Investigating the Efficiency of Piezoelectric Transducers

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Introduction

Piezoelectric devices can be found in our everyday lives but often go unnoticed by most people even though they serve vital applications in clocks, microphones, sensors, etc. Lighters no longer use flint for ignition, but instead a small electric spark. This struck me as strange as if a battery were used, it would not only be hazardous, but the battery would also eventually be discharged. By taking apart a lighter and looking into how the spark is generated, it surprised me that it was from a small switch. With further research, I discovered the piezoelectric effect, which can convert mechanical work into electrical energy. Though these tiny devices appear to be very space efficient, there seems to be very little to no use of them as a means of energy production. So, I wanted to determine the efficiency of piezoelectric transducers and compare it with other methods of energy production to see if they can be implemented on a larger scale as a source of renewable energy.

Research Question: How efficient are piezoelectric materials in converting mechanical energy into electrical energy?

Background Information

Piezoelectric Effect

The piezoelectric effect is a phenomenon demonstrated by certain crystalline structures and can be defined as a reversible effect that can convert mechanical stress into electrical energy (Damjanovic, 2005, 300-309). The effect is based on principles of polar-covalent bonds, and the creation of dipoles within a crystalline molecular structure. Though natural materials which demonstrate piezoelectric properties are mostly limited to quartz crystals, there are a variety of piezoelectric manmade materials, more commonly known as ferroelectric ceramics.

Silicon dioxide, more commonly known as quartz, is a substance formed from oxygen and silicon atoms in a tetrahedral shape (figure 1). However, when examined from a certain angle, it can appear hexagonal formed from alternating oxygen and silicon atoms (figure 2).

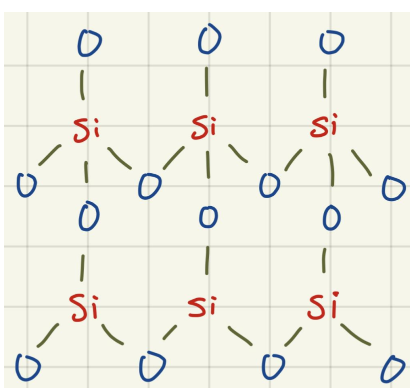


Figure 1. Tetrahedral network covalent structure of quartz crystal

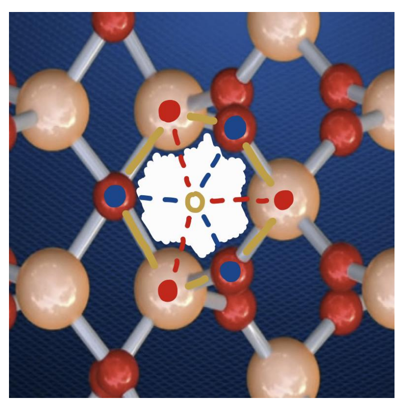


Figure 2. Hexagonal shape of quartz crystal from specific angle

The electronegativity difference between oxygen and silicon is 1.54, making the bond polar covalent, hence an uneven sharing of electrons in the bond. Oxygen has a higher electronegativity, meaning that it has a greater attraction toward electrons. This is due to oxygen atoms having more protons in comparison to silicon atoms, therefore having a greater positive charge at the nucleus. Thus, in a bond between an oxygen atom and a silicon atom, the shared electron lies closer to the oxygen atom. Oxygen hence attains a slight negative charge, and silicon has a slight negative charge.

In the hexagonal structure found in quartz, the slightly negative and positive charges cancel as the charge centres overlap, as described in figure 3. However, if the crystal were put under mechanical stress, the structure would be distorted and the charges would no longer cancel out. A dipole would be formed between the two varying charge centres and an electromotive force (EMF) would be produced. (figure 4) The EMF within a single "cell" is minuscule, however, when large amounts are put together in a crystal structure, there exists enough charge (electrical output) to produce the EMF.

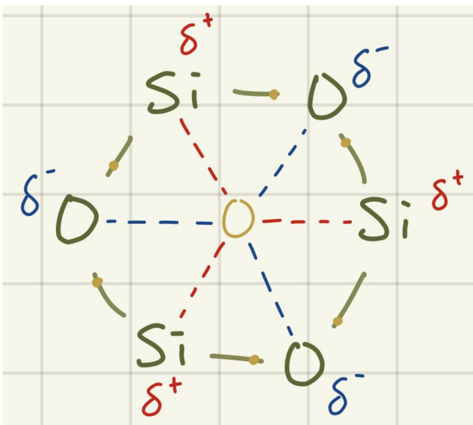


Figure 3. Diagram of hexagonal shape of quartz crystal in a neutral state

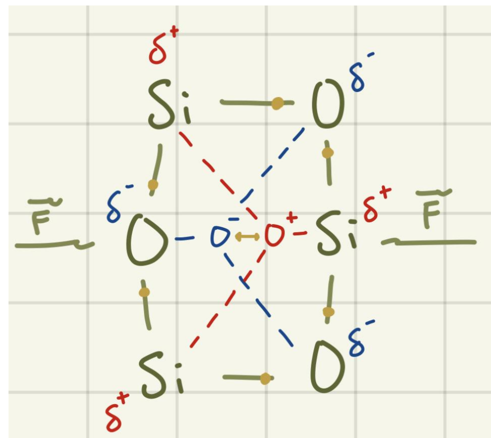
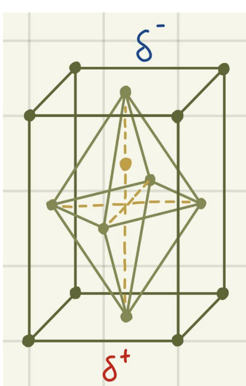
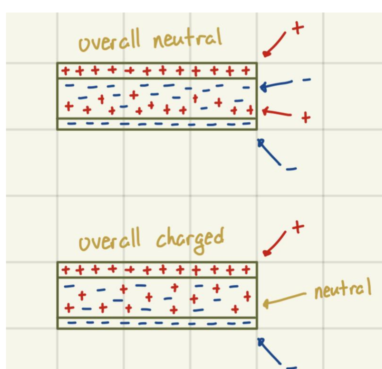


Figure 4. Diagram of hexagonal shape of quartz crystal being compressed forming a dipole

Quartz has a major flaw in that the force must be applied from a very specific angle. Today, man-made Ferro-ceramics have become the industry standard with PZT (lead zirconate titanate) ceramics being the most widely used. The structure is quite different from quartz crystal, but they function similarly. PZT can also be viewed as a large number of 'cells' put together, however, these cells exist naturally in a charged state (figure 5). The surfaces of each piece of ceramic, naturally tend towards neutrality and collect charges resulting in the entire ceramic having a net neutral charge. (figure 6). When force is applied and the material is compressed, the dipoles within each PZT 'cell' are neutralised and the entire ceramic gains an EMF (figure 7).





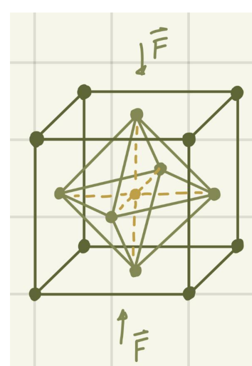


Figure 5. Molecular structure of piezoelectric ceramic in its charged rest state

Figure 6. Diagram of a piece of piezoelectric ceramic in its different charge states

Figure 7. Molecular structure of piezoelectric ceramic when mechanical force is applied

A piezoelectric igniter containing a PZT ceramic (figure 8) will be experimented with to determine the efficiency of piezoelectric transducers. Where the inputted mechanical work will be compared with the outputted electrical work to estimate a value for efficiency. The ignitor functions using a spring mechanism which is charged up and released to hit the ceramic, applying mechanical stress on it and producing an electrical spark.

Figure 8. Piezoelectric igniter used in this investigation

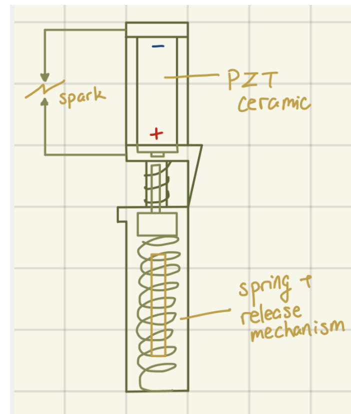


Figure 9. Diagram of internals of piezoelectric igniter

Design

Hypothesis: Due to the low application and implementation of piezoelectric transducers as a major source of energy production, the efficiency of the piezoelectric effect should be relatively low, proving as an inefficient and ineffective method of generating electricity.

Variables:

Controlled variable(s): Temperature, pressure, resistance of electrical components, resistance of resistor, mechanical force applied

Dependent variable(s): Voltage produced

Unknown variable(s): Work done by spring, work done by electric circuit

Apparatus:

- Piezoelectric switch
- Oscilloscope
- Force gauge
- 2 ohm resistor
- Ruler
- Wires

Methodology:

1. Use a ruler to measure the length of the piezoelectric switch when it is fully extended and when it is fully contracted. Record readings for later calculations.
2. Set the force gauge to take readings for 30 seconds with a frequency of 20 readings per second.

3. Place the force gauge on a level surface, start the reading and activate the piezoelectric switch on top of the force gauge 5 times. Record readings for later calculation.
4. Create a circuit where the oscilloscope, the resistor, and the piezoelectric igniter are all connected in parallel

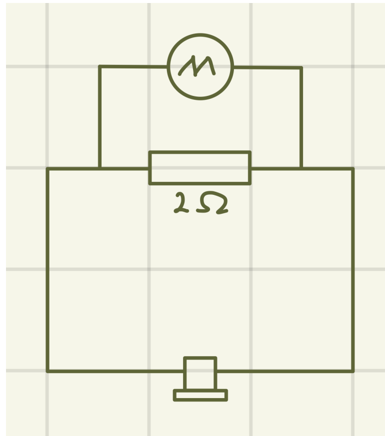


Figure 10. Diagram of electrical apparatus used

5. Set the oscilloscope to appropriate settings (1V, 1mS)
6. Start recording the screen of the oscilloscope.
7. Activate the piezoelectric switch 5 times.
8. Stop the recording of the oscilloscope, and parse through the captured readings for later use.
9. Return equipment to their respective positions to avoid the loss or damage of lab equipment.

To prevent potential electrical shocks or sparks, wear proper insulating lab equipment when performing experiments (rubber gloves, remove metal).

Raw Accumulated Data

Length of piezoelectric switch when fully extended: 3.9 +- 0.05 cm
Length of piezoelectric switch when fully contracted: 3.4 +- 0.05 cm

Due to the large number of data points accumulated in the readings for the force gauge, only the initial and final readings and the force of the largest magnitude for each press will be displayed as those are the only data points which provide useful information. The initial and final force readings are taken to account for zero error and the innate force is consistent throughout the experiment.

Table 1. Captured initial and final readings and readings of highest magnitude for each trial

Trial Number	Largest force recorded (+/- 0.01) / N
1	-25.58
2	-25.39
3	-25.17
4	-24.26
5	-24.67

(There existed a rest reading of -0.62, which will be considered for zero error)

Captured graphs produced by oscilloscope through 5 trials

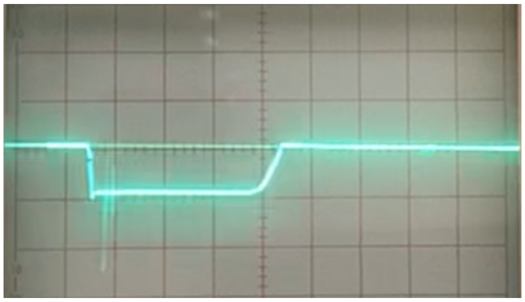


Figure 11. Voltage - time graph of trial 1

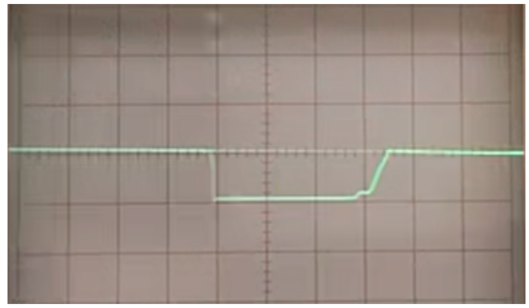


Figure 12. Voltage - time graph of trial 2

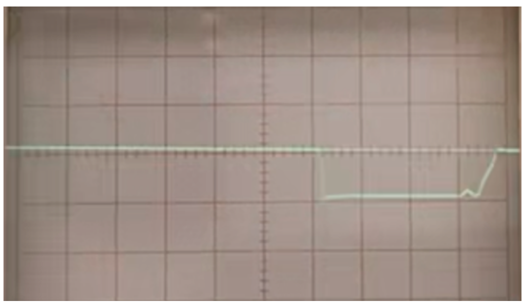


Figure 13. Voltage - time graph of trial 3

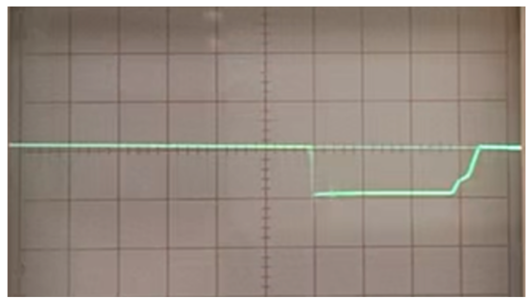


Figure 14. Voltage - time graph of trial 4

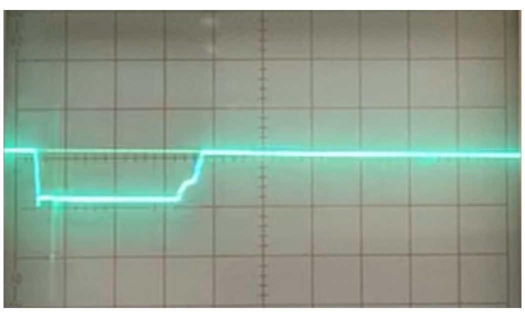


Figure 15. Voltage - time graph of trial 5

Processed Data

To obtain the efficiency of the piezoelectric effect in PZT ceramics, the following steps will be taken. As work is the visible form of invisible energy, and is equivalent, work will be considered instead of energy as it is easier to work with. The inputted mechanical work done by the spring and the outputted electrical work will each be calculated, then compared with each other to estimate a value for efficiency.

Finding work done by spring

Hooke's law states the force experienced by a spring is proportional to the __ experienced by it, and is given by the following equation, where k, is the proportionality constant also known as the spring constant.

$$F = kx$$

We know that the force gauge produced a constant reading of -0.62 prior to and after the trials took place. Therefore we can adjust for all the readings taken by subtracting -0.62 from each experimental value to account for this zero error. The absolute value for each reading will then be taken as the sign of force value only indicates the direction of the force. For this focus, the sign can be ignored, as we are only interested in the magnitude of the force.

Table 2. Raw and corrected values of force applied to activate the piezoelectric igniter

Trial Number	**Force reading taken / N (± 0.01)**	**Actual force applied / N (± 0.02)**
1	-25.58	24.96
2	-25.39	24.77
3	-25.17	24.55
4	-24.26	23.64
5	-24.67	24.05

The arithmetic mean of applied forces is taken with the formula noted in the appendix.

$$A = \frac{1}{5}((24.96 \pm 0.02) + (24.77 \pm 0.02) + (24.55 \pm 0.02) + (23.64 \pm 0.02) + (24.05 \pm 0.02))$$
$$A = \frac{1}{5}(121.97 \pm 0.1)$$
$$A = \frac{1}{5}(121.97 \pm 0.082\%)$$
$$A = 24.394 \pm 0.082\%$$
$$A = 24.394 \pm 0.02\, N$$

Therefore the average force required to press the piezoelectric igniter (to completion) is 24.39 ± 0.02 newtons of force. We can continue calculations using the value of force to find the spring constant of the spring in the igniter.

Using the measurements of the igniter when fully extended and when fully contracted. The difference between the final length and the initial length will give the displacement of the spring when activated.

$$x = (3.9 \pm 0.05\, cm) - (3.4 \pm 0.05\, cm)$$
$$x = 0.005 \pm 0.001\, m$$

$$F = kx$$
$$24.394 \pm 0.02 = k\,(0.005 \pm 0.001)$$
$$24.394 \pm 0.082\% = k(0.005 \pm 20\%)$$
$$k = \frac{24.394 \pm 0.082\%}{0.005 \pm 20\%}$$
$$k = 4878.8 \pm 20.082\%$$
$$k = 4879 \pm 979.7\, Nm^{-1}$$

With this new information, we can now deduce the inputted mechanical work done through the pressing of the piezoelectric igniter.

$$W = \frac{kx^2}{2}$$

$W = \frac{1}{2}(4879 \pm 979.7)(-0.005 \pm 0.001)^2$
$W = \frac{1}{2}(4879 \pm 20.082\%)(-0.005 \pm 20\%)^2$
$W = 0.061 \pm 60.082\%$
$W = 0.061 \pm 0.037\,J$

Therefore, we can conclude that 0.061 $\pm$ 0.037 joules of work was done in activating the piezoelectric igniter and the same amount of energy was inputted into the system in the form of mechanical work.

Finding work produced as electrical output

Numerical values will be taken from the graphs produced by the oscilloscope to perform calculations. The oscilloscope is set to 1 volt, and 1 millisecond without any multipliers, meaning each major segment on the graph is represented by these values on the y and x-axis respectively. In the account of zero error, we will take the difference between the rest reading and the reading of the greatest magnitude for each trial similar to what was done with the force gauge data. The time elapsed will be taken between when the time during which the voltage was at its maximum voltage to account for the time when the electricity was dissipated.

Table 3. Numerical readings taken on the basis of graphical depictions produced by oscilloscope

Trial Number	**Rest value / V (± 0.2)**	**Reading of highest magnitude / V (± 0.2)**	**Voltage produced / V (± 0.4)**	**Time elapsed / sec (± 0.0004)**
1	0.1	-0.9	-1.0	0.0033
2	0	-1.0	-1.0	0.0029
3	0.1	-0.9	-1.0	0.0028
4	0	-0.9	-0.9	0.0029
5	0.2	-0.8	-1.0	0.0029

This information will be used to calculate electrical power using the electrical power formula noted in the appendix. *Note*: though there would be no effect on the results, the absolute value of the voltages is taken as we are only interested in the magnitude of the voltage produced.

Table 4. Power of spark produced in each trial

Trial	**Power / W (± 85%)**
1	$P = \frac{V^2}{R}$ $P = \frac{(1.0 \pm 0.4)^2}{2 \pm 0.1}$ $P = \frac{(1.0 \pm 40\%)^2}{2 \pm 5\%}$ $P = 0.5\,W \pm 85\%$

2	$0.5\,W \pm 85\%$
3	$0.5\,W \pm 85\%$
4	$0.45\,W \pm 85\%$
5	$0.5\,W \pm 85\%$

With the power values obtained for each of the trials, we can further our calculations and find the electrical work done or electrical energy obtained in each of the trials by multiplying it by the elapsed time of each trial. As power is the measurement of work done over time, we can multiply power values by the amount of time the voltage was supplied to obtain the total work done in each trial.

Table 5. Work of spark produced in each trial

Trial	**Work / J**
1	$W = Pt$ $W = (0.5 \pm 85\%)\,(0.0033 \pm 12.12\%)$ $W = 0.00165\,J \pm 97.12\%$
2	$W = 0.00145\,J \pm 98.79\%$
3	$W = 0.0014\,J \pm 99.29\%$
4	$W = 0.001305\,J \pm 98.79\%$
5	$W = 0.00145\,J \pm 98.79\%$

The arithmetic mean (formula in appendix) of the work done throughout all the trials is 0.00145J ± 0.00143 compared with the inputted mechanical work.

Determining the efficiency of the piezoelectric effect through experimental results

Efficiency can be generally defined as a ratio between the amount of input versus the amount of output. It determines how efficient a system is in converting inputs to outputs with minimal waste. In a perfect system we should expect the efficiency to be 100% as nothing placed into the system would be lost. Though the law of conservation of energy remains absolute and all energy should be conserved in this process, energy can be lost in many different forms during the experimental process, through both controllable and uncontrollable variables. The formula for efficiency for this particular scenario is given as follows:

$$efficiency = \frac{outputted\ energy}{inputted\ energy} \times 100\%$$

Inputted mechanical work / energy: 0.061J ± 0.037
Outputted electrical work / energy: 0.00145J ± 0.00143

$$efficiency = \frac{0.00145 \pm 0.00143}{0.061 \pm 0.037} \times 100\%$$
$$efficiency = \frac{0.00145 \pm 98.48\%}{0.061 \pm 60.082\%} \times 100\%$$
$$efficiency = (2.38 \pm 158.562\%)\%$$

$efficiency = (2.38 \pm 3.77)\%$

Our result can also be compared to a literature value for the efficiency of the piezoelectric effect to determine a percentage error to determine how accurate our results are. Percentage error measures how far our result deviates from the expected result given by literature values. The literature value is the published value of quantitative values from reproducible experiments and is usually taken from the CRC handbook for chemistry and physics.
Literature value for the efficiency of piezoelectric effect: 6% - 12% = 9 ± 3 (Yang et al., 2017, #)

$$\% \, error = \frac{literature\ value - experimental\ value}{literature\ value} \times 100\%$$
$$\% \, error = \frac{(9 \pm 3) - (2.38 \pm 3.77)}{(9 \pm 3)} \times 100\%$$
$$\% \, error = \frac{6.62 \pm 6.77}{9 \pm 3} \times 100\%$$
$$\% \, error = \frac{6.62 \pm 102.3\%}{9 \pm 33.33\%} \times 100\%$$
$$\% \, error = (73.55 \pm 99.756)\ \%$$

Results

No qualitative results were taken into consideration as they are not significant to the purpose of this investigation.

Qualitative results from the experiment are noted as follows:

Inputted mechanical work (energy): 0.061 ± 0.037 joules
Outputted electrical work (energy): 0.00145 ± 0.00143 joules
Experimental efficiency of the piezoelectric effect: (2.38 ± 3.77) %
Percentage error: (73.55 ± 99.756) %

Discussion

The results obtained from the experiment show a great difference from the literature values. Experimental results showed much lower efficiency and much greater uncertainty than literature values from accepted sources. The main reasons behind the problems with the results lie mainly with the precision of the instruments and the type of piezoelectric inducer used. The errors and limitations of the investigation will be discussed in a later section.

With the final results, however, we can deduce that firstly, the piezoelectric effect is extremely inefficient in converting mechanical energy into electrical energy and therefore proves as a very ineffective means of energy production. We can consider the literature value of the efficiency of the piezoelectric effect and compare it with other renewable energy sources as a judgement of reliability and application.

Table 6. List of renewable energy sources and their respective efficiencies

Energy Source	**Efficiency**
Piezoelectric transducers	6% - 12%
Photovoltaic cells	15% - 20%
Hydroelectricity	90%
Wind turbines	20% - 40%

Oscillating water columns	70%
Pelamis	90%
Tidal power	80%

(*Power Plant Efficiency*, n.d.)

From the results attained, the hypothesis made can be verified as piezoelectric transducers are extremely inefficient to where the amount of power produced is negligible. Water-based energy production appears to be the most efficient, and even the most inefficient PV cells are still more efficient by about 10%. This is most likely why the application of the piezoelectric effect remains in detection systems and sensors. Nonetheless, there is still some amount of application of piezoelectric transducers in large bridges as a means of harvesting energy.

Evaluation

There are several major problems with this investigation, including experimental errors, inherent unavoidable flaws, and with the design of the experiment itself. These issues mostly revolve around the conservation of energy and the loss of energy to other sources throughout the experimental process. The following errors listed could have had large effects on the measurements taken during the experiment and the final results of the investigation.

Table 5. List of experimental errors with respective effects on result and potential corrections

Error	**Type of Error**	**Effect on result**	**Correction**
Large uncertainty value	Systematic	Resulted in very imprecise readings, which lead to very high uncertainty value after all calculations have been completed. This not only resulted in a very imprecise result with high range of uncertainty, but also efficiency being ranging into negative values due to uncertainty which does not make sense in the given scenario.	Utilisation of measurement devices with higher precision such as callipers instead of a ruler or by setting oscilloscope settings to a smaller interval and therefore higher precision in order to decrease uncertainty values and to obtain a final efficiency of higher precision.
Loss of energy through nature of piezoelectric igniter	Systematic	Due to the inherent nature of the piezoelectric igniter, several components were likely to consume the inputted mechanical energy. These include energy losses to the friction in the spring, as well as losses of energy through the forms of sound and heat energy which arose from the metal striker striking against the ceramic.	A piezoelectric lever could have been used instead of the igniter. The piezoelectric lever does not use a spring contraption to strike the ceramic but instead is a sheet of ceramic which can be bent and compressed at will. Though this certain device would result in

			less loss of energy, it would also be difficult to determine the amount of force being applied onto it.
Resistances of components within the apparatus	Systematic	During the calculations we did not account for the internal resistances of the wires as well as the electrical components. This resulted in slightly inaccurate results due to internal resistances consuming some amount of energy which would not have been outputted on the oscilloscope	We can correct for this error by measuring the internal resistances of each of the components and account for these resistances in our final calculations for more accurate results.
Measurements using force gauge	Random	Due to the nature of how the force gauge apparatus was set up, the force applied onto the igniter and therefore the gauge was not consistent and resulted in variable amounts of forces being applied onto it which therein could result in inaccurate readings by the maximum force affecting the rest of the results.	This error can be corrected through the use of a non-human method of measuring or applying force. A potential correction for this error as well as the error of loss of energy is to apply force onto a piezoelectric lever magnetically. We can place a magnet onto the lever and apply a magnetic force onto it through the use of a magnetic field generator. This would result in higher precision in measurement of force applied as we can control that through supplying the generator with different amounts of electricity.

Conclusion

Though the piezoelectric effect remains an extremely inefficient process of energy conversion, there is potential for application in the future. Today only 12.4% of energy produced is from renewable energy sources (*Frequently Asked Questions (FAQs) - U.S. Energy Information Administration*, 2022). As the world is moving towards a world of 100% renewable energy as a means to counter pollution and climate change, hydroelectric systems still remain as the number 1 priority due to their high efficiency. As a matter of fact, most fossil fuels are only 60% efficient, making hydroelectricity 30% more efficient than the burning of fossil fuels. Though hydroelectric plants are highly efficient, they are also highly restive in terms of location and are socially inefficient. On the other hand, piezoelectric transducers are very small, and can be placed in almost all places. Especially under the floors of areas with high foot traffic, large quantities of energy can potentially be produced. Though the main purpose of piezoelectric devices will remain in sensor and clock technology, further investigation into different materials can change the course of piezoelectric technology. This topic can also be furthered through investigation of not just the efficiency of energy sources, but the actual amount of energy produced as a comparison for the viability of different energy sources. As we are moving into a world where renewable energy is gaining much greater attention and a scarcity of space, piezoelectric transducers can potentially become a leading source of renewable energy in coming years.

References

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Appendix

Arithmetic mean:

$$A = \frac{1}{n}\sum_{i=0}^{n} a_i$$

Where:

- A = arithmetic mean
- n = count of terms within the dataset
- a = value of data

Hooke's law:

$$F = kx$$

Where:

- F = Applied force
- k = spring constant of spring
- x = linear distortion of spring

Work done on spring:

Work is given by the formula: $W = Fs$

Where:

- W = work
- F = applied force
- s = displacement

Substituting $F = kx$, the following formula is obtained.

$$W = \frac{kx^2}{2}$$

Electrical power formula:

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

Where:

- P = power
- V = voltage
- R = resistance of load (2 ohm resistor)

Work (from power):

$$W = Pt$$

Where:

- W = work
- P = power
- t = time