Using Piezoelectricity to Create Energy From Sound Waves and Vibrations

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Introduction

The Energy Crisis

The energy crisis is a global issue driven by a multitude of factors, including population growth, overreliance on fossil fuels and poor energy infrastructure. Global energy demand is expected to grow steadily at a rate of 1.5% per year through 2040 (IEA, 2019). This steady increase in demand for energy leads to increasing costs of current resources to levels that cannot be met, and pressure to find new sources of energy.

One of the primary causes of the energy crisis is the overreliance on fossil fuels. Fossil fuels are limited in quantity, and their utilization has substantial indirect ecological consequences, resulting in intensified global warming. Further warming increases energy use eg. through increased air conditioning. The Intergovernmental Panel on Climate Change (IPCC) has stated that "it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century" (IPCC, 2014). This has led to calls for a transition to cleaner and renewable sources of energy, such as wind, solar, and hydroelectric power.

The energy crisis will also have significant implications for the world's economy. The rising prices in the energy market can potentially increase inflation and create a bubble in the industry that will eventually burst. Pushing for further regulation and innovation within the energy industry in order to combat the increasing prices is necessary for humans to beat this energy crisis. Advocating for further investment in combating the energy crisis could also help new economic opportunities and jobs that would have a positive impact on the world (WEF).

In order to address this energy crisis and reduce greenhouse gas emissions, it is necessary to develop new energy technologies that can help decrease our overreliance on fossil fuels. Researching and discovering new ways to produce clean energy is crucial in the fight against climate change. One reason that the transition to clean energy has been difficult is accessibility.

That accessibility problem comes in two parts, financial and logistical. For most clean energies, the cost to the consumer is greater than that of fossil fuels at this moment. However, as technology increases through development, the prices will decrease. In terms of logistical issues, not every country or community has the space for solar panels or wind turbines. Not every country has the capacity to install nuclear power plants to supplement their electricity requirements. But piezoelectricity has the potential to be implemented anywhere that there is consistent sound and vibrations. This requires new approaches to energy generation that allow people all over the world to reduce their carbon footprint.

The overall goal of our project is to explore the use of a novel technology to do just that: piezoelectricity. Piezoelectric material can generate an electric charge from mechanical stress. Mechanical stress that leads to piezoelectricity can come from various sources, including vibrations. When a piezoelectric material is subjected to a mechanical vibration, the material is compressed and released rapidly, causing a shift in the position of charged particles within the material (Cross, 1995). This project looks to create a piezoelectric device that converts sound waves generated by machines, a wasted form of energy, into usable electric energy. Additionally, our prototype will create a closed system for electricity use in an effort to limit battery usage.

What is Piezoelectricity?

Piezoelectricity can be produced by certain unique materials that have the capacity to convert mechanical (movement) energy into electrical energy. It has been shown that energy can be produced when piezoelectric materials such as quartz, tourmaline, and Rochelle salt, can produce voltage on the surface of the crystal (Britannica). There has been research into technology that harnesses the pressure exerted by humans onto a piezoelectric material when walking or driving and it is relatively well-proven. For example Heathrow Airport installed "energy-harvesting" floor tiles that are designed to flex slightly when people walk on them, generating small amounts of electricity from the piezoelectric effect (Mihai, 2011). The energy is then used to power low-energy LED lights and display screens in the terminal (Mihai, 2011). However, this is an expensive technology that does not typically produce large amounts of energy. Nevertheless, this type of material has many potential practical applications, particularly when using otherwise wasted forms of energy, such as sound vibrations.

The Energy of Sound

Sound waves and vibrations are forms of energy produced in daily life that, when properly harnessed, have the potential to be turned into electricity. While there are no estimates of global sound energy potential, noise is considered a significant environmental health threat (WHO). Some examples of major sources of noise pollution (which are also great potential energy sources) are factories, airports, concert halls, sports stadiums, etc. Piezoelectricity allows for a new form of flexibility when it comes to energy harnessing since places with consistent noise pollution are easily accessible.

Piezoelectricity devices are currently employed in a number of common products; they have been used successfully at a much lower level in varying types of products such as headphones, motors, and cars.

The benefit of capturing otherwise wasted sound energy is that it is a clean energy source that does not produce any carbon dioxide. This makes it an important form of electricity generation in the fight against climate change since, if it is developed and implemented properly, piezoelectricity has the potential to take a wasted by-product of daily life and turn it into electricity. The vibrations of someone walking, the roar of an airplane's engine, and the noise in a factory or concert hall, are all ways of creating vibrations that could be transformed into electricity. This would be crucial in terms of improving the energy efficiency of various industries and thus reducing the overall reliance on CO_2-producing energy resources.

Methodology

Ideation/Brainstorming

In order to determine the best mechanical structure, the engineering team began with a stringent ideation process to decide what mechanical structure would be best to capture the most concentrated sound. The first shape we evaluated was a parabolic dish in which the piezo crystal was positioned at the focus. Initial considerations included if the distance away from the sound source would impact the shape utilized, what material would work best for such a parabolic dish that could reflect sound waves the best, and how to suspend the piezo material at the focus of the dish.

The second shape considered was a cylindrical prism in which the piezo material would be placed at the bottom base and all sound would be reflected onto the crystal. With the prism, the team considered an elastic end of the cylinder that would act as an oscillating spring and at the sound source, as shown below.

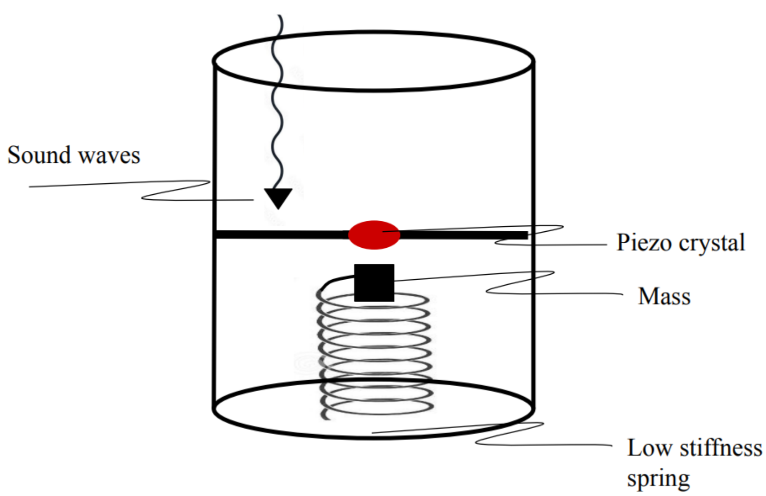

Figure 1: Cylindrical Design Drawing

The third shape considered was a trapezoidal tapered prism widest at the open end. The piezo crystal in this configuration would be placed on the base and the sound waves would reflect off of the walls of the prism. Originally, the engineering team had hoped to construct a cylindrical shape with an elastic diaphragm, but after initial prototyping it was found to be difficult to bend sheet metal to the desired configuration. The team then pivoted to a trapezoidal tapered prism, as sheet metal can be easily cut to this shape and after consultation with Dr. Knight, the team determined that this sort of shape would not require an external suspension mechanism for the piezo material which would make it more feasible for construction by the team.

Mechanical Frame Construction

Moving forward with the trapezoidal tapered prism, the engineering team wanted to construct a frame that could hold up the prism and keep it from simply resting on the ground. The design criteria for this frame included angular adjustment to point the prism towards a sound source. The frame was built of slotted aluminum extrusion (80/20) which made a sturdy platform resistant to movement and disturbances that could occur in a loud sound producing environment. For construction of the prism itself, the team sourced aluminum sheet metal of uniform dimensions from the lab space. Aluminum was used because of its very elastic properties, meaning when exposed to sound waves of high decibel levels, it would vibrate more than other materials and thus provide high pressure to the piezo crystals. The smallest piece available was used to be the base for the rest of the cuts, and trapezoids were cut accordingly maximizing as much material available as possible. The four pieces cut were taped together with aluminum HVAC tape, which would prevent sound from escaping the prism as it is normally used for sealing HVAC systems off from energy losses, which is what the engineering team was hoping to accomplish with the sealant.

After construction of the cone, the team decided to attach the cone to the constructed stand via shorter 80/20 bars and screws. An image of the built structure is shown below in Figure 2.

Figure 2: Top Down View of Mechanical Component

The original prototype of an attachment mechanism was a 3D printed knob device that would fit over a ¼ inch screw and drill into the lateral faces of the prism. This design iteration proved to not be efficient and thus the engineering team decided to pivot away from knobs as over time, the PLA material they were printed on would wear down and break as shown through testing. The final prototype has the knob mechanism replaced with screws that can be loosened and tightened to change the angular variability of the prism. This was the most simple mechanism to achieve our desired criteria.

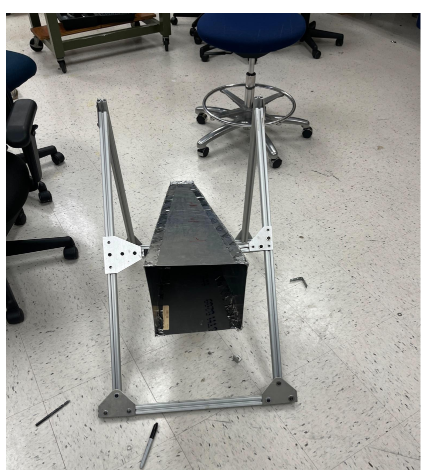

Figure 3: Top Mechanical frame with Trapezoidal Prism

Electrical System

The second component of the engineering team's design is the electrical circuitry and related materials of the project. The goal of the electrical circuit is to take a vibration as an input through the piezo crystal, and store the charge in a capacitor as an output, which can then be discharged into electronic components such as light emitting diodes, which is what the engineering team used in their prototype. The first step in creating the electronic circuitry was to perform research and consultation into the types of electronic components that would be needed to successfully produce the desired outcome. The engineering team's circuit consists of three main components.

The first of these components is the piezo crystals which act as the input signal. These crystals are arranged in stacks of 3 in parallel with washers placed on top as additional masses. This accomplishes two tasks: it sums the currents produced by these sources and adds pressure to the piezo crystal to output more current. 6 of these stacks are connected in series, to sum the voltages produced. These 18 total crystals were placed on top of the trapezoidal prism near the wide opening, the location where maximum vibration occurred. When the sound waves enter the prism, they become amplified and provide pressure to the crystals to produce a current. This configuration of these crystals on top of the prism is shown in Figure 4.

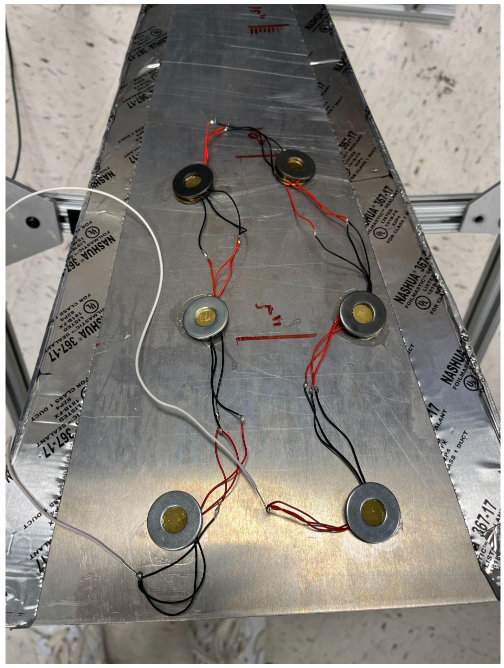

Figure 4: Piezo Crystal Arrangement

The second component is the rectifier bridge. The input signal from the piezo crystal is an AC current, however capacitors can only store DC current so the circuit must include some way to convert this current. A rectifier bridge is a combination of diodes arranged in series and parallel that convert a multi directional and fluctuating AC wave into a constant and one directional DC current wave. This is achieved because diodes only allow current to flow one way, and by being in a bridge arrangement they cut the sinusoidal waves produced by an AC current into only positive values and bridge the discontinuity between peaks. Essentially, the diodes do not allow flow of current backwards, so they turn both the negative and positive half cycle of the AC current into a pulsating DC current.

The third component is the output of the circuit which is a capacitor. The capacitor and piezo crystals are attached at opposite ends of the rectifier bridge, which is arranged as a diamond. the diamond. This allows the input to be on one end, and the output on the opposite end. A capacitor acts as a filter across the output terminal in parallel to increase the smoothing within the pulsation of the DC current produced. It does this by providing a reservoir of charge that can be utilized during periods when the rectified voltage is lower than the average DC voltage produced. During the negative half cycle of the AC current, the diodes block the flow of current from the capacitor due to their unidirectional property allowing the capacitor to discharge through a load. With all of these components arranged in an appropriate manner, the engineering team was able to construct a circuit that could turn the desired input into the desired output. Figure 5 shows the components of the electrical system and their arrangement, and Figure 6 shows the circuit itself on a breadboard which was implemented on the final device.

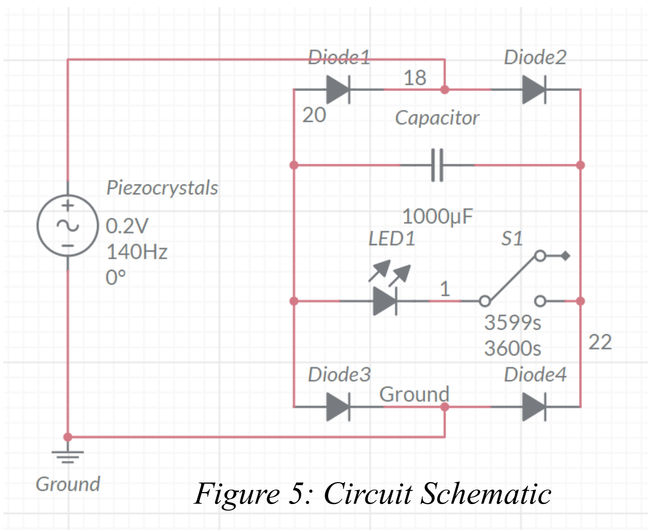

Figure 5: Circuit Schematic

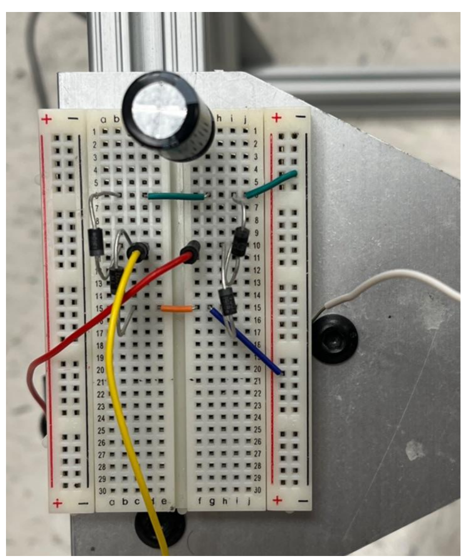

Figure 6: Circuit on Breadboard Implemented on Device

To determine what frequency the piezo crystal would be optimal at, the engineering team performed sound testing at different known frequency values. An oscillometer and voltmeter were used to determine the resulting voltages produced at different tested frequencies ranging from 120-180 Hz. Through testing, it was found that 140 Hz was the most optimal as it resulted in the highest voltage of 0.04 mV. Although this is a relatively small number, stacking the piezo crystals physically, as well as connecting 18 units increases this number. Testing was done by attaching the leads of the oscillometer to the positive and negative leads of the piezo crystal. A known frequency sound was played out of a speaker ranging from 120-180 Hz at a max volume of around 85 decibels. Each frequency was played 4 times, and the highest reported voltage was noted. The result was found to be that 140 Hz consistently produced the highest voltage at around 0.04 mV. At first, the engineering team placed the piezo on a flat, non-vibrating surface and was not able to read any voltage. The team then pivoted to placing the piezo on the vibrating surface of the cone and was able to get multiple readings that can be seen in the table below.

Table 1: Sound Frequency related to Voltage based on Sound Testing

Frequency (Hz)	**Voltage (mV)**
120	0.03
140	0.02
160	**0.04**
180	0.02

Final Testing and Analysis

In order for the engineering team to determine if the device was successful, extensive sound testing with a 100 dB speaker was performed. The engineering team took a very large speaker, which mimicked factory sounds, and put it next to the cone as shown below in Figure 7. An oscilloscope was attached to the AC-DC conversion circuit in the middle of the rectifier bridge as the output, and a 140 Hz tone was played. From this, successful results could be seen as a signal was clearly visible on the oscilloscope of anywhere between 1 and 5 millivolts. This was with a constant tone, but when the engineering team would tap on the piezo crystals in harmony, or provide a forceful external vibration, the signal would jump up momentarily to much higher values. This test showed a successful proof of concept for the engineering team and shows clear potential for scaling up the device in order to capture larger amounts of energy with louder sounds

Figure 7: Final Testing Setup

Cost-Benefit Analysis

Analysis of Energy Production

Given the lab research that has been conducted, we can estimate the amount of energy production one prototype could generate. A JBL flip speaker was used at maximum volume, which generates 85 decibels. These estimates will be more conservative since most of our target markets have higher decibels (*see Target Markets section*). For example, the Chiller Plant has an average noise level of 94dB and concerts have an average noise level of 107.5dB.

The output voltage of the prototype varied between 0.02V to 0.04V, depending on the frequency of the sound waves. We are assuming the use of a capacitance of 0.01 microfarads and a 0.01 ohms resistance, which is considered a reasonable assumption. In our circuit, there is no resistor in order to maximize the amount of charge we can store, so the resistance assumed in this calculation is that of the wires and other circuit elements i.e. natural resistance. The capacitance value depends on how much charge one wants to store, and for the engineering team's purposes, a 0.01 microfarad capacitor was utilized.

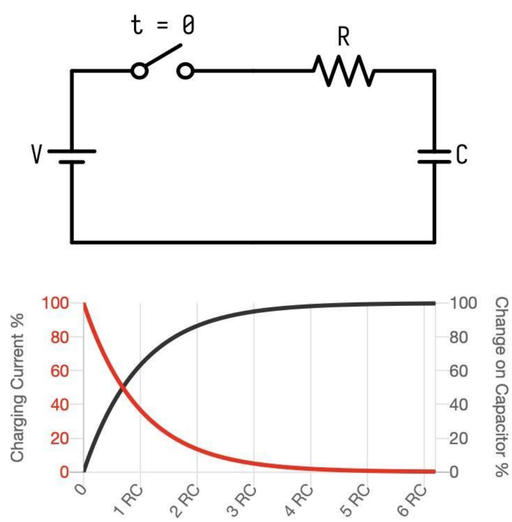

Figure 8: Change on Capacitor % vs. Time

Hence, for 100% charge of the capacitor, it would take 6 times the time constant of 1e-10 (*see Figure 8 above*). If we assume that the capacitor is working at 80% full efficiency (i.e. 80% of the time), we can calculate the amount of kilowatts generated in an hour, using the following equation. The upper bound is assuming an output voltage of 0.04V whilst the lower bound assumes an output voltage of 0.02V.

Hourly Upper bound: $\frac{3600\ seconds}{6 \cdot 10^{-10}\ seconds} \times 80\% \times \frac{0.04\ V^2 \cdot 0.01 \cdot 10^{-6} F}{2} \times \frac{1\ kW}{1000W} = 0.0384kWh$

Hourly Lower bound: $\frac{3600}{6 \cdot 10^{-10}} \times 80\% \times \frac{0.02\ V^2 \cdot 0.01 \cdot 10^{-6} F}{2} \times \frac{1\ kW}{1000\ W} = 0.0096kWh$

The annual electricity production for the prototype, given the lower bound estimate, would be 82.02 kWh; given the upper bound estimate, the annual electricity production would be 328.09 kWh.

Costs and Break-Even Point

The prototype costs $86 to build (*see Appendix 1 for list of materials)*. The average cost of electricity in North Carolina is 13c/kWh, which is 32% lower than the national average of 19c/kWh (EnergySage, 2023). Since we are assuming that our prototype would be used in North Carolina, we can expect the plant to save between $10.7 and $42.7 per year. The break-even point (cost of electricity saved = cost of prototype) would be reached in 2.0 to 8.0 years. Given these break-even points and the long-term durability of piezo crystals, one could argue that this prototype is economically viable.

Economic Analysis

Target Markets

The piezoelectric product created in this project would be best deployed in spaces that have a lot of loud, consistent sound generation. This is due to the fact that for optimal energy generation one would want to optimize the amount of time sound waves that produce energy are generated. Without consistent and loud enough sound waves, this product will harvest very small quantities of energy and will not be cost effective.

Table 2: Decision Matrix

		Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Factors	Weight	**Cameron**	**Chiller Plant**	**Airport**	**Concerts**	**Race Tracks**
Noise level **(deviation from *96dB)**	[(dB-96dB)] * 100 points *96dB literature value ideal[1]	74 decibels* -22.9	94 decibels* -0.20	140 decibels[2] -45.8	107.5 decibels[3] -12.0	85 decibels[4] -11.5
Noise consistency **(Scale 1 poor - 5 great)**	(C-3)*10 points	Poor (Value 1) -20	Very Good (Value 4) 10	Fair (Value 2) -10	Poor (Value 1) -20	Fair (Value 2) -10
Accessibility **(Scale 1 poor - 3 great)**	(A-3)*40 points	Average (Value 2) -40	Great (Value 3) 0	Poor (Value 1) -80	Average (Value 2) -40	Average (Value 2) -40
	Sum: (points)	-82.9	9.8	-135.8	-72.0	-61.5

Based on these considerations there are a few markets that could use a product like this:

Chiller plants: these devices can be used to harness the loud excess soundwaves that the chiller plant generators create to help power different parts of the building. Chiller plants typically run most of the day, especially in the warmer months of the year, and produce ample sound and frequency to be harnessed. This is also a great target market because of subsidies that may exist to increase the efficiency of plants.

Automotive industry: These devices can be used to convert sound waves generated by testing sites similar to the one found in the Duke Motorsports Garage. Those spaces create high decibel sound values, but not over large periods of time, so these spaces may be limited.

Airport Application: Piezoelectric devices can be used to generate power from the sound waves caused by aircrafts during takeoff and landing. This energy could be used to power the lighting on runways tracks as well as other sensors that are used around the airport.

Concert / entertainment industry: Large entertainment venues would be a good target market for these devices. The excess vibrations from the ground and the enormous amount of soundwaves these events produce would create a good synergy for this device. We measured the decibel levels of Cameron Indoor during a basketball game and on average we found an average decibel level of 74, but the peaks of sound would create a good amount of energy. At a concert those peaks are relatively consistent, they are just shorter events. These devices could help power the lighting for stadiums and concert venues to start and then if there is excess energy help power other places.

To test this product in a potential market, we partnered with staff at the Duke Chiller Plant. Prototype 1 was initially tested at multiple locations in the plant, and based on our findings we extrapolated to estimate the amount of energy an ideal piezoelectric device in a chiller plant could produce.

Environmental Analysis

Piezoelectricity is a promising technology that has the potential to harness sound pollution and convert it into electricity. By utilizing our piezoelectric prototype, we can reduce our dependence on fossil fuels, particularly in the mining and battery industries. This reduction in emissions would have a positive impact on our environment, helping to protect the ozone layer and decrease anthropogenically intensified global warming.

To quantify the success of our efforts, we will compare the energy harvesting capabilities of our piezoelectric device to that of a single lightbulb. By measuring the amount of electricity generated, we can demonstrate the potential of piezoelectricity to significantly reduce emissions and pave the way for a cleaner, more sustainable future.

Powering a Lightbulb

Lighting is a significant consumer of electricity in the United States, accounting for approximately 25% of the country's total electricity usage (Tufts Climate Initiative Lighting Brochure, 2012). Unfortunately, a vast majority of this electricity is produced by burning fossil fuels, resulting in significant environmental pollution. In fact, as of 2021, 61% of the total electricity in the US is produced from fossil fuels, such as coal, natural gas, and petroleum, as well as biomass and municipal and industrial wastes (EIA, 2023).

The emissions associated with lighting are substantial, with an average 50W light bulb emitting between 1,000-2,000 pounds of carbon dioxide and 8-16 pounds of sulfur dioxide over its lifetime (Tufts Climate Initiative Lighting Brochure, 2012). The majority of the electricity for these light bulbs comes from non-renewable sources, with 37% coming from oil, 31% from coal, 22% from nuclear, and 7% from natural gas, and only 1% from hydro, and none from solar or wind sources (Tufts Climate Initiative Lighting Brochure, 2012).

Our piezoelectric prototype, with an estimated average output of 24 watts per hour, offers a promising solution to this problem. By implementing our prototype at the Duke chiller plant, we can potentially power a lightbulb and reduce our reliance on non-renewable sources of energy. The average wattage for light bulbs ranges from 10-60 watts, depending on whether they are fluorescent or LED (Energysage, 2023). With an hour of piezoelectric energy collection, we can power almost half an hour of the average lightbulb, offering a significant reduction in emissions and a cleaner, more sustainable future.

Decrease in CO_2 Emissions

By utilizing emissions offset, we can significantly decrease carbon dioxide emissions. On average, our piezoelectric prototype can offset 70-281 lbs of CO_2, 1.3-5.1 lbs of SO, and 0.8-3.1 lbs of NO annually. These reductions help protect our environment and promote a cleaner, more sustainable future. According to the Intergovernmental Panel on Climate Change (IPCC), the concentration of carbon dioxide in the atmosphere has increased by around 50% since the pre-industrial era, largely due to human activities such as burning fossil fuels. The large increase in carbon dioxide has been linked to an increase in global warming impacting rising sea levels, extreme weather conditions, and melting glaciers (NASA).

Decreasing Lithium Ion Battery Use

Lithium batteries are a significant contributor to carbon emissions, emitting 73 kg CO_2-equivalent/kWh. The production of lithium batteries results in significant water waste, with 400-2 million liters of water used per Li kilo (Obbekaer, 2019). Our prototype offers a closed system for electricity production cutting out the use of lithium batteries. By decreasing our reliance on lithium batteries, we can reduce our carbon footprint and conserve precious resources. On average, annually reducing 64-256 batteries of 12v lithium batteries depending on our lower and upper bound voltage generation estimates.

Environmental Drawbacks:

Although there is a net environmental benefit from using our prototype it is important to know there are environmental drawbacks from mining of piezoelectric materials. The piezoelectric ceramic material is made of lead zirconate titanate (PZT), barium titanate, and lead titanate (APC International, 2023). The mining of these metals can create negative externalities such as erosion of mineralized waste rock. This erosion can seep into surface drainage systems that may lead to concentrations of metals in stream sediments (American Geosciences Institute, 2018). Additionally, acid rock drainage leads to an oxidation process which produces acidic conditions that can inhibit plant growth at the surface of a waste pile (American Geosciences Institute, 2018). Further, air contamination can result from mining. Mining releases sulfur dioxide which is dangerous for the ozone and contributes to acid rain when water vapor comes into contact with sulfur dioxide (American Geosciences Institute, 2018).

Piezoelectric materials, such as nylon 66 and tetrafluoroethylene, are used to generate electricity from mechanical energy for various sectors and products. However, the environmental impacts of these materials have not been quantified. More research needs to be conducted into piezoelectric technology to find life cycle impacts (Mahmud, 2018). To mitigate the environmental cost of mining metals it would be beneficial to upcycle metal (Copper Reliance, 2018). The largest physical disturbances at a mine site are the actual mine workings, such as open pits and the associated waste rock disposal areas.

Government Analysis

Duke Energy Carolinas offers rebates to non-residential customers who improve the energy efficiency of their facilities. Specifically, customers who install variable frequency drive (VFD) data center chilled water pumps ranging from 5-50 horsepower can receive rebates ranging from $825 to $3,376. Additionally, North Carolina's Database of State Incentives for Renewables & Efficiency (NC DSIRE) offers information on interconnection standards and distributed generation technologies to help businesses and individuals navigate the state's energy policies. Similarly, SCE's Non-Residential Energy Efficiency Programs cover up to 100% of equipment costs and 50% of total project costs for qualifying projects. The Commercialization Industrial Decarbonization Grant offered by SCE incentivizes the increase of energy efficiency and the removal of carbon emissions in industrial and commercial sectors. These programs and grants demonstrate a growing trend in incentivizing energy efficiency and carbon reduction in the business community.

Social Benefit Analysis

The continued development of piezoelectricity as a form of sustainable energy has many overall benefits for society. The use of piezoelectricity and implementation into various markets improves social awareness of the different types of renewable energy that exists. It creates more options for energy sources that people may have not even thought were previously possible. Increased public knowledge of clean energy is incredibly important because in order to become a carbon-neutral society, everyone must work to make that change possible. Without public support, the implementation of any form of clean energy would be unsuccessful. Because if the technology exists but people continue to use oil or gas, then no change to our carbon output would occur.

The use of piezoelectricity will also have a positive impact on public health since the harvested energy can offset carbon emissions and air pollution in the value chain otherwise produced by burning fossil fuels. For example, if the electricity that is running a factory might be coming from a coal-fired power plant. The power plant is producing a lot of air pollution for the people living in the surrounding area and can cause various health problems. Exposure to high levels of CO_2 can cause short-term health effects such as headaches, dizziness, and fatigue. In the long term, it can lead to respiratory and cardiovascular diseases, as well as developmental problems in children. According to the UN, “Air pollution is the greatest environmental threat to public health globally and accounts for an estimated 7 million premature deaths every year.” (UN). The majority of the world's population lives in areas with insufficient air pollution guidelines.

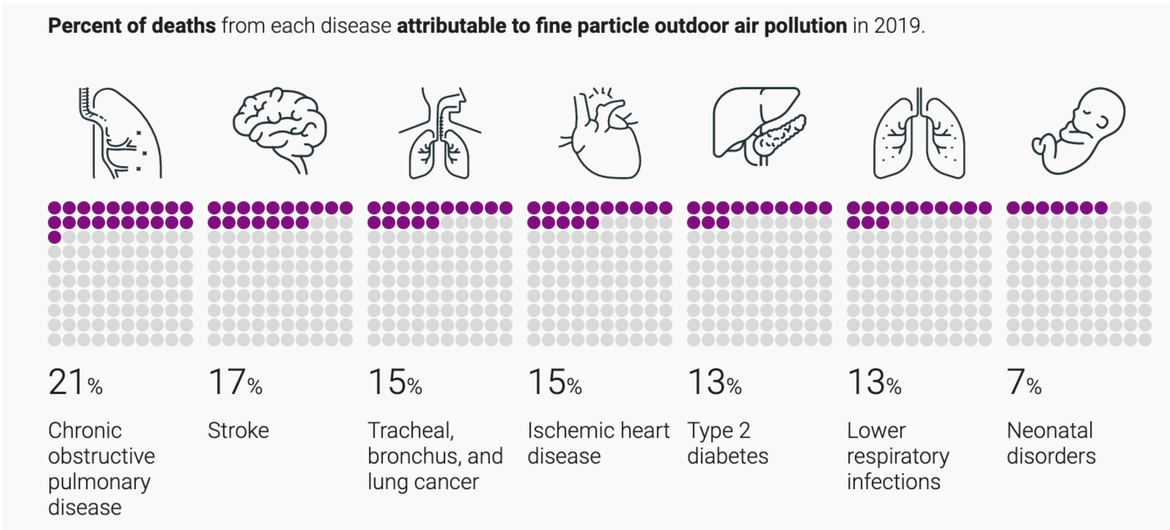

Figure 9: United Nations Environment Programme - Deadliest illnesses link to $PM_{2.5}$ air pollution

The continued use of carbon dioxide producing energy sources will only cause these numbers of deaths to rise. Therefore, it is crucial to reduce CO_2 emissions and implement sustainable practices to mitigate its negative impacts on the environment and human health.

By using a piezoelectric device like our model, the amount of electricity being demanded from that power plant decreases, causing a reduction in carbon dioxide output and the amount of coal being mined to fuel that plant. If there is less coal being burned, the amount of carbon dioxide going into the atmosphere will decrease as well. This also reduces the demand for the coal being mined, which also has serious harmful health effects on miners. By providing a more sustainable source of energy, there is also a net social benefit by reducing the over-use of natural resources.

Conclusions

Our prototype aims to demonstrate the feasibility of utilizing sound pollution as a source of electricity. Our findings show that we would be able to power 30 minutes of lightbulb energy for every 1hr of electricity generation. Piezoelectric material is a new technology that has great potential. Economics, social and environmental analysis has revealed the importance of investing in renewable energy alternatives for electricity. Further testing with the chiller plant will reveal the scalability of using piezoelectricity for energy production.

Future Recommendations:

To optimize the performance of a piezoelectric device, the arrangement of the piezo crystals can be changed to favor high voltage or high current depending on the load. It is also important to make the device more portable and easily movable within a factory setting. Scaling up the device by adding more piezo crystals along the surface of a prism can increase energy production. Further experimentation with a flexible membrane for additional energy storage, heavier washer masses, and different types of crystals can also improve the device's performance. Additionally, testing different structural materials can help identify the highest resonant frequency for different elastic materials, allowing for even more efficient energy production.

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Appendix 1: List of Materials

Materials	**Amount**	**Cost**
Piezo Crystals	6	$6
Sheet Metal	1	$50
Capacitor	2*	$5
Connection Wires	5*	$5
Resistors	2*	$5
Breadboard	1*	$10
Diodes	4*	$5
[redacted]	Total	$86

*These components could not be bought individually, so the price shown is for multiple units, or the lowest number sold available together