Team PISO

Rithik Sebastian, Catherina Samson, Ian Brady, Liam Mc Carthy, Mark Wedzielewski, Mikaila Esuke, Sanjali Yadav

I pledge on my honor that I have not given or received any unauthorized assistance on this assignment/examination.

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Abstract

The growing excess of carbon dioxide in the atmosphere - a result of burning natural gasses and coal to produce energy - has been causing devastating effects on this planet and its inhabitants for several decades. Global temperatures are rising exponentially, in turn endangering and eradicating species and ecosystems of every type. Renewable energy is a relatively newfound solution to this broad issue, but even these modern technologies have complications of their own.

Team PISO recognizes the catastrophic effects of climate change and the urgency of sustainable energy, along with the qualities of certain piezoelectric materials that generate a charge with an applied force. Team PISO will investigate the existing principles, design considerations, and integration of piezoelectric tiles, with the objective of widespread implementation and a conscious consideration of sustainability and efficiency.

Our research is dedicated to designing an optimized piezoelectric floor tile to harness the pressure of pedestrian traffic, as a novel source of renewable energy for implementation in public, heavily-traveled areas. In the future, the team will attempt to conduct experiments in a lab in order to increase the output of piezoelectric tile designs.

Chapter 1: Introduction

1.1: The Need for Clean Energy Production

Humanity can attribute its accelerated cultural and technological progression of recent centuries to the obstacle of energy generation and consumption. Simply put, the fundamental discovery of energy and electricity became the foundation on which civilization developed. Due to experimentation with basic circuitry in the eighteenth century, societies have been able to reach heights in communication, transportation, artificial intelligence, and manufacturing through engineering and science. However, all of these agricultural and industrial advancements from hundreds of years ago could not have happened without the utilization of natural or manufactured materials to generate power. Most of the world's current methods of power generation rely on exhaustible energy sources like coal and other fossil fuels, which in turn has caused detrimental effects to the atmosphere.

Fossil fuels such as coal are utilized through combustion, which expels massive amounts of carbon dioxide into the atmosphere. The excess of carbon dioxide from these processes has lasting effects on the environment, affecting the populations of countless species and changing meteorological patterns more each year . **Arctic amplification**, the phenomenon that contributes to the melting of ice reserves at the poles has led to lasting damages in ecosystems around the globe: rising sea levels, devastating wildfires, tumultuous storms, and a continuously growing global temperature [1]. Densely populated areas in countries like China and India are especially affected by air pollution and smog, posing serious health risks for their own residents [3]. Coal and fossil fuels are also depletable, so as the world population and technological developments continue to grow exponentially, the world's supply plummets. Therefore, the need to search for more sources of renewable energy becomes increasingly urgent with time.

1.2: Issues with Existing Solutions

Due to the noticeable pollutive characteristics of fossil fuels and coal, renewable energy has been in high demand in recent years, making it the fastest growing energy source within the United States. The demand for renewable energy is soaring, while the total coal consumption in the United States is decreasing to 11.3 quadrillion **British thermal unit** (Btu), its lowest recorded level since 1964, and total renewable energy surpassing that with 11.5 quadrillion Btu, being the highest it has been on record. As the use of coal consumption has dramatically decreased over the past 6 years, renewable energy such as solar, wind, biofuels, and hydro have increased significantly over the past 4 years. The year 2019 marks when the use of renewable energy and consumption of said energy has overshadowed that of non-renewable sources such as coal.[4] [5]

This can all be attributed to renewable energy's efficiency and lack of pollution compared to its predecessors. A large number of sources have been discovered and developed to meet this growing need: solar farms, wind farms, hydroelectric generators, and nuclear power plants are the most promising sources of renewable energy thus far, but they all require large start-up costs, impacted by **intermittency** and are limited to specific landscapes and/or meteorological conditions in order to work most efficiently [6] [7]. One example of this can be seen with solar energy because it specifically requires large sections of land, a substantial amount of water for cooling and cleaning, and continual maintenance to be comparatively productive [8].

Another example can be seen in wind energy. In order for wind energy to work optimally and at its top efficiency, these wind turbines must be located on farms, rural communities, and coastal areas with little to no barriers to obstruct the flow of air. The energy produced by harnessing the wind is immense, but the energy obtained from wind turbines is far away from the cities that actually need the energy [9] [10] [5].

Another unintentional disadvantage of wind power is the impact on wildlife and habitats and the same ecological impact can be said for solar energy [11]. Cities are just not equipped for the engineering specifications that wind turbines need but our proposal of utilizing piezoelectric materials as a renewable energy source can be easily implemented into a city setting and structure. Additionally, the quality of the energy generated through solar panels and wind turbines does not yet stand up to that of fossil fuels, as the technology is still relatively new and is still being improved upon [12]. While these sources of energy are by no means inefficient or detrimental, none of them fill the commercial niche of efficient, cost-effective low-power generation requiring comparatively small startup costs.

In regards to the startup costs associated with renewable energy sources, the initial cost for a nuclear power plant increased in the years of 2002 and 2008 from 2 billion US dollars and 4 billion per unit to approximately 9 billion per unit within the United States [7]. The cost of a solar farm is approximately 3 million, including development. But, on a per acre scale the cost is approximately 500,000 US dollars with the return on investment varying significantly based on one's location [13]. A source of clean energy usable in urban areas with a low initial cost would fill a yet unused niche in the energy industry, and encourage the global conversion from fossil fuels to renewable energy.

1.3: Our Solution

To investigate energy sources with lower startup cost, we are looking to expand on an until recently overlooked source of power, which can be collected in highly populated areas and with minimal down payment: footsteps [14]. Public buildings, especially transportation hubs, see a huge amount of pedestrian traffic every day [15]. The action of both putting your foot down and picking it back up causes the floor to move a measurable amount, deforming and producing heat by way of friction. Harnessing the kinetic energy of the movement might prove to be a viable method of energy production in highly trafficked areas, and will probably cost less than solar arrays of a similar size.

To put in perspective the low down payment required for piezoelectric generation, the initial cost of a single dollar per watt sized solar panel is about 250 US dollars [15]. In comparison, the cost per cubic centimeter of the piezoelectric material lead-zirconate titanate (PZT) ceramic is $0.155. Approximately 100 sheets of the material, at about 11 cubic centimeters each, costs approximately $165. With only a few sheets of piezoelectric material being used per intended floor tile, from the perspective of the cost of renewable energy resources our solution has a significantly lower startup cost [13] [15]. From the perspective of wide-spread benefits and availability, a piezoelectric tile on the market could be priced much lower than a comparable solar panel.

The idea of producing energy from pedestrian traffic only emerged within the last ten to twenty years, but there is a good amount of research on the topic outlining the basic principles of harnessing energy with piezoelectric materials, which convert stress into electricity, and converting kinetic energy to electricity with **dynamos** [16].

A few organizations have made a foray into collecting energy from pedestrian traffic, most notably the British company Pavegen, the US government, and the East Japan Railway Company. However, the technology is underdeveloped compared to the alternatives, and so the piezoelectric tiles currently available on the market exist largely as proofs of concept, with minimal cost effectiveness or profitability [17] [18] [19].

Team PISO seeks to consolidate existing research on piezoelectric energy and pedestrian traffic energy harvesting to develop a novel design for a piezoelectric floor tile. By applying and optimizing existing research, and developing upon prior designs for piezoelectric generators, PISO aims to increase cost efficiency and power generation in its prototype by using prior research to design a power-efficient energy harvester and developing a cheap and durable chassis to house the harvester, all while ensuring our design remains ecologically friendly and easy to implement in public areas.

Chapter 2: Literature Review

2.1: Piezoelectricity

Piezoelectricity is an underutilized resource of clean energy. Like wind power, it has the ability to convert mechanical energy into usable electricity. However, unlike wind power, piezoelectricity also has the property to convert electrical energy back into mechanical energy. These properties, collectively known as the **piezoelectric effect**, are the focus of this project. We want to look at ways that we can use this unique effect to generate renewable energy.

When a piezoelectric material experiences mechanical motion or friction, the stress distorts the material and creates electrical charge, which can then be collected [20]. This effect is observed because piezoelectric materials have natural dipole moments due to their crystalline structure. This means that there are areas inside of them with concentrations of either positive or negative charge. When the piezoelectric material becomes distorted, so do the dipoles, and an electric charge is generated. Conversely, when an electric current is run through piezoelectric material, the current forces the charges to create a stronger dipole, which in turn distorts the material and exerts a mechanical force.

Piezoelectric materials can come in a variety of forms. They are divided into four different categories based upon their characteristics: ceramics, single crystals, polymers, and composites [20]. Each category has its different benefits and drawbacks.

Piezoelectric ceramics are notable due to their remarkable electrical properties and their stability resulting from the formation of a morphotropic phase boundary [21]. The most popular type of piezoelectric material, Lead-Zirconate-Titanate (PZT), falls under the ceramic classification. One downside is that ceramics like PZT, which are made with lead, produce toxic byproducts when manufactured [22]. While there are ceramics that are made without lead, they are not nearly as effective.

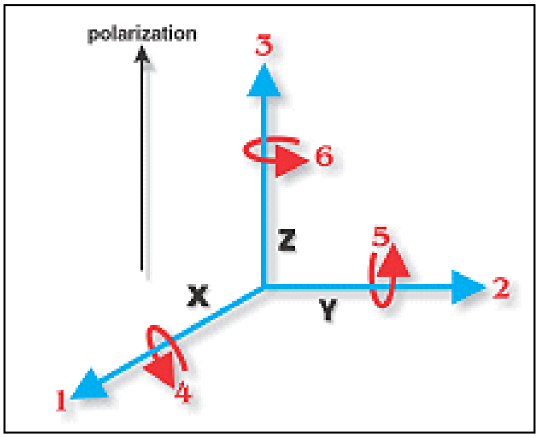
Single crystals are the single crystalline counterparts to ceramics. They are preferable to ceramics in cases where there can only be a small amount of material used. One study showed that by using a certain energy harvesting technique, single crystals could output 20 times the amount that a ceramic could [14]. One of the drawbacks of single crystals, however, is that the cost of manufacturing is higher than that of ceramics [20].

Lastly, piezoelectrics that come in composite and polymer form and are characterized by their heightened flexibility compared to the other forms [23]. Since composite piezoelectrics are a combination of ceramics or single crystals with polymers, they share a lot of the same characteristics as polymers, namely the flexibility. However, unlike polymers, composites (as well as the other forms) exhibit the ferroelectric property. As such, composites produce more output in comparison to polymers

The strength of the electric field produced when a piezoelectric material is stressed is determined by its **piezoelectric constant**, denoted with a lowercase d. The constant is determined by the material used and the direction of the force with respect to the direction of the material's polarization, also called the **coupling mode**. The constant for any coupling mode can be described with respect to four major modes [24] [25]:

- 3-3, where force is applied parallel to the poling direction .
- 3-1, where force is applied perpendicular to the poling direction.

- 1-4, where torque is applied parallel to the poling direction.
- 1-5, where torque is applied perpendicular to the poling direction.



Visualization of coupling modes in the cardinal directions [25]

The piezoelectric constant for each of these coupling modes are denoted $d_{31,}$ d_{33}, d_{14}, and d_{15}, respectively [25]. Each of these coefficients have different values, dictated by the composition of its material. Using these values and vector analysis, the electric field generated from a force of any direction and magnitude can be predicted.

Using the piezoelectric constant, it is possible to calculate the voltage produced by the deformation of a piezoelectric material.

2.2: Impact and Lifespan of Piezoelectric Materials

Piezoelectric ceramics, a perovskite material, is what allows for the conversion of pressure, vibrations, and other configurations of motion into electrical signals. For our purposes, this conversion would allow us to convert the energy harvested from the force or pressure exerted on the piezoelectric material from human interactions into energy that can be repurposed for other uses [26]. Commonly used piezoelectric materials, which are also piezoelectric ceramics, include lead zirconate titanate (PZT), barium titanate (BT), and strontium titanate (ST). Materials that have precedent for the direct application of converting the pressure exerted on piezoelectric floor tiles into energy includes PZT, Polyvinyl Indene Fluoride (PVDF), and quartz.

PZT is unarguably the most effective material, its effectiveness compared to its more environmentally friendly counterparts or those who are lead free is simply better and we are somewhat ways away from developing a lead-free piezoelectric material with the equal or better capacities as PZT. But, with restrictions to using hazardous materials (like lead) rising in the world, development of these materials is on the forefront of many minds and research. PZT is a (solid) combination of lead zirconate (PZ) and lead titanate (PT) which both have great piezoelectric properties which attributes to PZT's overall peak performance. It is proven that lead can be very toxic to people, living organisms, and the overall environment leading lead poisoning to be a significant environmental health hazard. But, the main way in which people are exposed or suffer from lead poisoning is from inhaling or ingesting the lead. PZT is highly dangerous and toxic because of its volatilization at high temperatures, more specifically during calcination and sintering which in turn can cause pollution [29]In addition, PZT submerged in water has been observed to have left trace amounts of lead in the water supply. PVDF is a polymeric material that can be used in tandem with PZT for power generation and or energy harvesting. As a piezoelectric material, quartz is more precise but has a higher cost compared to PZT and other piezoelectric ceramics. It has a high acoustic quality and a low acoustic loss, making it more precise and effective against its other piezoelectric material counterparts [30].

Bismuth-Based ceramics (BLSF), sodium potassium niobate (KNN), and NBT. KNN is a solid combination or solution of NN and KN compounds. KNN is believed to be the more environmentally safe alternative to PZT, but some research indicates that KNN in the early stages of its life cycle can actually be just as or more environmentally harmful than PZT [27], [28].

In terms of usability and lifespan of these piezoelectric materials and PZT being the most effective of them all, it is actually not suited for frequent cyclic loading. PZT can be considered a fragile material as an inorganic ceramic and must be protected from either strenuous or harsh environments. If PZT is overstrained, it loses a significant amount of piezoelectric properties only its over-strained (500 mu) and may not even have visible deformation/cracking. However, PVDF can be considered virtually unbreakable when exposed to these same strenuous conditions and quite long lasting. PVDF as a polymer material is competitively flexible, with an elastic modulus 25x larger than PZT, which makes it more resistant to both mechanical stresses and destruction forces [29] [33].

2.3: General Applications of Piezoelectric Material

The converse effect of piezoelectric materials to exert force when exposed to a voltage is well-documented and often used in a broad range of industries, especially where precision is involved. Atomic force microscopes, ultra-precise machine tools, actuators, and structural damping mechanisms all take advantage of piezoelectric materials for their capacity to make small adjustments to their shape as the electric field around them changes [24]. On the other hand, their direct effect of creating a voltage when deformed is relatively underused until recently, as research has mostly been focused on technologies that promise to yield larger quantities of power.

That said, piezoelectric power generation does exist. The most widely used piezoelectric material in energy harvesting is Lead Zirconate Titanate (PZT), a titanium-based material which is both easy to manufacture and capable of generating a large amount of energy compared to other piezoelectric materials, due to its large charge coefficient [31].

Piezoelectric power harvesting largely makes use of piezoelectric materials coupled in the 3-1 mode or the 3-3 mode, since these coupling modes generally have the largest charge coefficients out of the four listed in the previous section. Generators in different modes work best under different circumstances [32]. For example: 3-1 generators, often designed as vibrating plates or rectangular cantilevers, have a lower charge coefficient but are easier to make vibrate at resonance. This allows them to be more responsive to low-frequency or low-amplitude vibrations, or irregular inputs. 3-3 generators, often arranged as several alternating layers of **piezoelectric wafers** and electrodes, have a higher charge coefficient but vibrate less freely, making them well-suited in situations with high-powered, regular inputs which drive their oscillation [33].

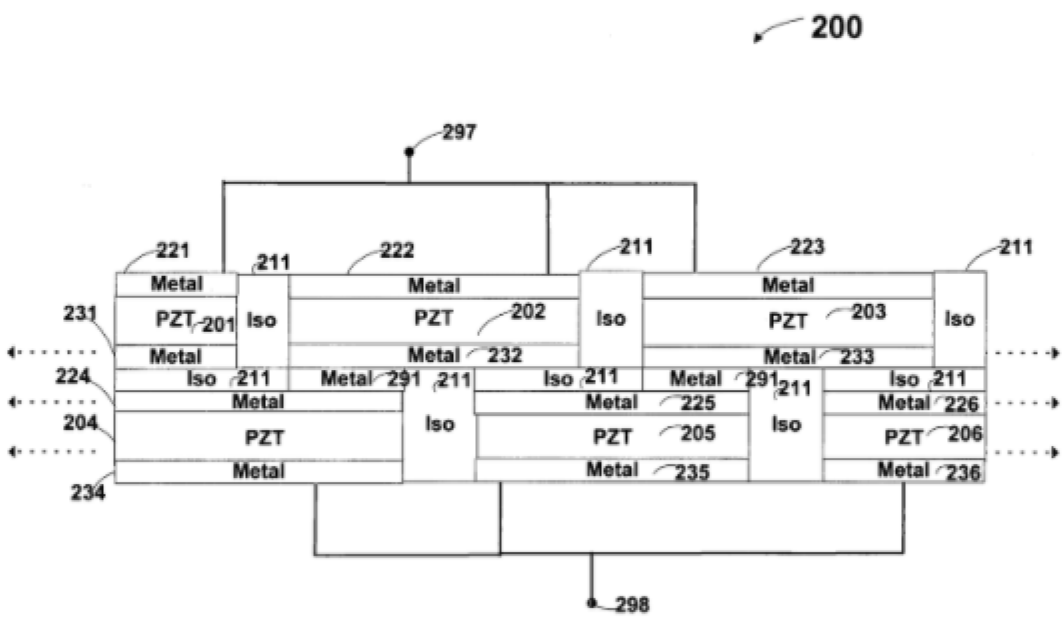
Any type of piezoelectric generator operates at peak performance when exposed to a vibration of the same frequency as its resonance. At resonance, the piezoelectric material experiences its maximum deformation as it vibrates, and so outputs the maximum amount of voltage it is theoretically able to. As the vibration of the system strays away from resonance, piezoelectric output drops sharply, especially if the system's vibration becomes lower than the resonance frequency [34]. This will be a problem we will have to face as we design out floor tile, since pedestrian traffic typically occurs at low frequencies and irregular intervals.

2.4: Piezoelectricity in Floor Tiles

The properties of the piezoelectric effect have the potential for use in many fields, but the focus of this project is utilizing piezoelectric materials to generate energy through a floor tile.

The general concept of this consists of creating an area of floor which contains piezoelectric materials which will interact with pedestrian traffic, thus generating current. While this idea has seen minimal application so far - restricted only to isolated uses in very specific facilities - various researchers have conceptually designed or prototyped floor tiles which implement piezoelectric energy generation.

Piezoelectric floor tiles typically are multilayered constructs: the actual piezoelectric material is placed on the surface where it can receive mechanical input, and circuits are placed below this layer for spacing, usually in the form of a converter where the produced current is made usable in some way [35]. The surface layer is allowed to deform, while the circuit layers underneath are made rigid and stable.



Example of Piezoelectric Tile layering [36]

Actual piezoelectric floor tiles have mostly been made for demonstrative purposes due to the relatively slow rate of energy generation, but efforts have been made to integrate these tiles with other generation methods for more optimal output. It has been attempted to add **photovoltaic cells** to the top layer, thus allowing the surface layer to act as both a piezoelectric generator and a solar generator [37]. This potentially supplements outside floor areas by allowing the tiles to generate energy, even when pedestrian traffic is relatively low; this concept could receive use in outdoor train stations or market areas.

Other prototypes have explored implementing magnetic inductors, which would be affected by the moving charge from piezoelectric displacement to create additional induced current [38]. Since **magnetic induction** would use some already existing functions of a piezoelectric tile to produce current - instead of adding completely new circuits - the efficiency of the piezoelectric tile with regard to its basic form is increased.

Furthermore, while efficient piezoelectric tiles presents a good first step, research groups such as one at Tongji University in China, as well as the Israel-based Innowattech, have looked into applications of piezoelectric traversal energy general for other surfaces, such as roads and railways [39]. While these surfaces may not see high pedestrian traffic like walkways, they are frequently travelled over by heavy vehicles, which can easily provide piezoelectric charge with regularity. Any efficiency boost to piezoelectric generator systems has the ability to increase the technology's applicability, and thus its impact on alternative power production.

2.5: Optimizing Piezoelectric Floor Tiles

The energy generated from piezoelectric tiles depends significantly on foot pressure distribution while walking, duration of pedestrian traffic, shape of the tile and energy harvester model. In order to optimize the output of the tiles, these factors need to be taken into account.

Analysing pedestrian traffic is an integral part of maximizing the input for piezoelectric tiles. There is a vast difference in the foot pressure distribution during walking between young and old adults. The elderly (60+ age) have lower maximum pressure and force as compared to the young (20 - 40 age) population [40]. Since pressure is a key element in maximizing energy input, it is important to consider factors that can increase or decrease the pressure.

Additionally, input energy can be increased if the tiles receive consistent pedestrian traffic. In fact, consistent traffic for a shorter duration (4 hours) generates twice as much energy as compared to an inconsistent pedestrian traffic for a longer duration (12 hours) [41]. Everytime the piezoelectric tile senses a footstep, the downward force drives an energy-storing flywheel inside the tile, which spins to convert kinetic energy into electrical energy [42]. It's like a generator in motion and with consistent load, the energy generated will be much higher as compared to inconsistent pedestrian traffic. Thus, installing piezoelectric tiles on crowded walkways or dance floors will generate more energy as the traffic pattern is more consistent. Further, lobbies and common areas in apartments and offices are also good candidates for receiving consistent pedestrian traffic for certain intervals of the day [43].

Further, the shape of the piezoelectric tile significantly affects the energy output. Pavegen, an established company, is using kinetic technology for generating energy from footsteps. They changed their tile shape from square to triangular because they are able to capture much more energy with triangular tiles [17]. Each footstep triggers three or four generators in the Pavegen floor tiles [44]. With their square tiles, only 20% of steps would fall in the right place and trigger the generators. However, with triangular tiles, they are able to achieve 100% accuracy [44]. Thus, the shape of the tile is a crucial factor in optimizing the piezoelectric tiles.

The piezoelectric harvester can be coupled with other types of harvester to amplify the energy output. For instance, a piezoelectric-thermoelectric hybrid energy harvester can collect energy from two different types of sources: thermal and kinetic [45]. By harvesting from two different sources at the same time, the total harvested energy is increased. Even when one of the energy sources is not present, harvesting energy from another source continues and it allows for an uninterrupted energy collection [45]. Therefore, a hybrid energy harvester is more beneficial.

In conclusion, pedestrian traffic, foot pressure, tile shape and energy harvester model are key players in optimizing the output of piezoelectric floor tile.

2.6: Power Generation and Storage

Electrical energy storage is the process of converting energy from one form (usually electrical) into a storable form that can be held in a medium and converted back to electricity to use [46]. There are a variety of options for storing energy: including compressed air, pumped hydro, or supercapacitors. However, our project will most likely involve the use of batteries, known to be excellent for integration in renewable energy collection [47]. Their energy transfer does not generate carbon emissions, they are flexible in power and energy characteristics, have long cycle lives, and are low maintenance, all of which align with the ideals of our project.

Batteries have a primary use as support for large scale renewable energy storage, such as solar or wind, because they stabilize and regulate frequency in order to interface the system's output with the rest of the grid [48]. One study also found batteries had the lowest power interface costs among energy storage systems [49], which means that it is cheapest for batteries (specifically Nickel-Cadmium batteries) to convert the electricity they generate into storable energy.

This leads to an important point, there are a wide variety of battery types available to use in our study. We might be recommended to look into flow batteries, especially the vanadium redox flow battery, as those are ideal for smaller battery energy storage systems [48] and have lower levelized costs of delivery (which involves a ratio between the storage system's cost and its electrical output over its lifetime) [50]. Alternatively, Lead-Acid batteries score consistently for bulk energy storage, distributive storage, and power quality [51].

However, while batteries do not produce carbon dioxide directly through their use, they can have a variety of negative environmental impacts, which in part depend on the type of battery used. For instance, while Nickel-Cadmium batteries are highly effective at storing electrical energy, the cadmium they contain is highly toxic [52] and notably damaging to aquatic environments. They have been replaced with Lithium-Ion batteries in most places, noted for their "high energy efficiency, high power density, and environmental friendliness" [53]. Specifically LFP ($LiFePO4$) batteries are widely praised for their low cost, high safety, and long cycle lives. These traits align strongly with our project's goals of creating a relatively inexpensive and long lasting form of energy generation and storage. The carbon footprint of Li-Ion batteries is further reduced because they can be recycled [54]. The Lithium-Ion battery recycling industry has been expanding, as the need grows with the increase in electric vehicles in use. As such, when the life cycle of our design does finally complete, the user should be able to return the battery to a designated location to minimize the environmental impact.

2.7: Piezoelectric Equations

This project will use various piezoelectric equations to make important calculations for the creation of tiles. Here are some equations we encountered in our research that we have deemed potentially valuable as we construct our own models and perform experiments.

The equation for strain in a piezoelectric material is as follows:

$$S_p = s^E_{pq} T_q + d_{kp} E_k$$

In this equation, S is the strain, T is the stress (pascals), E is the electric field (volts/meter), s is the elastic compliance in a constant electric field (1/pascal), and d is the piezoelectric constant (meter/volt).

The equation for electric displacement in a piezoelectric material is as follows:

$$D_i = d_{iq} T_q + \varepsilon^T_{ik} E_k$$

In this equation, E is the electric field (volts/meter), T is the stress (pascals), D is the electric displacement (Coulombs/meter^2), d is the piezoelectric constant (meter/volt), and ε is the permittivity of the material at constant stress (Farad/meter).

The equation for charge in a piezoelectric material is as follows:

$$Q = -\iint D_3 dA = -\frac{1}{t_p}\iiint D_3 d\Psi = -\frac{d_{31}}{t_p}\iiint T_1 d\Psi + \frac{\varepsilon_{33}^T A}{t_p}\cdot V$$

$$= -\frac{d_{31}}{t_p}\iiint T_1 d\Psi + C_p V$$

where Ψ is volume , $V = -\int E_3 \times dz$, and defined $C_p = \frac{\varepsilon_{33}^T A}{t_p}$

In this equation, Q is the charge (coulombs), t is time (seconds), T is the stress (pascals), D is the electric displacement (Coulombs/meter^2), d is the piezoelectric constant (meter/volt), and ε is the permittivity of the material at constant stress (Farad/meter). All other components are explained in the image.

Magnetic induction may be used in components to increase efficiency. The equation for magnetic induction in a piezoelectric material is as follows:

$$B = d_{33}^{*}\sigma + \mu^{\sigma} H$$

In this equation, B is the magnetic induction (tesla), Sigma is the compress stress (pascals), Mu is the relative magnetic permeability at a constant stress (Henry/meter), H is the magnetic field (tesla), and d33 is the parameter of the magneto-mechanical effect:

$$d_{33}^{*} = \partial B / \partial \sigma |_{H=const}$$

2.8: Summary

Our project will be developing the underutilized clean energy source of piezoelectricity. The piezoelectric effect allows for the conversion between mechanical and electrical energy, and is exhibited in a variety of materials. Each classification of material has its own properties, with unique benefits and drawbacks.

The use of piezoelectric materials to generate electricity is currently very limited. Therefore, this study is meant to expand on the knowledge of piezoelectric tiles for energy harvesting. It will also focus on optimizing the performance of existing piezoelectric technology.

The research will primarily focus on piezoelectric materials integrated in floor tiles, to harvest energy from pedestrians walking across the surface. The technology may incorporate additional energy-generating technologies, such as solar panels, or rely on an alternative source of mechanical motion.

There are other ways to increase the efficiency of the piezoelectric device. For example, the floor tiles should be strategically placed to maximize energy collection, as well as specifically designed to harvest as much energy per footstep as possible. Lastly, the energy harvesting mechanism can be improved to minimize the wasted energy in the conversion process.

Lastly, the group will need to decide on a method of storing the collected energy. Batteries provide an attractive option, due to their variety of properties as well as their history of being integrated into large-scale power generators. However, the team will have to remain conscious of their dedication to environmental consciousness and ease of access to the design, through low maintenance and simple installation.

Chapter 3: Methodology

3.1: Research Questions

In order to effectively develop the new technologies required to realize Team PISO's end goal of making foot traffic a viable energy source, the team has developed three research questions to guide our studies and focus our efforts:

1. How can existing piezoelectric energy harvesting technology be improved?
2. How can we optimize the shape, design, and materials used to comprise the tile to maximize energy production?
3. Which materials can the components be fabricated from in order to minimize environmental impact?

These questions will be used as a baseline gauge of progress and as a guideline for planning future steps in the project and where to focus for maximum effect. Throughout the entire project, consideration will also be set aside for the question of equity. Specifically, PISO will consider how this technology improves or detracts from the lives of both the general public and specific demographics?

While not necessarily a guiding question for research, this question is important to keep in mind as the project continues, in order to avoid straying from the end goal or focusing too much on one avenue of testing and creating a substandard final result with minimal applications in the real world. Every step of the way, the team must consider how the item that they're developing will behave when exposed to the real world.

Within the study, the overarching question or thought is whether it is possible for us to improve on the technology for piezoelectric floor tiles in order to make them viable sources of energy. In order to both analyze and answer this question, the team will need to conduct multiple experiments to collect both quantitative and qualitative data to determine the effectiveness of the technology. Information such as energy yield, energy lost to nonconservative forces, the damping effect of hysteresis, the maximum acceptable “give” of the tile, and the significance of Curie’s Law will need to be measured or calculated in order to develop an effective design, among many other factors.

3.2: Lab Experimentation and Physical Testing

Due to the fact that our project is centered around engineering and development, the proposed research design for this project would consist primarily of lab research and conducting experiments on varying materials and mechanisms in order to optimize the prototype. Preliminary testing and analysis will involve comparing multiple different piezoelectric materials against each other in categories such as stiffness, Curie temperature, density, malleability, price, and piezoelectric constant in various circumstances.

In order to collect data on the piezoelectric constants and energy outputs of the materials, a hydraulic press will be used to apply a specific amount of force to a piezoelectric component to gauge its effectiveness. This method could be used not only to test different piezoelectric materials, but also to test different configurations and applications of piezoelectric components, and so will likely be used at multiple points throughout the testing process.

This project may also require experiments utilizing human testing. These experiments would involve having volunteers step on prototype components, in order to observe the tiles’ strength in practice, as well as to gauge the user experience. It is crucial to note, however, that human testing would potentially be used to test PISO's tile design; it would not be to test power output, since human footsteps vary widely in applied force and impulse, even when considering a single person. Power output testing will be tested with a hydraulic press or similar design, in order to collect more accurate quantitative data.

The data that is required in order to thoroughly answer the research questions formulated starts with the amount of energy that can be accumulated from both a single footstep and a single piezoelectric floor tile. This data is essential to the process of manufacturing a prototype of our piezoelectric floor tile. Data on the various materials that can be used to build the tile is also needed to find the ideal material. Lastly, data on optimal models for storing energy either onsite or offsite will be crucial for the storage of the energy produced for the piezoelectric tile.

In the physical experiments, we would test properties such as maximum current output, maximum voltage output, and overall durability of various piezoelectric materials. Lastly, in order to collect data on an optimal model for storing the generated energy, we would create another experiment in which we test different designs for storing the energy in batteries, whether the energy can be stored more effectively onsite or at an offsite location, measure how efficient the storage system is, and the overall strength of the design. Once we collect the basis data on the various methods of construction, power storage, and efficiency, we can begin design and construction and testing of the prototype. Of course, as we construct numerous models of the tile, we will learn more about which materials, energy storage methods, and circuitry cooperate best with each attempt, and continuously work to produce an effective prototype.

3.3: Data Collection Through Simulations

In order to fully answer our research questions, we need to consider additional data, like the number of steps received by a single floor tile in varying structures, the energy that can be collected from those tiles, compatible materials for the floor tiles, and both a feasible and optimal way to store the amassed energy. To find and collect data on pedestrian patterns and optimal energy consumption we would need to formulate algorithms and run simulations.

We can also obtain this data from online surveys. Both pre-existing studies on the materials and their applications as well as conducting our own testing can provide us with data on the best materials to use and find a favorable method of storing the energy collected. Research more on the subject can certainly help with collecting data on the best ways to store the energy being generated from the floor tiles.

In terms of collecting data to determine the number of steps per tile in a given time period, there are a few methods that can be used. The first method would be using a simulation of an area with high pedestrian traffic to see how often people walk through a specified section. Alternatively, we could fabricate an area on the University of Maryland's campus to track how many people walk over a certain area at a given time. For collecting data on the different materials that can be used, we would need to construct a physical experiment (as referred to above) in which we produce floor tiles utilizing different materials that all exhibit the piezoelectric effect.

Simulations would also be utilized in the form of modeling designs using engineering softwares. This way, we can create digital prototype blueprints that we can refer to in order to have a uniform design. Because piezoelectric materials are also generally very expensive, the ability to digitally consider different designs before physically modeling them would save us hundreds of dollars, as well as resources and time. Once the prototype models are made on the computer, digital stress and strain testing can also provide an idea of the real product's durability. We expect to use computer software to configure circuitry for the power storage elements, as well as solving the aforementioned equations for optimum power input.

3.4: Specialized Subteams for Optimum Research

A chosen design has yet to be selected for this project, but both qualitative and quantitative data as well as information collected from literature reviews will certainly influence the selection of the design that is best suited for this project. The formal decision of which design to continue with will be made either during the course of this current semester or the following semester. When the design is selected, it will be chosen with regard to its output, efficiency, financial feasibility, durability and longevity. This will be done to not only ensure that the device functions properly and is capable of generating electricity, but to also ensure its feasibility for development and widespread use.

Once the design is generally decided upon, the team will most likely separate into two subteams, one subteam focused on the electronics and circuitry of the chosen design and another subteam focused on selecting the optimal material and on the construction of the piezoelectric floor tile. The subteam concentrating on the electronics and circuitry of the design will approach the project by combining electrical components in order to make the piezoelectric tile as coherent and efficient as possible. The subteam concentrating on the construction and material of the piezoelectric tile will approach the project by designing the structure for the tile and integrating the circuitry component into the final build. Together the two subteams will produce a final design that synthesizes the approaches of both subteams in order to maximize the ability of the tile to generate power.

3.5: What We Hope To Accomplish

Based on the state of our current research, the findings of our project would be most beneficial to the fields of material sciences and mechanical engineering, as piezoelectric materials in floor tiles is a relatively new concept that has yet to be widely implemented in the general public. With this, the team's ultimate goal is to successfully coalesce piezoelectric floor tiles and the technology it possesses into the general public. By determining a specific design for the piezoelectric floor tile, we can conduct various experiments and research in the realm of utilizing piezoelectric materials in a way that generates energy from not only pressure but through pedestrian traffic. This is a somewhat new application of the piezoelectric technology that still has a lot of unknown variables that need to be studied.

The anticipated results of this research study consists of the development and creation of a functional prototype of the piezoelectric floor tile or pressure plate, which would collect and either store the energy accumulated onsite or transfer the energy to be stored at an offsite location. Additionally, we anticipate having the piezoelectric tile estimate how long it could be expected to perform. We also hope to formulate how much it would cost to put our optimal piezoelectric tile into action. If our initial calculations indicate that a reliable source of energy from footsteps is infeasible, we may need to reevaluate our plans to pursue a different route.

In the best case scenario, Team PISO's research will yield a novel design for collecting vibrational energy with enough efficiency to make the process as efficient as comparable clean sources of energy, such as wind or solar. In this case, Team PISO has the potential to advance the field of renewable energy and bring the concept of piezoelectric energy generation one step closer to commercial viability. Our research could ultimately lower the cost of energy for both businesses and residents in major metropolitan areas, as well as encourage further research into applications of piezoelectric materials.

Most likely, PISO's research will result in a design whose efficiency may not be up to par with other clean energies, but which may have the potential to be refined and iterated upon by future research in order to further investigate the energy source. In the event that Team PISO's efforts do not result in a working prototype or a viable energy harvesting method, its findings will still be useful to future researchers both as a summary of piezoelectric energy harvesting, and as a chronicle of what avenues of research do have already been explored and found to be not worthwhile. In any case, our research will serve to advance fields such as electrical engineering, sustainable energy, materials science, and more.

Appendices

Appendix A: Glossary

Arctic Amplification - the phenomenon that occurs due to the excess of carbon dioxide in the atmosphere; any change in the planet's net temperature balance will have a pronounced effect in the poles

British thermal unit - a unit of heat, formally defined as the amount of heat needed to increase the temperature of a single pound of water by one degree fahrenheit

Coupling Mode - a method of examining the interconnectedness of vibrational systems, either mechanical, electrical, or more, within time or space

Intermittency - is capable of stopping for certain periods of time and then alternately ceasing and starting once again

Dynamo - an electrical generator that utilizes electromagnetism in order to create direct current

Magnetic Induction - the creation of voltage in an electrical conductor within a magnetic field

Piezoelectric Charge Coefficient - The conversion rate between newtons of force to coulombs of charge

Photovoltaic Cells - also known as a solar cell, a device that transforms solar energy, or the energy from light, into electrical energy utilizing the photovoltaic effect

Piezoelectric Effect - the ability of piezoelectric materials to create electricity due to mechanical stress

Appendix B: Budget

Expenses from materials and services were estimated based on the components Team PISO predicts it will require for its research. These values are not final and are subject to change.

Object/material:	**Price (dollars):**
Arduino	$100
Circuitry	$100
Sheet metal	$2,500
PZT(J)/piezo mats	$1,000
Misc. materials	$2,500
Pavegen Tile	$480
Software (3D modeling, simulations)	$2,000
Conferencing	$1,750
Travel	$10,500
Total:	**$20,930**
Total without travel:	**$10,430**

Appendix C: Timeline

- **Spring 2021:**
  - Thesis proposal
  - Materials acquisition
  - Get a lab
  - Begin testing and data collection
- **Autumn 2021:**
  - Data collection (Materials and battery work)
  - Finalize outline
  - Do-Good Showcase
- **Spring 2022:**
  - Data collection (Construction and Design of Prototype)
  - Presentation at Undergraduate Research Day
- **Autumn 2022:**
  - Data analysis
  - Prepare thesis
- **Spring 2023:**
  - Finalize thesis
  - Thesis conference
  - Citation ceremony

Appendix D: Equity-Impact Analysis

Team PISO's research, if successful in developing an efficient method of collecting energy, would affect the accessibility, and by extension, price, of energy. This would likely make energy cheaper for those living wherever piezoelectric tiles are put into practice, and thus will indirectly benefit people of the lower class by reducing their expenses.

Depending on the requirements of the tile design and the implementation of those tiles, the terrain underfoot created by the tiles may be more malleable than wood, stone, or concrete. This would affect people using wheeled vehicles, such as wheelchairs, bikes or powered scooters, by making the terrain slightly harder to cross. However, it must be noted that this impact is dependent on the final tile design, and so is not set in stone and can be avoided.

Additionally, piezoelectric tiles can be an incentive to encourage walkable urbanism, which tracks how many errands can be accomplished on foot. Walkable urbanism is correlated with higher per-capita GDPs [55]. According to analysis conducted by George Washington University, encouraging walkable urbanism is a potential strategy for regional economic development [55]. Hence, piezoelectric tiles can be an important factor in contributing towards economic development.

Economic development also brings about gentrification as a consequence of higher land value, and so the implementation of piezoelectric tiles in urban areas could contribute to a higher rate of gentrification. This would disproportionately affect the resident lower-class population by raising rent prices beyond what some people can afford, requiring many of them to find a home elsewhere. Thus, widespread use of piezoelectric tiles could contribute to a rise in homelessness and a widening of the wealth gap.

Works Cited

[1] A. (ORCID:000000025371917X) Dai, D. Luo, M. Song, and J. Liu, “Arctic amplification is caused by sea-ice loss under increasing CO2,” *Nat. Commun.*, vol. 10, no. 1, Jan. 2019, doi: 10.1038/s41467-018-07954-9.

[3] Y. (ORCID:0000000326670697) Zou, Y. (ORCID:000000272902551) Wang, Z. (ORCID:0000000159825056) Xie, H. Wang, and P. J. Rasch, “Atmospheric teleconnection processes linking winter air stagnation and haze extremes in China with regional Arctic sea ice decline,” *Atmospheric Chem. Phys. Online*, vol. 20, no. 8, Art. no. PNNL-SA-149191, Apr. 2020, doi: 10.5194/acp-20-4999-2020.

[4] “U.S. renewable energy consumption surpasses coal for the first time in over 130 years - Today in Energy - U.S. Energy Information Administration (EIA).” https://www.eia.gov/todayinenergy/detail.php?id=43895 (accessed Oct. 26, 2020).

[5] “Renewable energy explained - U.S. Energy Information Administration (EIA).” https://www.eia.gov/energyexplained/renewable-sources/ (accessed Oct. 26, 2020).

[6] “Nuclear Power Economics | Nuclear Energy Costs - World Nuclear Association.” https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx (accessed Oct. 07, 2020).

[7] “Nuclear Power Cost | Union of Concerned Scientists.” https://www.ucsusa.org/resources/nuclear-power-cost (accessed Oct. 07, 2020).

[8] S. Bukhary, S. Ahmad, and J. Batista, “Analyzing land and water requirements for solar deployment in the Southwestern United States,” *Renew. Sustain. Energy Rev.*, vol. 82, pp. 3288–3305, Feb. 2018, doi: 10.1016/j.rser.2017.10.016.

[9] “Renewable Energy and Energy Efficiency,” *Western Resource Advocates*. https://westernresourceadvocates.org/clean-energy/renewable-energy/ (accessed Oct. 26, 2020).

[10] “What Are The Most Efficient Forms of Renewable Energy,” *Born to Engineer*, Aug. 02, 2017. https://www.borntoengineer.com/efficient-form-renewable-energy (accessed Oct. 26, 2020).

[11] “Environmental Impacts of Renewable Energy Technologies | Union of Concerned Scientists.” https://www.ucsusa.org/resources/environmental-impacts-renewable-energy-technologies (accessed Oct. 26, 2020).

[12] “Review of Power Quality Issues in Solar and Wind Energy,” *Mater. Today Proc.*, vol. 24, pp. 2137–2143, Jan. 2020, doi: 10.1016/j.matpr.2020.03.670.

[13] “How to Start a Solar Farm,” *Cam Solar*. https://www.gocamsolar.com/blog/how-start-solar-farm (accessed Oct. 26, 2020).

[14] A. Badel, A. Benayad, E. Lefeuvre, L. Lebrun, C. Richard, and D. Guyomar, “Single crystals and nonlinear process for outstanding vibration-powered electrical generators,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 53, no. 4, pp. 673–684, Apr. 2006, doi: 10.1109/TUFFC.2006.1621494.

[15] “Solar Panel Cost In 2020 [State By State Data] | EnergySage,” *Solar News*, Jul. 02, 2020. http://news.energysage.com/how-much-does-the-average-solar-panel-installation-cost-in-the-u-s/ (accessed Oct. 26, 2020).

[16] A. Toprak and O. Tigli, “Piezoelectric energy harvesting: State-of-the-art and challenges,” *Appl. Phys. Rev.*, vol. 1, no. 3, p. 031104, Sep. 2014, doi: 10.1063/1.4896166.

[17] “Tech: Pavegen – the technology behind the tile | EG News,” *EGi*. https://www.egi.co.uk/news/pavegens-the-technology-behind-the-tile/ (accessed Oct. 14, 2020).

[18] “Piezoelectric Tiles Light the Way for Kennedy Space Center Visitors,” *Gadget Reviewed*, Jan. 10, 2018. https://gadgetreviewed.com/piezoelectric-tiles-light-way-kennedy-space-center-visitors/ (accessed Oct. 26, 2020).

[19] “Power Generating Floor Tested at JR Tokyo Train Station | JFS Japan for Sustainability,” *JFS Japan for Sustainability*. news_id027023.html (accessed Oct. 26, 2020).

[20] H. Li, C. Tian, and Z. D. Deng, “Energy harvesting from low frequency applications using piezoelectric materials,” *Appl. Phys. Rev.*, vol. 1, no. 4, p. 041301, Nov. 2014, doi: 10.1063/1.4900845.

[21] D. Damjanovic, “Contributions to the Piezoelectric Effect in Ferroelectric Single Crystals and Ceramics,” *J. Am. Ceram. Soc.*, vol. 88, no. 10, pp. 2663–2676, 2005, doi: 10.1111/j.1551-2916.2005.00671.x.

[22] J. Wu, “Perovskite lead-free piezoelectric ceramics,” *J. Appl. Phys.*, vol. 127, no. 19, pp. 1–13, May 2020, doi: 10.1063/5.0006261.

[23] A. Eddiai, M. Meddad, R. Farhan, M. Mazroui, M. Rguiti, and D. Guyomar, “Using PVDF piezoelectric polymers to maximize power harvested by mechanical structure,” *Superlattices Microstruct.*, vol. 127, pp. 20–26, Mar. 2019, doi: 10.1016/j.spmi.2018.03.044.

[24] R. Tavares and M. Ruderman, “Energy harvesting using piezoelectric transducers for suspension systems☆,” *Mechatronics*, vol. 65, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0957415819301266.

[25] “Piezoelectric Charge Constants.” https://www.americanpiezo.com/knowledge-center/piezo-theory/piezoelectric-constants.html (accessed Oct. 24, 2020).

[26] H. Sodano, D. Inman, and G. Park, “A Review of Power Harvesting from Vibration using Piezoelectric Materials,” *Sage Publ.*, vol. 36, pp. 197–205, May 2004, doi: 10.1177/0583102404043275.

[27] S. Thomas R. and Z. Shujun J., “Lead-free piezoelectric ceramics: Alternatives for PZT?,” *Springer*, 2007.

[28] P. K. Panda, “Review: environmentally friendly lead-free piezoelectric materials,” *Springer*, Jul. 2009, doi: 10.1007/210853-009-3643-0.

[29] I. M. Reaney *et al.*, “Life cycle assessment and environmental profile evaluation of lead free piezeletrics in comparison with lead zirconate titanate,” *J. Eur. Ceram. Soc.*, vol. 38, 2018.

[30] S. Zhang, R. Xia, L. Lebrun, D. Anderson, and T. Shrout, “Piezoelectric materials for high power, high temperature applications,” *Elsevier*, Jun. 2005, doi: 10.1016/j.matlet.2005.06.016.

[31] M. Goldfarb and L. D. Jones, “On the Efficiency of Electric Power Generation With Piezoelectric Ceramic,” *J. Dyn. Syst. Meas. Control*, vol. 121, no. 3, pp. 566–571, Sep. 1999, doi: 10.1115/1.2802517.

[32] X. Chen, T. Yang, W. Wang, and X. Yao, “Vibration energy harvesting with a clamped piezoelectric circular diaphragm,” *Ceram. Int.*, vol. 38.

[33] J. Baker, S. Roundy, and P. Wright, “Alternative Geometries for Increasing Power Density in Vibration Energy Scavenging for Wireless Sensor Networks,” presented at the 3rd International Energy Conversion Engineering Conference, San Francisco, California, Aug. 2005, doi: 10.2514/6.2005-5617.

[34] Z. Xu, W. Wang, J. Xie, Z. Xu, M. Zhou, and H. Yang, “An Impact-Based Frequency Up-Converting Hybrid Vibration Energy Harvester for Low Frequency Application.”

[35] S. Chang, S. Ham, S. Kim, D. Suh, and H. Kim, “Ubi-Floor: Design and Pilot Implementation of an Interactive Floor System,” in *2010 Second International Conference on Intelligent Human-Machine Systems and Cybernetics*, Aug. 2010, vol. 2, pp. 290–293,

doi: 10.1109/IHMSC.2010.172.
[36] J. D. Mullen, “Maximizing power generation in and distributing force amongst piezoelectric generators,” US7304416B2, Dec. 04, 2007.
[37] B. Kaur, A. Agnihotri, D. Thapar, and N. Arora, “Piezoelectric Energy Harvester Design and Power Conditioning with Solar Integration,” in *2019 3rd International Conference on Electronics, Materials Engineering Nano-Technology (IEMENTech)*, Aug. 2019, pp. 1–6, doi: 10.1109/IEMENTech48150.2019.8981015.
[38] B. Yan, C. Zhang, L. Li, H. Zhang, and S. Deng, “Design and construction of magnetostrictive energy harvester for power generating floor systems,” in *2015 18th International Conference on Electrical Machines and Systems (ICEMS)*, Oct. 2015, pp. 409–412, doi: 10.1109/ICEMS.2015.7385068.
[39] H. Zhao, Y. Tao, Y. Niu, and J. Ling, “Harvesting energy from asphalt pavement by piezoelectric generator,” *J. Wuhan Univ. Technol.-Mater Sci Ed*, vol. 29, no. 5, pp. 933–937, Oct. 2014, doi: 10.1007/s11595-014-1023-3.
[40] M. J. Hessert, M. Vyas, J. Leach, K. Hu, L. A. Lipsitz, and V. Novak, “Foot pressure distribution during walking in young and old adults,” *BMC Geriatr.*, vol. 5, p. 8, May 2005, doi: 10.1186/1471-2318-5-8.
[41] Winger, Seth, “Piezoelectricity From Dancing,” Oct. 24, 2010. http://large.stanford.edu/courses/2010/ph240/winger1/ (accessed Sep. 28, 2020).
[42] “These tiles could be the next step toward a sustainable future.” https://www.ipwea.org/newzealand/blogs/intouch/2016/06/23/pavegen-tiles-could-be-the-next-step-toward-sustainable-future (accessed Oct. 26, 2020).
[43] A. M. Elhalwagy, M. Y. M. Ghoneem, and M. Elhadidi, “Feasibility Study for Using Piezoelectric Energy Harvesting Floor in Buildings’ Interior Spaces,” *Energy Procedia*, vol. 115, pp. 114–126, Jun. 2017, doi: 10.1016/j.egypro.2017.05.012.
[44] “Pavegen - Global leader in harvesting energy and data from footfall.,” *Pavegen*. https://pavegen.com/ (accessed Oct. 14, 2020).
[45] Y. Oh *et al.*, “Flexible Energy Harvester with Piezoelectric and Thermoelectric Hybrid Mechanisms for Sustainable Harvesting,” *Int. J. Precis. Eng. Manuf.-Green Technol.*, vol. 6, no. 4, pp. 691–698, Aug. 2019, doi: 10.1007/s40684-019-00132-2.
[46] X. Luo, J. Wang, M. Dooner, and J. Clarke, “Overview of current development in electrical energy storage technologies and the application potential in power system operation,” *Appl. Energy*, vol. 137, pp. 511–536, Jan. 2015, doi: 10.1016/j.apenergy.2014.09.081.
[47] B. Dunn, H. Kamath, and J.-M. Tarascon, “Electrical Energy Storage for the Grid: A Battery of Choices,” *Science*, vol. 334, no. 6058, pp. 928–935, Nov. 2011, doi: 10.1126/science.1212741.
[48] A. Poullikkas, “A comparative overview of large-scale battery systems for electricity storage,” *Renew. Sustain. Energy Rev.*, vol. 27, pp. 778–788, Nov. 2013, doi: 10.1016/j.rser.2013.07.017.
[49] B. Zakeri and S. Syri, “Electrical energy storage systems: A comparative life cycle cost analysis,” *Renew. Sustain. Energy Rev.*, vol. 42, pp. 569–596, Feb. 2015, doi: 10.1016/j.rser.2014.10.011.
[50] C. S. Lai and M. D. McCulloch, “Levelized cost of electricity for solar photovoltaic and electrical energy storage,” *Appl. Energy*, vol. 190, pp. 191–203, Mar. 2017, doi: 10.1016/j.apenergy.2016.12.153.
[51] H. L. Ferreira, R. Garde, G. Fulli, W. Kling, and J. P. Lopes, “Characterisation of electrical energy storage technologies,” *Energy*, vol. 53, pp. 288–298, May 2013, doi: 10.1016/j.energy.2013.02.037.
[52] “MEPs ban cadmium from power tool batteries and mercury from button cells | News | European Parliament,” Oct. 10, 2013. https://www.europarl.europa.eu/news/en/press-room/20131004IPR21519/meps-ban-cadmi

um-from-power-tool-batteries-and-mercury-from-button-cells (accessed Oct. 26, 2020).
[53] "Sustainable Recycling Technology for Li-Ion Batteries and Beyond: Challenges and Future Prospects | Chemical Reviews." https://pubs.acs.org/doi/10.1021/acs.chemrev.9b00535 (accessed Oct. 26, 2020).
[54] "Effective Recycling of Electric-vehicle Batteries | SpringerLink." https://link.springer.com/article/10.1007/s38311-018-0139-z (accessed Oct. 26, 2020).
[55] C. B. Leinberger and P. Lynch, "Ranking Walkable Urbanism in America's Largest Metros," p. 36.