEW</b>		1.04	0.46	2.25	5.19	0.98	5.3	300	30.0 (1.18)	30.0 (1.18)	3.7 (.146)
1261G-7L31-04CQ		1.01	0.60	1.69	5.1	1.31	3.89	300	40.0 (1.57)	40.0 (1.57)	3.4 (.134)
1261G-7L31-05CQ		1.15	0.86	1.34	7.15	1.97	3.63	300	40.0 (1.57)	40.0 (1.57)	3.4 (.134)
1261G-7L31-10CX1		3.24	1.74	1.86	14.7	3.5	4.2	300	56.0 (2.21)	56.0 (2.21)	4.4 (.17)
1261G-7L31-24CX1 <b>NEW</b>		3.54	2.41	1.47	19.1	4.9	3.90	300	56.0 (2.21)	56.0 (2.21)	5.0 (.197)

Figure 4. Seebeck TEG generator power specifications [18]

### Solar Module

A solar module used for test purposes was a 65Watts Kyocera (KC65T 65W 12V Solar Panel with J-Box). The photograph of the solar panel is shown in Figure 5 with all specifications. Ten of these solar panels were available in the lab for teaching purposes. For this project, we used one module to make a comparison study with students. Solar module specifications may vary based on manufacturers. No research has been done to find a solar module that is lightweight and small in dimensions with high power outputs [19].



	Watts (W)	Isc (A)	Imp (A)	Voc (V)	Vmp (V)	Length	Width	Depth	Weight
<b>KC 65T</b>	65	3.9	3.75	21.7	17.4	29.6"	25.7"	1.4"	18lbs

Figure 5. 65W Kyocera Solar Panel with specifications [19]

## Simulation and Implementation of TEG Module

The project team conducted a simulation for the TEG module using Solid Works Simulation software tools [20]. Students gathered all the information from the TEG specification sheets. They then determined a test bed to implement the TEG unit in a real world environment, instead of heating and cooling both sides of the TEG module artificially in the lab environment. The HVAC unit used for the study was an operational unit that provides air conditioning to the main laboratory building classroom and office area. Students decided to use an Air Conditioner (HVAC) unit to test the TEG unit and do simulation according to the temperature environment in the unit. The simulation is a thermal analysis using the finite element method. There is no structural analysis. The components are oriented out of plan with each other, not because of structural deformation, but because the hot and cold lines in the condenser unit were not parallel to each other and we wanted to avoid putting a mechanical load on the thermoelectric unit. A flexible component was later added to the system to prevent mechanical loading of the thermoelectric module due to either thermal stress/strain or vibration. Here are the steps are followed:

- Students studied the overall HVAC unit to determine potential sources of waste energy and devised methods for energy harvesting
- Predesign measurements were made to determine operational time based on seasons (temperature differentials).
- Measurements were taken and compared to calculated potential power to be harvested from the unit.
- Acquire test and measurement data required to simulate the TEG module with SolidWorks simulation thermal finite element analysis. The simulation was based on finite element analysis. It was a thermal simulation to determine the temperature distributions in the copper plates and pipes.

For assembly and clamping of the TEG module to the pipes (cold and hot side) of the compressor unit in the HVAC system, students investigated the compressor and the copper lines in the surrounding area. Then a 3D CAD design was created to determine what materials are needed to assemble a TEG module to the pipes with high efficiency in terms of power output. Below are the parts purchased and integrated to clamp the TEG to the pipes of the compressor .

- Copper 122 Tube (0.75" X 0.0065" X 0.62")
- Copper 122 Tube (0.875" X 0.0065" X 0.745")
- Copper 1110 H04 Rectangle (0.25")

In the simulation process, aluminum, copper, brass, and bronze were evaluated for the TEG assembly mounting components. Copper was used as the material of choice because of its thermal characteristic's and availability, but it was expensive. The copper as drawn (see simulation results below) resulted in a 56.2° F difference from one side of the module to the other. However, this might be improved by making the part that is in contact with the thermoelectric thicker and insulate it on the side away from the thermoelectric module. Other materials can be used later for test purposes when the project is extended in the future. The photographs of the clamped TEG module are shown in Figure 6. The summary of SolidWorks

Simulation results are followed in Figure 7 and a related table with a short summary description of how simulation was conducted. The off-axis tilt of the two pipe clamps with respect to each other shown in Figure 7 is not due to mechanical deformation, but is designed that way on purpose so that the clamps could be clamped to the copper tubing in the HVAC unit (which were not parallel) without putting mechanical stress on the TEG module. In Figure 6, a flexible component was added to assist with alignment and vibration issues.



Figure 6. The photographs of the TEG module clamped to the pipes of the compressor

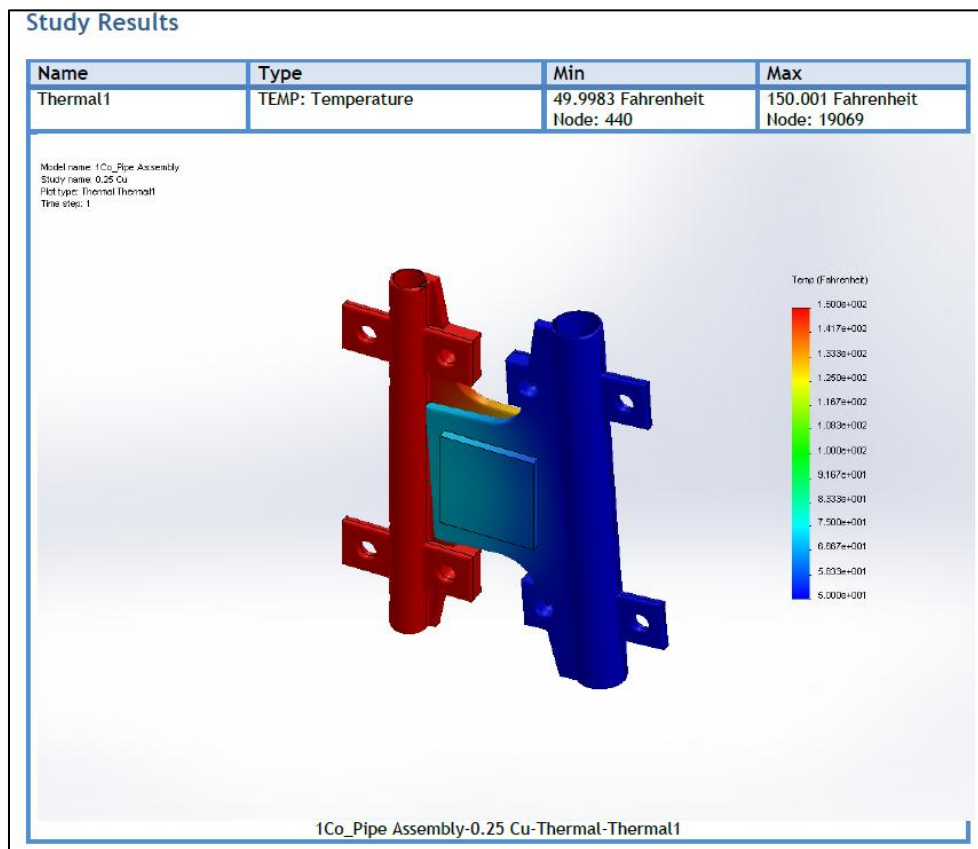


Figure 7. Simulation of TEG module (Analysis Type: Thermal -Steady state finite element)



## Simulation Description

Copper clamp

Heat transfer flange 0.25" thick

Standard thermoelectric module at 3.88 W/m<sup>2</sup> K (from manufacturer's data)

Total of 3 modules, one sandwiched, 2 on outside

- Heat transfer was much better for the 1/4" thick sandwich than for the 1/8" sandwich. Median temperature difference from one face of the sandwiched module to the other was about 32.7°F for the 1/8" flange while the difference was about 59.8°F for the 1/4" sandwich.
- Various insulators were tried on the surface of the flanges (e.g. rubber, fiberglass, etc.) to minimize heat loss to ambient conditions. However, none of these were as effective as increasing the flange thickness.
- Putting an additional thermoelectric element on the outside of the flanges to collect a small additional amount of energy was tried. This only resulted in about 10°F gradient across these outer elements, so it may not be worth doing.

Individual element probing was not done. The mesh is fairly coarse and, if refined further, may produce more accurate results through the thermoelectric device if the elements are small enough to eliminate spanning the thickness of the thermoelectric device. However, refining the mesh would only be of significant value if the material properties of the internal components of the TEG modules were known and varied through the thickness. The manufacturer's "aggregate" material property information for the TEG module as a "black box composite part" was therefore used in the analysis. Optimization of the flange design was not performed using the automatic optimization features in SolidWorks, but some trial and error optimization was performed by altering the model and re-running the analysis manually. Aluminum and brass do not seem to be viable materials for the project. This claim was based on heat capacity/conductivity data and heat transfer finite element simulations. Because the temperature difference between the hot and cold side lines was known prior to performing the computer modeling analysis, and because it was recognized early in the process that we were dealing with a marginal temperature difference for power generation, it was necessary to go with the best material for providing a heat conduit to the thermoelectric module that we could afford, and that material was copper.

In the simulation, the mesh was not refined because information on the internal component material properties was not available. Therefore, an aggregate set of mechanical and thermal properties for the TEG module was used based on available manufacturer's data. Because the thermoelectric device was modeled as a single piece with a single set of material properties, the mesh automatically generated efficient elements that spanned the thickness (i.e. had nodes on each surface of the module in a single element). Without manufacturer's data on the exact internal makeup of the thermoelectric module relative to variation of structural and thermal material properties within the module itself, there is no reason to refine the mesh.

The size of the copper sandwich is the critical dimension. While insulating materials do not seem to make much difference to the temperature gradients, it is still recommended to insulate the assembly in practice. It may or may not be worthwhile to use the outside mounted thermoelectric

elements (temperature gradient will depend on ambient temperature and may not be a huge gradient).

After the simulation of the module and measurements were taken from the TEG module inside the HVAC unit, students identified issues with the assembly of the TEG unit and clamping to the compressor. Below are the some issues that were determined by the students. Figure 8 shows the measurements results from the installed TEG module.

- Improper installation and insulation between copper stacks
- Voltage = ~435mV (not enough voltage output) due to improper installation
- Reassembly and installation needs to be improved
- Cold and hot side are not parallel; this makes it difficult to install
- Solder: Silver/Copper Alloy

Ambient °F	Pipe Hot °F	Plate Hot °F	Tube Clamp Hot °F	Pipe Cold °F	Plate Cold °F	Tube Clamp Cold °F	Screws °F	Strap Ground Braid °F
80	118	129	107	62	100	73	113	96

Figure 8. Testing results of TEG module

According to the temperature measurements, there is not enough temperature difference between hot and cold plates of the TEG unit due to improper installation of the TEG unit. The temperature of the hot plate is about 129° F and the temperature of the cold plate is 100° F. The hot side conducts the temperature to the cold plate through the screws used to attach copper on both sides having a TEG module in between. Students removed the assembly from the condenser unit and tested the TEG module in a lab environment again to find out if there was damage on the TEG module. The lab testing showed appropriate power output according to the specification sheet provided by the manufacturer.

### Comparison of TEG and Solar Module

Students worked on a comparison table after the implementation of the both modules. The data in the following table is not a perfect way to compare these two energy generating modules because of the several reasons listed below.

- Ease of implementation depending on application
- Applicability and viability depends on what is needed for power generation
- Working environments

The data in the table (Table 1) only compares cost, size, weight, and power characteristics. The values in the table were based on module specifications from the manufacturers (See figures 5 and 6). This is initial comparison of the two modules without any test results. Actual test results

are listed and discussed based on test values in Figure 8. Depending on the application, one of the two modules maybe is preferred. In some applications, the size of the energy generation module maybe a concern; in this case, a TEG may be considered if there is sufficient input available to generate power output. The TEG module implemented in this research necessitates more components so that the TEG module will generate an appreciable amount of power, such as the use of copper plates for efficient thermal conductivity in some applications. For the solar module, as long as sunlight is available, the solar module will generate power. For interior design applications TEGs are effective candidates to generate power. However, it is not easy to reach an appreciable amount of temperature difference such as 150° F – 300° F as would be suggested by the data in Table 1.

Table 1. Comparison Table of Solar Module vs. TEG Module

	Cost (each) (\$)	Cost (4) (\$)	Size (each) Area (sq. in)	Size (4) (sq. in)	Weight (lbs)	Weight (4) (lbs)	Power At 212°F Differ. (W)	Power At 518°F Differ. (W)	Power output (1 solar) (4 TEGs) (W)
<b>Solar</b>	250		760		18				65
<b>TEG</b>	99.75	400	5	20	0.14	0.56	3.54	19.1	76.4

\*Green: Advantage - Red: Disadvantage

Costs of solar modules have been rapidly dropping, making them good candidates for energy generation in appropriate climates. For the space required, TEGs are good modules when compared with solar panels. TEGs are better than a single solar module in terms of weight. There is a huge difference when weight of both modules is compared. To match the power output of a single solar module there should be four TEGs connected together which increases the cost of the total number of TEGs. This becomes a disadvantage of TEGs when compared with solar panels. However, weight and size (area) are still advantages of TEG modules for the appropriate application, environment and power requirement.

### Educational Outcomes

Three electronics and two design and development major students were involved in this project; all were graduating seniors. The most common feedback from the students centered on skillsets gained for team work and their increased knowledge of thermoelectric and solar energy. Two of the electronics major and design minor students showed interest in extending the project to overcome some of the issues they faced during the study of the TEG module. Students also want to study a TEG power output increase with less temperature differences. Two students will enroll in an independent study course to work on this project during the spring 2013 semester. For demonstration purposes, developed modules are being used in two renewable-energy related classes offered in the program. These courses are “Alternative Energy Technology” and “Energy Harvesting from Renewable Energy Sources”. This type of projects produces hands-on activities and demonstration modules for the students enrolled in energy classes. For example, the outcomes of this study created several lab activities for the students. The lab activities are

overview of solar energy, making measurements (voltage, current, resistance, temperature, pressure), overview of thermoelectric energy and TEG modules, learning materials (aluminum, brass, copper), simulation study (finite element analysis), soldering (copper), machining (machine the plates), design work (2D/3D design), couples design, theoretical analysis, implementation and evaluation of the technology, how to make a literature review for a project etc. In this study, students get to see firsthand the relative merits and disadvantages of both technologies. Figures 9 shows the photos of the solar panels are being tested by the students and test structure where solar panels and other components mounted.

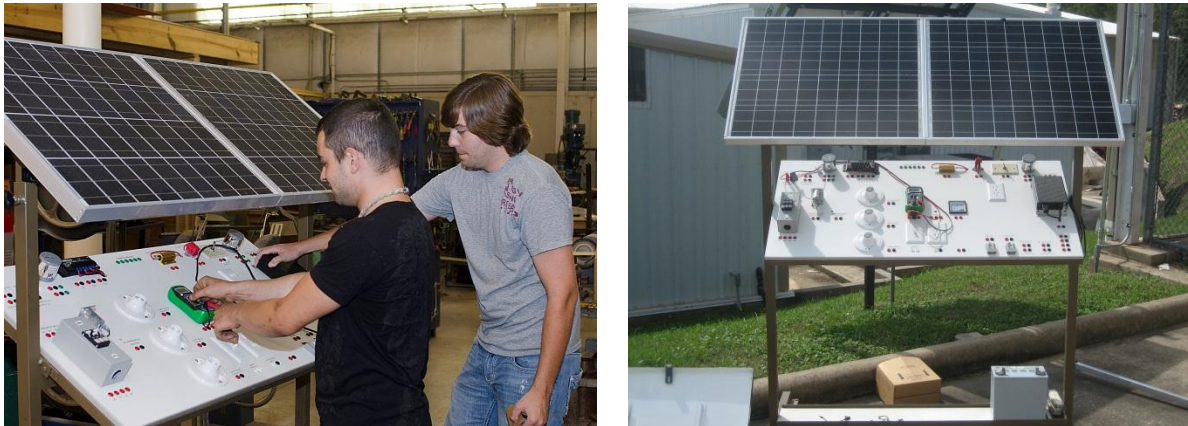


Figure 9. Students are testing solar panels and the custom-made metal stand panels are mounted

## Conclusion

Solar modules and TEGs with the power generating capacity of 20W to 65W were compared in in this study. Experimental and theoretical results relating to solar-to-electrical and thermoelectric-to-electrical conversions using TEG and solar modules were shared. This project was mainly accomplished by the students. Student feedbacks were very positive about this study. Undergraduate students gained skillsets on a renewable energy project and learned to complete a market search for the best match products needed for this research. The cost of the TEG modules is still high, but the size of modules is considerably smaller than the solar modules; this is an advantage, for the projects have space limitations. Solar cell prices have been dropping the past three years because of the interest to solar energy. At the same time, there are many research attempts to increase efficiency of the TEGs and determine potential applications. With the expected development of more efficient TEGs, the number of TEG based applications will be used in most energy projects where sunlight is not available.

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