Design of a Solar Thermoelectric Generator (STEG)

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Abstract

In a world where fossil fuels dominate as energy sources, the need for an economically and commercially viable renewable energy source is dire. The processes through which fossil fuels are formed do not occur fast enough to replenish their sources to meet society's demands, and combustion of fossil fuels produces carbon dioxide, a greenhouse gas linked to global warming. Solar energy has proven itself to be a promising alternative, with the field dominated by photovoltaics on the consumer-scale and solar thermal power on the plant-scale. Yet solar thermal systems have an innate advantage in their use of all wavelengths of incident radiation as opposed to just light. In this research, thermoelectrics are being explored as a viable option for small-scale solar thermal applications. Thermoelectrics are based on the Seebeck effect, stating that a voltage is induced when a temperature gradient is applied to the junctions of two differing materials; in the case of a solar thermoelectric generator (STEG), the hot side is the solar absorber and the cold side is the heat sink. This research proposes to design, build, and test a prototype STEG to contribute to the further development of STEGs as reasonable solar thermal energy sources for the consumer market. The design process involved calculating and optimizing the energy balance across the absorber, minimizing heat losses, analyzing heat transfer through the thermoelectric elements, and analyzing the electrical power system. The testing process involved assembling the system, measuring the balance of heat and heat losses, and measuring the electrical power generated by the thermoelectric module connected to varying resistive loads in order to ultimately measure the STEG's efficiency. Literature suggests that STEGs can reach 5.2% efficiency when operating in a vacuum without optical concentration, although this STEG only reached a peak efficiency of approximately 0.03% since an evacuated environment was not used.

Thermoelectric Theory

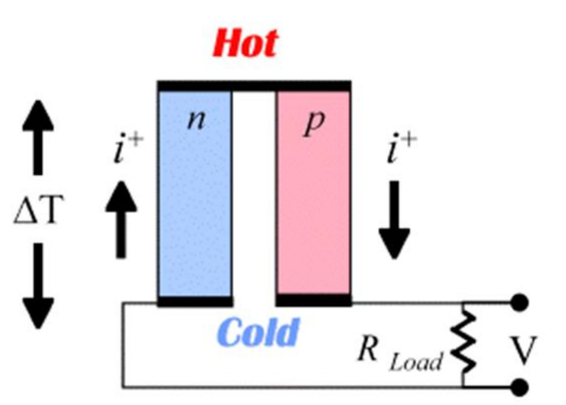


Figure 1: Thermoelectric Couple [2]

- The Seebeck effect states that when the junctions of two differing materials are placed between a temperature gradient, a voltage is induced[1]
- Thermoelectrics apply this principle to semiconductors to obtain a usable output

- N-type thermoelectric materials have an effectively negative charge, with their electrons causing conduction[2]
- P-type thermoelectric materials have an effectively positive charge, with their holes (space an electron could occupy but is not) causing conduction[2]
- Thermoelectric modules alternate n-type and p-type thermoelectric materials connected electrically in series

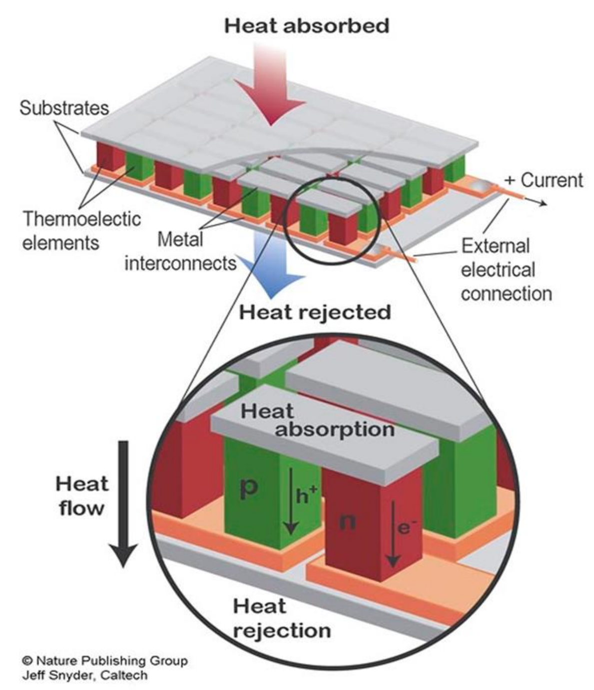
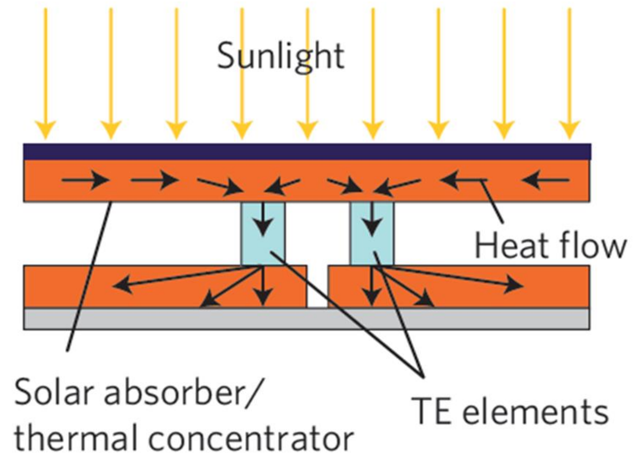


Figure 2: Thermoelectric Module [2]



- A STEG contains a solar absorber that concentrates heat onto a thermoelectric module[3]
- Heat then flows through the module to a heat sink[3]

Figure 3: Heat Flow through a STEG [3]

Theoretical Analysis and Design

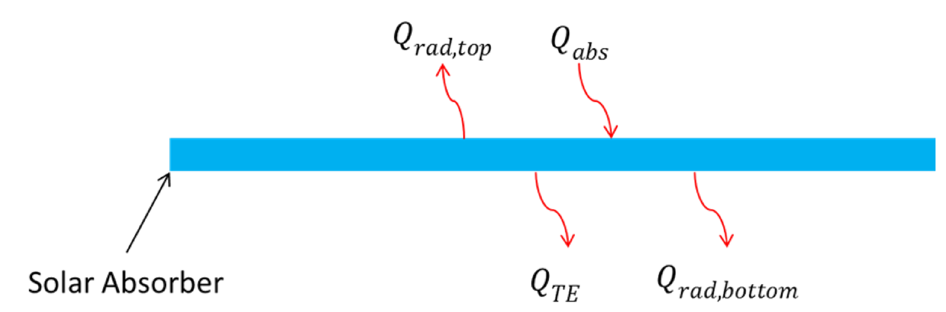


Figure 4: Energy balance across the solar absorber; heat is transferred into the top of the absorber from the sun then from the bottom of the absorber to the thermoelectric module with losses being due to radiation from the top and bottom; the system was designed to be in a vacuum in order to eliminate convective heat losses

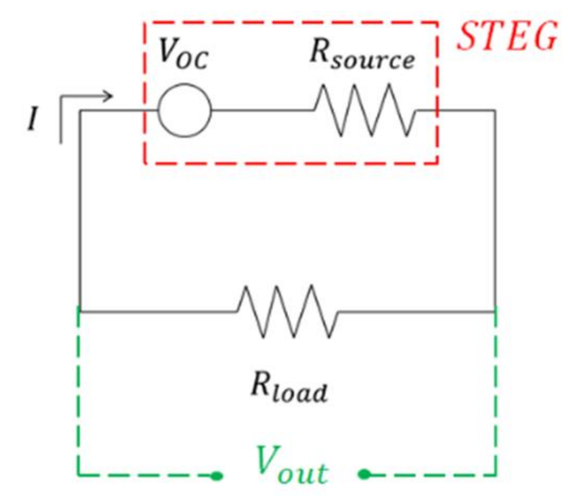


Figure 5: Electrical schematic of STEG with a load; output voltage is maximized when the load resistance is equal to the source resistance[1]

$$C_{th} = \frac{A_{abs}}{A_{TE}} \approx \frac{246}{1}$$

Thermal concentration is equal to the ratio of the absorber area to the thermoelectric area[3]. The ratio for this system correlates to approximately one thermoelectric module per square foot of absorber area. With this design, 100 W of solar power is to give approximately 179°C of temperature gradient across the thermoelectric module.

Methods

Figure 6: The chamber was designed to work under evacuated conditions to eliminate convective heat losses from the solar absorber and thermoelectric module. Once an airtight seal was achieved and the evacuation process started, the glass covering could not maintain the pressure differential and ultimately imploded. The evacuation method was abandoned, and foam insulation was added between the solar absorber and the heat sink instead. The lack of a vacuum introduced convective heat losses into the system that were not accounted for in the design.

Open Circuit Test (Indoors):
- Overhead light used as energy source
- Open circuit voltage recorded at time intervals until steady-state was reached
- System did not maintain steady-state open circuit voltage because the temperature gradient was not maintained due to the heat sink not dissipating enough heat with its mass alone

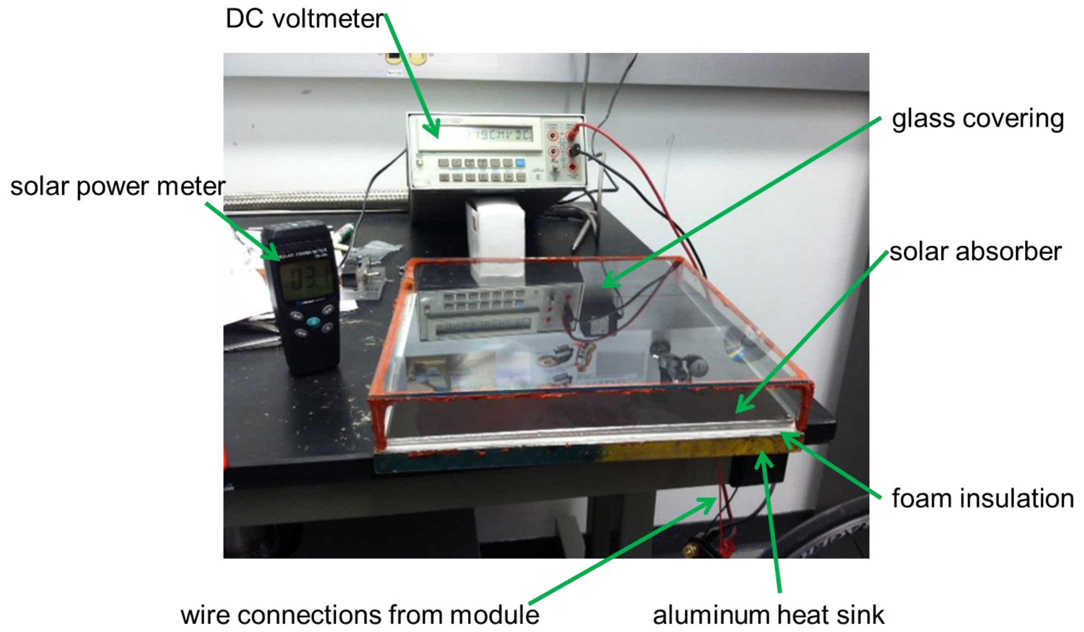


Figure 7: Indoor Test Setup

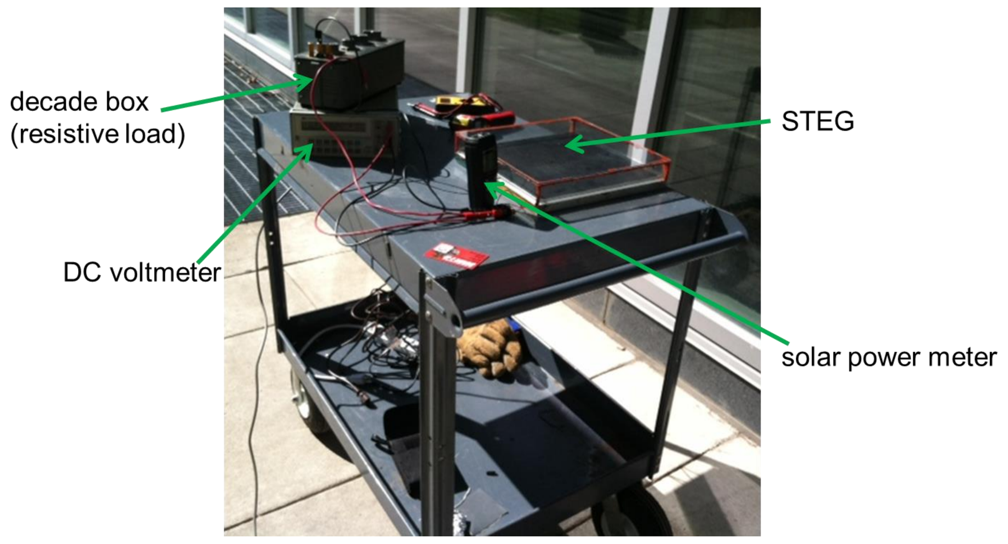


Figure 8: Outdoor Test Setup

Loaded Test (Outdoors):
- Entire device given time to reach ambient temperature with absorber covered in foil to reflect sunlight
- STEG placed in direct sunlight
- Open circuit voltage measured every minute until steady-state was reached
- Output connected to a decade box, load increased from 0Ω to 110Ω and output voltage recorded at each resistance interval
- Test repeated in another location, starting at 110Ω and decreasing to 0Ω

Results

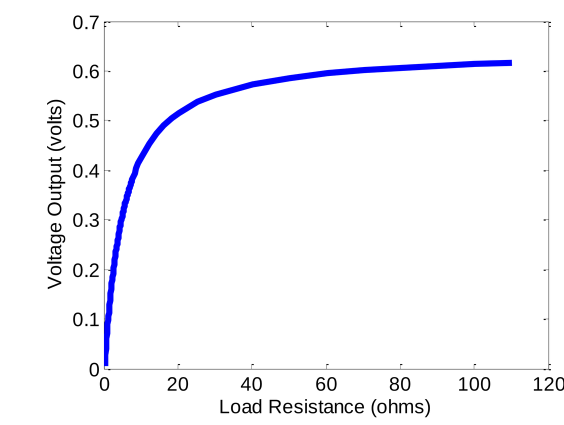


Figure 9: Voltage Output vs. Load Resistance

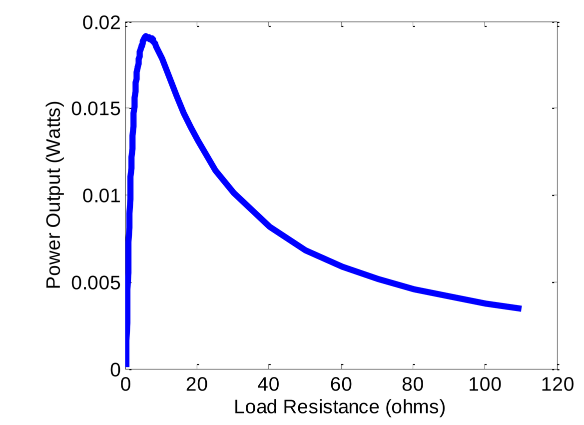


Figure 10: Power Output vs. Load Resistance

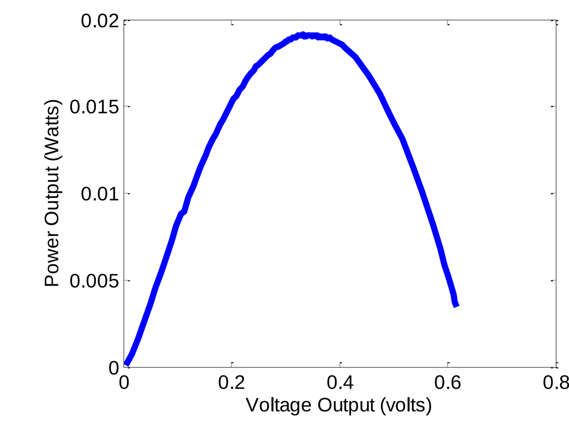


Figure 11: Power Output vs. Voltage Output

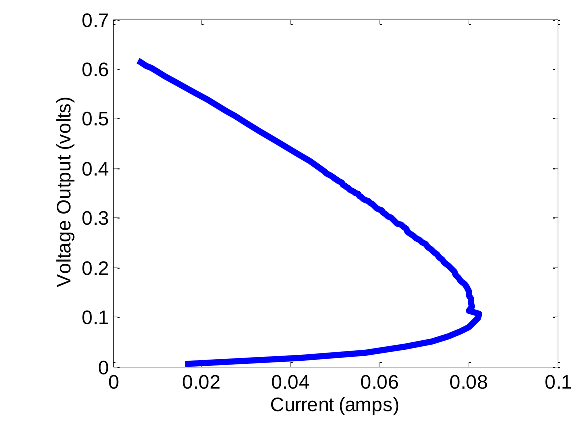


Figure 12: Voltage Output vs. Current

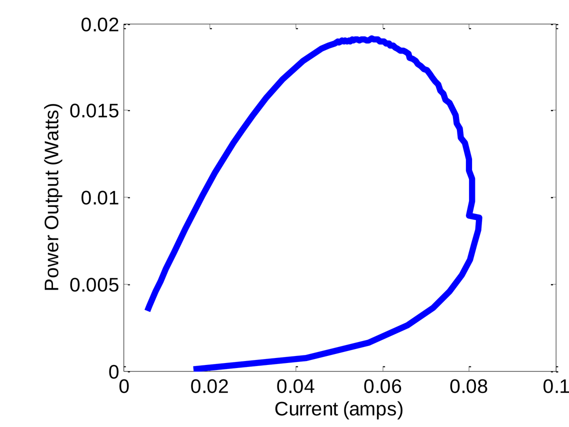


Figure 13: Power Output vs. Current

	Loaded Test 1	Loaded Test 2
Input Solar Power (W)	71.16	63.99
Open Circuit Voltage (V)	0.660	0.640
Maximum Power Output (W)	0.0209	0.0191
Peak Module Efficiency	0.0302%	0.0285%
Peak System Efficiency	0.0293%	0.0299%

Conclusions

- A study at MIT reached a peak STEG efficiency of 5.2% in a vacuum but only about 0.5% when operating in air, both cases without optical concentration[3]. The peak efficiency of this system was around 0.03%.
- The main problem in this device was the low temperature gradient across the thermoelectric module (about 15°C compared to the 179°C in the original design). This could be improved through operation in a vacuum, as had been assumed in the initial design.
- The Carnot efficiency of the thermoelectric module scales with the temperature gradient[4]. Thus, if the theoretical design had been followed (including having an evacuated environment), this efficiency could have been improved by at least a factor of 10.
- The heat sink needs further capability to dissipate heat in order to maintain the system's temperature gradient, which would also improve efficiency. This could be achieved through a finned heat sink or a heat sink with water cooling.
- For STEGs to be a marketable energy source, their efficiencies need to greatly increase and at least match those of photovoltaic solar panels.

References

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