An Approach to Utilize Piezoelectric Materials to Convert Kinetic to Electrical Energy with Sustainability

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Abstract— **The global reliance on fossil fuels continues to drive climate change, contributing to 60% of greenhouse gas emissions and localized air pollution. This research investigates the potential of piezoelectric materials to harness kinetic energy from vehicles as a renewable source of electricity. A device, the Smart Energy Meter, was designed to measure the voltage and power generated by piezoelectric materials placed on a moving vehicle. Experimental trials varied vehicle speeds and piezoelectric surface areas, with results indicating that increasing both parameters enhances energy generation. Although the energy produced was small, the findings suggest that large-scale application of piezoelectric materials could power peripheral vehicle systems. This approach offers potential for developing alternative clean energy sources, with implications for electric vehicle technology, energy harvesting, and other sustainable applications. Future research may optimize this system for broader energy production through advancements in materials, vehicle integration, and smart technology.**

Index Terms—**Piezoelectric materials, renewable energy, kinetic energy harvesting, smart energy systems.**

Significance Statement - This study demonstrates how piezoelectric materials can convert vehicle motion into clean energy, offering a novel, scalable solution for reducing fossil fuel reliance and supporting sustainable energy systems.

I. Introduction

ACCORDING to the United Nations Sustainable Development Goals, energy is the dominant contributor to climate change, accounting for approximately 60 percent of total global greenhouse gas emissions. Fossil fuels, which include coal, petroleum, natural gas, oil shales, and heavy oils, are the primary source of energy consumption worldwide. In addition to releasing planet-warming greenhouse gas emissions, the combustion of fossil fuels generates localized air pollutants that increase the risk of death from stroke, heart disease, lung cancer, and respiratory illness. Therefore, society must seek alternatives for clean energy sources.

Here are some alarming statistics that further underscore the urgency of transitioning to clean energy:

- According to the EIA, about 61% of electricity generation comes from fossil fuels—coal, natural gas, petroleum, and other gases—making them the largest sources of energy for electricity generation [1].
- The EPA reports that carbon dioxide is the most significant cause of global warming, with the majority of carbon dioxide emissions resulting from the burning of fossil fuels, which are used to generate electricity [2].
- The U.S. Energy Information Administration states that non-renewable energy sources cannot be replenished in a short period [1].
- According to the EPA, hybrid and plug-in electric vehicles can offer significant emissions benefits over conventional vehicles, with electric vehicles (EVs) producing zero tailpipe emissions [2].
- Electric vehicles, emitting the equivalent of 128 g of CO_2 per kilometer, pollute half as much as the average gasoline car, which emits 258 g of CO_2 per kilometer.

These statistics highlight the environmental benefits of electric vehicles and their potential to serve as a catalyst for the consumption of clean energy, facilitating the transition from fossil fuels to renewable energy sources.

In 2019, more than half of the people in Least Developed Countries (LDCs), approximately 570 million people, had no access to electricity. In a quarter of the 46 LDCs, over 75% of the population remains without electricity, and rural electrification is particularly low, with two-thirds of the rural population, about 458 million people, completely lacking access. Even in urban centers, up to one-third of the population in LDCs lacks reliable electricity access, which is critical for health-care services. Despite some progress since 2000, achieving universal energy access by 2030, a key Sustainable

Development Goal (SDG 7), remains elusive, as the pandemic has further exacerbated energy poverty, hindering personal welfare, human capital development, and economic growth in LDCs. UNCTAD's Productive Capacities Index highlights the low energy scores of LDCs, where the lack of energy for productive purposes limits firms' competitiveness and export potential. Addressing this requires significant investments in electricity generation, distribution, and end-use technologies, along with policies that balance affordability and financial viability. Renewable energy, particularly hydropower, offers potential for greener recovery and rural electrification, but realizing this requires investment in physical capital, skills, technological capabilities, and international support for green technologies and innovation systems, all critical for the global transition to a low-carbon energy system [3].

ExxonMobil's 2023 Global Outlook highlights the critical need for energy access in developing countries as a driver of economic growth and poverty reduction. As these nations experience rapid population growth and industrialization, their energy demands are set to rise significantly. However, this growth poses environmental challenges, particularly with increased greenhouse gas emissions. The report advocates for a balanced approach that combines investments in diverse energy sources, including renewables and fossil fuels, with technological innovations and effective policies to ensure sustainable development while minimizing environmental impact. This strategy emphasizes the importance of international cooperation and financial investment to help developing countries transition to cleaner energy sources, ultimately supporting global climate goals without hindering economic progress [4].

Burning one gallon of gasoline produces 8,887 g of CO_2, and diesel generates 10,180 g per gallon, contributing significantly to environmental harm. The average passenger vehicle emits around 400 g of CO_2 per mile, resulting in approximately 4.6 metric tons of CO_2 annually, which exacerbates climate change. In addition to CO_2, vehicles also emit other harmful greenhouse gases like methane and nitrous oxide, further intensifying their environmental impact. Although electric vehicles produce no tailpipe emissions, the production and distribution of electricity still generate some greenhouse gases, though typically less than traditional vehicles. The significant amount of CO_2 and other pollutants released by vehicles highlights the urgent need for cleaner energy alternatives and stricter emission controls to mitigate environmental damage [2].

Piezoelectricity is a phenomenon where certain crystals, such as quartz, can convert mechanical energy into electrical energy and vice versa, making it widely utilized in various devices we encounter daily, such as quartz watches and microphones. When these crystals are subjected to mechanical stress, they generate an electrical potential across their surfaces; this is known as the piezoelectric effect. This occurs because, although the atoms in piezoelectric crystals are not symmetrically arranged, they are electrically neutral until a force is applied, causing the balance of positive and negative charges to shift and produce a net electrical charge on opposite faces of the crystal. Conversely, applying a voltage to a piezoelectric crystal deforms its structure, leading to the reverse piezoelectric effect. The orderly arrangement of atoms in a crystal allows this unique behavior, which has made piezoelectric materials essential in many applications, from generating sound in smoke alarms to energy harvesting in wearable technology [5].

II. Hypothesis

In this study, the possibility of using piezoelectric materials to harvest kinetic energy from a vehicle in motion as electricity was investigated. The hypothesis of this study was that by measuring the voltage and power generated across piezoelectric materials while varying factors like motion velocity and surface area, it could be demonstrated that kinetic energy could be converted into electrical energy. This energy could then be harnessed as renewable energy for vehicles, leveraging the unique property of piezoelectric materials to generate voltage when subjected to motion or pressure. The hypothesis aimed to explore the relationship between kinetic energy and the clean generation of electrical energy for practical applications such as electric vehicles.

III. Materials and Methods

A. *Experimental procedure*

The research experiment involved various variables, controls, and constants. The independent variables, which were changed during the experiment, included the velocity of the vehicle, surface area of the piezoelectric material, and the piezoelectric configuration (series). The dependent variables, which changed as an outcome, were the voltage output (Volts, V), power generated (Watts, W), and energy generated (Joules, J). The constants, which remained unchanged, included temperature, humidity, type of piezoelectric film material, and type of motion/vehicle.

As part of conducting the research experiment, a device was designed and assembled to measure the clean energy from the piezoelectric material. The device was named the Smart Energy Meter. Using the Smart Energy Meter, data was collected from the piezoelectric setup. To generate kinetic energy from motion, the piezoelectric film (in various series configurations) was mounted and assembled on the dashboard of a Honda Odyssey. The aerodynamic drag from the car's motion at various speeds generated electric energy from the piezoelectric film in the form of voltage and power. The collected data was analyzed and conclusions were developed based on the mentioned variables.

B. *Experimental overview*

The following is the stepwise method and procedure of the experiment:

1. Gather all materials (listed below).
2. Assemble / Construct Smart Energy Meter for Piezoelectric Energy Readings.

3. Connect the Smart Energy Meter from the outside of the vehicle to the inside.
4. Attach wire to computer for readings.
5. Turn on vehicle and put in motion.
6. Test various speeds such as 10 mph, 20 mph, 30 mph, 40 mph and 50 mph with a 1-minute intervals.

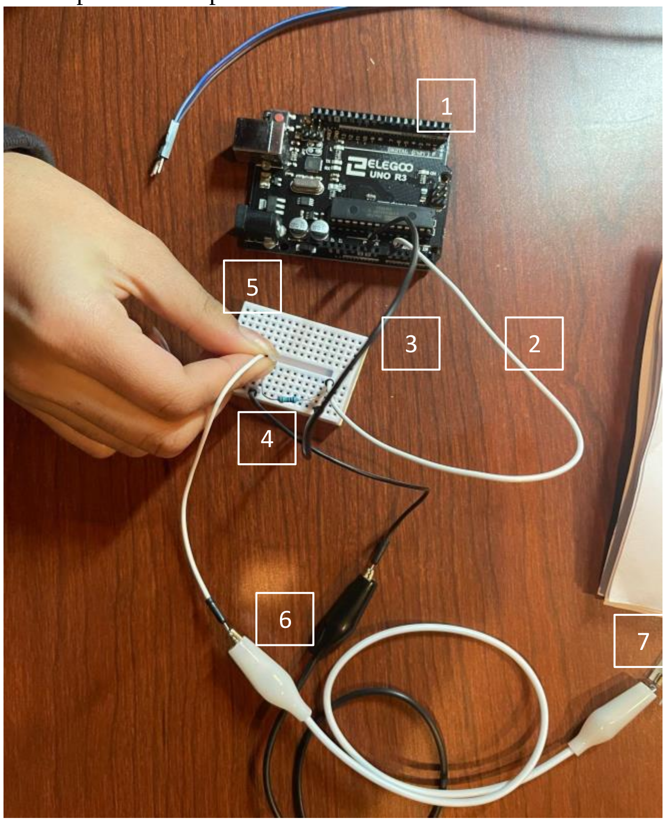


Figure 1. Assembly of the Smart Energy Meter. 1. Arduino UNO controller. 2. Circuit wires connecting the Arduino UNO Controller to the breadboard. 3. White wire, analog input. 4. Black wire, ground/baseline. 5. Breadboard. 6. Alligator clips connecting the wires from the breadboard to the piezoelectric film. 7. Piezoelectric film.

7. Measure the voltage produced by the motion created from the vehicle.
8. Test different piezoelectric film surface area configurations by connecting 1, 2, 3, 4 and 5 films in series, hence increasing the surface area.
9. Observe results from voltage produced.
10. Repeat for 5 trials.

A total of 5 trials with 5 readings (with various variables) were conducted:

1. Control Trial 1: (1 piezoelectric film) - 10, 20, 30, 40, 50 mph.
2. Trial 2: (2 piezoelectric films) - 10, 20, 30, 40, 50 mph.
3. Trial 3: (3 piezoelectric films) - 10, 20, 30, 40, 50 mph.
4. Trial 4: (4 piezoelectric films) - 10, 20, 30, 40, 50 mph.
5. Trial 5: (5 piezoelectric films) - 10, 20, 30, 40, 50 mph.

C. *Equipment*

- Piezoelectric material strips.
- Alligator clips.

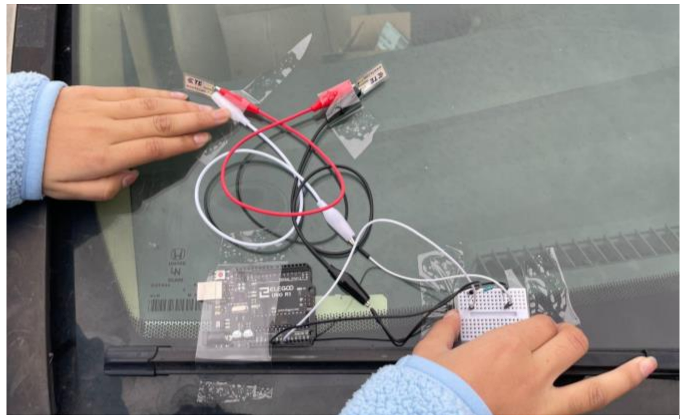


Figure 2. Mounting of the Smart Energy Meter (SEM) on the windshield of the vehicle. The SEM is then connected via a USB cable to the personal computer inside the vehicle.

- Personal computer.
- Multimeter.
- Arduino UNO controller.
- Adhesive.
- Arduino Sketch for Coding.
- Notebook and pencil for manual data recording.
- Vehicle (Honda Odyssey).
- Timer.

IV. Results

A. *Assembly of the equipment*

As part of the experiment, a device was designed, assembled, and programmed, named the Smart Clean Energy Meter (SEM). The function of the device was to measure the voltage and power generated by the piezoelectric material and serve as the source of data collected to investigate the novel approach (Figure 1 and Figure 2).

B. *Function of piezoelectric effect*

The piezoelectric effect refers to the generation of an electrical potential (voltage) across the surfaces of a crystal when subjected to mechanical stress, such as compression. This phenomenon enables the crystal to function as a miniature battery, exhibiting a positive charge on one face and a negative charge on the opposite face. When the two faces are connected to form a circuit, an electric current flows (Figure 3).

The experiment incorporated various forms of energy and the principles of Ohm's Law. Kinetic energy is defined as the energy that an object or particle possesses due to its motion. Electrical energy arises from the movement of electrons from one atom to another. According to Ohm's Law, the electric current is directly proportional to voltage and inversely proportional to resistance. The formula for Ohm's Law is utilized to calculate the relationship between voltage, current, and resistance.

$$Ohm's\ Law: Voltage\ (V) = Current\ (A) * Resistance\ (O)$$

$$Energy\ (J) = Power\ (W) * time\ (s)$$

$$Power = Voltrage * Current$$

$$Power = \frac{Voltage^2}{Resistance}$$

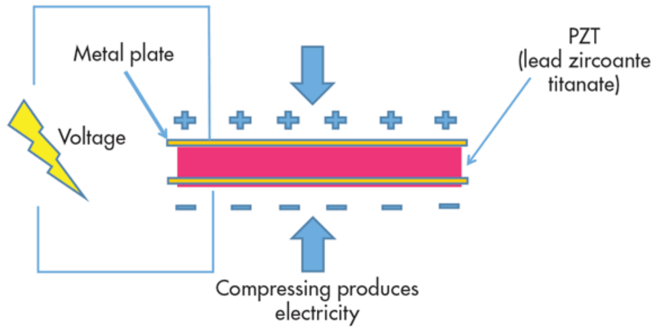


Figure 1. Diagram explaining the piezoelectric effect.

The principle investigated in this study consider the kinetic energy of the vehicle under motion generating aerodynamic drag that is transformed into a voltage by the piezoelectric material mounted on the windshield of the vehicle (Figure 2). This voltage is then converted into electrical energy measured by the resistor mounted on the breadboard connected to the Arduino controller (Figure 1 and Figure 2).

C. Data collection and analysis

A total of five trials were conducted, including a control group (Figure 4). Each trial comprised five data points and calculations for power and energy generated (Figure 4). The surface area was incrementally increased by adding a piezoelectric element, to a maximum of five elements. Additionally, within each trial, the velocity was incrementally increased by 10 miles per hour to assess the corresponding kinetic energy and its conversion to electricity.

The lowest voltage was recorded with 1 piezo element at the lowest velocity of 10 mph, corresponding to 0.08 V. The highest voltage of 0.38 V with 1 piezo element was recorded at 50 mph, corresponding to 4.75 times the voltage recorded at 10 mph. This shows that from 10 to 50 mph there is an efficiency loss of about 5%. The highest voltage of 1.87 V was measured at 50 mph with 5 piezo elements corresponding to 4.92 times the voltage with 1 piezo element at the same speed and an efficiency loss of 1.6%. This data also shows that there is a linear increase in the voltage registered with the increase in the velocity of the vehicle.

Analysis of energy generation by different piezoelectric configurations indicated that the maximum energy generated by one piezo element was 14.44 nJ (Figure 4), while the maximum energy generated by five piezo elements reached 350 nJ (Figure 4). These figures suggest a relatively small amount of power and energy. Also, it is visible from Figure 5 that the increase in power and energy with the increase in velocity is not linear, but exponential.

It was determined that the surface area of one piezo element was 5.4 square centimeters, while the surface area of five piezo elements was 27 square centimeters. For comparison, the surface area of a Honda Odyssey was found to be 25,000 square centimeters. Mathematically, if the entire vehicle were covered with piezoelectric material, the energy produced by one vehicle could be calculated as follows:

$$Hestimated\ energy\ from\ the\ vehicle$$

$$\frac{25000\ cm^2 * 1.4\ nJ}{5.4\ cm^2} = 66.9\ \mu J$$

This amount would be sufficient to power some accessories and peripherals of the vehicle.

V. Discussion

The analysis of the data that was collected during this study, revealed several key observations. Voltage, power, and energy exhibited a direct proportional relationship, indicating that an increase in voltage corresponded to an increase in power and energy generation. As velocity increased, the power and energy produced also increased. The addition of more piezoelectric elements in series further increased the surface area, resulting in higher voltage and corresponding power and energy outputs. A comparison of the control group with the trial data demonstrated a multiplier effect of surface area on the voltage, power, and energy produced; for instance, doubling the surface area approximately doubled the power and energy generated. By varying both velocity and surface area, it became evident that kinetic energy could be effectively converted into clean electrical energy.

VI. Conclusions

The experiment successfully produced and measured voltage, power, and energy generated by piezoelectric materials, taking into account variables such as motion velocity and surface area. This validated the hypothesis that kinetic energy can be converted into electrical energy for smart energy applications, including enhancements to electric vehicles.

Several conclusions supported the hypothesis:

- As velocity increased, more kinetic energy was generated and converted into electrical energy.
- As surface area increased, more kinetic energy was converted into electrical energy.
- The produced electrical energy was measured to confirm the hypothesis.

VII. Future Perspectives

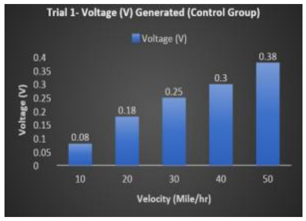
During the experiment, several modifications were identified that could enhance its effectiveness. These include utilizing different independent variables, such as incorporating various modes of vehicle transportation (e.g., bicycles, scooters) and expanding surface areas. Additionally, integrating smart energy features, such as Wi-Fi or Bluetooth connectivity, adding more piezoelectric films, and testing different speeds (e.g., 60, 70, and 80 mph) could further enhance the results.

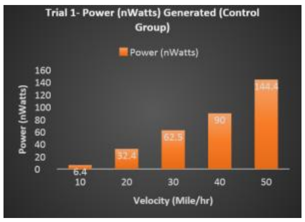
The applicability of the experiment extends beyond its initial scope, offering potential for implementation in various settings. These include:

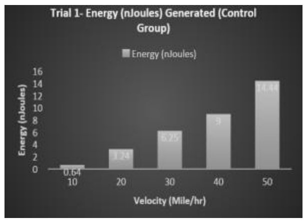
- Instrumenting electric vehicles and exploring road harvesting techniques, as well as developing wearable accessories like phone chargers.
- Utilizing the findings as an alternative energy source for vehicles, both electric and gasoline-powered.
- Investigating the use of smart energy in daily life, providing electrical energy for personal accessories, charging applications, household tasks, and biomedical uses of bio-piezoelectric platforms in health monitoring, disease diagnosis, heart stents, and cancer treatment.
- Delving deeper into the realms of physics and aerodynamics to understand their implications for smart energy systems.
- Employing artificial intelligence and machine learning in conjunction with smart energy meters to predict and simulate clean energy production levels.

(1)

Velocity (mph)	Voltage (V)	Power (nW)	Energy (nJ)
10	0.08	6.4	0.64
20	0.18	32.4	3.24
30	0.25	62.5	6.25
40	0.3	90	9
50	0.38	144.4	14.44

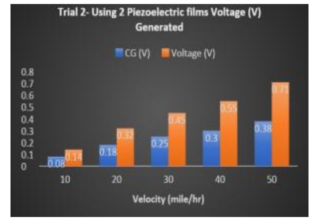


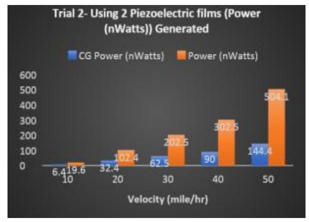


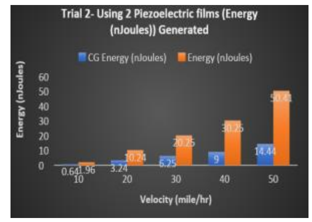


(2)

Velocity (mph)	Voltage (V)	Power (nW)	Energy (nJ)
10	0.14	19.6	1.96
20	0.32	102.4	10.24
30	0.45	202.5	20.25
40	0.55	302.5	30.25
50	0.71	504.1	50.41

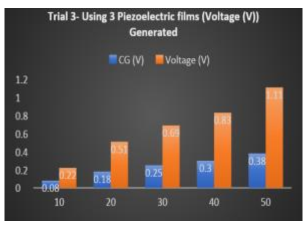


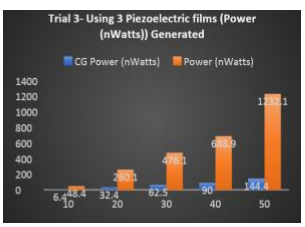


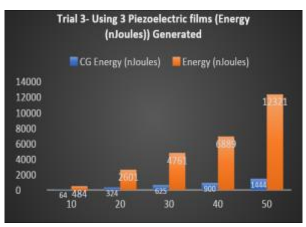


(3)

Velocity (mph)	Voltage (V)	Power (nW)	Energy (nJ)
10	0.22	48.4	4.84
20	0.51	260.1	26.01
30	0.69	476.1	47.61
40	0.83	688.9	68.89
50	1.11	1232.1	123.21

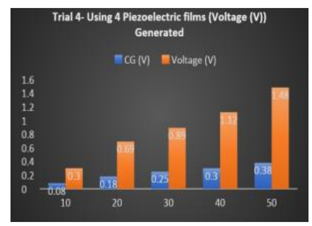


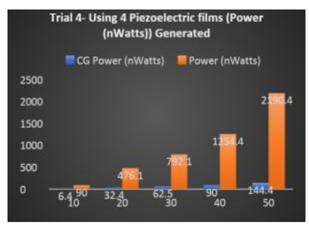


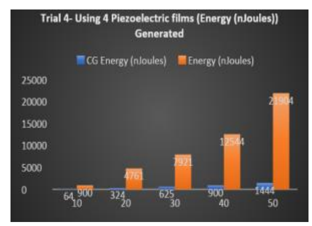


(4)

Velocity (mph)	Voltage (V)	Power (nW)	Energy (nJ)
10	0.3	90	9
20	0.69	476.1	47.61
30	0.89	792.1	79.21
40	1.12	1254.4	125.44
50	1.48	2190.4	219.04

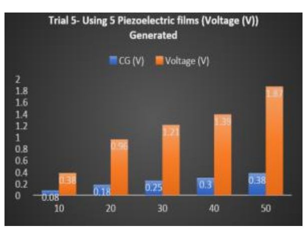


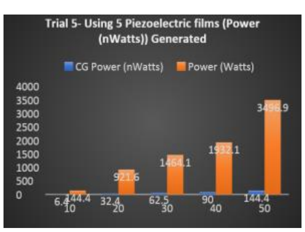




(5)

Velocity (mph)	Voltage (V)	Power (nW)	Energy (nJ)
10	0.38	144.4	14.44
20	0.96	921.6	92.16
30	1.21	1464.1	146.41
40	1.39	1932.1	193.21
50	1.87	3496.9	349.69





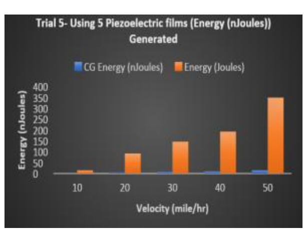


Figure 2. (1) Data for Control Trial 1. (2) Data for Trial 2 compared to Control Trial 1. (3) Data for Trial 3 compared to Control Trial 1. (4) Data for Trial 4 compared to Control Trial 1. (5) Data for Trial 5 compared to Control Trial 1.

Figure 3. Comparison of all the measurements takes during the five trials at the different vehicle speeds.

Overall, these enhancements and applications can significantly impact real-world situations and warrant further investigation.

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