Examining Heat Recovery from Electric Light Bulbs Using Thermoelectric Generators

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Summary

In 2015, the US consumed about 400 billion kilowatt-hours (kWh) of electricity for lighting. According to the US Environmental Protection Agency (EPA), one third of the US energy consumption is wasted as heat. Light (solar) and vibration (piezoelectric) are common energy harvesting sources. Thermoelectric generators (TEGs), based on the Seebeck effect, have the capability to generate electricity from temperature differences. This study evaluates the feasibility of using TEGs by utilizing the thermal gradient of a household light bulb with ambient air as a viable source of energy. Initial results using TEGs with a Light Emitting Diode (LED) bulb shows up to 0.9 mW of harvestable energy. The experiments show that a better heat-sink enhanced setup can maximize the thermal gradient across both sides of the TEG, resulting in a ninefold increase in the energy efficiency to 8.3 mW. Finally, a 3D-printed TEG model, custom designed to fit conventional electric bulbs, demonstrates the promise of the proposed solution. Every bit of energy-recycling matters. The impact of using TEG-enabled light bulbs throughout millions of households will greatly benefit the lives of many by encouraging energy recycling and reducing the amount of fossil fuels being consumed.

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Introduction

According to Environmental Protection Agency (EPA), over one third of produced energy is wasted as heat (12). In 2016, the USA spent one billion dollars in order to purchase two billion light bulbs (12). Each of these light bulbs can reach temperatures well over 90˚C (1). Light emitting diode (LED) bulbs are more popular than incandescent bulbs because they are more energy efficient, but even LED lamps can reach temperatures over 70˚C (1). **Figure 1a** shows a simulated thermal profile of an LED bulb with the temperature map (1). The average American home is also stated to have approximately 40 light bulbs (11). With many bulbs being used throughout the world, a large fraction of the generated heat is wasted. The thought of recycling even a small portion of this excess heat is exciting and the recycled energy could potentially be used to power several house-hold electronic devices.

Thermoelectric generators (TEGs) produce a voltage due to a difference in temperature known as a thermal gradient. The larger the difference in temperature across the two sides of a TEG module, the larger the amount of energy generated (2). A thermoelectric module requires a pair of dissimilar pieces of metal, or positively (p-type) and negatively (n-type) doped semiconductors (2). The semiconductor pellets inside a TEG are serially linked together like a chain so the most power can be extracted as shown in **Figure 1b**. The Seebeck effect occurs when there is a temperature gradient across both sides of a TEG. Inside a TEG, the p-type elements carry positive charges while the n-type elements carry negative charges. When one side is heated and the other side is cooled, the p-type and n-type elements in the TEG will become active and will cross the electric field between each other, causing a current to flow and creating a potential or a voltage difference. A voltmeter connected to a TEG shows that a small voltage is produced as soon as the TEG surface makes contact with skin, just from the body heat as shown in **Figure 1c**. This energy can be consumed instantly or stored in a battery or super capacitor for later use.

Thermoelectric generators can also run in reverse. If electricity is provided, the TEG will be able to produce heat or cold. As a result of the Peltier effect, when a current is passed through two different materials, heat is absorbed at one end of the junction and released at the other (3). This will cause one side to be cold and the other to be warm (3). It was not until the year 1855, that William Thomson found a connection between the Seebeck and Peltier effects. He discovered that if a metal rod is heated on one end and cooled on the other, there will be a temperature gradient along the rod. He stated that the power from Peltier heat is proportional to the current (I), time (t), and temperature drop (T2-T1) along the length of a material rod. Lastly, he stated that as long as there is a temperature gradient along the rod, there will always be a current flowing with it. This is known as the Thomson coefficient (4).

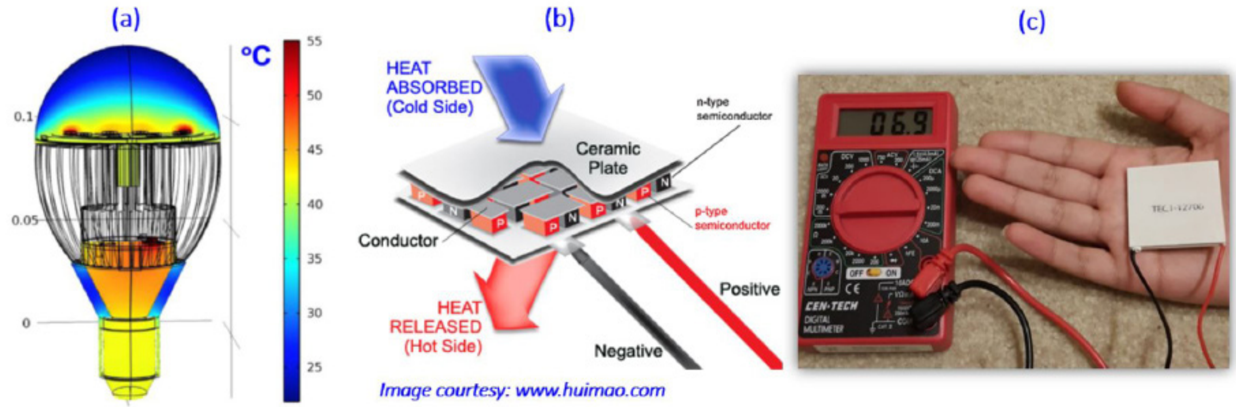

Figure 1. LED Bulb and TEG Module. (a) Simulated thermal image of an LED light bulb from prior work (1). (b) Cross-section of a semi-conductor TEG module and (c) a small voltage (6.9 mV) is produced as soon as the surface of the TEG module makes contact with the author's palm, as measured using a digital multimeter.

Remote thermal measurement was a key requirement for our experiments. When using TEGs, a simple and more accurate way to measure temperature without a thermometer is with an infrared camera. An infrared (IR) camera is a device that can detect infrared energy (heat) and convert it into an electrical signal (7). The IR camera uses this electrical signal to produce an image and perform temperature calculations (7). A useful feature is that it does not need to touch the surface of the object to measure its temperature. Some IR cameras are equipped with a laser to measure the temperature more accurately. An IR camera contains an optical system that focuses the energy onto a special chip. This chip contains thousands of detector pixels arranged in a grid pattern. When the infrared energy is focused onto the detector chip, each pixel produces an electrical signal (8). The camera's processor takes the signal and uses it to create an image that shows the temperature of the object. The IR camera may also come with a trigger to allow the user to take thermal images of various objects for accurate temperature measurement and analysis.

We hypothesized that light bulbs produce waste heat in addition to radiance, and finite, but useful amounts of energy can be recovered. We further hypothesized that there is a direct correlation between the thermal gradient of a bulb with its environment, and the amount of energy recoverable using TEGs. A series of experiments were designed to test our hypotheses by asking the following key questions: (a) How hot do conventional light bulbs get and where is the hottest location? (b) Can we express the relationship between the bulb's thermal gradient and the amount of voltage produced by the TEG as a mathematical expression? (c) Can waste heat be recovered as energy, and if so, how much energy is practically harvestable? (d) How many TEGs can be accommodated in various topologies to recover the best voltage? (e) What TEG environmental conditions can maximize the harvested power? Lastly, (f) can electronics be realistically powered using the harvested energy?

Results

The first task was conducted to get an estimate for the amount of voltage generated by a single TEG module. The voltage across the terminals of a TEG module was measured when placed on its flat side on the experimenter's palm. **Figure 1c** shows a voltage reading of 6.9 millivolts (mV) across the TEG's terminals. We tried placing an ice-cube on one side of the TEG and noticed that the voltages increased. Our observations indicate that the voltage produced is typically in the low tens of mV. This voltage is too small to be directly consumed and must be increased prior to use. An LTC3108 is one possible commercially available voltage booster that can take a voltage input as low as 20 millivolts, and use its current to boost the voltage output up to 5 volts (V), compatible with common universal serial bus (USB) chargers (5). The LTC3108 is a direct current (DC) converter made for harvesting small amounts of power and amplifying low voltages (5). The LTC3108 can also be used to boost to various other common voltage levels. For instance, it can be used to boost voltages to 2.35 volts, 3.3 volts, 4.1 volts, and 5 volts. Although the LTC3108 is only 20% efficient, it is necessary to increase the overall output voltage to practical levels.

The first experiment performed was to understand the thermoelectric relationship between TEG temperature and the output voltage produced. We were curious to know if the trend was linear, non-linear or exponential in nature. To accomplish this, a thermal gradient across both sides of the TEG was created as shown in **Figure 2a.** A bar of frozen butter was used to cool one side of the TEG and a hair dryer was used to warm the other

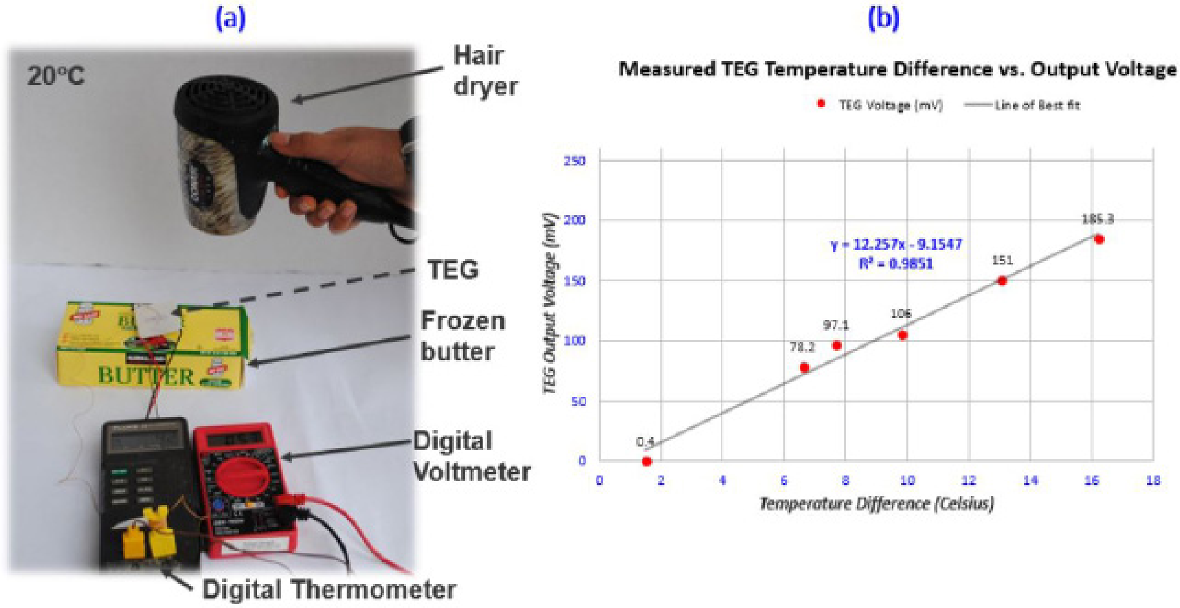

Figure 2. Temperature Difference vs. Output Voltage. (a) During the experiment, one side of the TEG was placed on a bar of frozen butter and the other side was heated with a hair dryer creating a thermal gradient. The ambient temperature of the room was 20˚C. (b) the relationship observed between the temperature difference of the two sides of the TEG module and the output voltage is approximately linear over the measured range.

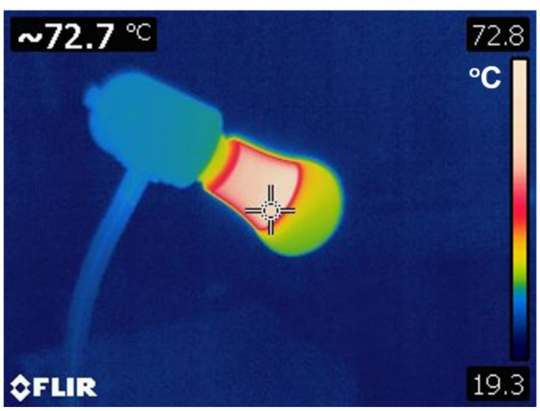

Figure 3. Thermal Image of a 10W LED Bulb. The thermal image, taken 30 minutes after light is turned on, shows the LED bulb base reaches the highest temperature of 72.7˚C.

side. A digital thermometer and voltmeter measures the temperature difference across both sides of the TEG and the output voltage over time. The graph in **Figure 2b** shows that the TEG output voltage increases from a few tens of millivolts (mV) to about two hundred mV, as the temperature gradient broadens. The data indicates that the trend has a positive correlation and is approximately linear with a measured slope of 12.26 mV/˚C across the measurement range. A single TEG produces an output voltage of 185 mV when the temperature gradient across the TEG is 16.2˚C. This recycled low TEG output voltage must be boosted prior to use.

The next experiment serves to better understand which portions of the bulb reach the highest temperatures and would be optimal for thermal energy harvesting. An infrared camera was used to thermally profile a conventional LED bulb. A common household 10W LED bulb was used for this purpose. The lamp was powered on for several minutes to allow the bulb to warm up and reach a steady-state temperature. A thermal image of the 10W LED bulb taken after 30 minutes is shown in **Figure 3.** The experiment shows that the LED bulb base reaches the highest temperature of over 72˚C. LED bulbs are known to be energy-efficient when compared to incandescent bulbs, but the thermal images indicate that they still generate substantial heat. This key data-driven observation motivated us to evaluate solutions to target the temperature difference of the bulb's base relative to its environment by using multiple TEG modules to harvest the excess thermal energy. The amount of output power P (measured in Watts) generated by the TEGs is calculated using the formula below, which is derived from Ohm's law:

$$P = V^2/R \quad \text{(Equation 1)}$$

Given the TEG output voltage (in volts, V) and resistance of the load (in ohms, R) connected to the TEG, we can calculate the generated output power. The energy output would be the power produced over a given interval (time).

The next phase of the experiment calculated the amount of output power harvested by TEGs from a typical light bulb. As shown in **Figure 4a-b,** four TEGs are secured (the maximum that would fit) around the base of an LED bulb using a rubber band. The TEG modules are electrically connected in series to allow the voltages to add up. A thermal image of the bulb with the TEGs (**Figure 4c**) taken after thirty minutes shows the lamp temperature reaching over 71˚C. The color bar from the thermal image in **Figure 4c** also shows that there is a temperature difference of 33.6˚C (71.3˚C-37.7˚C) between the two sides of the TEG module at the time of the measurement.

Discussion

During our research, we discovered information on finding the maximum power point (MPP) of a photovoltaic (PV) panel in order to optimize its efficiency at creating solar power (6). We were curious to learn if we could use this technique to locate the MPP for TEG-based energy harvesting, using Ohm's law and the power equation #1. A voltmeter and a variable resistor was connected to the TEG output and the resistance value slowly adjusted to start drawing a current from the TEG modules. At each step and at each resistance setting, the TEG output voltage (V) and resistance (R) values are recorded. The power generated from the TEG modules as a function of output voltage can be computed using equation #1 and the resulting plot is shown in **Figure 4d**, which shows the measured output power versus a variable load. The secondary Y-axis in the graph also shows the change in load resistance values for each measurement. An MPP is clearly detected when the resistance is set to an optimum value. At MPP, maximum power is extracted from the TEG modules. For this experiment, the MPP settled at a resistance of 22Ω, with the four TEGs regenerating 0.93 mW of power.

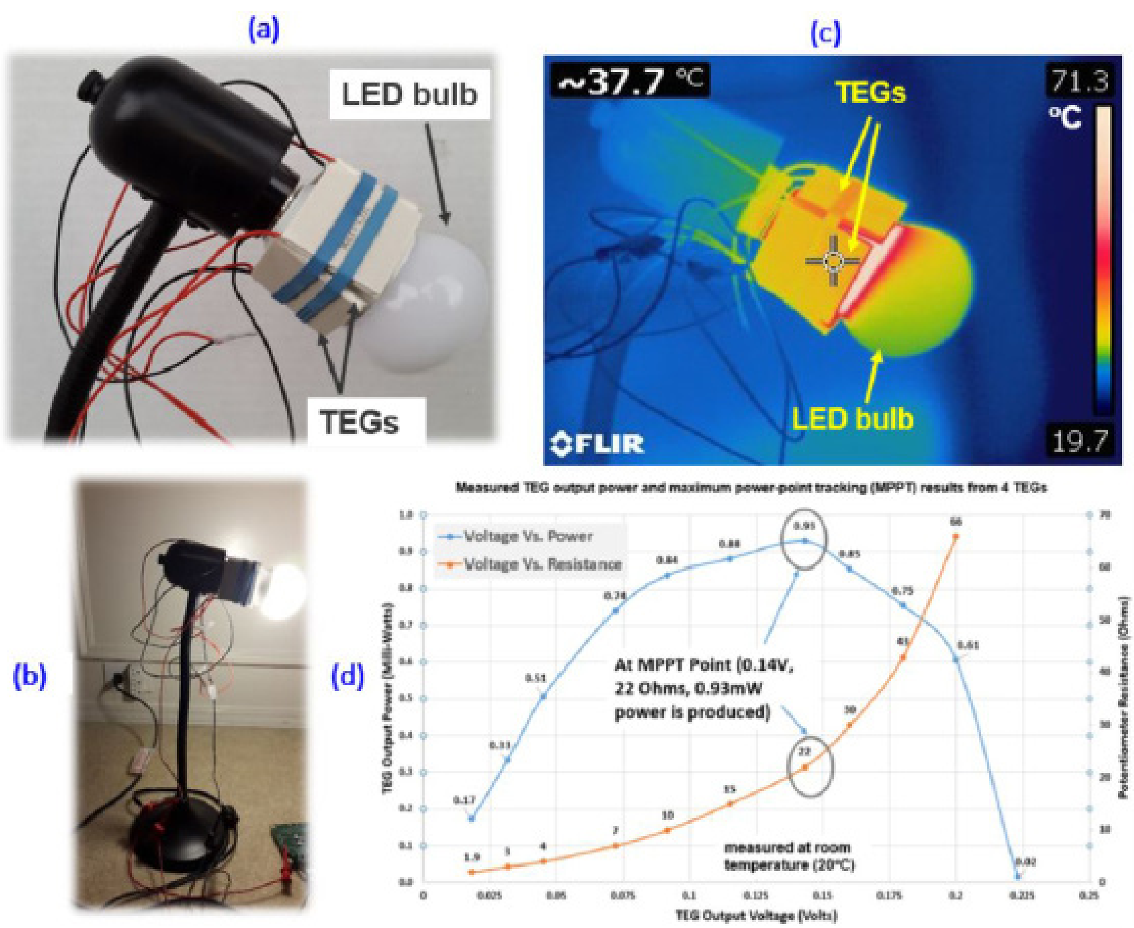

Figure 4. Maximum Power-Point Tracking. (a) Experiment setup with the 4 TEGs wrapped around the base of a 10W LED bulb (b) the experiment with bulb turned on (c) a thermal image taken with four TEGs mounted on the LED bulb and (d) the measured power curve shows that at MPP, almost 1 mW of power is regenerated by the four TEGs. The secondary Y axis plots the varying resistance values for each power point on the graph. At MPP, the optimum resistance is observed to be 22 ohms.

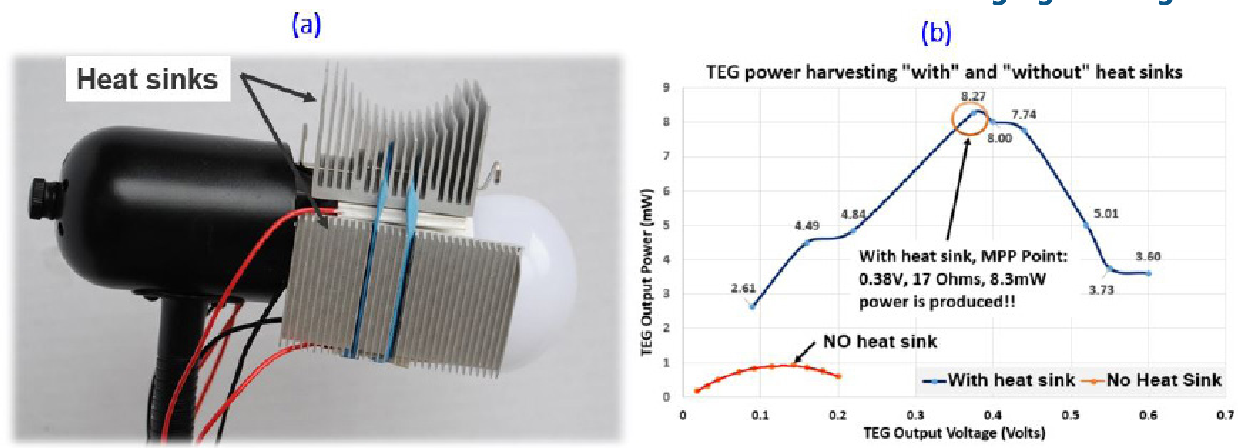

Figure 5. Output with and without Heat Sinks. (a) Experiment setup enhanced with four aluminum heat sinks and (b) the MPP measurement is again repeated after the heat sinks are applied. The graph compares the measured TEG output power with and without the heat sinks, indicating a maximum of 8.3 mW was generated at the MPP, due to better air cooling.

The data from **Figure 4d** was critical and led us to deduce that maximizing the thermal gradient across the two sides of the TEGs is key to recycling the most amount of energy. The role of heat sinks in computer equipment to cool the system is well known in the literature. Our intuition suggests that a good heat sink can potentially increase the energy produced and improve the overall efficiency of the system. We experimented with adding heat sinks to better expel heat and cool the TEG surface and were able to fit four aluminum heat sinks over the TEGs as shown in **Figure 5a**. The MPP measurement with a variable resistor was repeated again and the output power produced was recomputed. In this experiment, more power was generated, likely due to a better thermal gradient between the TEG heat sinks and the bulb. Thermal images confirmed that the heat sinks help disperse the heat across the TEGs surface better. The results from MPP, with and without the heat sinks, are displayed in **Figure 5b**. The data shows that over 8.3 mW of power is recycled by the enhanced heat-sink setup. This is a ninefold (9X) improvement in regenerated output power when compared to the original solution without heat sinks.

A voltage booster circuit (LTC3108) is used to enhance the voltage level and power electronic devices. The experimental setup is shown in **Figure 6a** and a block diagram of the setup is seen in **Figure 6b**. The TEG output wires connect to the input of the LTC3108 circuit, and a stopwatch was used as an electronic load, connected to the output terminals of the LTC3108 board. An image of the functional stopwatch without any batteries and powered completely from harvested TEG power is shown in **Figure 6c**. Charging other electronic devices like MP3 players and cell phones from the TEG source via the USB port proved to be less successful. It is clear that more power must be generated to successfully charge and operate higher power-consuming devices.

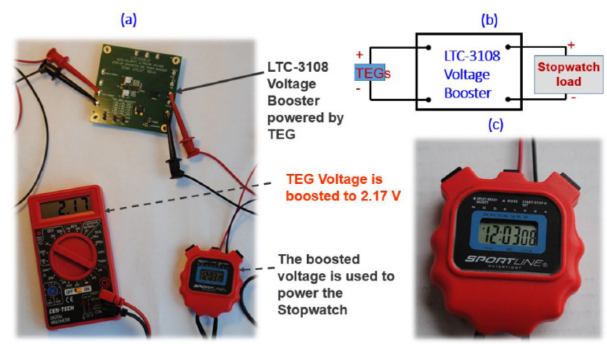

Figure 6. Experimental Setup. (a) The LTC3108 and stopwatch load were connected to the experimental TEG setup (b) diagram of the energy flow from the TEGs to the stopwatch and (c) the stop-watch worked solely from TEG power without any batteries.

While the initial "rubber band secured" experimental setup in **Figure 5** was successful in recovering heat, a more robust and practical design was necessary. We designed a three dimensional (3D) model of an integrated TEG energy harvester for light bulbs using a software known as Tinkercad (9). Tinkercad allows you to custom design 3D creations with a variety of tools using a computer. Using the software, we designed a sleeve for the base of a conventional bulb. As shown in **Figure 7a**, the tapered cylindrical sleeve is made with a TEG material along the inner lining. To further improve the cooling efficiency, additional external metal heat sinks (fins) were added to cool the outer surface. We measured the dimensions of an LED bulb to custom fit the bulb base accurately. To make this specific design using the software, we needed to take a cylinder and enlarge the top while shrinking the base to create a tapered cylinder. The base also needed to have an opening large enough to accommodate the bulb and fit the lamp base perfectly. The final 3D model dimensions (in millimeters)

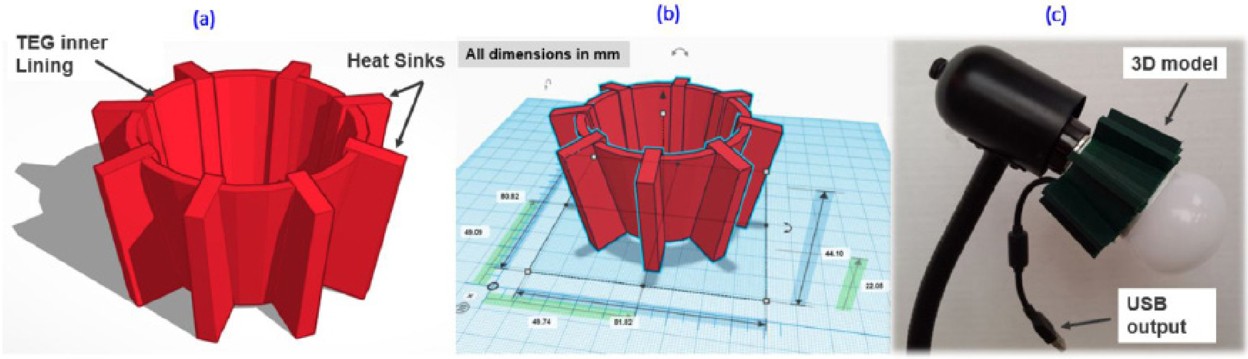

Figure 7. Energy Harvesting Lamp Sleeve. (a) Diagram of energy harvesting lamp base sleeve created using Tinkercad software, and (b) its dimensions highlighted, in mm. (c) 3D-printed model powering a 5V USB output cable to charge other devices.

are given in **Figure 7b**. A plastic 3D printed model in **Figure 7c** demonstrates the final concept, comprised of a semi-conductor TEG inner lining and an integrated, metal heat sink on the outer surface for efficient heat dissipation.

The average household has about 40 light bulbs (11). Assuming 10 of them are powered on at any time, about 80 mW of energy can be recycled. If TEGs are integrated directly into the base of the light bulbs, the energy harvested from multiple bulbs could be stored in a super capacitor for powering various devices. Several household electronic devices can possibly be powered with milli-watts of recycled energy. **Figure 8** summarizes the ranges of power consumed by various household electronics and electrical appliances and the range of devices that could be potentially powered by TEG recycled energy. For example, if 25 energy recycled bulbs were powered on, enough power would be regenerated to fully charge and operate a 200mW MP3 audio player without any batteries.

The discussions thus far are based on thermal energy harvesting of an energy-efficient, 10W LED light bulb. However, several non-LED (e.g. older filament based incandescent light and compact fluorescent) bulbs are still widely used. The observations from thermal imaging incandescent bulbs suggest that they do reach much higher temperatures (as compared to LED bulbs) and consume much more power. Naturally, for such non-LED bulbs, the potential to harvest the thermal energy would be greater.

Efficiencies for commercial TEGs are estimated in the 5-6% range (5). This is lower than solar panels, which average about 15-20% efficiency (5). Research is necessary to further improve the efficiencies of TEGs with new thermoelectric materials. In addition, reducing the cost of TEGs is necessary to enable global adoption and usage. A single 1.5 inch by 1.5 inch TEG currently costs several US dollars (5). Cheaper TEGs

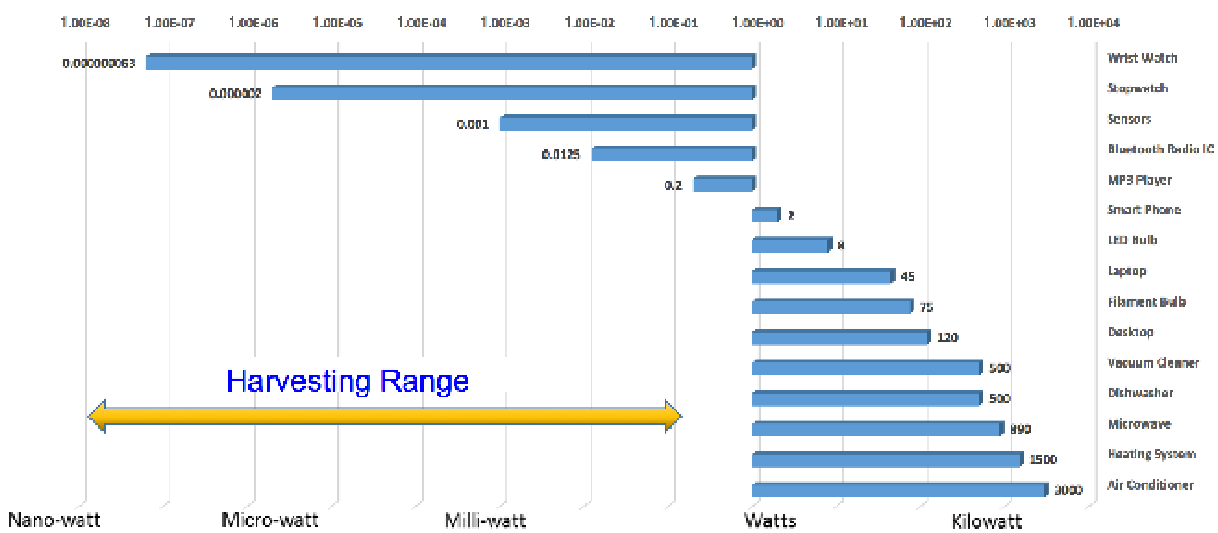

Figure 8. Power Consumption of Various Electronic Devices and Applicances. A range of household devices that can potentially be powered by the TEG devices.

are necessary to allow for wide-scale deployments in a cost-effective manner.

With billions of light bulbs being used around the world, TEGs show promise with recycling the large amount of excess waste heat. The above results confirm our original hypothesis that the thermal difference of an LED bulb (versus ambient air) can be used to generate a useable and sustainable source of energy. This work reveals that milli-watts of power can be successfully recycled, stored, and consumed in household environments. This can be sufficient to run low power electronic devices (including sensors) without any batteries. There are several suggested next steps to further improve on this work in the near future: (1) The TEG module cost must be lowered. It may be valuable to evaluate if TEGs can be built using cheaper, recycled scrap silicon. (2) Different materials inside the TEG could potentially increase its energy conversion efficiency. A promising semiconductor material could be Gallium Oxide (10) and (3) Better integration of the TEG, LTC-3018 and the heat sink directly into the ceramic base of an LED bulb. Bulb manufacturers could sell this as a complete solution. Over time, such a product would pay for itself using the recycled energy.

Over the last decade, the amount of energy used by the common household has increased by 33% from the year 2000 to 2014 (12). It is estimated that there are over two billion cellular phones on earth, with an additional 13% increase predicted this year (12). This increase in the number of electronic devices will add to the burden on the electricity grid. If this trend continues, then additional power plants must be built to meet the demand. Renewable sources like thermoelectric generators can be a key part of the solution to meet the growing consumer demand for power.

Methods

The following materials were used for the experiments: four commercially available semiconductor TEG (TEC1-12706) modules, one LTC3108 voltage booster board from Linear Technologies, an electronic measuring multi-meter instrument, a digital thermometer, a FLIR E60 thermal imaging infrared (IR) camera, a 10W LED bulb with a lamp socket, several aluminum heat sinks, one variable resistor (1-10K ohms), one 0.5 Farad super-capacitor to store the regenerated energy and a stopwatch for use as an electronic load.

The work was carried out over several steps with one experiment leading to the next procedure. The first step required securing the four TEGs around the base of an LED bulb (**Figure 4**); rubber bands were used for this purpose. Several mistakes were made initially with the series electrical connections and the team realized that it was important to ensure that all four TEGs were facing the same way (polarity) to allow the voltages to cumulatively add up. The bulb along with the TEGs is then inserted into a lamp socket and powered on. An infrared camera is used to thermally monitor the temperature of the bulb as it warmed up. We waited approximately thirty minutes to allow the LED bulb to reach a steady state temperature. The TEG's output was measured using a voltmeter. Various heat sink placement options were explored to better dissipate the heat on the TEG's external surface, thus enabling the TEG surface to stay cool (**Figure 5**). An electronic variable resistor was attached to the TEG output terminals for MPP measurements. To boost the TEG output voltage, we connected the output wires to the input of the LTC3108 (voltage booster), set to the desired output voltage using the adjustable jumpers on the board. A stopwatch was added to the output terminals on the LTC3108 as a load (**Figure 6**) to consume the recycled energy and confirm battery-less operation. An optional super capacitor or battery can be added to the setup to store any excess energy generated. Finally, a 3D model (**Figure 7**) of the custom TEG sleeve was designed using the Tinkercad software using a computer by carefully measuring the physical dimensions of the LED bulb base.

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