JOURNAL OF
EMERGING INVESTIGATORS

Article

Thermoelectric power generation: Harnessing solar thermal energy to power an air conditioner

Jennifer Lew[1], Derek Fong, PE[2]

[1]Palos Verdes Peninsula High School, Rancho Palos Verdes, California

[2]California Public Utilities Commission, San Francisco, California

SUMMARY

We researched the feasibility of using thermoelectric modules as a power source and as an air conditioner to decrease reliance on fossil fuels. Thermoelectric modules have a "hot side" and a "cold side." Based on the Seebeck Effect, when the hot side is heated, and the cold side is cooled, the module generates a voltage. Based on the Peltier Effect, when a voltage is applied to a module, the hot side becomes hot, and the cold side becomes cold. We constructed a "battery" using thermoelectric modules operating in the Seebeck Effect: solar thermal energy was used to heat the hot side, and tap water was used to cool the cold side to generate a voltage. The battery was then used to power a "thermoelectric air conditioner" made of one thermoelectric module operating in the Peltier Effect, where the cold side of the module absorbs ambient heat like a traditional air conditioner. We hypothesized that the battery would generate more power per square inch than a solar panel and that the thermoelectric air conditioner would operate without voltage regulation. The results showed that, at its peak, the battery generated 27% more power – in watts per square inch – than a solar panel, and the thermoelectric air conditioner operated despite an unsteady input voltage. The battery has incredible potential, especially if its peak power output can be maintained. However, the thermoelectric air conditioner is a viable alternative to commercial air conditioners only when space is an extreme limiting factor.

INTRODUCTION

Climate change is a proven and immediate danger. Indeed, according to the United Nations, global warming more than 1.5ºC above pre-industrial levels will lead to coral reef death, diminished crops, melting ice caps, and animal extinction (1). Although there are several reasons for climate change, the main driver is CO_2 emissions from the burning of fossil fuels. For an individual, one of the biggest uses of fossil fuel is air conditioning. The available data shows two staggering statistics about air conditioners and fans: they are responsible for 10% of global electricity consumption, and the number of air conditioners is expected to nearly triple in the next 30 years (2). To lower CO_2 emissions, thereby mitigating climate change, we designed an air conditioner powered by clean solar thermal energy. Specifically, we constructed a "battery" that converts solar thermal energy into electricity, which is then used to power a homemade "thermoelectric air conditioner."

The key to both the battery and the thermoelectric air conditioner is the thermoelectric module, a device containing thermoelectric couples (comprised of bismuth telluride) sandwiched between two ceramic plates. One ceramic plate is designated as the "hot side" while the other ceramic plate is designated as the "cold side." One of the most widely used modules is the TEC1-12706. The number 127 indicates that the module contains 127 couples; the number 06 indicates that the maximum amount of current that the module can support is 6 Amperes. According to the Seebeck Effect, if the hot side is heated and the cold side is cooled, the module will develop a voltage, thereby becoming a power source (3). Furthermore, the greater the temperature difference between the hot side and cold side, the more power the module can generate. The opposite phenomenon – known as the Peltier Effect – is also possible: if a power source is applied to the module, then the voltage will cause the hot side to become hot and the cold side to become cold (3). Mathematically, the Seebeck and Peltier Effects can be expressed with the following equation:

$$P_{module} = \frac{(S \cdot \Delta T)^2}{4 \cdot R}$$

In this equation, P_{module} is the power generated in one thermoelectric module, S is the Seebeck Module Coefficient (which is temperature dependent), R is the module's internal resistance, and ΔT is the temperature difference between the hot and cold sides of the module. This equation shows that there is a direct relationship between the power generated by the module and the temperature difference across the module and vice versa. Based on the Seebeck Effect, we built a battery using 30 TEC1-12706 thermoelectric modules ("battery modules"). The hot sides of the battery modules were heated via direct contact with a "battery hot reservoir" consisting of three "hot water boxes" filled with solar thermal heated water (**Figure 1**). The cold sides of the battery modules were cooled via direct contact with a "battery cold reservoir," which is a single box filled with cool water (**Figure 1**). Based

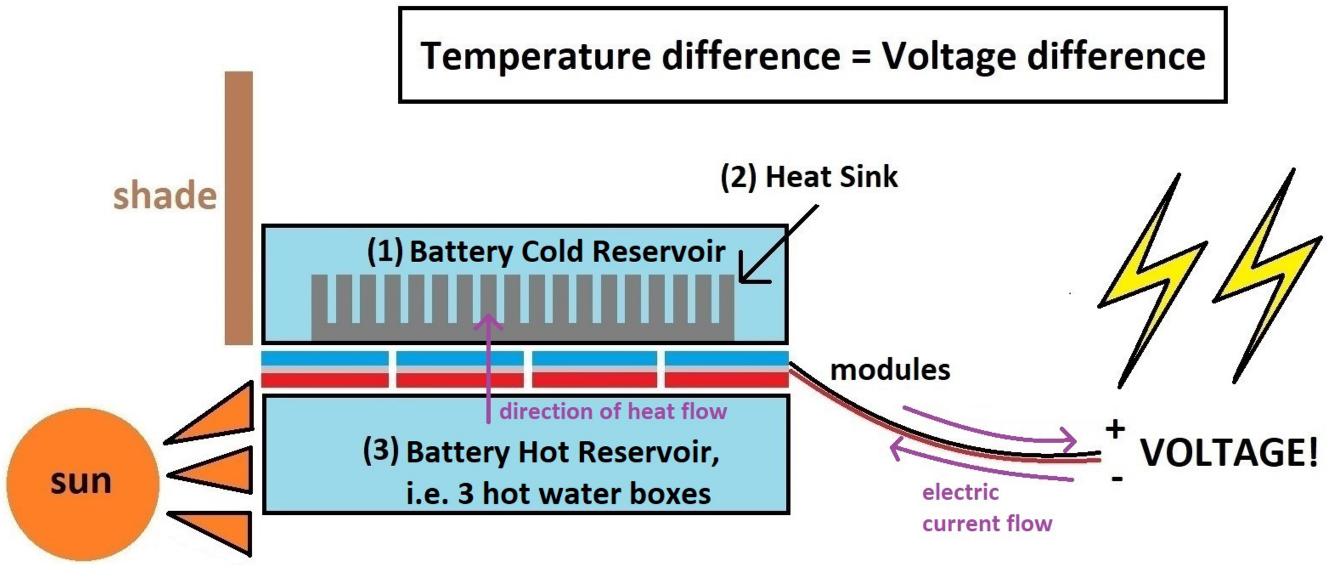

Figure 1. A battery was designed using 30 TEC1-12706 thermoelectric modules. A "battery hot reservoir", made of three "hot water boxes" filled with solar heated water, was placed below the hot sides of the battery modules. A "battery cold reservoir", made of a box filled with cool water, was placed on top of the cold sides of the battery modules. When the hot and cold sides of the battery modules are heated and cooled, respectively, the output of the battery modules develops a voltage.

on the Peltier Effect, we built a thermoelectric air conditioner using one module ("AC module"), where the cold side of the AC module absorbs ambient heat like an air conditioner.

We attempt to address two overarching questions: can the battery generate sufficient power for everyday household use, and can the thermoelectric air conditioner function as a smaller, cheaper (albeit less-efficient) air conditioner? For the first question, we hypothesized that the battery, using only solar heating, can generate more Watts per square inch than a current, commercially available solar panel, which generates approximately 0.10 Watt/in² regardless of make, model, panel size, or power rating. The reason we benchmark the performance of the battery against a solar panel is that a solar panel is the best competing green technology in terms of power generated per square inch, wide adoption, and ease of installation. For the second question, we hypothesized that the thermoelectric air conditioner can generate some cooling effect regardless of the voltage produced by the battery.

RESULTS

We designed an experiment and constructed prototypes to test the peak power output of the battery and the operability of the thermoelectric air conditioner. The battery prototype consists of a battery hot reservoir (i.e., three hot water boxes), a battery cold reservoir wrapped in pink insulation, and thirty battery modules sandwiched between them (**Figure 2**). Specifically, the battery hot reservoir sits atop the hot side of the battery modules. Similarly, the cold side of the battery modules sit atop the battery cold reservoir. The actual construction (**Figure 2**) closely resembles the original design (**Figure 1**). The thermoelectric air conditioner prototype (**Figure 3**) consists of the AC module mounted onto an aluminum heat sink that is embedded into an "AC cold reservoir." The AC cold reservoir holds water to cool the hot side of the AC module. The cold side of the AC module, which is facing the viewer, serves as a simple air conditioner by absorbing heat from the ambient environment. To create the finished product, we wired the battery in parallel to the AC module.

In the experiment, the battery hot reservoir absorbed enough solar thermal heat (while the ambient temperature was 35ºC) to create a temperature on the hot side of the battery modules of $T_{h,\ battery}$ = 67.50ºC. We poured water into both the AC cold reservoir and the battery cold reservoir

Figure 2. This figure depicts the battery after it was fully constructed. Three hot water boxes, wrapped on all sides except the bottom with bubble wrap, was placed on top of the hot sides of the battery modules. The bubble wrap allowed the hot water boxes to trap heat, which enabled the hot water boxes to remain as hot as possible. A battery cold reservoir was placed below the cold sides of the battery modules. The pink insulation around the battery cold reservoir allowed the cool water inside to remain as cool as possible.

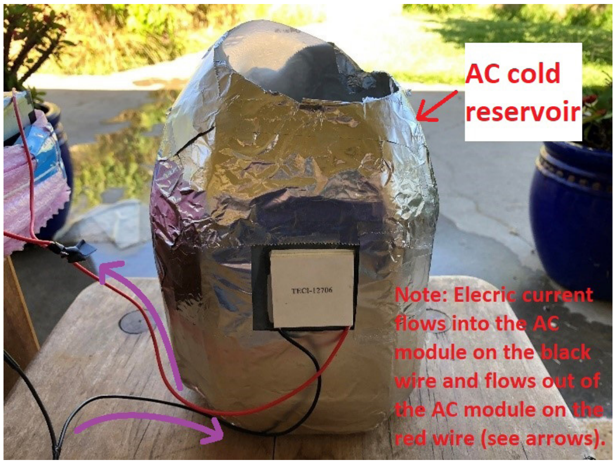

Figure 3. The thermoelectric air conditioner consisted of one TEC1-12706 thermoelectric module embedded in a milk jug. The hot side of the module, on which a heat sink was attached, faced inside the jug. The jug contained water that was used to cool the hot side of the module. Tin foil is wrapped around the jug to keep the water as cool as possible. When a voltage was applied between the black and red wires, the cold side of the module began absorbing heat from the environment.

• Calculate the voltage V_{AC} and current I_{AC} for the AC module (5):

$$\alpha = \frac{V_{max}}{T_{h,AC}\,(in\ Kelvin)} = \frac{14.4}{297.43} = 0.048415$$

$$V_{\alpha} = \alpha\Delta T_{AC} = (0.048415)(5.34) = 0.2585$$

$$I_{AC} = 2.5\ A\ (make\ an\ initial\ guess\ then\ iterate\ as\ needed)$$

$$V_{AC} = \alpha\Delta T + I_{AC}R = 0.2585 + (2.5)(1.98) = 5.2085\ V$$

Note: $T_{h,AC}$ is the hot side temperature of the AC module, and ΔT_{AC} is the temperature difference between the hot and cold sides of the AC module.

Check the manufacturer performance curve for $T_h \approx 25$ ºC. If ($\Delta T_{AC} = 5.34$ ºC, $I_{AC} = 2.5$ A, $V_{AC} = 5.2085$ Volts) does not exist, then repeat process with a new guess.

Figure 4. The battery's voltage and current can be calculated by understanding two electrical concepts: the voltage across the battery is equal to V_{AC}, the voltage across the AC module; and the current going into the battery is equal to I_{AC}, the current going into the AC module. In turn, VAC is equal to the sum of Vα, the voltage drop across the AC module necessary to create the thermoelectric effect, and $I_{AC}R$, the voltage drop across the AC module due to the parasitic resistance of the AC module.

such that the temperature of the hot side of the AC module, $T_{h,\ AC}$, and the temperature of the cold side of the battery modules, $T_{c,\ battery}$, were $T_{h,\ AC} = T_{c,\ battery} = 24.28$ºC. Therefore, the temperature difference between the cold and hot sides of the battery modules was $\Delta T_{Battery} = T_{h,\ battery} - T_{c,\ battery} = 67.50$ºC – 24.28ºC = 43.22ºC. This temperature difference activated the battery. The instant the battery became activated, we took temperature reads of the cold side of the AC module, $T_{c,\ AC}$: the initial temperature was 24.28ºC, which was the same as the temperature of the water in the AC cold reservoir; the temperature then quickly dropped to a low of 18.94ºC. During this time, the value of $T_{h,\ AC}$ did not change appreciably due to the high heat capacity of water. Thus, the maximum temperature difference between the cold and hot sides of the AC module was $\Delta T_{AC} = T_{h,\ AC} - T_{c,\ AC} = 24.28$ºC – 18.94ºC = 5.34ºC. This result indicates that the battery could sufficiently power the AC module to create a cooling effect. The maximum cooling effect ($T_{c,\ AC} = 18.94$ºC or within half a degree) was achieved for roughly a dozen seconds before it slowly increased.

A strategy to calculate $P_{Battery}$ (the peak power output of the battery) is to calculate the power received by the AC module, P_{AC}. To calculate P_{AC}, we need to calculate the voltage V_{AC} and the current I_{AC} received by the AC module. To calculate V_{AC} and I_{AC}, we need to know two other values: V_{max}, which is the maximum voltage that can be applied to a TEC1-12706 module, and R, the internal resistance of the TEC1-12706 module. According to the manufacturer's specifications, a TEC1-12706 module has $V_{max} = 14.4$ Volts and R = 1.98 Ω when the hot side temperature is 25ºC (4). In the experiment, the hot side temperature of the AC module was $T_{h,\ AC} = 24.28$ºC, which is reasonably close to 25ºC. Therefore, we adopted the values $V_{max} = 14.4$ V and R = 1.98 Ω. Using the four values $T_{h,\ AC}$, ΔT_{AC}, V_{max}, and R, we can calculate V_{AC} and I_{AC} (5). The calculations revealed that the AC module received a voltage of $V_{AC} = 5.21$ V and a current of $I_{AC} = 2.5$ A (**Figure 4**). We verified the calculation by locating the three-dimensional coordinate – $\Delta T_{AC} = 5.34$ºC, $I_{AC} = 2.5$ A, $V_{AC} = 5.21$ V – on the manufacturer performance curve applicable to a module with a hot side temperature of approximately $T_{h,\ AC} \approx 25$ºC (4).

The power received by the AC module can now be calculated as $P_{AC} = V_{AC} {*} I_{AC}$ = (5.21 V)*(2.5 A) = 13.02 W. Consequently, the power generated by the battery, denoted as $P_{Battery}$, must have been at least 13.02 W (as some power would have been lost due to resistive heating in the wiring or sub-optimal impedance matching). We can also use a digital multimeter to measure the power produced by the battery; however, we decided to describe an analytical approach using the manufacturer datasheet. Finally, to make the result more useful, the value $P_{Battery}$ was normalized over the total surface area (104 in²) occupied by the battery modules to produce a power output of 0.125 W/in².

The experiment described above occurred when the outdoor temperature was 35ºC. We repeated the experiment with lower and higher outdoor temperatures (with all other variables constant) and yielded lower and higher power output, respectively. The three experiments yielded a power output of 0.097 W/in² at $\Delta T_{Battery} = 38.0$ºC, 0.125 W/in² at $\Delta T_{Battery} = 43.2$ºC, and 0.144 W/in² at $\Delta T_{Battery} = 46.8$ºC, which we then compared to the expected maximum output from a solar panel of approximately 0.100 W/in² (**Figure 5**). The results revealed that at temperature differences above $\Delta T_{Battery} \approx 38$ºC, the battery generated more power in W/in² than a current, commercially available solar panel at "Peak Sun."

DISCUSSION

Like with a solar panel, the actual power output of the battery depends on the amount of sunlight available. Assuming that the outdoor temperature is commensurate with the amount of sunlight, we believe that an outdoor temperature of 35ºC (95ºF) is representative of the amount of sunlight that can be regularly attained in peak season in a sunny area such as Southern California. Even if the outdoor temperature was less than 35ºC, this does not mean that a power output of 0.125 W/in² is unachievable. The power output of the battery can be augmented by using Fresnel lenses to concentrate sunlight or by applying selective absorptive paint on the battery hot reservoir (6). Another method to increase the power output of the battery is to replace the TEC modules with TEG modules, which are specially designed for power generation (7). As such, a normalized peak power output of 0.125 W/in² is deemed reasonable, especially when one considers that a solar panel is rated at "Peak Sun," i.e., a hypothetical situation that is approximately equal to a solar panel exposed to sunlight at noon time in the Equator.

In the experiment highlighted above, we used 30 TEC1-12706 modules and heat from the sun to create a temperature difference of $\Delta T_{Battery}$ = 43.22ºC, which allowed the modules to generate a peak power of 13.02 W or 0.434 W per module. Halloran, in 2012, used a heater to create a temperature difference across a TEC1-12706 module of ΔT = 44.9ºC and a power output of 0.55 W per module (8). John, in 2014, used waste heat from the back of a refrigerator to create a temperature difference across a TEC1-12706 module of ΔT = 41ºC and a power output of 0.40 W per module (9). Our literature review shows that the amount of power the battery generated in our setup is consistent with other reports but our use of solar thermal heating as the ultimate source of heat (and thus energy) is unique.

The experiment revealed two drawbacks with the existing design. First, the battery hot reservoir had to be exposed to sunlight for a couple hours to absorb enough solar thermal energy to achieve $T_{h,\ battery}$ = 67.50ºC. The lengthy time it took to thermally charge the battery hot reservoir is attributable to the considerable volume of water inside the reservoir. Thus, this issue can be resolved by simply replacing the battery hot reservoir with a thin sheet of copper coated in selective absorptive paint. Second, the temperature of the battery cold reservoir will inevitably increase with time, meaning that the power output of the battery will decrease with time. This issue can be resolved by replacing the battery cold reservoir with a copper water piping system, which will bring a continuous flow of new water to draw away heat.

The battery is very promising and future experiments should be completed. A possible experiment would be to use an arrangement of batteries, a buck-boost converter, and a power inverter to create a 120 V residential power system. The thermoelectric air conditioner, on the other hand, is less promising than the battery. The experiment showed that if a fan were to be installed, the thermoelectric air conditioner (at the battery peak power) would produce air with a temperature of 18.94ºC (66.1ºF). However, at the same time, the commercial air conditioner in the author's home blew out air with a temperature of 15ºC (59ºF). As a result, further investigation into using thermoelectric modules as air conditioners may not be warranted.

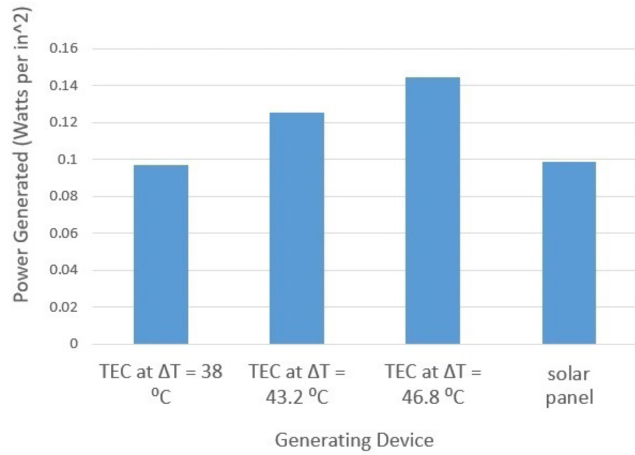

Figure 5. Three experiments were performed to determine the battery's power output in W/in² under different temperature conditions. The first three columns of the graph represent the results of the three experiments. TEC refers to the battery, which was made of 30 TEC1-12706 modules. ΔT (or $\Delta T_{Battery}$) refers to the temperature difference between the cold and hot sides of the battery. The experiments yielded a power output of 0.097 W/in² at $\Delta T_{Battery}$ = 38.0ºC, 0.125 W/in² at $\Delta T_{Battery}$ = 43.2ºC, and 0.144 W/in² at $\Delta T_{Battery}$ = 46.8ºC. These results compare favorably to the expected maximum output of a solar panel of approximately 0.100 W/in² as shown in the fourth column.

MATERIALS AND METHODS

Our battery design consisted of a battery cold reservoir, 30 battery modules, and a battery hot reservoir. The thermoelectric air conditioner consisted of an AC module and an AC cold reservoir.

The battery cold reservoir contained a heat sink that was embedded into the box. The heat sink was created by gluing together smaller heat sinks using epoxy. The frame of the battery cold reservoir was made of sheet metal (**Figure 6**). The ideal material is thin and thermally conductive, such as thin gauge aluminum or copper. The sheet metal was cut into the outline of a box. The sheet metal was then folded into a box. On the bottom of the battery cold reservoir, an opening was cut to mount the heat sink. The opening was sized perfectly so that the heat sink was able to fit in snugly (**Figure 7**). The heat sink was then secured using epoxy.

The 30 battery modules were wired in six parallel sets of five modules in series. This arrangement of modules had two benefits: it allowed for good impedance matching with the AC module, and it generated sufficient voltage to operate the AC module. Once the 30 battery modules were properly connected, the cold side of all the modules was taped to the

Figure 6. The frame for the battery cold reservoir was made of thin gauge aluminum. The frame was cut using tin shears and a Dremel tool.

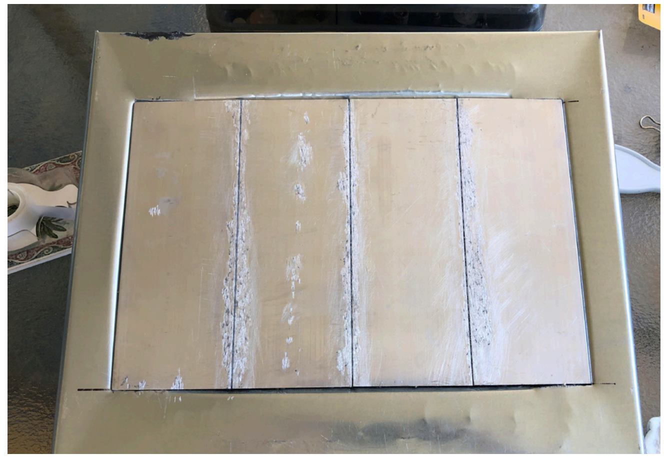

Figure 7. An opening was cut into the bottom of the battery cold reservoir to mount the heat sink. The opening was sized so enable a snug fit. The heat sink was then secured using epoxy.

battery cold reservoir using thermal conductive tape (**Figure 8**).

Because the modules were arranged in a pattern that produced three distinct rectangular areas (**Figure 8**), the battery hot reservoir was built using three hot water boxes, with each hot water box fitting exactly on one of the rectangular areas to maximize the surface contact with the hot side of the battery modules. Each hot water box was cut from thin aluminum or copper sheet metal, folded into a box, and then sealed using epoxy. To absorb solar thermal energy, the hot water box was colored black. To retain the absorbed solar thermal energy, the hot water boxes were covered in bubble wrap.

To complete the battery, the hot reservoir was placed on top of the battery (**Figure 2**). Effort was made to insulate the exposed surfaces of the battery cold reservoir as much as possible.

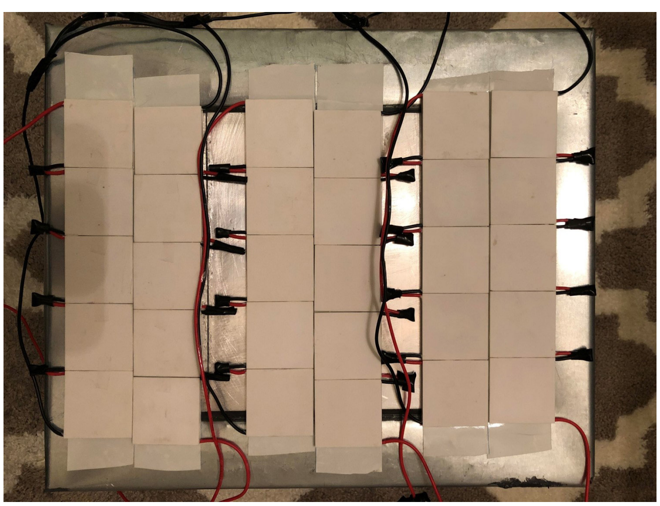

Figure 8. To make the battery, 30 TEC1-12706 thermoelectric modules were wired in six parallel sets of five in series. The modules were then attached to the battery cold reservoir using thermal conductive tape.

The thermoelectric air conditioner was made by mounting the AC module onto a small aluminum heat sink and then embedding that heat sink into the AC cold reservoir (**Figure 3**). The AC cold reservoir was then insulated to prevent the water in it from heating up. Finally, the battery was wired in parallel to the thermoelectric air conditioner.

ACKNOWLEDGEMENTS

The construction of the prototype was funded by the Spellman High Voltage Electronics Corporation as part of the 2020 Spellman High Voltage Clean Tech Competition Finals Event.

Received: September 2, 2020
Accepted: May 6, 2021
Published: July 6, 2021

REFERENCES

1. "Global Warming of 1.5°C: An IPCC Special Report on the impacts of global of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty." *Intergovernmental Panel on Climate Change*, https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf.
2. "The Future of Cooling." *International Energy Agency*, https://www.iea.org/reports/the-future-of-cooling.
3. "Thermoelectric Technical Reference." *Ferrotec*, https://thermal.ferrotec.com/technology/thermoelectric-reference-guide/thermalref11.
4. "Peltier Datasheet." *Hebei I.T. (Shanghai) Co. Ltd.*, https://

peltiermodules.com/peltier.datasheet/TEC1-12706.pdf.
5. Ajiwiguna, Tri Ayodha. "Method for thermoelectric cooler utilization using manufacturer's technical information." *AIP Conference Proceedings*, vol. 1941, no. 1, 2018, pp. 1-5.
6. "Sponge creates steam using ambient sunlight." *MIT News*, http://news.mit.edu/2016/sponge-creates-steam-using-ambient-sunlight-0822.
7. Tranggono, Alfi. "Study of effect comparison thermoelectric characteristics of TEC and TEG by considering the difference in temperature and variable resistance." *International Research Journal of Advanced Engineering and Science*, vol. 3, no. 4, 2018, pp. 225-228.
8. O'Halloran, Steven. "Power and efficiency measurement in a thermoelectric generator." *American Society for Engineering Education*, 2012, pp. 1-12.
9. John, T Stephen. "Highly efficient thermoelectric device for power system design and efficiency calculation: A review of potential household appliances." *International Journal of Computer Applications*, vol. 97, no. 18, 2014, pp. 37-42.