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# Small Scale Energy Harvesting Using Piezoelectric Tiles

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**ABSTRACT**

The increased reliance on the electric grid causes susceptibility to cyber attacks, power outages, and environmental impacts. Amidst these growing concerns, finding alternative energy harvesting sources that are sustainable is key to reducing dependency on the traditional grid infrastructure. This research explores detecting energy from piezoelectricity, an energy harvesting source, and sufficient energy is determined through whether a mini-LED lights up. A piezoelectric tile was developed to convert mechanical stress into electric voltage. By connecting the components to an Arduino Uno and programming it to read the voltage output ($V_O$) through Arduino IDE, a threshold was established for activating the LED based on the $V_O$. With the device, two experiments were conducted: the first analyzed the $V_O$ in response to increasing dumbbell weights applied to the tile's center, whereas the second focused on the effects of the displacement of a fixed weight away from the tile's center. The first experiment's results indicate a directly proportional, but logarithmic, relationship between the variables, with low standard deviations and error bars establishing high consistency in the data. Conversely, the weight's displacement and the $V_O$ maintain an exponential decay relationship, supported by similarly low variability in the data. While the device operates on a smaller scale, the fundamental ideas of piezoelectricity exhibited hold potential for larger-scale applications in the future if further research and materials are developed. Yet, the project showcases a possible pathway for reducing the demand on our grid and promoting sustainable energy harvesting solutions.

## INTRODUCTION

The power demand of America's electrical power grid is expected to rise substantially, while the capacity for power generation is struggling to keep pace with this anticipated electricity usage. For reference, the power grid in the U.S. generates 240 volts AC for each house, split into two 120-volt halves. The North American Electric Reliability Corporation (NERC) has voiced concerns about the stress on power systems due to increasing demand[1]. In simple terms, the NERC pointed out that these potential risks can be traced back to the escalating demand for electricity. On top of this increased demand, the power grid's effectiveness is determined by factors like weather, cyber vulnerabilities in transmission systems, and aging infrastructure. According to recent studies, extreme weather is the main cause of outages in the U.S., and efforts to modernize the grid have not been too successful yet[4]. Most importantly, excessive use of the grid would result in more frequent power outages.

Figure 1a builds on to this outcome as a NERC diagram illustrates the probability of whether the electrical grid will meet each state's power demands during the summer. Southern, central, and western states are at greater risk of not being able to meet their own summer energy demands. For example, Texas, a southern U.S. state, was the leading electricity-consuming state in 2022, consuming around 475 terawatt-hours of electricity[2]. The regions highlighted in orange represent the elevated potential for insufficient power reserves under heat, which causes power outages. The regions shaded in red show a high risk for power outages during the summer, while the areas shaded in gray represent sufficient power reserves. Lighting systems, however, are responsible for around 20% of the electricity use in the US residential areas, according to GSB Ganandran, TMI Mahlia, Hwai Chyuan Ong, B Rismanchi, and WT Chong. These researchers conducted a "cost-benefit analysis and emission reduction of energy efficient lighting" at the Universiti Tenaga Nasional. According to their study, since lights are widespread and often left running for extended periods, reducing their energy draw minutely can help decrease stress on local power infrastructure[3]. Solutions that target lighting systems, especially in high-traffic indoor environments, represent a scalable opportunity for supplemental energy generation.

To tackle this overuse of the power grid, researchers utilize energy harvesting tactics. (Discussed further in Discussion section 5.3). Energy harvesting is the process in which energy is captured from a system's environment and converted into a usable form of electrical energy. One major type of energy harvesting is piezoelectricity. There are two types of piezoelectricity: the direct effect and the converse effect. The direct piezoelectric effect is the electric charge that accumulates in certain solid materials, most notably crystals and ceramics, in response to applied mechanical stress[6]. The converse piezoelectric effect is the deformation of a crystal in response to an applied electric field, producing mechanical stress[7]. Figure 1b provides a diagram that demonstrates how both effects work on a molecular level. Both effects occur due to the asymmetric arrangement of atoms in piezoelectric materials. When subjected to pressure or vibration, the internal polarization of the atoms shifts, creating measurable electric charge across the material[7]. This spontaneous polarization of the atoms is a phenomenon where polarization appears without the application of an external electric field, as seen in Figure 1c. However, the direct piezoelectric effect is more useful for energy harvesting. Its responsiveness to small mechanical stress makes it a strong candidate for floor-based systems that rely on human motion. Since footsteps naturally create pressure, floor tiles with piezoelectric elements could create consistent low-voltage signals when in areas with high foot traffic.

However, the majority of this work has been applied to infrastructure like roads, where the mechanical energy input is very large and sporadic. Indoor applications, like stress coming from walking, have been less studied. Yet, these environments offer an opportunity to generate smaller but more frequent energy outputs that, if accumulated or stored efficiently, could be used to power simple systems such as low-energy LEDs or signaling devices. This paper demonstrates a prototype device that shows how a piezoelectric tile can generate voltage through mechanical stress. Rather than attempting to fully power lighting systems, the project shows that it is possible to produce detectable and usable voltage spikes under foot pressure, which could later be stored or conditioned for low-power applications.

While piezoelectricity has been studied and researched, its applicability to lighting systems is something that scientists are still comprehending and exploring. In this work, the device used a programmed threshold voltage of 2.5V to switch on a mini LED, which visually shows if sufficient voltage had been generated. This means that the LED was lit as long as pressure was exerted; however, pressure immediately decreases after the initial push, so the LED flickers out. The tile and its components were selected for their affordability and accessibility, but also due to a lack of ability to attain strong piezoelectric disks. The disks chosen were acoustic disks used in instruments, so they weren't as strong as needed for the scope and applicability of this project into the modern world. The Arduino was not powered by the piezo tile, but was externally powered to maintain accurate voltage readings and reliable control of the system. However, it had no influence powering the LED in any way, as that was solely lit based on the voltage accumulated from the piezoelectric tile. The Arduino read the analog signal from the boost converter, converted it through its built-in analog-to-digital converter, and displayed it on the LCD. The Arduino also stored the code and logic that the system used to determine if the sufficient voltage criteria was met to activate the LED.

To test the device's functionality, two experiments were conducted: one measuring how different weights affected the voltage generated, and another studying how the radial displacement of a weight affected the voltage generated. These experiments, while adjusted due to the short-scoped nature of this project, can demonstrate potential applicability in the real world given that there are stronger piezoelectric disks developed that produce more voltage based on the scenario of a human weight being applied.

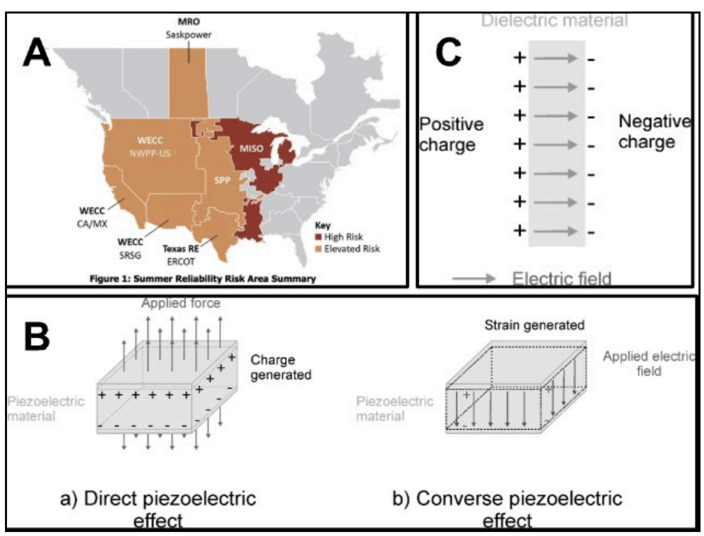

**Figure 1.** Introduction and Background Schematics. a) A NERC diagram showing the summer reliability risk levels of different states across the U.S. (can be used as long as it is cited)[1], b) a schematic of how the direct and converse piezoelectric effect functions[7], and c) a diagram of spontaneous polarization without an external electric field[7].

## MATERIALS AND METHODS

This section explores the engineering solution and prototype that was built, including the materials used and procedures developed. The materials section shows the device's hardware and software components.

### *Materials*

A list of the materials used in constructing the prototype is provided in Table 1.

**Table 1**. Prototype materials and corresponding information table.

| Material | Quantity | Price | Purpose |
|---|---|---|---|
| 27mm Piezo Amplifiers Discs with 13" Lead | 1 | $7.99 (for 15 pcs) | Converts pressure into tiny bursts of electricity (harvests energy). |
| Electrolytic Capacitor (470uF, 16v) | 1 | $16.99 (Assorted Pack) | Stores harvested energy in order to smooth voltage fluctuations. |
| XL6009 Boost Converter Module DC-DC | 1 | $9.49 (for 5 pcs) | Increases the harvested voltage to power the LED. |
| Breadboard (830 Tie-Points) | 1 | $8.99 (for 2 pcs) | Temporary platform to connect the components without soldering. |
| Jumper Wires | 20 | $5.99 (for 40 pcs) | Conducts electricity between the components on the breadboard. |
| Arduino Uno (Microcontroller) | 1 | $16.99 | Used for data logging (not powered by harvested energy). |
| 4.25 x 4.25 Inch Square Ceramic Tile | 1 | $15.99 (for 12 pcs) | Weight and footsteps are applied here; the piezo disk is attached in the center. |
| Resistor (220 ohms) | 1 | $5.99 (for 100 pcs) | Limits current flow and protects the LED from damage. |

| | | | |
|---|---|---|---|
| LED Light (Blue) | 1 | $11.99 (Assorted Pack) | Illuminates when enough harvested energy is available. |
| LCD1602 Module (with pin header) | 1 | $9.99 | To display the voltage readings more visibly to the user. |
| Multimeter (Optional, but Suggested) | 1 | $12.99 | Measures the voltage and current to ensure the circuit's functionality. |
| Arduino IDE (Version 2.3.2) | N/A | Free (Download) | Software environment for writing and uploading code to the Arduino. |

Hardware Build

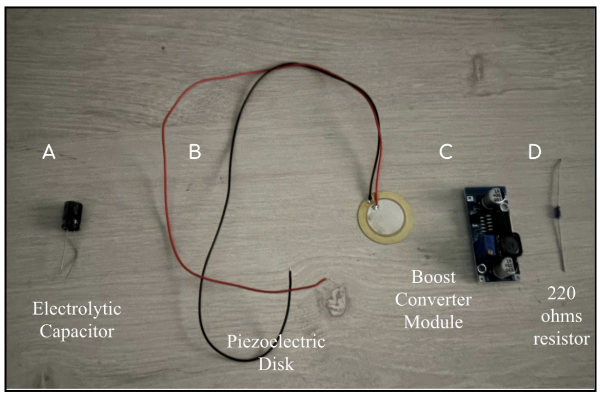


**Figure 2**. The Important Materials of the Prototype Device. a) Picture of one electrolytic capacitor (470uF, 16V is present), b) Picture of one piezoelectric disk, c) Picture of one DC-DC Boost Converter Module with adjustable output voltage, d) Picture of one 220-ohm resistor.

In this work, a device that harnessed the piezoelectric effect for energy harvesting applications, was created. The device used a piezoelectric tile that generated a small electrical voltage when exposed to mechanical stress. The applied mechanical stress was mostly in the form of vibrations. The primary hardware component of the device is the piezoelectric disk, which serves as the source of harvested energy. Another important component is the breadboard circuit, which consists of a low boost converter module (input 1-3 V, output 5 V), and an optional electrolytic capacitor that temporarily stores the voltage[9]. The circuit takes the feeble electrical charge from the tile and stores/converts it into a readable voltage that can be processed by the Arduino. The circuit also includes an LED light, which powers on if sufficient voltage is present. Furthermore, an LCD display is employed in order to visualize the voltage level of the storage element. This device allows for programmability, therefore alternative information regarding the harvested energy could be displayed. All the components were interconnected through jumper wires on a breadboard. An Arduino Uno microcontroller was utilized to power the device and manage the energy harvesting process by monitoring the individual voltage levels. Figure 3 depicts two diagrams that illustrate the hardware device that was built. Figure 3a shows a TinkerCAD sketch of the device. In Figure 3b, a picture of the device is shown with labels of the important hardware materials that were used in the construction of this device.

The piezoelectric disk used was a 27mm diameter disk (PZT-based, 3.2 kHz frequency), commonly available from manufacturers like TDK or CUI Devices[8]. This disk generates voltage from 0.1–3V under force. The boost converter used was a low-voltage DC-DC step-up module rated to start operation at ~0.9V and output up to 5V, assuming sufficient input current[10]. Although the boost converter was rated for low startup voltage, its ability to raise voltage from a piezo source was inconsistent. For most trials, the piezo output did not deliver enough current to fully utilize the converter. The 470 µF capacitor helped gain charge over ~2–3 seconds of compression before triggering the LED. This method provided enough current for brief load activation but not continuous power.

The full circuit schematic is shown in Figure 3. The piezoelectric disk was connected in parallel with a 470 µF capacitor to store initial voltage spikes, and the boost converter then processed all that voltage. The boost converter's output was connected to the analog pin A0 of the Arduino to convert the voltage from analog to digital, which the LCD can read. The blue LED was connected to a digital output pin (D9) with a 220-ohm resistor. The LCD display was wired to pins A4 and A5[11].

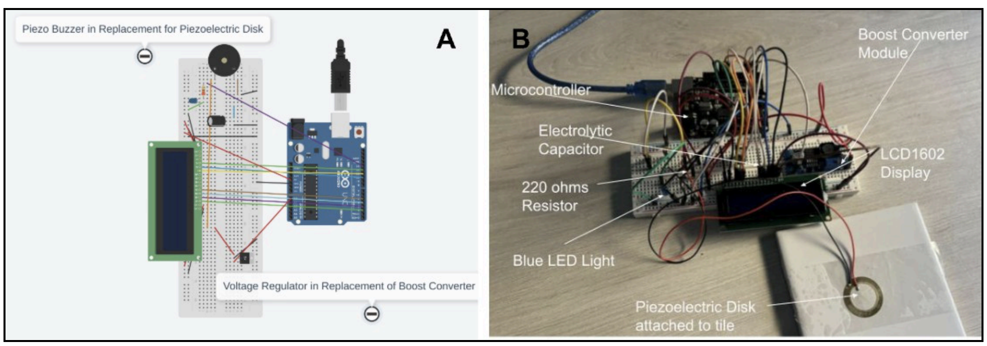


**Figure 3**. Engineering Hardware Components Diagrams. a) TinkerCAD schematic of the breadboard circuit attached to a microcontroller, b) picture of the finalized device with labels of each important hardware component.

## Software Code

In order to control the hardware components of the device, software code was written on Arduino IDE. This code controlled each component to ensure that the device operated correctly. The code focused on three important functions: data acquisition, data visualization, and a conditional statement to power the LED. First, in data acquisition, the code is engaged with the hardware by reading the voltage levels that are generated from the breadboard circuit. This process is connected through an analog pin on the Arduino. The code then utilizes the Arduino’s built-in Analog-to-Digital Converter to convert the analog voltage signal from the circuit into a digital value that the code can understand and process. The second key function is data visualization, where the code interfaces with an LCD connected to the Arduino using the LiquidCrystal library. It processes the digital voltage readings and converts them into a format that humans can read, which is the numerical system. The third function is the conditional statement to power up the LED, where the threshold voltage was set to 2.5V. Thus, if the circuit outputs greater than 2.5V, the LED lights up. Code is attached to this repository: Energy-Harvesting-Arduino-Code.

## *Methods*

Prior to the construction of the device, datasheets regarding each component were studied. This was completed to gain knowledge on how to connect each material to the breadboard and Arduino Uno. The overall cost for the materials needed to construct one device was around $56, making for an affordable prototype. The LCD, the LED (via a 220 Ω resistor), and the electrolytic capacitor were all connected to their default connections onto the Arduino, as demonstrated in their respective datasheets. Typically, a breadboard has two railings on both ends: the positive red power rail was connected to the 5V pin on the Arduino, and the negative blue power rail was connected to the ground pin of the Arduino. For this device, it was important to ground the breadboard for proper circuit operation because grounding creates a common reference point for voltage measurements in the circuit.

The Arduino and LCD were powered via external USB power (5V). They did not run off the harvested energy. The Arduino just read voltage from the boost converter, displayed the value on the LCD, and switched on the LED once a threshold voltage of 2.5V was reached. This threshold was programmed in software and was used solely for demonstration; this however does not suggest real lighting capability. To wire the device, the ground pin of the Arduino Uno was connected to the negative power rail on the breadboard to establish a common ground point. Notably, this device did not use the 5V power connection from the microcontroller, except for powering the LCD. The red wire of the piezo disk was connected to the VIN+ pin of the boost converter module using a jumper wire. Next, the black wire of the piezo disk was connected to the ground power railing on the breadboard. The VOUT+ pin on the boost converter module was connected to an analog pin on the Arduino Uno, and the VIN- pin on the boost converter module was connected to the ground power railing on the breadboard. Finally, the round piezo disk was taped onto the center of the small tile. A housing was constructed to contain the device.

After gaining familiarity with coding, the latest version of Arduino IDE was installed, and the LiquidCrystal library was downloaded for the LCD. Next, the LCD was encoded to visualize the collected information by: creating a LiquidCrystal object specifying pin connections; initializing the LCD with the lcd.begin function; using the *lcd.print* and *lcd.setCursor* functions for text display; and integrating voltage readings with *lcd.print(voltage)* for display.

After encoding the LCD, the *analogRead()* function, a built-in function in Arduino IDE, was used to get voltage readings from the boost converter output. The pin connected to the boost converter's output voltage was specified. This is important since the code reads the voltage at a specific pin (*A0*). Finally, a conditional statement was added using a threshold voltage of 2.5 V. This ensures the code controls the LED based on the voltage. The *digitalWrite()* function was used to illuminate the LED; this checks if the threshold is met and executes as planned.

To ensure the boost converter module was functioning properly, the circuit was powered, and a multimeter was used to measure the voltage difference across the module. This test ensured that less voltage entered the module and more voltage exited it. Additionally, this test guaranteed that the voltage did not exceed 5V, which is the maximum electric capacity of the Arduino. If the boost converter's output voltage exceeded 5V, a screwdriver was used to twist the adjustable resistor to calibrate the output voltage. If the output voltage was low, for example around 0V, then the adjustable resistor was also twisted slightly for calibration.

The system was designed to capture instantaneous moments of generated voltage, something that was not sustainable for a long period of time. The device executed no long-term energy storage or new discharges of energy loads. The lit LED is a binary indicator that the voltage has exceeded 2.5V, but it doesn't mean this can apply to real-life lighting power unless scaled appropriately. The Arduino ran once connected to a computer with appropriate code, and the LCD ran from a small amount of power generated by the Arduino.

## EXPERIMENTAL SETUP

Two experiments were conducted in this research study to address how the mass and displacement of a weight applied on a piezoelectric tile affect the voltage output. It was hypothesized that increasing weight would increase voltage output, while displacement of the weight from the tile's center would reduce voltage output. The energy input in each trial came from the placement of dumbbell weights onto the tile. Each trial had the weight placed firmly to mimic a footstep in the best way possible. The boost converter's input voltage ranged from 1.5V to 3.28V depending on weight and location. Output voltage reached up to 5V for a brief amount of time, as energy output was stored in the capacitor and not sustained. Voltage readings were collected through the Arduino's analog-to-digital converter. For each trial, the voltage that exited the sorted capacitor was recorded independently for observation of proper current flow, in case any electrical incidents occurred. Each condition was repeated ten times, and the highest peak voltage observed during each event was logged and averaged. Trials were spaced about 15 seconds apart to allow the capacitor to discharge fully between trials. This also meant that each test was reset back to 0V with no force applied, providing more accurate results for finding the voltage under those specific trials. In both experiments, the highest peak voltage reached during each trial was recorded from the LCD display. Additionally, both experiments saw the dumbbells being placed onto the tile from about a height of 0.40 meters. This height remained constant for each trail of each respective weight/distance.

The current output was measured using I = V / R (Ohm's law), where R was calculated using the base resistor value of 220 ohms when the LED turned on. Power was calculated using the peak voltage spikes, and energy was demonstrated through the used specific capacitor.

### *Experiment 1: Weight Vs. Voltage*

For the first experiment, the $V_O$ generated from the piezoelectric tile was tested by placing eight distinct dumbbell weights: 2 lbs, 5 lbs, 7 lbs, 10 lbs, 12 lbs, 15 lbs, 17.5 lbs, and 20 lbs dumbbells. The experiment's independent variable was the weight applied to the circuit. The dependent variable, on the other hand, was the voltage produced per weight. The dumbbell was positioned near the center of the piezoelectric tile and this placement remained constant throughout the trials. After powering the Arduino microcontroller, the device stabilized for 30 seconds before recording the data. The $V_O$ was displayed on the LCD, and the LED switched on if the threshold voltage was met. Each dumbbell weight was tested ten times to ensure consistency in the data collection. Following the testing trials, the averages and standard deviations were calculated for each of the eight weights. This helped visualize the data through bar graphs incorporating error bars. Using this data, the various electrical and physics formulas, discussed in the Results section, were used to determine the current, the power at specific voltage spikes, the energy stored in the capacitor, and mathematically proving efficiency and energy harvesting through the collected data.

### *Experiment 2: Displacement Vs. Voltage*

The second experiment examined how the displacement of a fixed weight from the center of the tile impacted the voltage generated. This study investigated the effect of varying radial displacement of a 7-lb weight on energy efficiency relative to the tile's center. The independent variable is the displacement distance (all distances from 0 cm to 6 cm), while the dependent variable is voltage produced, quantified through the $V_O$. A ruler was used to measure each placement. To collect data, seven equidistant points were marked along the radial axis, and a 7-lb weight was placed at each position across ten trials. After stabilizing the Arduino system, voltage readings were recorded from the LCD, and LED activation was observed. The results were analyzed using averages and standard deviations to assess data variability. Energy efficiency was computed using the Energy Efficiency Ratio. A contour plot, generated via Matplotlib in Python, further illustrated the relationship between radial displacement and the $V_O$. Considering the aim of the experiment was to explore how the distribution of the force affected the voltage from the piezo tile, it was important to consider and calculate the stress placed on the tile to correctly determine if there is a drop in pressure distribution applied across the tile. This was calculated based on the results and analysis of this experiment's data.

## RESULTS

As explained in the Experimental Setup section, two experiments were conducted. This section explores the results that were derived in each experiment and gives some commentary on the respective graphs and tables that showcase these results from the experiment.

### *Experiment 1: Weight Vs. Voltage*

This experiment studied how the weight of the dumbbell affects the voltage outputs. After conducting a series of tests, the following results were obtained, as summarized in Table 2. The results of this experiment illustrate that as the weight of the dumbbell increased, the voltage of the output also increased. In other words, the weight applied to the piezoelectric disk and the voltage produced are directly proportional while also logarithmic.

**Table 2**. Experiment 1 Data Collection and Analysis. The table displays the recorded voltage ($V_O$), their averages, standard deviations (σ), calculated efficiency (%), and current for eight dumbbell weights.

| Weight (lbs) | Trial 1 (V) | Trial 2 (V) | Trial 3 (V) | Trial 4 (V) | Trial 5 (V) | Trial 6 (V) | Trial 7 (V) | Trial 8 (V) | Trial 9 (V) | Trial 10 (V) | Avg. (V) | σ | Efficiency (%) | Current (mA) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 1.09 | 1.24 | 1.19 | 1.05 | 1.04 | 1.09 | 1.11 | 1.16 | 1.20 | 1.11 | 1.13 | 0.067 | 31.78 | 5.14 |
| 5 | 1.81 | 1.88 | 1.74 | 1.73 | 1.77 | 1.79 | 1.82 | 1.81 | 1.77 | 1.78 | 1.79 | 0.043 | 20.13 | 8.14 |
| 7 | 2.53 | 2.47 | 2.60 | 2.55 | 2.40 | 2.51 | 2.42 | 2.64 | 2.61 | 2.49 | 2.52 | 0.080 | 20.25 | 11.45 |
| 10 | 3.35 | 3.50 | 3.39 | 3.40 | 3.55 | 3.63 | 3.38 | 3.68 | 3.65 | 3.39 | 3.49 | 0.127 | 19.63 | 15.86 |
| 12 | 3.93 | 4.11 | 3.99 | 4.04 | 4.04 | 4.03 | 4.14 | 4.10 | 4.01 | 4.06 | 4.05 | 0.062 | 18.98 | 18.41 |
| 15 | 4.33 | 4.34 | 4.43 | 4.34 | 4.39 | 4.35 | 4.32 | 4.47 | 4.43 | 4.40 | 4.38 | 0.051 | 16.42 | 19.91 |
| 17.5 | 4.60 | 4.71 | 4.78 | 4.79 | 4.61 | 4.64 | 4.67 | 4.72 | 4.73 | 4.63 | 4.69 | 0.068 | 15.07 | 21.32 |
| 20 | 5.0 (max) | 5.0 max | 5.0 max | 4.95 | 4.97 | 5.0 (max) | 4.88 | 5.0 (max) | 5.0 (max) | 4.93 | 4.97 | 0.041 | 13.98 | 22.59 |

Table 2 illustrates the cumulative result of this experiment. On the left side of the table, there are eight rows for each weight used in the experiment. The next eleven columns next to the dumbbell weight shows the voltage outputs for all ten trials and the calculated average of each trial. In the following column, the standard deviations (σ) were calculated using the voltage collected for each dumbbell weight. The final two columns contain data regarding the efficiency and current flowing through the device for each dumbbell weight tested. These values were calculated using Equations 1 and 2, respectively. Finally, it was indicated whether the applied weight powered the LED light in the last column.

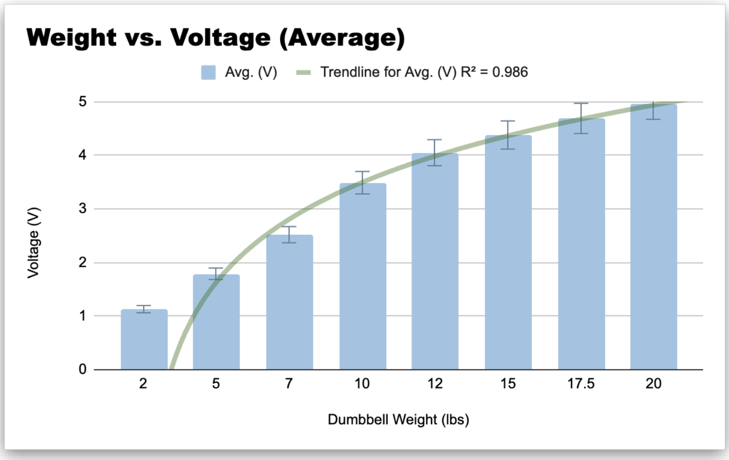


**Figure 4**. Bar Graphs w/ Error Bars. Error bars were attached to the averages using the standard deviations calculated for each weight.

Figure 4 presents a bar graph created using the data recorded in Table 2. The bar graph shows one bar for each dumbbell weight, which represents the average voltage produced at that specific weight. The error bars, implemented using the calculated standard deviations, illustrate how much variability is present in the data. A logarithmic trendline was created with the equation stated near the top of the figure.

Various qualitative observations regarding the functionality of the device were collected. First, the device required a few seconds to stabilize before providing the output voltage. The device also heated up every time a dumbbell weight was pressed on top of the disk; this may indicate that the device is taking on the extra electrical charge and processing it through each component before being read by the Arduino Uno microcontroller. It's also worth noting that the LED brightness is not dependent on the applied weight to the piezo tile. For example, a 15-lb dumbbell did not induce a brighter LED than a 10-lb dumbbell. Another observation was that a 10-second delay occurred between each voltage reading. This was intentionally designed in the device's programming in Arduino IDE, showing that the device is properly functioning. The LED light immediately switched on once the threshold was met, with no subsequent lag in between. And finally, the voltage stayed the same value for about 8-10 seconds after the weight was applied before going back to zero.

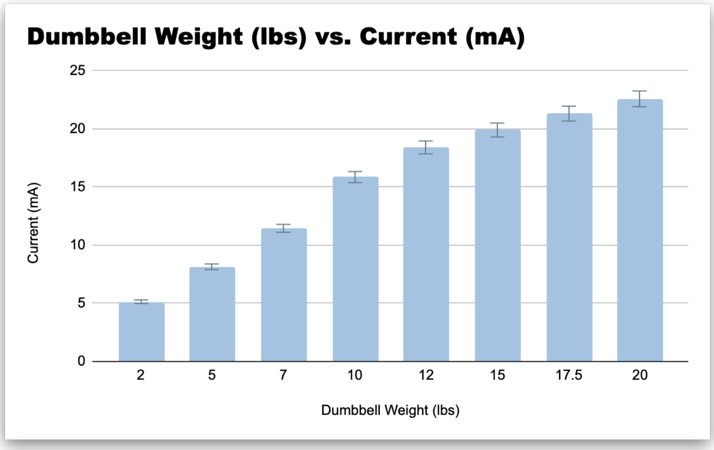


**Figure 5**. Current Bar Graph. Error bars were attached using standard deviations calculated in Table 2. The bars, and the attached error bars

Figure 5 showcases the current generated for increasing dumbbell weights. The weights increased from 2 lbs to 20 lbs, with a 2-3 lbs increment each time. The plot & error bars were created using Excel.

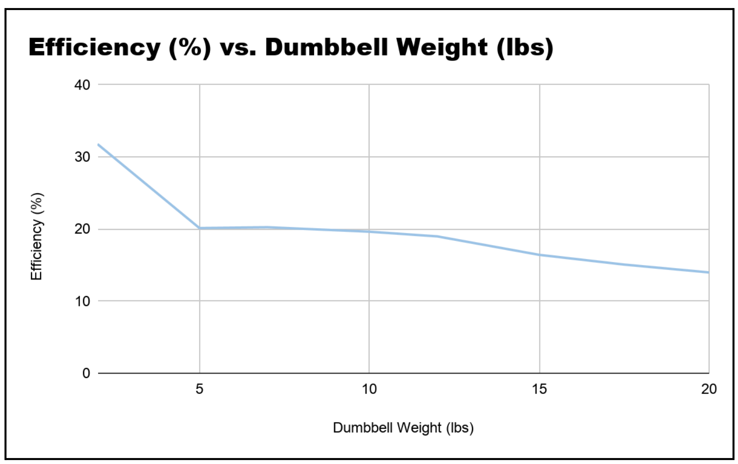


**Figure 6**. Line graph showing energy efficiency as a percentage for varying weights.

In Figure 6, the energy efficiency as a percentage is plotted in a line graph. Efficiency is measured by how many volts were needed to power the miniature light bulb, compared to the usual amount that gets generated from the Arduino to power that lightbulb (e.g., 2V in comparison to 5V). This efficiency matters because it helps track whether this device serves as a sustainable alternative energy source. Testing the efficiency throughout the different trials of the experiments informs us of the factors needed for this prototype device to function as initially intended.

**Equation 1**. Ohm's Law

$$I = \frac{V}{R}$$

The current was calculated using Ohm's Law (Equation 1), which states that the current is equal to the voltage divided by the resistance. The resistance of the circuit is 220 ohms – the resistor value.

**Equation 2.** Energy Efficiency Ratio

$$Efficiency = \frac{(Electrical\ Output)}{(Mechanical\ Input)} \times 100$$

The energy efficiency ratio (Equation 2) is defined as the electrical energy produced divided by the initial mechanical energy of the system, multiplied by 100[12]. The initial mechanical energy of the placed dumbbell was calculated using gravitational potential energy when placing the dumbbell, assuming that the system didn't transfer any energy during the conversion from potential to kinetic energy; this simplified calculations. The equation used to calculate the gravitational potential energy was: U = (mass) * (acceleration due to gravity) * (height displaced). The mass was calculated using kilograms, after converting lbs to kg, and height was measured in meters. The acceleration due to gravity is the constant g = 9.8 m/s$^2$. The electrical output was used by the average voltage produced from a particular dumbbell.

Other important equations when considering any possible practical applications for this work are energy density, energy storage, and power output.

**Equation 3**. Power Output (as a function of time)

$$P = \frac{V^2}{R}$$

Equation 3 states how power (P) is equal to voltage (V) squared divided by the resistance of the system (R), which is the resistor value. Results for the equation were collected in a similar manner to that of finding the current. Power duration looks at how long a generated voltage can sustain a device, which is important for applications that need continuous or time-specific functioning. Power output is measured in watts[13].

**Equation 4**. Equation of Energy Stored in a Capacitor

$$E = \frac{C * V^2}{2}$$

Equation 4 looks to relate stored energy (E) to voltage (V) and the capacitor's capacitance (C). The capacitance is a fixed value of 470 uF (or 4.7 x $10^{-4}$ F) as that was the type of capacitor used in the circuit, and the voltage is the average voltage of each weight tested. The energy storage calculations, through monitoring the size and discharge, ensure that short energy spikes are captured and utilized. It's also helpful in estimating  how much energy was generated for specific usage. While these energy calculation values are small, it can be a starting point for practical applications like lighting low-power LED lights or sending short-frequency signals, as long as it is scaled appropriately with more advanced technology. This also connects stress and electric displacement to real world energy performances. Both are explained further in the discussion. The amount of energy storage is measured in joules[14].

**Table 3**. Values of the Power Output and Energy Storage of the tested weights based on the equations stated before. Calculated using average voltage displayed in Table 2.

| | Power Output (watts) | Energy Storage (joules) |
|---|---|---|
| 2 lbs | $5.8 \times 10^{-3}$ | $1.022 \times 10^{-5}$ |
| 5 lbs | $1.5 \times 10^{-2}$ | $2.563 \times 10^{-5}$ |
| 7 lbs | $2.9 \times 10^{-2}$ | $5.080 \times 10^{-5}$ |
| 10 lbs | $5.5 \times 10^{-2}$ | $9.744 \times 10^{-5}$ |
| 12 lbs | $7.5 \times 10^{-2}$ | $1.312 \times 10^{-4}$ |
| 15 lbs | $8.7 \times 10^{-2}$ | $1.535 \times 10^{-4}$ |
| 17.5 lbs | 0.10 | $1.760 \times 10^{-4}$ |
| 20 lbs | 0.11 | $1.976 \times 10^{-4}$ |

Without scaling these factors, it would be difficult to determine whether the system contributes to a lighting system or sensor detection when walking on the tiles. The light bulb's effectiveness cannot be determined without meeting those criteria first, which indicates to users how much respective steps they need to take to effectively power the system.

### *Experiment 2: Displacement Vs. Voltage*

The experimental results supported the hypothesis, as an inversely proportional relationship between the weight's displacement on the tile and the voltage produced was observed. This means that as the 7-lb dumbbell moves further from the center of the disk, the voltage decreases. It was also noticed that the voltage produced from 6 cm away is relatively close to the voltage produced from 4 cm away.

**Table 4**. Experiment 2 Data Collection and Analysis. The table displays the recorded voltage outputs ($V_O$), their averages, standard deviations (σ), and efficiency (%) for different weight displacements from the tile's center.

| **Weight Placement (cm)** | **Trial 1 (V)** | **Trial 2 (V)** | **Trial 3 (V)** | **Trial 4 (V)** | **Trial 5 (V)** | **Trial 6 (V)** | **Trial 7 (V)** | **Trial 8 (V)** | **Trial 9 (V)** | **Trial 10 (V)** | **Avg. (V)** | *σ* | **Efficiency (%)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 (Tile's Center) | 2.53 | 2.47 | 2.60 | 2.55 | 2.40 | 2.51 | 2.42 | 2.64 | 2.61 | 2.49 | 2.52 | 0.080 | 20.25 |
| 1 | 2.01 | 1.97 | 1.99 | 2.21 | 2.23 | 2.18 | 2.09 | 1.94 | 1.90 | 2.11 | 2.06 | 0.118 | 16.55 |
| 2 | 1.65 | 1.68 | 1.60 | 1.66 | 1.54 | 1.70 | 1.73 | 1.68 | 1.72 | 1.59 | 1.66 | 0.061 | 13.34 |
| 3 | 1.44 | 1.47 | 1.50 | 1.30 | 1.46 | 1.51 | 1.39 | 1.35 | 1.38 | 1.46 | 1.43 | 0.068 | 11.49 |
| 4 | 1.28 | 1.24 | 1.29 | 1.27 | 1.30 | 1.19 | 1.17 | 1.21 | 1.24 | 1.17 | 1.24 | 0.049 | 9.96 |
| 5 | 1.16 | 1.16 | 1.17 | 1.14 | 1.13 | 1.10 | 1.09 | 1.12 | 1.10 | 1.15 | 1.13 | 0.029 | 9.08 |
| 6 (Edge of Tile) | 0.96 | 0.94 | 1.03 | 0.80 | 0.88 | 1.02 | 1.07 | 1.01 | 0.83 | 0.90 | 0.94 | 0.090 | 7.55 |

Table 4 focused on how the weight placement (in cm) away from the tile's center affected the voltage produced. There are seven rows under the independent variable column, each representing a different measured distance used to test the device. On the right, the voltage output for a specific distance was displayed. Ten trials were collected for each distance, and the average voltage from those ten trials was presented. The results for 0 cm away used the same data collected during Experiment 1 when testing how a 7-lb dumbbell applied in the center of the tile affects the voltage produced. The standard deviation was also collected in this experiment. Similarly to Experiment 1, the Efficiency of Energy (as a percentage) was also collected. The calculations also involved using the averages from each placement of the 7-lb dumbbell.

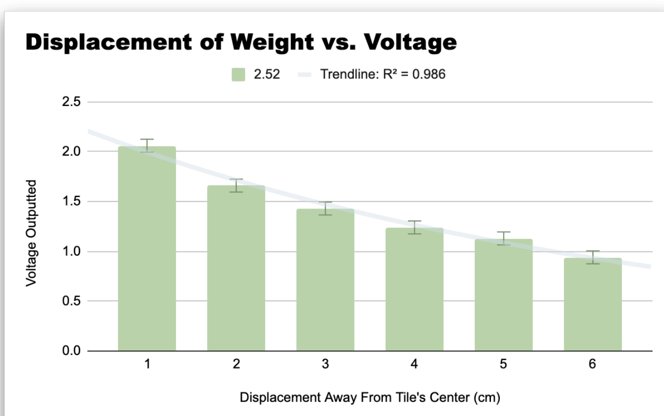


**Figure 7**. Bar graph showing voltage output for varying weight displacements. Error bars represent standard deviations.

Figure 7 showcases a bar graph created using the data recorded in Table 4. There is one bar for each dumbbell displacement, which represents the average voltage in that particular area. The bars represent the average voltage output of that particular weight based on all the ten trials. Error bars were attached to the bar for each displacement, using the standard deviation collected from the table.

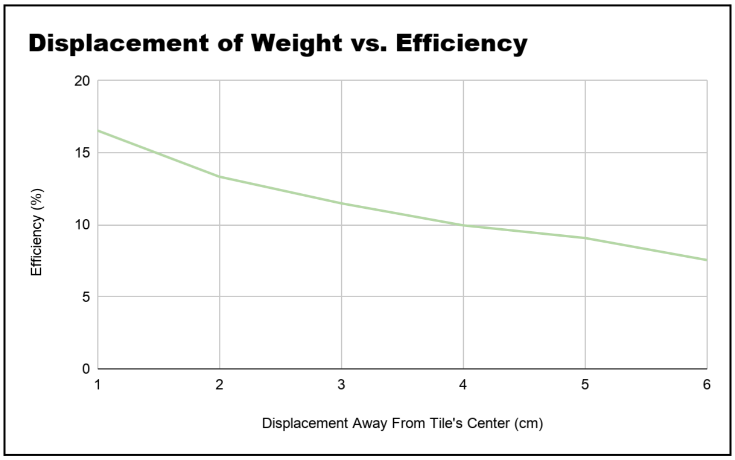


**Figure 8**. Line graph showing energy efficiency as a percentage for varying weight displacements.

Figure 8 explores the energy efficiency as the dumbbell is placed further away from the center of the tile. The efficiency of energy is calculated and plotted in the form of a line graph. The energy efficiency (as a percentage) used the same ratio shown in Equation 2. The line graph was created using Microsoft Excel.

In this experiment, qualitative observations were also collected. When the dumbbell was placed 6 cm away, more vibrations were produced. This may have caused the data to generate a somewhat close voltage to the 4 cm away mark (the other distances did not output as many vibrations). This may not be applicable in a real world scenario because tiles are usually glued together, and not individually sticking out. The device also took a few seconds to stabilize before giving the expected voltage. The device did not heat up like in Experiment 1 when the weights were placed at different distances from the tile's center. Like the first experiment, a 10-second delay occurred between voltage readings, as programmed in the code, and the voltage also remained the same value for about 8-10 seconds after the weight was placed, despite whether the weight was still placed or not.

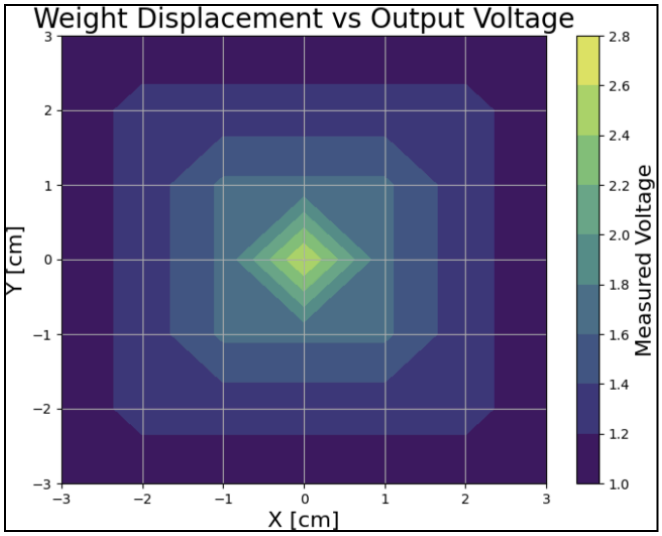


**Figure 9**. Contour plot showing voltage output for varying weight displacements. Lighter colors indicate higher voltage output closer to the tile's center.

Figure 9 shows a contour plot, which visualizes how the different displacements of the dumbbell from the center of the tile affect the output voltage. The x-axis and y-axis represent the tile's dimensions in centimeters. On the other hand, the z-axis, or the colormap sidebar, tracks the measured voltage of a particular radius inside the tile's dimensions. A lighter-colored area insinuates a higher voltage produced, whereas a darker-shaded area indicates a smaller voltage.

## DISCUSSION

Following the conducted experiments, a thorough statistical analysis was conducted to determine the validity and reliability of the findings produced in this research. The qualitative/quantitative analysis, for both experiments, is key to making it clear on what the importance of both experiments are, which develops into the overall importance of the research itself. It also explores how it compares to previous theories developed based on the used equations. This is also important in helping potential future researchers build on this work, demonstrating experiment reproducibility. It ultimately sheds light on how this project is applicable in the real world.

### *Experiment 1: Weight Vs. Voltage*

As seen in Table 2 and Figure 4, the weight applied and the output voltage ($V_O$) are directly proportional. One error that could influence the results is the placement and applied force of the weight, as human error may cause one to exert more force on the dumbbell, as well as slightly displace the dumbbell away from the exact center of the tile, which could potentially affect the voltage readings. Another variable that could have affected the results is the tape used to attach the piezoelectric disk to the tile. The tape may have generated a small voltage in the disk due to the slight force applied when attaching it to the center of the tile.

An interesting trend was that the average $V_O$ of the 10-lb dumbbell was 1.95x the $V_O$ from the 5-lb dumbbell, but the average $V_O$ of the 15-lb dumbbell was only 1.26x the $V_O$ from the 10-lb dumbbell. This demonstrates how the data resembles a logarithmic relationship, as a logarithmic curve fits the data shown in the graph. As the independent variable increases, the rate of change of the dependent variable decreases, while the function increases overall. The averages and standard deviations for each weight were calculated and then used to create error bars on the bar graphs. In this experiment, there was little variation in the standard deviations of all eight weights (as seen in Table 2), indicating that the data points were clustered around the averages; this implies that there is a high value of consistency in the data.

The error bars, calculated using the standard deviations of the data set, visually represent this minute variability. With this information, confidence levels can be built to determine a precise voltage based on a certain applied weight. For example, using a 10-lb dumbbell, there is a 95% confidence that the voltage will lie somewhere between 3.24 and 3.74V if other trials are conducted in a similar environment. Finally, the current was calculated to illustrate the optimization of electrical energy, as depicted in Figure 5. The data supports the conclusion that as the dumbbell weight increases, the current also increases. This is because the voltage output and the current are directly proportional, as supported in Equation 1. Since the weight applied and the voltage produced are directly proportional, the weight and the current should also be directly proportional. The results obtained show an acceptable amount of current flowing through the device, meaning that there will not be an overload of current or too little current that would cause the device to malfunction.

A logarithmic trendline was created to model what the theoretical values would look like based on previously established piezoelectric principles and equations (explained further in section 5.5). Based on this trend line, the main outlier in the data is when the 2-lbs dumbbell is applied, in which the expected output is around 0V. However, due to the possibly fragile nature of the piezoelectric disk, a mechanical stress may have more easily been induced upon being in contact with the 2-lbs dumbbell. The theoretical voltage values for other pressed dumbbell weights lie within range of the produced error bars (or very close to them), making those data points in line with theoretical foundations. The model is a demonstration of a concave down logarithmic function[16].

### *Experiment 2: Displacement Vs. Voltage*

The displacement of the weight (from the center of the tile) and the voltage output ($V_O$) are inversely proportional in this experiment. The experimental data resembles an exponential decay for increasing distances; for example, $\Delta V = \sim 0.9V$ between 0 cm and 2 cm, but $\Delta V = \sim 0.4V$ between 2 cm and 4 cm. Similarly to the first experiment, the exact position of the dumbbell can vary and therefore may have affected the voltage results. This is due to human error, as the dumbbell was placed at seven marked distances away from the center of the tile. However, not all the dumbbell placements can be precisely at the same location, creating variability in the data. The force applied to the dumbbell when placed on a specific part of the tile could also play a role in the differing voltage values, as previously explained.

The standard deviation is small for each distance, as visually indicated by the error bars in Figure 7. This represents a small variability and uncertainty regarding the measured data. With this knowledge, it was calculated that for a 95% confidence level, the $V_O$ from a 7-lb dumbbell placed 4 cm from the center lies between 1.14V and 1.34V; granted, if the experiment is conducted in a similar manner and environmental as done so in this research paper. The results of this experiment are demonstrated in a contour plot, as shown in Figure 9. The plot supports the results collected in this experiment, as it shows how the radii closer to the center of the tile have a higher voltage (indicated by lighter shading, representing a higher $V_O$). However, as the radius of the displaced weight moves farther from the center, the shaded color becomes darker, indicating a lower VO, as shown by the sidebar.

An exponential trendline was created as it best modeled the data, seen in Figure 7. The trendline of the data collected in the displacement experiment is the inverse function of the data collected in the weight experiment, which is fitting given that one experiment is directly proportional with voltage while the other is inversely proportional, so they are the inverse of one another. An exponential relationship demonstrates a greater decrease in voltage initially, but the rate of the decrease in voltage becomes smaller as displacement increases, modeling a concave up exponential function.

## FURTHER DISCUSSIONS

In both experiments, the energy efficiency (%) was collected using Equation 2. The efficiency calculated for both experiments reflected the overall nature of the experiment itself. Experiment 1 reveals a directly proportional and logarithmic relationship between the two measured variables, but the relationship between weight and efficiency leans more inversely proportional. Experiment 2's variables are inversely proportional, and this time, the efficiency also reflects this relationship. Both experiments ultimately demonstrate that an increase in either weight or distance will still result in decreasing levels of energy efficiency, something to keep in mind for further applications of the research. This project was a small-scale demonstration of an energy harvesting device, meaning more advanced technology may be needed if this idea were to address America's overloading grid crisis. However, it remains a good start in the right direction. Considering the average human weight of about 180 lbs and the potential for stronger piezo disks in the future, this project highlights the importance of piezoelectricity as an alternative energy source in various applications for society. Previous work has investigated using piezoelectricity in roads to power traffic signals[17][18]. Other works include using piezoelectric materials in cycling lanes to power biking lights during dark times[19], and also using Arduino Uno to create piezoelectric sensors for highways, bridges, and tunnels, which light up during the dark as well[20]. However, this work expands the principles of piezoelectricity by creating a demonstration of a custom piezoelectric floor tile for powering indoor lights, where some research has been similarly conducted[28]. While my work produced different quantitative results than conducted in those particular researches focusing on piezoelectric energy harvesting for lights, similar conclusions can be drawn.

While the voltage from one tile was tested in this experiment, a person will typically walk across a floor consisting of numerous tiles. This would mean more voltage coming from the collective set of tiles, as humans generally weigh enough to produce voltage upon walking across a set of tiles and place their feet near the center rather than the edges. These factors potentially provide enough voltage to power individual components. Thus, the device demonstrated that it could convert the weight applied to a piezoelectric tile to an acceptable output charge.

The research showcases the stability of the VO, indicating energy that can be harnessed for lighting systems. Society can adapt to this new methodology of harvesting power, as humans constantly walk on the ground.

## FUTURE OUTLOOK

After conducting and analyzing the experiments, several questions arise for further study:

- How does the surface material that the piezoelectric disk is attached to affect the VO?
- How does the walking pattern of a human affect the voltage produced?
- In a full-scale environment, will the $V_O$ affect the luminosity of the LED light bulb?
- How does the time to light up an LED differ based on the weight applied to a piezo tile?

## PIEZOELECTRIC PHYSICS

Piezoelectric energy generation can be described through electromechanical coupling, which is when mechanical forces interact with the electrical charge inside the material. This relationship can be modeled by the following two constitutive equation:

**Equation 5**. Piezoelectric Constitutive Equation 1: Strain of Material

$$S = (s^E * T) + (d * E)$$

Here, the equation measures how the mechanical strain of a piezoelectric material (S) is equal to the material's compliance to deform (sE) times its mechanical stress (T), plus the piezoelectric coefficient (d) times the electric field of the material (E)[21].

**Equation 6**. Piezoelectric Constitutive Equation 2: Electric Displacement of Material

$$D = (e^T * E) + (d * T)$$

Equation 6 models how the electric displacement (D) is equal to the permittivity ($e^T$) times electric field (E), plus the piezoelectric coefficient (d) times the mechanical stress (T)[21]. Electric displacement is how much charge is produced over an area, permittivity measures how the ability of a material to form electric fields within, and mechanical stress refers to the force per unit area applied to the material (Force / Area).

In the first conducted experiment, increasing the weight increased the stress because more force is being applied over the same amount of area[24]. This, through the piezoelectric coefficient, allowed the electric displacement to increase[22]. The charge was stored in the capacitor and was displayed as a voltage (through a digitalized Arduino conversion number) on the LCD. A logarithmic, not linear trend was observed, which means that as the weight increased, the applied stress created smaller increases in voltage values. This occurs because the domain from piezoelectric disk becomes saturated, meaning at higher applied forces, the domain's ability to realign and produce voltage charge slowly to levels off as increasing forces approach a constant value[27]. This is significant because the internal electric dipoles, which respond to mechanical stress, are free to align at lower stress levels (which produce stronger voltages) but at increased stress levels they get saturated due to most of the dipoles already being aligned. In the second experiment, when weight was placed away from the center, the pressure of the disk gets reduced, which leads to a smaller strain[23] and smaller electric displacement as a result of smaller electric field and mechanical stress values. And since voltage is reliant on the total produced charge (through D being proportional to d*T), the further displaced positions create weaker signals for the disk and subsequently produce weaker voltages.

The piezoelectric disk also exhibits hysteresis, or that the electrical response of the system isn't just dependent on the current stress applied to disk but also on how the disk was stressed in previous trials[25]. The cumulative stress from previous loads can cause fluctuations in the voltage output even when the same weight is used. In the experiment, the voltage values varied on a small scale, as marked by the smaller standard deviations and error bars, but may be increased if the scale of the experiment is also amplified. Hysteresis occurs due to function internally and a subsequent lag in how the dipoles of the material reshape themselves under different levels of stress. This could be why there were changes to voltage that varied by trial for a certain weight in the experiment.

It was also observed that the faster the weight was placed, the higher the voltage spikes were. The speed varied from trial to trial, which could also be the reason as to the fluctuating voltage values per each trial. This was the case even if the actual force applied remained the same. This is due to the strain rate dependence, or how the rate at which a material is being deformed affects its mechanical properties[26]. A rapidly changing stress, marked by the derivative dT/dt, conducts a stronger ephemeral electric field, which in turn increases the electric displacement. A stronger electric displacement generates slightly higher peak voltages.

## POTENTIAL SCALING

To demonstrate the effectiveness of how this device is in providing solutions to powering real-world devices, like an LED light, the system's output was compared to the typical energy demands of indoor lighting components. A 5mm white LED needs around 20 mA of current, with a voltage of ~ 3.1 V, so its total power consumption is at 60 mW or 0.05W. The data from the research demonstrates how ~0.11 W was produced from a 20-lbs of load, which was enough to power the single 5mm LED. However, since this output was mostly in spikes, a larger piezoelectric array or stronger disks with higher energy density and storage capacity are required for more sustained performance. Keeping a continuous 60 mW load in mind, the experimental setup must produce 60 mJ per second. However, the current energy storage for 20 lbs was $1.976 \times 10^{-4}$ W-h, or about 0.711 J, so it can power an LED at peak output for around 12 seconds. Therefore, 300-350 steps are needed in a current model for a regular appliance. Also, light bulbs usually consume about 9 watt-hours per hour, so about 45,000 steps are required in an hour to power internal light appliances. A single step needs to yield about 0.06 W-h, which is around 300x greater than what is currently offered. One would need high-strain multilayer piezoelectric actuators, mechanical amplifiers, or higher-efficiency materials such as single-crystal PMN-PT to achieve the energy requirements, but keeping in mind an average human weight being significantly greater than a dumbbell, those materials alone do not have extreme emphasis. Also, storing energy from footsteps in battery arrays with more capacity and using it for intermittent lighting (i.e. motion-sensing lights) can be a quicker and feasible approach in near-term usage.

## CONCLUSION

The objective of the study was to assess the energy-harvesting potential of a piezoelectric tile when subjected to increasing mechanical loads. The outcome of the first trial suggested a logarithmic relationship between the weight applied and the output voltage, rather than the linear relationship found in previous studies. The maximum weight applied to the piezo tile was 20 lbs; the tile had a mean voltage of 4.97 V and mean current of 22.59 mA, with a mean peak power output of 0.11 W. The energy harvested per step, $1.976\ 10^{-4}$ W-h, had an efficiency return which increased steadily through the trials in a cumulative manner to 13.98%. Overall this study demonstrates that piezoelectric tiles are capable of converting mechanical energy from a human body through motion (step) into an electrical output that can be measured; however in this study with diminishing returns at higher stress level/due to domain saturation of the piezo ceramic material.

A second experiment was conducted to see how the position of the applied force impacted voltage output. It was found that when weight was applied to the center of the tile (directly above the piezoelectric disk), the largest generated voltage output was created. If the same weight was placed toward the edge, there was a significant reduction in voltage indicating that the system has a high sensitivity to strain localization. Quantitatively, there were voltage drops of 30–40% due to this directional dependence depending on the distance of which the load was off set. This high sensitivity should be considered when designing real-world installations since foot traffic cannot be predicted in terms of location or positional displacement. Considering these results means that in order to maximize energy harvesting, multiple disks must be installed strategically or mechanical load could be distributed.

Piezoelectricity offers a promising alternative for small-scale energy harvesting. Though not enough to power an entire house, piezo disks can capture energy from vibrations or movement, and this harnessed energy can be used to power individual components. By harnessing small voltages from stress on tiles, enough energy can be generated to determine whether or not it can power individual lighting appliances, thus reducing our reliance on conventional energy sources. With further development by electrical engineers to optimize energy conversion, piezoelectric tiles could become a practical solution for buildings. Addressing energy harvesting and power transfer is critical, and this can inspire one to explore these challenges to make a meaningful impact.

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