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Conversion of Mechanical Energy to Electrical Energy Using Piezoelectric Materials for Bicycle Lane Lighting Systems

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Abstract: This study examined the electromechanical characteristics of piezoelectric materials, which constitute a compact renewable energy source; these materials can convert mechanical energy (such as pressure or a cumulative impact) in the form of mechanical stress to electricity. This study further explored systems that require moderate energy and utilize piezoelectric materials to create an energy-generating floor. The electrical characteristics of these piezoelectric materials were studied, including the feasibility of installing them as a power source for road lighting, particularly cycling lanes. Furthermore, the effects of riders' weights and cycling speeds were investigated. The results indicate that the electric power generated is adequate for the installation of these materials and can thus help improve visibility in the event of insufficient lighting.

Keywords: piezoelectric; energy conversion; bicycle lane; lighting system

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1. Introduction

Current world energy scenarios suggest that the electrical energy demand will increase substantially in the future. Apart from comfort, the quality of life, and promising technologies, electric power is another significant factor with regard to modern living, especially in this era of technological advancement. To this end, alternative energies are beneficial because they generate sufficient electricity for meeting energy needs; they are also clean, i.e., they do not lead to environmental pollution. According to the Statistical Review of World Energy 2021, reported by BP PLC, primary energy consumption rose by 1.3% last year, less than half its rate in 2018 (2.8%). Oil continues to hold the largest share of the energy mix (33.1%). Coal was the second-largest energy source in 2020, accounting for 27.2% of the total primary energy consumption, representing a slight increase from 27.1% in the previous year. The Annual Energy Outlook 2022 report provided by the U.S. Energy Information Administration (EIA) revealed that the proportion of energy consumption in the transportation sector is the third highest. Thus, energy consumption has continued to increase over time [1,2]. Therefore, it can be concluded that energy demand is likely to increase further in the future. Consequently, energy conservation plans and the implementation of renewable energy technologies should be the emphasis of research and development worldwide. Although alternative energy production can generate electricity without causing pollution, it suffers from certain limitations. Energy harvesting entails the accumulation of natural energy from human activities and machine operations and the transformation of this energy into a usable form that is flexible and convenient for installation [3].

Considering the numerous reports on this topic, it is evident that researchers are keen on investigating and developing alternative energy technologies. For instance, a dynamic model substitution of non-renewable energy with an alternative energy source determined that the productivity gap between oil and renewable energy represented its substitutability and encouraged a change in energy shares, enhanced economic growth, and reduced carbon emissions [4–6]. The comprehensive policy framework and assessment for discovering sustainable development compared their advantages and disadvantages to determine the most appropriate role for each fuel, analyzing their performance and economic feasibility [7–9]. Thus far, several studies have discussed the role of energy harvesting technologies, e.g., solar energy, wind energy, vibrational energy, and thermoelectric generators in supporting energy generation; the optimization of the energy sources and their efficiency across reliability were determined [10–18]. The performance and economic evaluation of a renewable energy system achieved a profitability index, IRR, and DPP under the feed-in tariff scheme proposed [19]. The monitoring systems for prolonging the lifetime of wireless sensors by using energy from energy harvesting are also being studied. Owing to its ease of installation, pricing, and capabilities, energy harvesting technology has been tested for numerous everyday applications. In view of this, energy harvesting technology was further researched in this study.

Transportation accounts for 30% of all energy consumption, and numerous studies have focused on the growth rate of energy consumption in the transportation sector and explored the potential of reducing energy consumption [20–23]. Mathematical models have been created to estimate the energy demand of the transportation sector [24,25]. Therefore, ensuring the production of clean energy and the implementation of energy-saving measures is crucial for the transportation sector. The use of alternative energy sources, including new technologies for energy conservation and the adoption of vehicle-sharing policies, is being considered worldwide [26–28]. Energy harvesting on a vehicle by transforming low-frequency vibrations from the rotating motion into electrical power were also presented. Identifying regions with high saving potential allows for targeted marketing and transition-supporting incentives for reducing greenhouse gas emissions [29–31]. According to current news reports, micro-mobility is being used to reduce energy consumption in the transportation sector, and smart cities are also transforming energy consumption. For instance, bicycle lanes or pavement in smart cities can be used to generate electric power with energy harvesting systems; this power can then be employed for electrical equipment and lighting systems in the area, resulting in energy savings and improved road visibility. This is consistent with the ideas discussed in this study.

In this study, piezoelectric energy harvesting was used to convert mechanical energy into electrical energy. The energy produced from vibrations, which occur in almost every activity, can be used to generate green energy. Recently, many researchers have studied the use of piezoelectric energy harvesting technologies [32–39]. A hybrid energy harvesting system under a various excitation was also reported [40–51]. The materials focused on energy harvesting, and the piezoelectric materials considered in the modeling and optimization of the load in order to generate maximum power were reviewed [52,53]. Thus, the application of piezoelectric materials for energy conversion is gaining popularity among researchers worldwide owing to the impressive characteristics of these materials. In particular, this study focused on energy harvesting with piezoelectric materials to convert mechanical energy into electrical energy. Several studies were conducted to explore the feasibility of constructing piezoelectric-powered pavements and evaluate the limitations of such equipment when practically installed [54–63]. Several studies thus far have demonstrated that piezoelectric materials are impressive and possess the potential to create energy-generating floors that can convert decayed energy from ambient to electrical energy.

Accordingly, in this study, an energy harvesting system using piezoelectric materials was employed for a bicycle lane; this system harnessed the energy accumulated in a battery during the day to illuminate the lane during periods of insufficient lighting to ensure safe driving. The subsequent section describes the design of the piezoelectric module and energy harvesting circuit, including the implementation of the system, to evaluate the factors determining the amount of energy that can be harvested. An overview of this working system is presented in Figure 1.

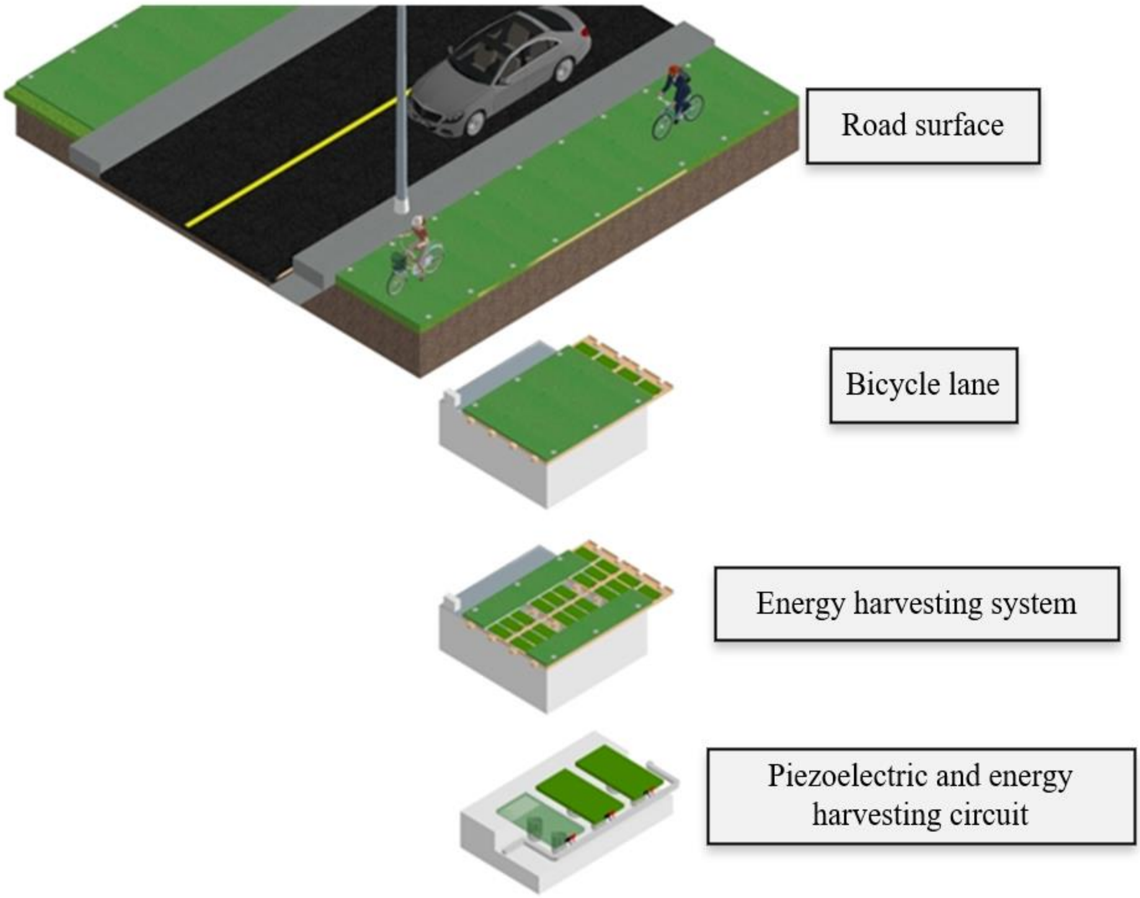


Figure 1. Conceptual framework of proposed system.

We hypothesized that a piezoelectric energy harvesting system could convert the naturally occurring energy of cycling to electricity in a form that sufficiently facilitated the cycling area. That is, the vibrations generated would be converted to electrical power with a piezoelectric energy harvesting system. The pedestrians would be aware of and observe the cyclists in the illuminated bike lane area. We hypothesized that once the actual installation was carried out and the energy generated could be used, the experimental set would modify the spring mounting structure to develop higher harvestable power. Subsequently, the bicycle usage factors, such as driving speed and cyclist weight, were reviewed to determine the effect on the energy harvested from the experimental set. The conversion of free energy into electrical energy that can be employed for low-power electrical appliances and its adaptability for use in systems with higher energy consumption will be addressed in a future study.

Laboratory and field studies were performed to evaluate the actual power output of piezoelectric energy harvesting. Table 1 summarizes the laboratory field study scenarios and method used for piezoelectric energy harvesting from pavement in previous research. Thus, the novelty and contributions of this study are summarized as follows:

- This study investigated the energy harvested from a piezoelectric energy harvesting system applied to the external environment and real-life activity, not only as a laboratory experiment.
- The proposed control algorithm offered an effective utilization and storage of energy for the bicycle lane or the area where visibility was inadequate.
- The proposed system can be further developed and implemented to support the concept of clean energy and inclusion in a smart city.

Table 1. Laboratory and field studies of piezoelectric energy harvesting.

Test Scenarios and Configurations	Method	Reference
Introduced piezoelectric energy harvesting from traffic-induced pavement vibrations	Comparative analysis of various disclosed piezoelectric harvesting device technology and material configurations was examined using different cover plates.	[55]
Prepared stacked piezoelectric energy harvesting units for pavements and evaluated their performance	Evaluated their application performance in terms of electrode structure (resistivity and cost) and technical characteristics (output power and durability)	[56]
Modeled and optimized an underfloor piezoelectric stacked energy harvester utilizing a force amplification frame	Optimized the device to suit a range of typical inputs, including walking, jogging, and multiple other pedestrian load conditions	[57]
Maximized the benefits from piezoelectric energy harvesting floor in buildings' interior spaces, despite their being low pedestrian-traffic spaces	Used various piezoelectric technology types and spreading to correlate between needed power and pedestrian density	[58]
Evaluated energy output and mechanical failure of piezoelectric energy harvester for roadway applications	Experimental testing and numerical modeling (finite element simulation) of energy harvester	[59]
Designed and assessed stacked piezoelectric energy harvesting power-generation devices for pavements	Mechanical testing and simulation (MTS) determined durability and power generation performance.	[60]

The following sections present the design of an energy-generating pavement using piezoelectric materials for converting mechanical energy into electricity. Furthermore, a spring settlement for improving piezoelectric oscillations was adopted to study the impact of an energy-generating floor on the harvested electric energy. The electrical schematics and practical circuits for this energy harvesting system as well as the electrical signals that were detected through the experiments are presented herein. Experiments comparing riders of different weights and cycling at different speeds are presented at the end of this paper. Lastly, the feasibility of applying piezoelectric materials in bicycle lanes is discussed.

2. Design of the Energy Harvester

This section focuses on the development of an energy-generating floor that converted mechanical forces into electrical energy using piezoelectric devices installed along a bicycle lane. This energy was divided into two components. First, the energy harvested during the day was used directly with low-power-consumption devices in the installation area (such as waiting lights, signals, and sensors); excess energy was stored in a battery to support the load at night. Second, a part of the energy harvested at night was utilized directly, along with that stored in the battery, to power the lighting system installed on the bicycle lane. This was expected to help cyclists navigate the lane, making road users safer.

2.1. Simulation

Based on a simulation, this section describes the process of energy harvesting from piezoelectric devices to obtain the maximum power from piezoelectric modules. This simulation, which was performed using LTspice, included an integrated piezoelectric energy harvesting circuit board (LTC-3588-1). The parameters used to simulate the piezoelectric energy harvesting circuit were an input voltage of 24 V, a frequency of 41 Hz, an internal resistance of 119 kΩ, an output voltage of 3.3 V, and an output current of 30 mA. In addition, the time step using for simulation software was 2×10^{-6} s. The electrical energy obtained via the excitation of the piezoelectric device, which was connected to a rectifier, was transmitted for conversion into a direct current (DC). It was passed through a capacitor to reduce output voltage ripples and subsequently through a synchronous buck converter circuit to realize a desirable, stable voltage level. Finally, the energy received by the battery charging circuit was stored in a lithium-ion battery to support the load demands. A schematic of the energy harvesting circuit using a piezoelectric device, as obtained from LTspice, is presented in Figure 2.

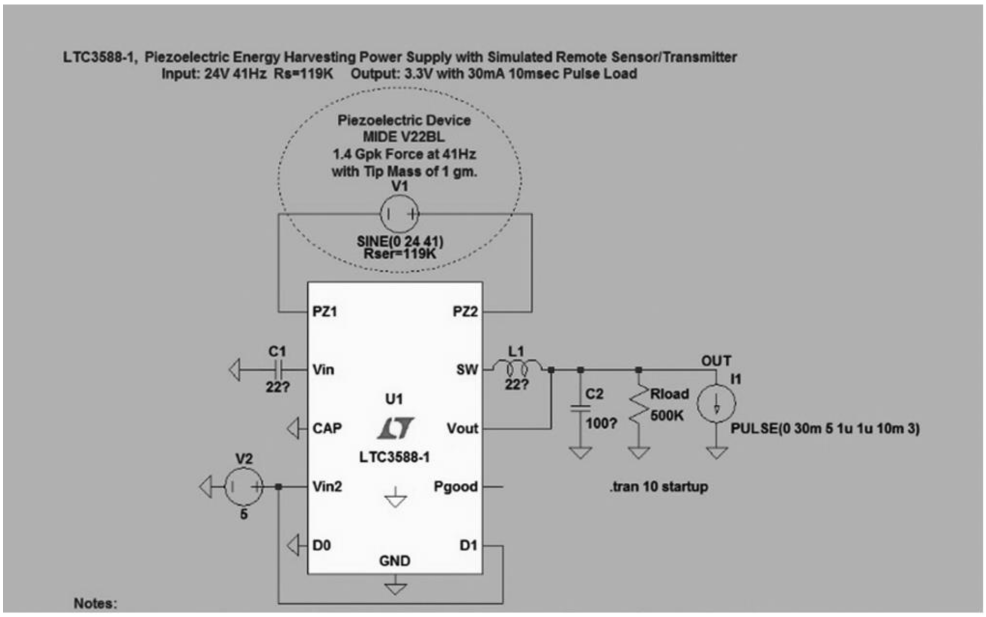
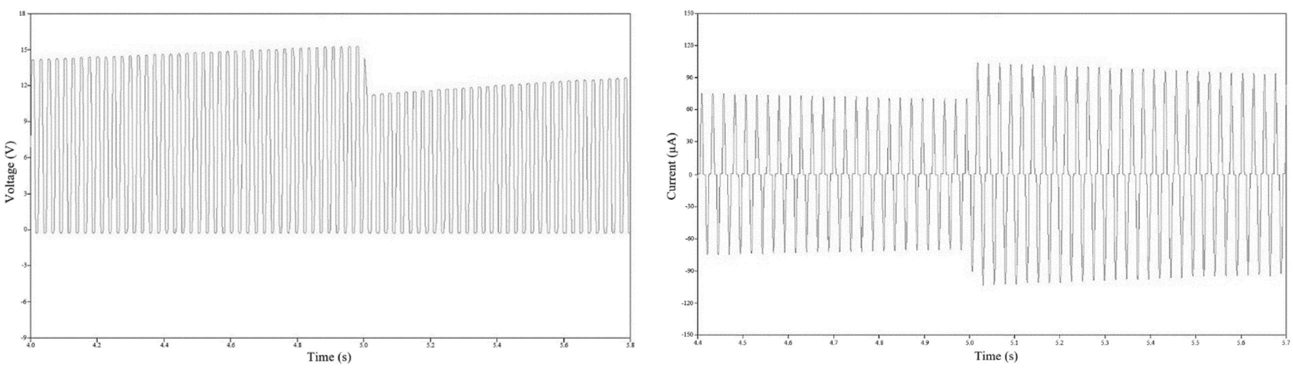


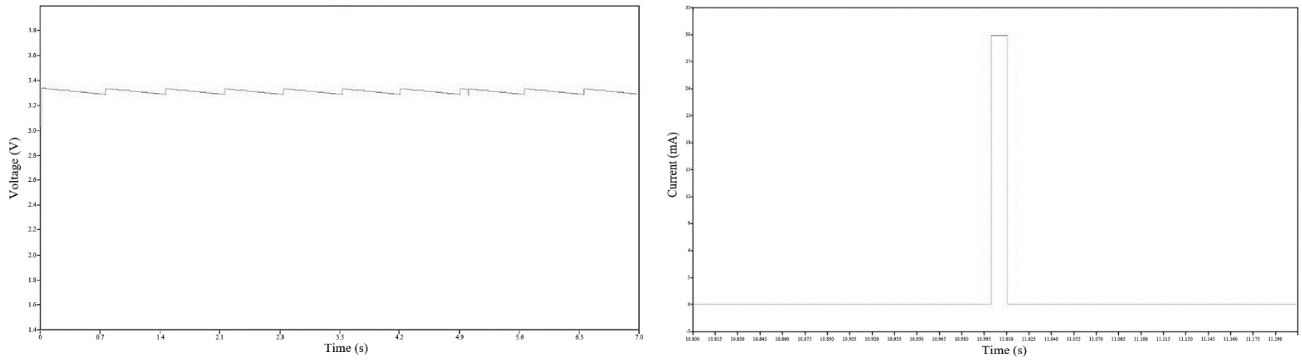
Figure 2. Schematic of energy harvesting circuit using piezoelectric device, obtained via LTspice.

The simulation results indicate that an alternating current (AC) voltage was generated when the piezoelectric device was excited by mechanical forces such as vibrations or pressures. The characteristics of the waves varied according to the mechanical force. The resulting voltage was relatively constant, approximately 10–15 V. When the piezoelectric device was continuously subjected to mechanical energy, the input current remained stable at approximately 70–115 μA, while the output side produced a rectified and stabilized voltage of approximately 3.3 V from the synchronous buck converter signal. The output current was characterized as a pulse signal according to the mechanical force obtained under a maximum current of approximately 30 mA, as shown in Figure 3.



(**a**) (**b**)

Figure 3. *Cont.*



(c) (d)

Figure 3. Voltage and current characteristics according to mechanical force: (**a**) input voltage of oscillating piezoelectric module; (**b**) input current of oscillating piezoelectric module; (**c**) output voltage of oscillating piezoelectric module; (**d**) output current of oscillating piezoelectric module.

2.2. Energy Harvesting from Piezoelectric Material

The proposed energy harvesting system operates under the principle that, when a force is applied to piezoelectric devices, mechanical stresses are accumulated. Under these conditions, when an electric current is passed through the polarity arrangement, an electric potential is generated at both terminals. Subsequently, the generated energy is passed through a rectifier circuit to transform the AC produced to a DC, which is then used for powering the operation of the battery and the connected electronics. For this system, an appropriate capacitor connection was essential to reduce ripple voltages at the output. The output was then transmitted to the Darlington circuit, which increased the current, in correlation with the boost converter and regulator, to maintain the expected output voltage serving the terminal devices.

The overall system operation is depicted in Figure 4. Furthermore, the designed schematics for the functioning of the energy harvesting circuit during daytime and nighttime as well as the entire system combining these two circuits are presented in Figure 5.

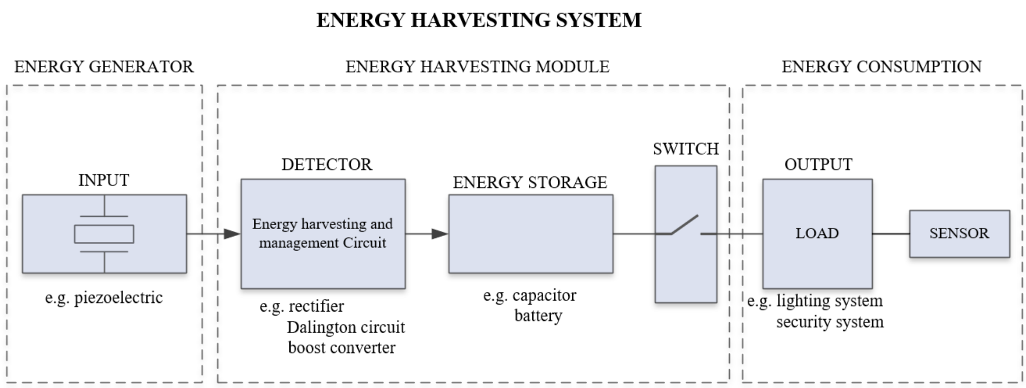
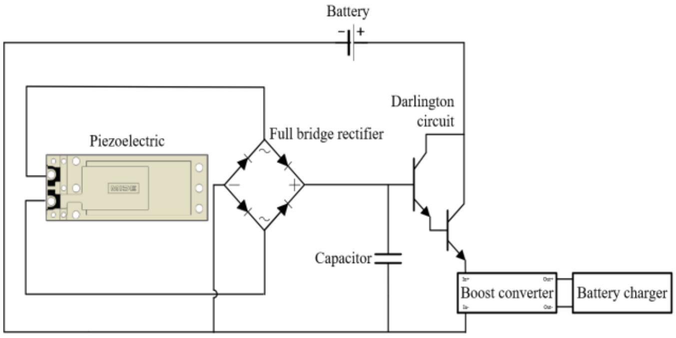
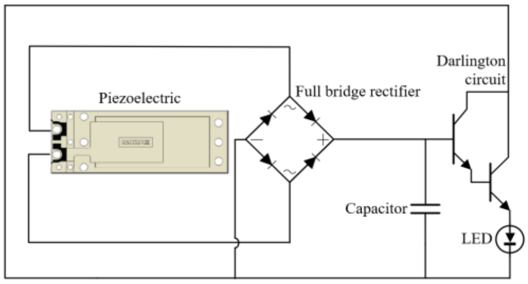


Figure 4. Overall working of piezoelectric energy harvesting system.

Initially, we assumed that using springs increased the harvested energy; when the first oscillating impulse moved further away, the spring would exert the reaction force back to the piezoelectric plate as if it were continuously excited. When the overall stiffness of the spring decreased, it would affect the natural frequencies of the system—the material would result in more extended oscillation periods, contributing to a more significant amount of harvested energy. Based on preliminary experiments, we determined that this assumption was accurate. Therefore, a miniature floor model was created; in this model, the excitation force from each piezoelectric device was phase-matched through the piezoelectric modules and an aluminum plate to deliver a constructive interference electric signal. The preliminary test kit using springs for vibration energy enhancement is depicted in Figure 6. The installation location of the aluminum plate was also adjusted accordingly. Thus, a pressure applied at the tip of the piezoelectric modules could produce vibrations with the highest amplitudes; however, this position should not be subjected to excessive force since it could result in material damage. A trial installation area of 2.7 m^2 was determined, and the installation of a total of 15 electricity-generating floors (dimensions: 0.3×0.3 m) was simulated, as shown in Figure 7.



(a)



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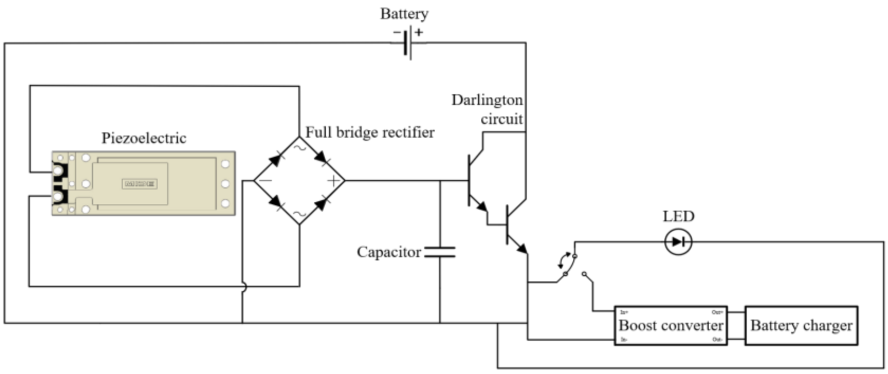


(c)

Figure 5. Proposed system for piezoelectric energy harvesting: (**a**) schematic of system for daytime operation; (**b**) schematic of system for nighttime operation; (**c**) schematic of entire system.

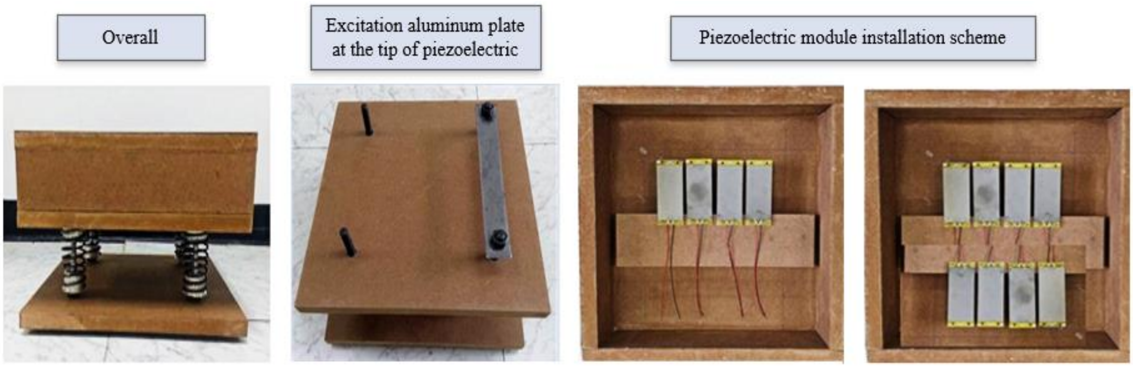


Figure 6. Preliminary test kit using springs for the enhancement of the vibration energy.

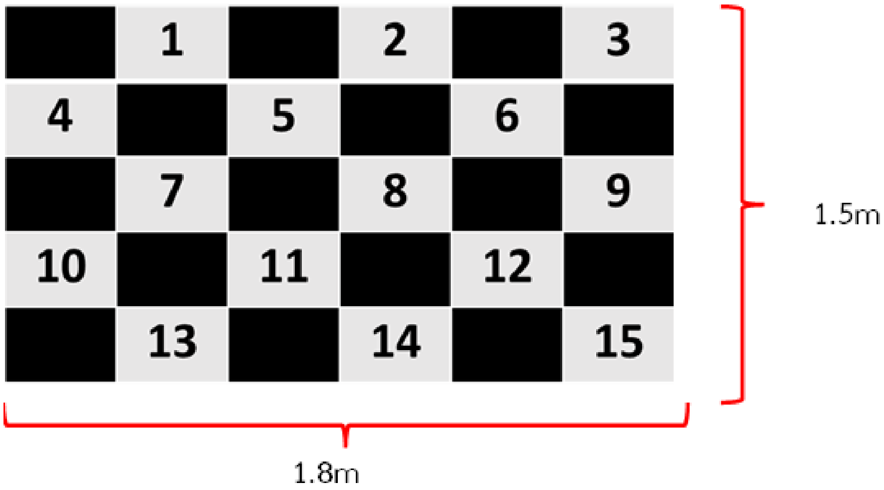


Figure 7. Trial installation area for preliminary test kit.

An observation of the areas with high traffic revealed that the ground generated energy every 1 s on average. Ten sets of mechanical forces were obtained simultaneously. Charging the lithium-ion battery required 3.5 s when eight piezoelectric plates were connected in parallel, serving as the energy source. The charging time for ten sets of ground power generators was 0.00683594 s, as shown in Table 2. Furthermore, a 2 mA lithium-ion battery could be charged within 0.01 s; this corresponds to a charging rate of 200 mA/s. Therefore, an 800 mAh lithium-ion battery could be fully charged within 4 h.

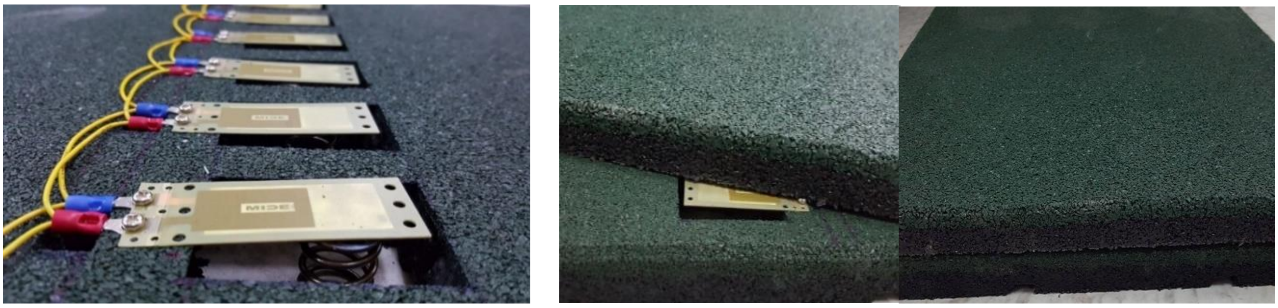
Table 2. Charging time needed for a preliminary test kit to generate energy when subjected to mechanical force.

Number of Mechanically Applied Preliminary Test Kit (Sets)	Charging Time(s)
1	3.50
2	1.75
3	0.88
4	0.44
5	0.22
6	0.11
7	0.05
8	0.03
9	0.02
10	0.01

2.3. Power-Generation Bicycle Lane Using Piezoelectric Material Conceptual

Bicycle-pedestrian surfaces can be composed of a diverse selection of materials. Regarding piezoelectric materials, PZT-type materials, which feature a high energy conversion capability but are still ceramic, are used. Such materials are brittle and can be damaged easily [52,53]. Therefore, selecting the appropriate materials for energy transfer is essential. Ethylene propylene diene monomer (EPDM) [64], which has a smooth surface, resists high impacts and temperatures and is also flexible, durable, and non-polluting. Hence, it was selected as the synthetic rubber flooring material. The designed dimensions per sheet were 50 cm $\times$ 50 cm $\times$ 25 mm. The piezoelectric device was sandwiched between two rubber sheets with a gap drilled to install the vibration enhancement spring, as shown in Figure 8.

The significant parameters that affect the conversion of mechanical energy into electricity are listed in Table 3.



(**a**) (**b**)

Figure 8. The material used and the piezoelectric installation area: (**a**) piezoelectric module installation; (**b**) surface material for bike lane.

Table 3. List of piezoelectric material properties.

Property	Value	Unit
Overall dimensions (length × width × thickness) of piezoelectric modules	71.0 × 25.4 × 0.76	mm
Density	7.8	g/cm^3
Dielectric constant (1 KHz)	3800	-
Piezoelectric voltage coefficient g_{33}	19.0	$V{\cdot}m/N \times 10^{-3}$
Piezoelectric voltage coefficient g_{31}	−9.5	$V{\cdot}m/N \times 10^{-3}$
Piezoelectric charge(displacement) coefficient d_{33}	650	$m/V \times 10^{-12}$
Piezoelectric charge(displacement) coefficient d_{31}	−320	$m/V \times 10^{-12}$
Capacitance	190	nF

Owing to their electrical characteristics, piezoelectric devices harvest electricity at high voltages and low currents. The voltage and current obtained from one piezoelectric sheet were approximately 10–15 V and 70–110 µA, respectively. However, using an efficient energy harvesting circuit can yield additional power. In the experiment, eight piezoelectric modules were connected in parallel along the intended bike path to maximize the energy produced within an area of 0.25 m^2; the system generated a power of approximately 1 W. When force was exerted on one piezoelectric sheet through the synthetic rubber sheet, over ten iterations, the average voltage received per load was 15.8 V, and the average current was 7.2 µA. Subsequently, a direct force was employed in the experiment, with springs placed under the piezoelectric modules such that the maximum displacement of the piezoelectric tip did not exceed the yield strength of the material; this helped prevent any damage and extend the period of continuous vibrations. The dimensions and mechanical characteristics of the spring influenced its natural frequency. When the spring was subjected to an excited frequency close to its natural frequency, the spring resonated; this resulted in vigorous and continuous oscillations of the piezoelectric tip, thereby producing the highest energy output. The piezoelectric sheet was overlaid with an EPDM synthetic rubber sheet to protect the piezoelectric modules from damage resulting from direct contact with the external forces. The actual piezoelectric energy harvesting circuit and the voltage signal captured from the oscilloscope are presented in Figures 9 and 10, respectively.

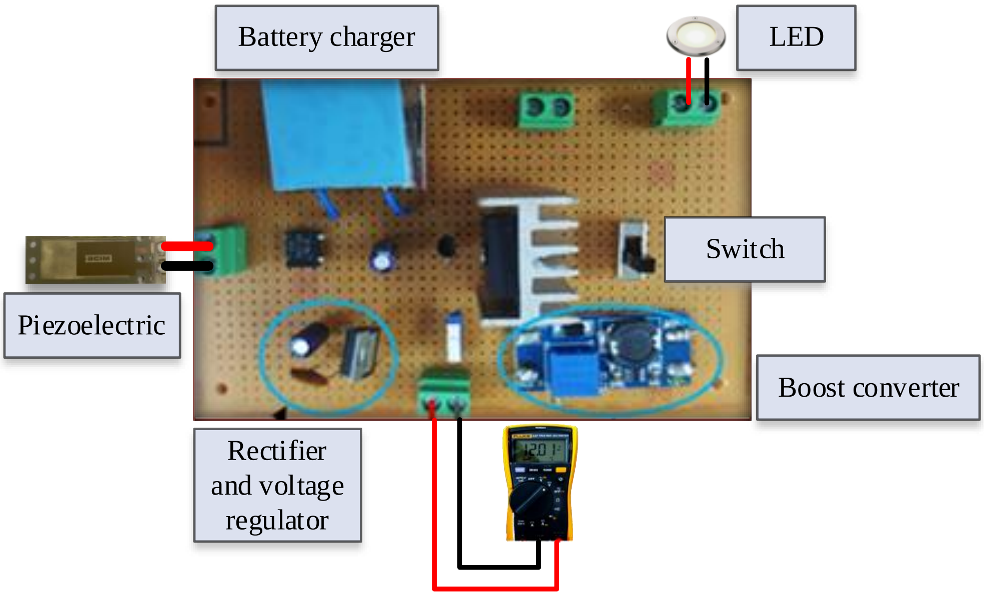
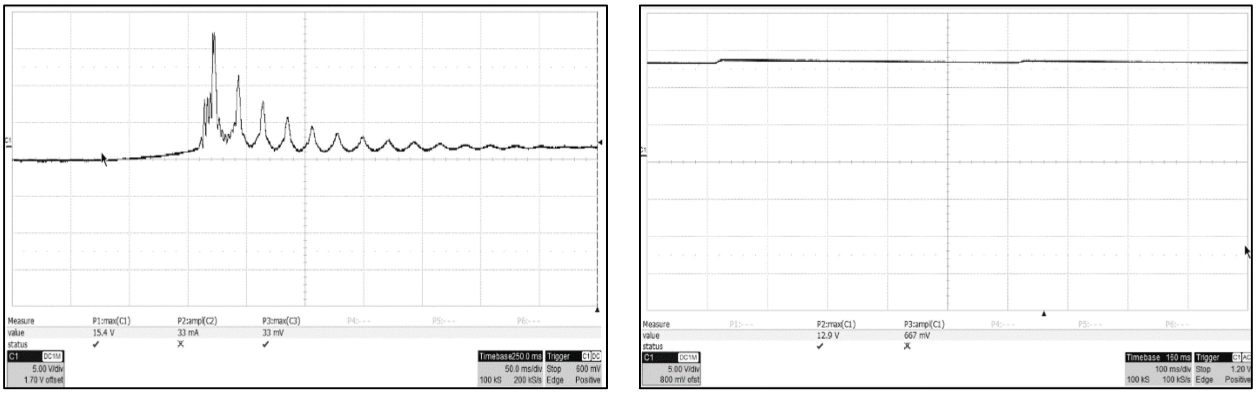


Figure 9. Piezoelectric energy harvesting circuit.



(**a**) (**b**)

Figure 10. Voltage signal under excitation by mechanical force, as captured from an oscilloscope: (**a**) rectified voltage signal; (**b**) voltage signal boosted by boost converter.

The voltages were measured across ten trials, each conducted with and without the spring installed on the power-generating floor; the average of the values thus obtained was calculated, as shown in Table 4. The experimental results indicated that, on installing the spring, the average voltage was higher than that without the spring. Due to the mounting of the spring, the piezoelectric material oscillated with higher amplitudes and frequencies.

A rectifier and a 1 μF capacitor were connected to the piezoelectric modules to convert the AC to DC at night. Moreover, the ripple voltage at the output was reduced, and the current was increased by transmitting it through the Darlington circuit for supplying the illuminating system. For the daytime battery charging circuit, a 12 V nickel–metal hydride (NiMH) battery was used to connect the boost converter and the Darlington circuit in order to maintain the expected voltage level. Furthermore, to confirm that the battery was chargeable, the 3-pin IC model MC7805 was used to provide a constant output voltage to the load. The combination of these circuits from both designs utilized electronic switches to separate day and night periods. During actual use, the Darlington circuit was powered using solar energy. The energy obtained from the piezoelectric device through the energy harvesting circuit increased to 72 mA and 3.1 V. Therefore, when a bicycle passed over the power generator, it excited four piezoelectric devices, increasing the power (3.1 × 0.072 = 0.8928 W) by a factor of 4. When passing through the step-up circuit, which was used to increase the voltage to 12 V, a current of 13 mA was obtained. Over a distance of 1 m, a total of 32 piezoelectric plates were installed. Thus, the electric power (12 × 0.0186 = 7.1424 W) increased by a factor of 32.

Table 4. Voltage measurements with and without the spring installed on the power-generating floor.

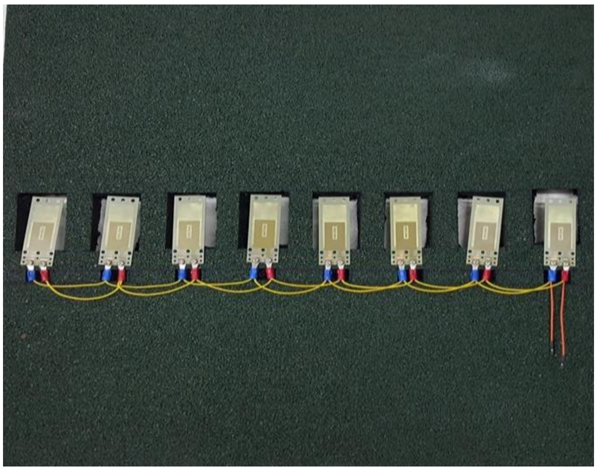
Trial Number	Voltage When the Spring Was Not Installed (V)	Voltage When the Spring Was Installed (V)
1	5.12	15.30
2	4.87	16.71
3	4.87	15.66
4	5.57	13.67
5	6.14	15.98
6	5.14	15.14
7	4.98	14.65
8	5.88	14.47
9	5.00	16.11
10	4.31	17.01

3. Experiment and Result

For the installation of the power-generating bike lane, parallel piezoelectric devices were placed along a straight line in the middle of the synthetic rubber floor. The design pavement was a section of 50 cm × 50 cm with the 0.5 W LED lamp installed on the edge of each side of the pavement, as shown in Figure 11a. Under the cover of each section, eight piezoelectric plates were installed as shown in Figure 11b. Thus, a total of 24 piezoelectric plates and six LED lamps (total power consumption of 3 W) were installed every 1.5 m along the track. Under this configuration, when a bicycle entered a certain area, that area and the ones ahead were illuminated; as the bicycle moved forward, the subsequent areas were illuminated, whereas the lamps located in the previous area were turned off. This helped indicate the bike's position on the lane and also helped improve visibility under insufficient lighting conditions.

(**a**)

Figure 11. *Cont.*



(b)

(c)

Figure 11. An overview of the power-generating bike lane demonstration section. (**a**) The overview of the 1.5 m pavement section. (**b**) An actual installation of piezoelectric plates. (**c**) Brightness of the lamps installed according to zoning.

The amount of energy generated was measured for riders of different weights and driving speeds, as shown in Tables 5 and 6, respectively. The experimental results showed that, when the piezoelectric devices were subjected to a pressure owing to the increase in weight, the electric power also increased; this was because the increased weight led to an increase in the force applied on the spring, causing the piezoelectric device to oscillate to a greater extent. In contrast, higher speeds resulted in lower load intensities, thereby reducing the amount of energy that could be harvested. The trial was a simulated experiment in an area where the main lighting was inaccessible, thus limiting the driving speed obtained by surveying its use in that area. The rider weight was the average weight based on the surveys of the actual users in the study area, divided into three periods. It was found that the operating weight and speed range were able to harvest energy from cycling for use in insufficiently illuminated areas for natural navigation lights. As shown in the experimental results, each weight and velocity condition obtained different electrical power. Moreover, the brightness of the lamps installed was deemed satisfactory according to the zoning regulations, as demonstrated in Figure 11c.

Table 5. Electrical quantities of the power-generating floor under different rider weights.

Weight (kg)	Voltage (V)	Current (A)	Power (W)
55	2.87	0.328	0.9414
75	3.17	0.363	1.1507
90	3.33	0.403	1.3420

Table 6. Electrical quantities of the power-generating floor under different driving speeds.

Speed (km/h)	Voltage (V)	Current (A)	Power (W)
5	3.20	0.352	1.1264
10	3.12	0.309	1.0976
20	3.20	0.343	0.9641

4. Conclusions

In this study, an energy harvesting system using piezoelectric materials was designed to serve as an energy source for bicycle paths; the operation of this system was divided based on day and night periods. EPDM was selected as the material for the rubber flooring, and springs were installed under the piezoelectric devices to boost the harvested energy. Furthermore, the appropriate selection and installation of the springs enabled the piezoelectric plates to vibrate actively and continuously, while also protecting the device from damage due to excessive bending.

When measuring the electrical quantities of the piezoelectric materials assembled on the energy-generating floor, the average voltage was determined to be 15.8 V. When a bicycle moved across the designed system, it applied a load on four piezoelectric plates, thus affording a power of 0.8928 W. In the daytime, energy was generated and stored in the battery. Over a distance of 1 m, 32 piezoelectric plates were installed, which generated a total power of 7.1424 W/m^2. A 12 V NiMH size was selected because it featured a voltage range suitable for a variety of applications.

To summarize, the energy harvested from this energy source depends on many factors, such as the continuation of the received mechanical force as well as the efficiency of the energy harvesting circuit and piezoelectric materials. Essentially, this study proposed recycling the waste energy from daily life activities and transforming it into electrical energy, to the greatest extent possible. In the future, this approach could be used for an alternative energy source.

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References

1. Reviewing world energy data for 70 years. In *Statistical Review of World Energy 2021*; BP p.l.c.: London, UK, 2022.
2. U.S. Energy Information Administration; Office of Energy Analysis; U.S. Department of Energy. *Annual Energy Outlook 2022*; Bipartisan Policy Center: Washington, DC, USA, 2022.
3. Paez-Montoro, A.; Garcia-Valderas, M.; Olias-Ruiz, E.; Lopez-Ongil, C. Solar Energy Harvesting to Improve Capabilities of Wearable Devices. *Sensors* **2022**, *22*, 3950. [CrossRef] [PubMed]
4. Barreto, R.A. Fossil fuels, alternative energy and economic growth. *Econ. Model.* **2018**, *75*, 196–220. [CrossRef]
5. Saidi, K.; Omri, A. The impact of renewable energy on carbon emissions and economic growth in 15 major renewable energy-consuming countries. *Environ. Res.* **2020**, *186*, 109567. [CrossRef]
6. Coram, A.; Katzner, D.W. Reducing fossil-fuel emissions: Dynamic paths for alternative energy-producing technologies. *Energy Econ.* **2018**, *70*, 179–189. [CrossRef]
7. Zafar, M.W.; Shahbaz, M.; Sinha, A.; Sengupta, T.; Qin, Q. How renewable energy consumption contribute to environmental quality? The role of education in OECD countries. *J. Clean. Prod.* **2020**, *268*, 122149. [CrossRef]
8. Stančin, H.; Mikulčić, H.; Wang, X.; Duić, N. A review on alternative fuels in future energy system. *Renew. Sustain. Energy Rev.* **2020**, *128*, 109927. [CrossRef]
9. Chiradeja, P.; Ngaopitakkul, A. Energy and Economic Analysis of Tropical Building Envelope Material in Compliance with Thailand's Building Energy Code. *Sustainability* **2019**, *11*, 6872. [CrossRef]
10. Choudhary, P.; Bhargava, L.; Singh, V.; Choudhary, M.; Suhag, A.K. A survey—Energy harvesting sources and techniques for internet of things devices. *Mater. Today Proc.* **2020**, *30*, 52–56. [CrossRef]
11. Wang, S. Current status of PV in China and its future forecast. *CSEE J. Power Energy Syst.* **2020**, *6*, 72–82.
12. Anderson, A.A.; Suryanarayanan, S. Review of energy management and planning of islanded microgrids. *CSEE J. Power Energy Syst.* **2020**, *6*, 329–343.
13. Lai, Z.H.; Wang, J.L.; Zhang, C.L.; Zhang, G.Q.; Yurchenko, D. Harvest wind energy from a vibro-impact DEG embedded into a bluff body. *Energy Convers. Manag.* **2019**, *199*, 111993. [CrossRef]
14. Sun, W.; Jo, S.; Seok, J. Development of the optimal bluff body for wind energy harvesting using the synergetic effect of coupled vortex induced vibration and galloping phenomena. *Int. J. Mech. Sci.* **2019**, *156*, 435–445. [CrossRef]
15. Mohammadnia, A.; Rezania, A.; Ziapour, B.M.; Sedaghati, F.; Rosendahl, L. Hybrid energy harvesting system to maximize power generation from solar energy. *Energy Convers. Manag.* **2020**, *205*, 112352. [CrossRef]
16. Leon, J.S.; Cioncolini, A.; Nabawy, M.R.A.; Revell, A.; Kennaugh, A. Simultaneous wind and solar energy harvesting with inverted flags. *Appl. Energy* **2019**, *239*, 846–858. [CrossRef]
17. Chiradeja, P.; Pothisarn, C.; Jettanasen, C.; Yoomak, S.; Songsukthawan, P.; Bunjongjit, S.; Leelajindakrairerk, M.; Ngaopitakkul, A. Solar water heating in residential building. *Int. J. Smart Grid Clean Energy* **2019**, *8*, 422–429. [CrossRef]
18. Sharma, H.; Haque, A.; Jaffery, Z.A. Maximization of wireless sensor network lifetime using solar energy harvesting for smart agriculture monitoring. *Ad Hoc Netw.* **2019**, *94*, 101966. [CrossRef]
19. Yoomak, S.; Patcharoen, T.; Ngaopitakkul, A. Performance and Economic Evaluation of Solar Rooftop Systems in Different Regions of Thailand. *Sustainability* **2019**, *11*, 6647. [CrossRef]
20. Kaza, N. Urban form and transportation energy consumption. *Energy Policy* **2020**, *136*, 111049. [CrossRef]
21. Xu, J.H.; Guo, J.F.; Peng, B.; Nie, H.; Kemp, R. Energy growth sources and future energy-saving potentials in passenger transportation sector in China. *Energy* **2020**, *206*, 118142. [CrossRef]
22. Pedro, L.; Verdezoto, C.; Vidoza, J.A.; Gallo, W.L.R. Analysis and projection of energy consumption in Ecuador: Energy efficiency policies in the transportation sector. *Energy Policy* **2019**, *134*, 110948.
23. Yoomak, S.; Ngaopitakkul, A. Investigation and Feasibility Evaluation of Using Nanogrid Technology Integrated into Road Lighting System. *IEEE Access* **2020**, *8*, 56739–56754. [CrossRef]
24. Sonmez, M.; Akgüngör, A.P.; Bektaş, S. Estimating transportation energy demand in Turkey using the artificial bee colony algorithm. *Energy* **2017**, *122*, 301–310. [CrossRef]
25. Lampinen, A. Dealing with victor's history in renewable energy education for transportation applications. *Solar Energy* **2018**, *173*, 272–276. [CrossRef]
26. Olivares, A.G.; Solé, J.; Osychenko, O. Transportation in a 100% renewable energy system. *Energy Convers. Manag.* **2018**, *158*, 266–285. [CrossRef]
27. Hung, N.B.; Lim, O. A review of history, development, design and research of electric bicycles. *Appl. Energy* **2019**, *260*, 114323. [CrossRef]
28. Shui, C.S.; Szeto, W.Y. A review of bicycle-sharing service planning problems. *Transp. Res. Part C Emerg. Technol.* **2020**, *117*, 102648. [CrossRef]
29. Yang, Y.; Pian, Y.; Liu, Q. Design of energy harvester using rotating motion rectifier and its application on bicycle. *Energy* **2019**, *179*, 222–231. [CrossRef]
30. Guanetti, J.; Formentin, S.; Corno, M.; Savaresi, S.M. Optimal energy management in series hybrid electric bicycles. *Automatica* **2017**, *81*, 96–106. [CrossRef]
31. Bucher, D.; Buffat, R.; Froemelt, A.; Raubal, M. Energy and greenhouse gas emission reduction potentials resulting from different commuter electric bicycle adoption scenarios in Switzerland. *Renew. Sustain. Energy Rev.* **2019**, *114*, 109298. [CrossRef]

32. Sarker, M.R.; Julai, S.; Sabri, M.F.M.; Said, S.M.; Islam, M.M.; Tahir, M. Review of piezoelectric energy harvesting system and application of optimization techniques to enhance the performance of the harvesting system. *Sens. Actuators A Phys.* **2019**, *300*, 111634. [CrossRef]
33. Ali, W.R.; Prasad, M. Piezoelectric MEMS based acoustic sensors: A review. *Sens. Actuators A Phys.* **2020**, *301*, 111756. [CrossRef]
34. Li, X.; Upadrashta, D.; Yu, K.; Yang, Y. Analytical modeling and validation of multi-mode piezoelectric energy harvester. *Mech. Syst. Signal Processing* **2019**, *124*, 613–631. [CrossRef]
35. Khalili, M.; Biten, A.B.; Vishwakarma, G.; Ahmed, S.; Papagiannakis, A.T. Electro-mechanical characterization of a piezoelectric energy harvester. *Appl. Energy* **2019**, *253*, 113585. [CrossRef]
36. Pal, A.; Sasmal, A.; Manoj, B.; Prasada Rao, D.S.D.; Haldar, A.K.; Shrabanee, S. Enhancement in energy storage and piezoelectric performance of three phase (PZT/MWCNT/PVDF) composite. *Mater. Chem. Phys.* **2020**, *244*, 122639. [CrossRef]
37. Zou, H.X.; Zhang, W.; Li, W.B.; Wei, K.X.; Gao, Q.H.; Peng, Z.K.; Meng, G. Design and experimental investigation of a magnetically coupled vibration energy harvester using two inverted piezoelectric cantilever beams for rotational motion. *Energy Convers. Manag.* **2017**, *148*, 1391–1398. [CrossRef]
38. Qian, F.; Xu, T.B.; Zuo, L. Design, optimization, modeling and testing of a piezoelectric footwear energy harvester. *Energy Convers. Manag.* **2018**, *171*, 1352–1364. [CrossRef]
39. Chen, Z.; Xia, Y.; He, J.; Xiong, Y.; Wang, G. Elastic-electro-mechanical modeling and analysis of piezoelectric metamaterial plate with a self-powered synchronized charge extraction circuit for vibration energy harvesting. *Mech. Syst. Signal Processing* **2020**, *143*, 106824. [CrossRef]
40. Iqbal, M.; Khan, F.U. Hybrid vibration and wind energy harvesting using combined piezoelectric and electromagnetic conversion for bridge health monitoring applications. *Energy Convers. Manag.* **2018**, *172*, 611–618. [CrossRef]
41. Izadgoshasb, I.; Lim, Y.Y.; Lake, N.; Tang, L.; Padilla, R.V.; Kashiwao, T. Optimizing orientation of piezoelectric cantilever beam for harvesting energy from human walking. *Energy Convers. Manag.* **2018**, *161*, 66–73. [CrossRef]
42. Wu, Y.; Qiu, J.; Zhou, S.; Ji, H.; Chen, Y.; Li, S. A piezoelectric spring pendulum oscillator used for multi-directional and ultra-low frequency vibration energy harvesting. *Appl. Energy* **2018**, *231*, 600–614. [CrossRef]
43. Wang, J.; Tang, L.; Zhao, L.; Zhang, Z. Efficiency investigation on energy harvesting from airflows in HVAC system based on galloping of isosceles triangle sectioned bluff bodies. *Energy* **2019**, *172*, 1066–1078. [CrossRef]
44. Chen, J.; Qiu, Q.; Han, Y.; Lau, D. Piezoelectric materials for sustainable building structures: Fundamentals and applications. *Renew. Sustain. Energy Rev.* **2019**, *101*, 14–25. [CrossRef]
45. Hu, G.; Tse, K.T.; Wei, M.; Naseer, R.; Abdelkefi, A.; Kwok, K.C.S. Experimental investigation on the efficiency of circular cylinder-based wind energy harvester with different rod-shaped attachments. *Appl. Energy* **2018**, *226*, 682–689. [CrossRef]
46. Sun, W.; Zhao, D.; Tan, T.; Yan, Z.; Guo, P.; Luo, X. Low velocity water flow energy harvesting using vortex induced vibration and galloping. *Appl. Energy* **2019**, *251*, 113392. [CrossRef]
47. Shan, X.; Li, H.; Yang, Y.; Feng, J.; Wang, Y.; Xie, T. Enhancing the performance of an underwater piezoelectric energy harvester based on flow-induced vibration. *Energy* **2019**, *172*, 134–140. [CrossRef]
48. Toyabur, R.M.; Salauddin, M.; Cho, H.; Park, J.Y. A multimodal hybrid energy harvester based on piezoelectric-electromagnetic mechanisms for low-frequency ambient vibrations. *Energy Convers. Manag.* **2018**, *168*, 454–466. [CrossRef]
49. Naseer, R.; Dai, H.L.; Abdelkefi, A.; Wang, L. Piezomagnetoelastic energy harvesting from vortex-induced vibrations using monostable characteristics. *Appl. Energy* **2017**, *203*, 142–153. [CrossRef]
50. Nowak, R.; Pietrzakowski, M.; Rumianek, P. Influence of design parameters on bending piezoelectric harvester effectiveness: Static approach. *Mech. Syst. Signal Processing* **2020**, *143*, 106833. [CrossRef]
51. Jettanasen, C.; Songsukthawan, P.; Ngaopitakkul, A. Development of micro-mobility based on piezoelectric energy harvesting for smart city applications. *Sustainability* **2020**, *12*, 2020.
52. Ghodsi, M.; Ziaiefar, H.; Mohammadzaheri, M.; Al-Yahmedi, A. Modeling and characterization of permendur cantilever beam for energy harvesting. *Energy* **2019**, *176*, 561–569. [CrossRef]
53. Mohammadzaheri, M.; AlQallaf, A. Nanopositioning systems with piezoelectric actuators, current state and future perspective. *Sci. Adv. Mater.* **2017**, *9*, 1071–1080. [CrossRef]
54. Cheng, C.H.; Wu, M.F.; Guo, S.H.; Chen, K.S. Realization and performance assessment of a force-sensing based smart floor panel for indoor localization applications. *Sens. Actuators A Phys.* **2019**, *285*, 468–481. [CrossRef]
55. Wang, C.; Zhao, J.; Li, Q.; Li, Y. Optimization design and experimental investigation of piezoelectric energy harvesting devices for pavement. *Appl. Energy* **2018**, *229*, 18–30. [CrossRef]
56. Wang, C.; Song, Z.; Gao, Z.; Yu, G.; Wang, S. Preparation and performance research of stacked piezoelectric energy-harvesting units for pavements. *Energy Build.* **2019**, *183*, 581–591. [CrossRef]
57. Evans, M.; Tang, L.; Tao, K.; Aw, K. Design and optimisation of an underfloor energy harvesting system. *Sens. Actuators A Phys.* **2019**, *285*, 613–622. [CrossRef]
58. Elhalwagy, A.M.; Ghoneem, M.Y.M.; Elhadidi, M. Feasibility Study for Using Piezoelectric Energy Harvesting Floor in Buildings' Interior Spaces. *Energy Procedia* **2017**, *115*, 114–126. [CrossRef]
59. Jasim, A.; Yesner, G.; Wang, H.; Safari, A.; Maher, A.; Basily, B. Laboratory testing and numerical simulation of piezoelectric energy harvester for roadway applications. *Appl. Energy* **2018**, *224*, 438–447. [CrossRef]

60. Wang, C.; Wang, S.; Li, Q.J.; Wang, X.; Gao, Z.; Zhang, L. Fabrication and performance of a power generation device based on stacked piezoelectric energy-harvesting units for pavements. *Energy Convers. Manag.* **2018**, *163*, 196–207. [CrossRef]
61. Tahami, S.A.; Gholikhani, M.; Nasouri, R.; Dessouky, S.; Papagiannakis, A.T. Developing a new thermoelectric approach for energy harvesting from asphalt pavements. *Appl. Energy* **2019**, *238*, 786–795. [CrossRef]
62. Song, G.J.; Cho, J.Y.; Kim, K.B.; Ahn, J.H.; Song, Y.; Hwang, W.; Hong, S.D.; Sung, T.H. Development of a pavement block piezoelectric energy harvester for self-powered walkway applications. *Appl. Energy* **2019**, *256*, 113916. [CrossRef]
63. Kim, K.B.; Cho, J.Y.; Jabbar, H.; Ahn, J.H.; Hong, S.D.; Woo, S.B.; Sung, T.H. Optimized composite piezoelectric energy harvesting floor tile for smart home energy management. *Energy Convers. Manag.* **2018**, *171*, 31–37. [CrossRef]
64. Chegenizadeh, A.; Aung, M.-O.; Nikraz, H. Ethylene Propylene Diene Monomer (EPDM) Effect on Asphalt Performance. *Buildings* **2021**, *11*, 315. [CrossRef]