



e-ISSN: 2319-8753 | p-ISSN: 2347-6710

IJRSET

International Journal of Innovative Research in
SCIENCE | ENGINEERING | TECHNOLOGY

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 12, Issue 7, July 2023

ISSN INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 8.423

9940 572 462

6381 907 438

ijirset@gmail.com

www.ijirset.com

Design and Field Testing of an Energy Harvester Based on Piezoelectric Ceramics

C. Schiefer¹, D. Xu², X. Cheng³, J. Plank^{4*}

PhD student, Dept. of Chemistry, Technical University of Munich, Munich, Germany¹

Professor, Shandong Provincial Key Lab for the Preparation and Measurement of Building Materials, University of Jinan, Jinan, China^{2,3}

Professor Emeritus, Dept. of Chemistry, Technical University of Munich, Munich, Germany^{4*}

ABSTRACT: Since a few years the demand for sources of renewable energy is strongly increasing and hence, energy harvesting has experienced substantial attention among researchers and stakeholders. Piezoelectric materials are able to convert mechanical into electrical energy and *vice versa*. The principle idea of piezoelectric energy harvesting is based on the conversion of pressure (impact) applied by pedestrians or vehicles traversing a floor or road into electricity. In this study, the design, realization and working experience of an energy harvesting floor tile (50 × 100 × 3.5 cm) installed at the administration center on the main campus of Technical University of Munich is presented. This demonstrator uses 117 sintered PZT piezoelectric ceramic boards (capacity: 23 μF) to produce electrical energy. The output of the floor tile was captured using an oscilloscope connected to a data logger. Over a one-year period nearly 80,000 steps producing an average voltage of 1.97 V and an energy amount of 288 μJ per step were recorded. This field experiment confirmed the robustness of the piezoelectric floor tile design which required virtually no maintenance over the one-year period. Thus, this concept is very promising for use in highly frequented areas such as subway stations or even roads to harvest energy without any CO₂ emission and to reach the target of climate neutrality.

KEYWORDS: Energy Harvesting, Piezoelectricity, Green Energy, Field Testing, Piezoelectric Floor

I. INTRODUCTION

The global demand for energy is expected to continuously increase in the next decades (see **Fig. 1a**) and hence, an increase from 542 quadrillion British thermal units (Btu) in 2010 to 886 quadrillion Btu in 2050 is anticipated which corresponds to an annual growth rate of 1.24 % and a total increase of 63 % according to the U.S. Energy Information and Administration (EIA) [1]. Moreover, the main increase in energy demand stems from countries outside the Organization for Economic Cooperation and Development (OECD). In particular, by 2050 non-OECD countries in Asia including India and China are expected to account for about 400 quadrillion Btu (45 %) of the global energy consumption. Even though the carbon intensity of energy generation is expected to decrease around the world because of the promotion of renewable energy sources, global carbon dioxide (CO₂) emissions will continue to rise as is shown in **Fig. 1b**. Worldwide annual CO₂ emissions will continue to increase to ~ 43 Gt in 2050 which is 30 % more than in 2010 [1]. While within OECD emissions are expected to slightly decrease, for non-OECD countries an increase of about 10 Gt from 2010 to 2050 is presumed [1]. This implies that the expansion of renewables will rather compensate the increasing energy demand than replace fossil sources in countries outside the OECD. With regard to global warming, starting from around 1920 and especially since 1970, the global temperature has increased steadily by about + 1.2 °C in 2022, which is far above the previous long-term average using data from Berkeley Earth organization (see **Fig. 1c**) [2]. This rise in temperature is mainly caused by the accumulation of CO₂ and other greenhouse gases (GHG) in the atmosphere. Considering the globally increasing demand for energy and the resulting emissions, a continuous increase in the atmospheric GHG concentration and even higher global temperatures are expected. Extrapolation of the trend observed since 1980 would result in a temperature increase of 2.0 °C by 2060, as is illustrated in **Fig. 1c**. Such noticeable temperature increase has substantial consequences including rise of the sea level, melting of glaciers, strong temperature fluctuations and, in addition to desertification of some areas, also unusually strong floods and intense rain falls. The latter result from a higher moisture uptake by a warmer atmosphere [3]. If the aim of the Paris Agreement on climate change of keeping the global temperature increase below 2 °C is to be reached, then a substantial progress in limiting GHG emissions needs to be made. Since the combustion of fossil energy carriers including coal, natural gas and liquid fuels was identified as the main source for CO₂ emissions, their replacement with sources of low or zero net CO₂ emission is required to control climate change.

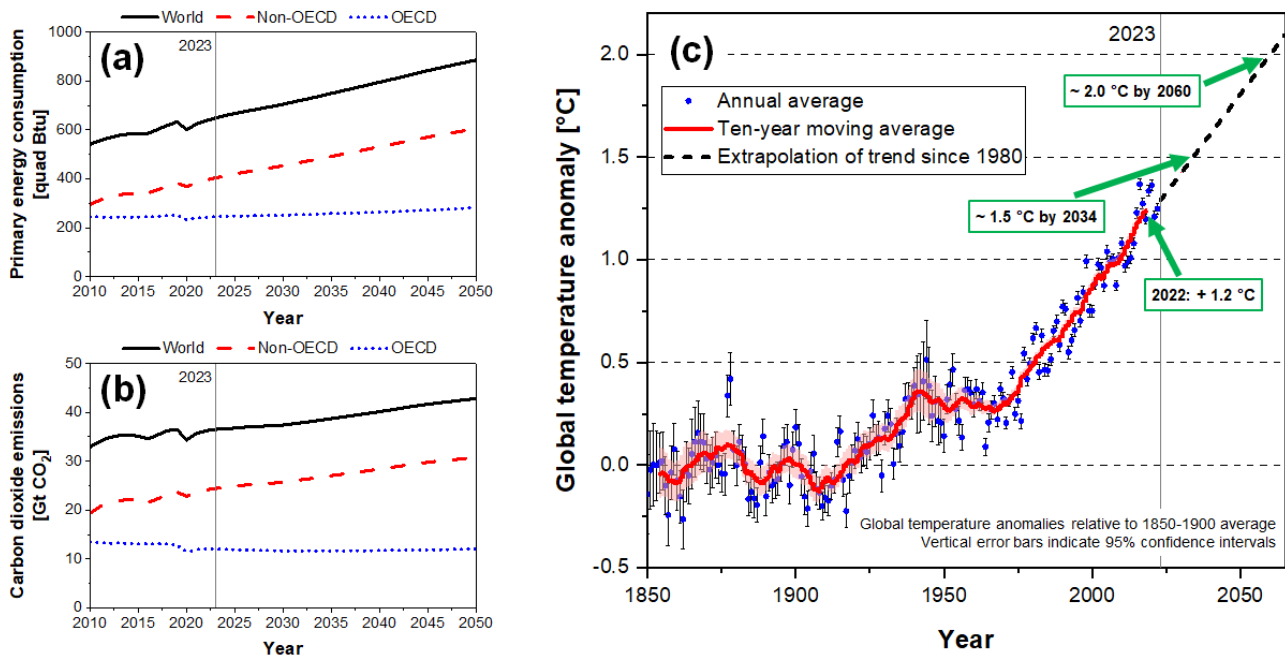


Fig. 1 (a) Global primary energy consumption; (b) global energy-related carbon dioxide (CO₂) emissions, starting from 1850 with projections to 2050 [1]; (c) development of median global temperature anomaly from 1850 – 2022 [2].

The idea of environmentally friendly energy harvesting is based on the generation of electrical power from natural (abundant and carbon-neutral) sources of energy. For high power generation in the range of megawatts, this is commonly achieved *via* wind, solar (photovoltaic), hydroelectric or geothermal energy harvesting. In the case of low power generation in the range of milliwatts, vibrations, RF (radio frequency), IR (infrared), light, motion, etc. can be utilized [4]. These energy sources have high potential to be used e.g. in low-power microelectronics, displays, sensors, etc., which enables the design of self-powered devices. Piezoelectric energy harvesters use impact and vibrations of machines or the motion of humans, animals or vehicles to generate electricity from mechanical stress. In this way, the “waste energy” e.g. from a pedestrian stepping and walking over a piezoelectric floor can be harvested and converted into electricity. Once manufactured, such tiles produce energy at zero CO₂ emission. This system can be used e.g. to power emergency lights on roads or signs on subway stations.

In this study, the design and implementation of an energy harvester based on a piezoelectric floor tile installed at the main campus in Munich’s downtown area is presented. The aim of this field test was to assess the energy output of the tile over a one-year period (from Sept 2021 to Aug 2022) and to test the robustness and applicability of such floor tile in an outdoor environment where it is exposed to seasonal weather and public users.

II. FUNDAMENTALS OF PIEZOELECTRICITY

The effect of piezoelectricity describes the reversible conversion of mechanical into electrical energy (direct piezoelectric effect) and vice versa (converse piezoelectric effect) and was first observed by Jacques and Pierre Curie in 1880 [5, 6]. Piezoelectricity only occurs in non-centrosymmetric crystalline materials such as α -quartz, BaTiO₃, Ba₂NaNb₅O₅, Bi₄Ti₃O₁₂, La₃Ga₅SiO₁₄, LiNbO₃, LiTaO₃ and Pb[Zr_xTi_{1-x}]O₃ with $0 \leq x \leq 1$. The latter – lead zirconate titanate, commonly known as PZT – presents the most common piezoelectric material used in various applications [7]. While its energy yield may be relatively low as compared to other piezoelectric materials, its affordability often makes it the material of choice.

In theory, piezoelectricity is a phenomenon involving electromechanical interconversion between mechanical stress, strain and electrical charges in the structure of piezoelectric materials. Their relationship is generally expressed by the linear coupling equations given in stress-charge form (Eqs. (1) and (2)) and strain-charge form (Eqs. (3) and (4)) as indicated below [6]. This implies that in the case of the converse piezoelectric effect, the total mechanical stress is presented by the sum of stress related to mechanical strain and stress caused by the applied electrical field, while the total electric charge results from the sum of the electric displacement due to mechanical strain and the displacement

caused by the applied electrical field. In contrast, for the direct piezoelectric effect the total mechanical strain yields from the sum of strain attributed to mechanical stress and the strain induced by the electric field, while the total electric charge is caused by the sum of the electric displacement caused by mechanical stress and the displacement due to the electrical field.

$$T = c^E S - e^t E \tag{1}$$

$$D = eS + \epsilon^S E \tag{2}$$

$$S = s^E T + d^t E \tag{3}$$

$$D = dT + \epsilon^T E \tag{4}$$

where:

T = stress;

S = strain;

D = electric charge density displacement;

E = electric field;

c^E = elastic stiffness coefficient at constant E ;

e^t = transposed piezoelectric stress coupling coefficient (converse piezoelectric effect);

e = piezoelectric stress coupling coefficient (direct piezoelectric effect);

ϵ^S = dielectric permittivity at constant S ;

s^E = elastic compliance coefficient at constant E ;

d^t = transposed piezoelectric strain coupling coefficient (converse piezoelectric effect);

d = piezoelectric strain coupling coefficient (direct piezoelectric effect);

ϵ^T = dielectric permittivity at constant T .

On a molecular level, the direct piezoelectric effect relies on the distortion of the crystal structure upon mechanical impact which leads to a charge separation due to displaced ions or ion clusters inside a non-centrosymmetric crystal. Consequently, when such charge separation occurs in a piezoelectric material, it induces ferroelectric polarization. This leads to an electrostatic potential across the material, which can be measured as voltage. **Fig. 2** depicts the crystal structure of a PZT material at non-pressurized condition (**Fig. 2a**), and under mechanical stress resulting in charge separation (**Fig. 2b**). The principle of voltage generation *via* mechanical force utilizing a PZT-based piezoelectric plate is shown in **Fig. 2c**.

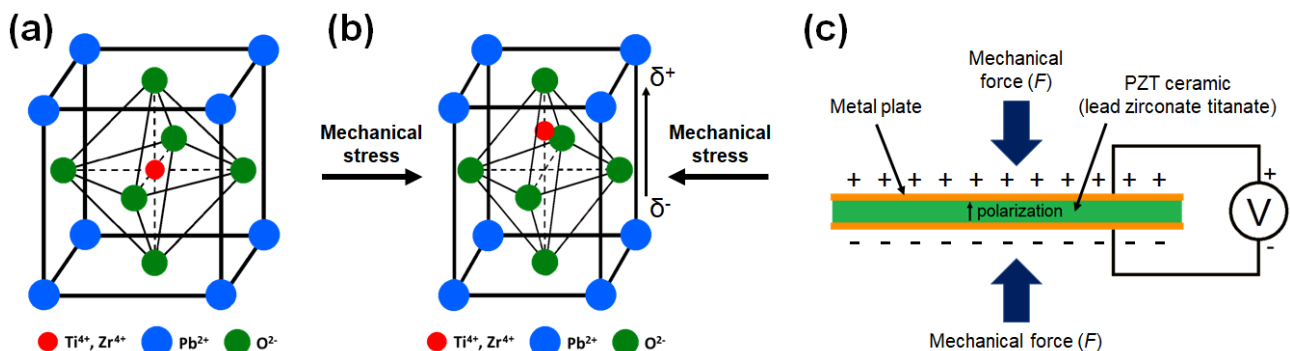


Fig. 2 (a) Crystal structure of a piezoelectric PZT material in non-pressurized state [8]; (b) crystal structure of PZT under mechanical stress [9]; (c) principle of voltage generation utilizing a PZT-based piezoelectric plate *via* ferroelectric polarization induced by mechanical force.

The charge separation process is completely reversible (= elastic), hence in theory a piezoelectric element can be used indefinitely. In this way, it is suitable for various piezoelectric sensors such as microphones and can be used as a power source, e.g. for energy harvesting. A common and well-known example of a piezoelectrically powered device is the quartz wrist watch which no longer requires a battery. Actuators, which utilize the converse piezoelectric effect to

transform electrical energy into motion, allow for precise and long-lasting movement. Popular examples for such device are piezoelectric speakers which generate sound by converting electrical signals into vibrations.

III. LITERATURE SURVEY

After the initial discovery of piezoelectricity and its subsequent manifold application in sensors, since the millennium several research works have focused on the concept of energy harvesting using piezoelectric materials. The aim was to seek practical technologies to harvest energy from vibrations or human and vehicle movements. In 2007, two students from the Massachusetts Institute of Technology (MIT), Thaddeus Jusczyk and James Graham, brought up the idea of energy harvesting by utilizing human movement in crowded areas which they referred to as “crowd farms” [10]. They had employed a prototype harvester at a train station in Torino, Italy, and were able to power four LEDs using the generated energy. In another project in 2008, the East Japan Railway Company installed a piezoelectric energy harvesting floor at the entrance of a train station in Tokyo where on average 0.1 W of electrical output was generated every second when a commuter walked two steps upon the floor tile [11]. In 2017, Shreeshayana *et al.* developed a prototype piezoelectric energy harvesting floor using PZT-based ceramic discs embedded in high-density foam to demonstrate the energy harvesting potential for India [12]. Similarly, in 2022, Moussa *et al.* presented such piezo floor installed inside an Egyptian metro station with an estimate of almost 57,000 passengers per day passing by who could produce enough electricity to self-power this metro station for the entire year [13]. In another study in 2022, Thainiramit *et al.* from Thailand reported on a triboelectric energy harvester built from polytetrafluoroethylene (PTFE) films and aluminum foil which was able to generate sufficient energy to power 150 LEDs by a 60 kg person who stepped less than two times per second onto the floor [14]. Furthermore, the potential of piezoelectric materials applied as energy harvesters in intelligent buildings has been discussed. For example, in 2014 Li *et al.* presented the concept of a piezoelectric energy harvester based on floor tiles which according to their model would roughly produce 1.1 MWh of electricity per year, if applied in a central hub building at Macquarie University in Sydney, Australia [15]. Moreover, the potential of energy harvesting from passing vehicles was studied. In 2017, Guo *et al.* compared the potential of piezoelectric and thermoelectric energy harvesting technologies based on the roadway network in Florida, USA. They found that theoretically the piezo-based system would be able to yield 4.04 MWh of electricity per day [16]. However, they conclude that a thermoelectric pipe-based system would be more cost-effective. In another study in 2020, Hong *et al.* reported on landfilled road-capable piezoelectric harvesters which can effectively convert stress induced by passing vehicles into electrical energy to be used for supplying emergency lights or delimiters [17].

This literature overview demonstrates the increasing interest on energy harvesting using piezoelectric materials and the high potential of this technology, especially in much crowded areas such as metro stations, and also in densely populated mega cities like in India or China. The possibility of sustainable energy generation without any GHG emissions while in use makes this approach highly attractive.

IV. ENERGY HARVESTING FLOOR TILE DESIGN

The piezoelectric ceramics (PZT, $60 \times 30 \times 0.2$ mm) used in this study were produced at the University of Jinan, China (group of Prof. Cheng) *via* a sintering process at ~ 900 °C followed by tempering near the *Curie* temperature in an electric field and successive cooling. This process provides memorized orientation of the *Weiss* segments and enables unidirectional ferroelectric polarization upon mechanical stress. These PZT layers were then coated on one side with a thin aluminum layer and fixed onto a brass base plate to yield the cantilever-type piezo elements shown in **Fig. 3a**. If such cantilever element is subjected to perpendicular deflection it will generate an electric potential on the PZT surface. To quantify the amount of energy produced by pedestrians walking across this floor tile, a total of 117 piezo elements were connected in parallel circuit and the voltage generated which dropped over the effective ohmic resistance of a voltage divider (R_{eff}) as a function of time was measured with an oscilloscope connected to resistor R1, as is depicted in **Fig. 3b**. The voltage divider was employed to protect the oscilloscope from any damage provoked by voltage spikes. The factor of voltage division is essentially determined by the R_{eff}/R_1 ratio. This correlation is presented in **Eq. (5)**.

$$U(t)_{piezo} = U(t)_{R1} + U(t)_{R2} = U(t)_{R1} \left(\frac{R1}{R1 + R2} \right)^{-1} = \frac{U(t)_{R1} \cdot R_{eff}}{R1} \quad (5)$$

where:

$U(t)_{piezo}$ = voltage induced by piezoelectric elements as a function of time;

$U(t)_{R1}$ = time-dependent voltage at ohmic resistor R1 and $U(t)_{R2}$ = time-dependent voltage at ohmic resistor R2;

$R_{eff} = R1 + R2$ = effective ohmic resistance of voltage divider with resistors R1 and R2 connected in series.

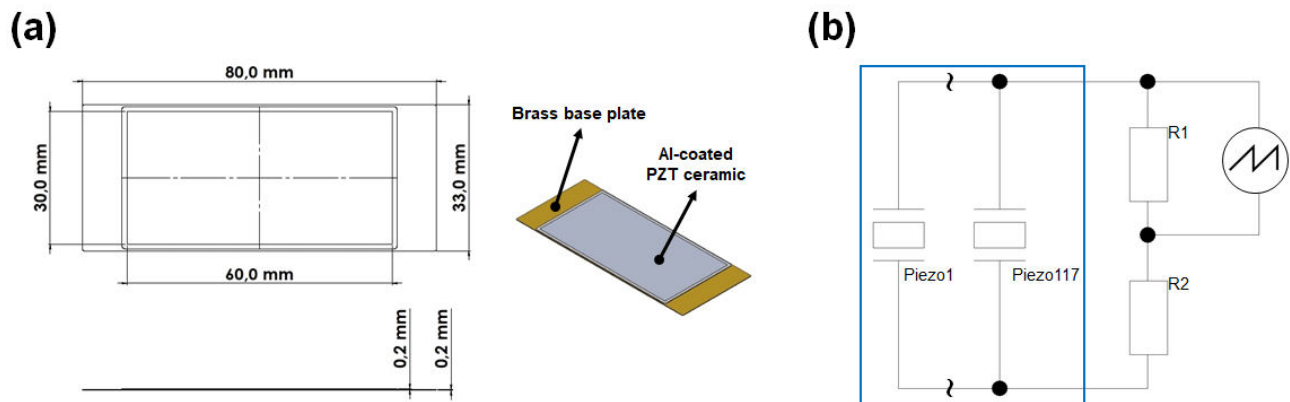


Fig. 3 (a) Design of the piezoelectric element used in the study: PZT ceramic supported on brass plate (cantilever); (b) Circuit design used for monitoring electricity generation achieved with a total of 117 piezoelectric elements incorporated into the device.

The utilized oscilloscope captured a set of 12,288 data points at a rate of 10 kHz (~ 1.23 seconds per data set) upon triggering (trigger level set for $U_{R1} = 20$ mV). The trigger allows for counting the footsteps and, without an active trigger level, the recorded data would be very noisy. In the following processing steps, at first the captured data were cut at 10,000 data points equal to 1.0 second of recording and hence, a data set of 10,000 intervals of 0.1 ms each was obtained for every trigger event (= each footprint). Secondly, from these voltage increments the electrical power was calculated according to **Eq. (6)** using the correlations $P = U \cdot I$ and $U = R \cdot I$.

$$P_i = \frac{U_i^2}{R_{eff}} = \frac{U_{i,R1}^2 \cdot R_{eff}}{R1^2} \text{ with } U_i = \frac{U_{i,R1} \cdot R_{eff}}{R1} = U_0 \cdot e^{(-t/\tau)} \text{ and } \tau = R_{eff} \cdot C_{piezo} \quad (6)$$

where:

P_i = electrical power increment;

U_i = voltage increment and $U_{i,R1}$ = voltage increment at ohmic resistor $R1$;

U_0 = initial voltage induced by piezoelectric elements;

t = time;

τ = time constant;

C_{piezo} = capacity of piezoelectric elements.

The capacity of all 117 piezo elements connected in parallel was measured as $C_{piezo} = 23 \mu\text{F}$. For the resistors, $R1 = 1.47 \text{ k}\Omega$ and $R2 = 3.04 \text{ k}\Omega$ were chosen which results in $R_{eff} = 4.51 \text{ k}\Omega$ and $\tau = 104 \text{ ms}$.

Finally, the amount of energy generated per data set (1.0 s) $E_{i,step}$ was calculated as the sum of the 10,000 increments of electrical power multiplied with the constant time increment $\Delta t = 0.1 \text{ ms}$, as is shown in **Eq. (7)**.

$$E_{i,step} = \sum_1^{10000} P_i \cdot \Delta t = \sum_1^{10000} U_{i,R1}^2 \cdot \frac{R_{eff} \cdot \Delta t}{R1^2} \quad (7)$$

The total amount of energy generated by the harvester, E_{total} was calculated from the sum of all $E_{i,step}$ recorded (see **Eq. (8)**).

$$E_{total} = \sum_1^n E_{i,step} \quad (8)$$

To harness electrical energy from cantilever-type piezo elements, it is essential to induce bending to the piezo ceramic elements and subsequently allow them to return to their original state. Typically, the higher the extent of deflection, the greater the electrical output obtained. However, excessive bending of the piezo elements increases the risk of breakage,

compromising their functionality. Therefore, a bending support was developed and incorporated into the floor tile which consists of a 5.0 mm PVC plate, two M2 screws and certain ring washers to hold the piezo element as well as a 3.0 mm high silicone spacer to ultimately limit the degree of deflection to 1.5 mm, as is depicted in Fig. 4a. In the final substructure of the floor tile (see Fig. 4b), several M10 setscrews were integrated to limit the deflection to 1.1 - 1.3 mm and a number of silicone buffers with a hardness of 55 °Shore A were installed to prevent premature bending caused by the weight of the top plate (made from 6 mm thick stainless steel and covered with a vinyl flooring). The bending support, deflection limiters and silicone buffers were mounted on a 6 mm thick stainless-steel base plate. Additionally, the piezo elements were fully coated with a thin rubber film after all the solder joints were completed to protect them from moisture and subsequent corrosion processes.

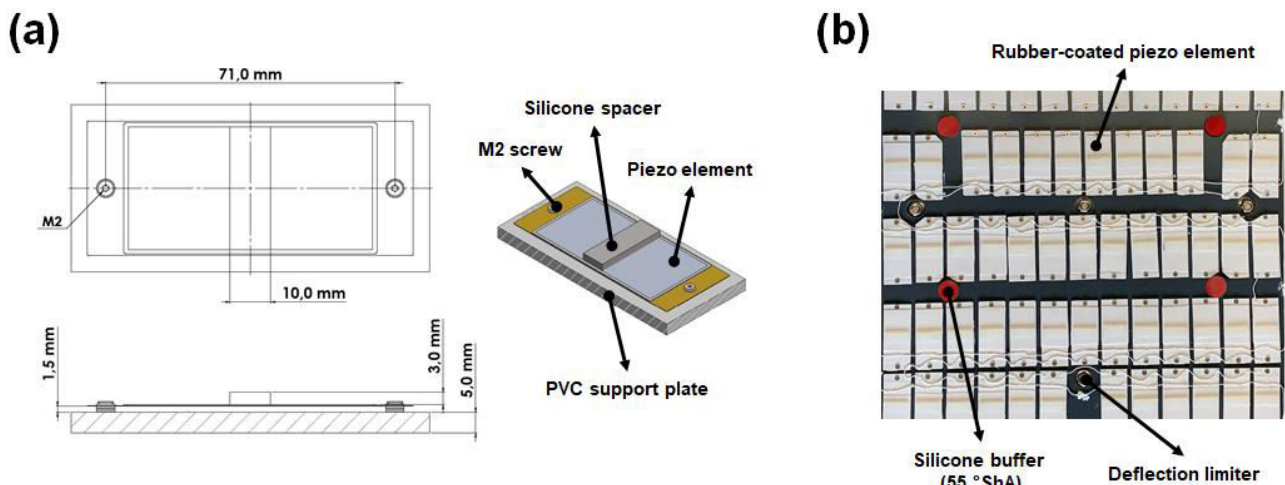


Fig. 4 (a) Design of the bending support for the piezo elements; (b) photograph of the final floor tile substructure.

Regarding data logging and displaying, an acquisition and processing electronic unit was designed, as is shown in Fig. 5. It can be seen there that at first, the raw signal from the piezo floor enters the voltage divider which is connected to an oscilloscope BitScope Micro via a BNC probe adapter. The oscilloscope captures the signals and transfers them to the connected Raspberry Pi 4 computer (8 GB RAM, RTC module, Class 10 MicroSD) which processes and logs the data using a Python script running on it. The final data is written into a .csv file stored on the MicroSD card of the Pi 4 and is also transmitted graphically to an information screen using a HDMI wireless extender. In addition, to power the Pi 4 and the HDMI sending unit, a 5 V DC power supply was necessary. Moreover, the base plate of the piezo floor was grounded to prevent electrostatic discharge.

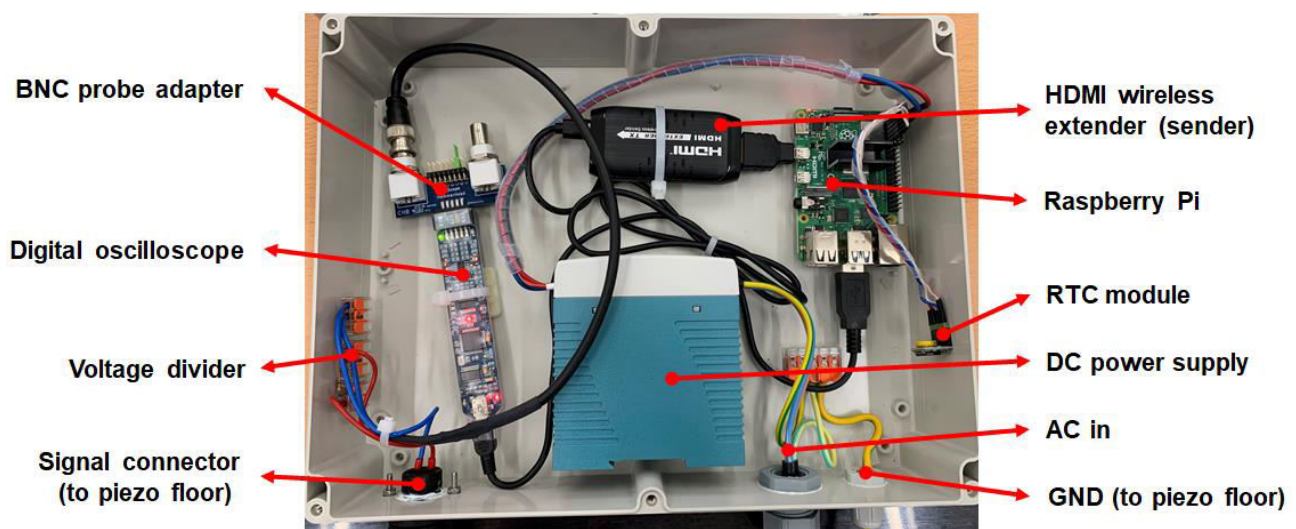


Fig. 5 Photograph of the data acquisition and processing electronic unit utilized for logging and displaying which was placed underneath the piezoelectric floor tile.

V. RESULTS AND DISCUSSION

In 09/2021 this piezo floor tile was installed by Prof. Plank’s group at the entrance of TUM’s main campus in downtown Munich and remained in service until 08/2022. **Fig. 6a** shows the installed setup including floor tile, information screen and information panel which explained the experiment. Additionally, **Fig. 6b** provides a closer view of the information screen featuring a graphical representation of the data, and **Fig. 6c** offers a detailed view of the substructure of the floor tile, illustrating the arrangement of the piezoelectric elements.

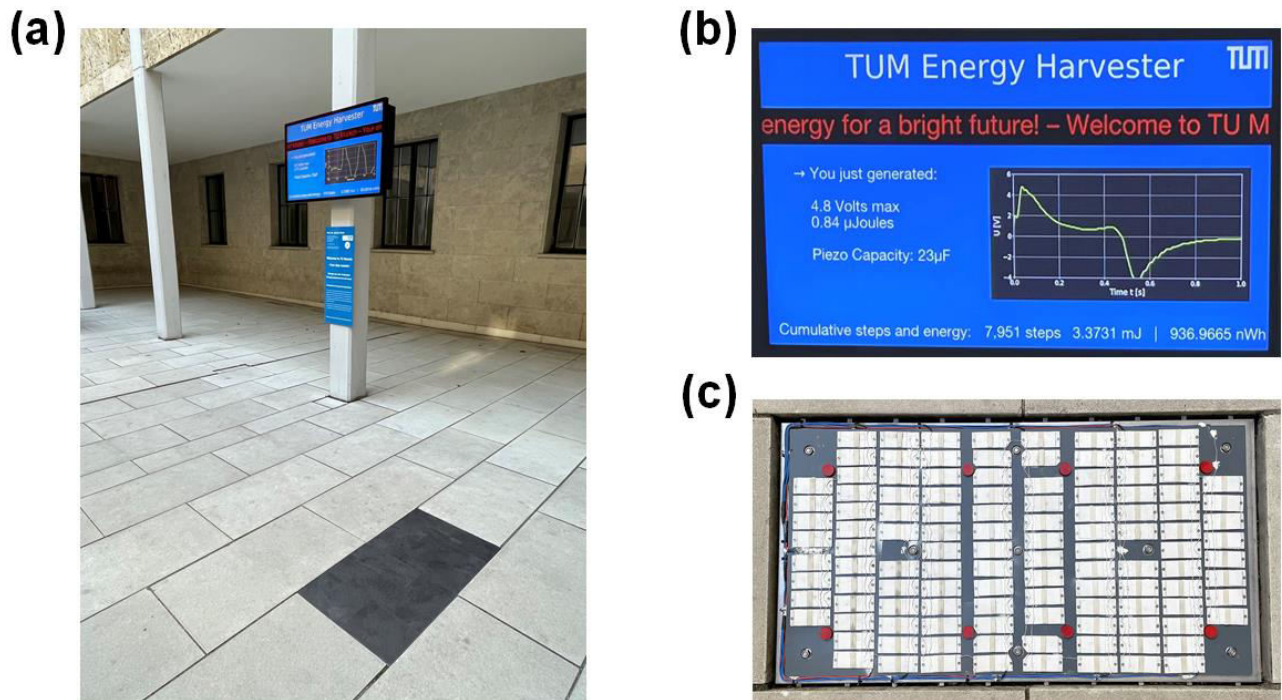


Fig. 6 (a) Setup of the energy harvesting floor tile in the entrance hall of TUM’s main campus in Munich; (b) information screen displaying the recorded data; (c) installed floor tile substructure holding the 117 piezo elements.

The harvester proved to be highly robust against seasonal weathering and also to students who often heavily jumped on it while taking selfies. Even under such heavy impact, the device did not collapse. Due to the use of comparatively massive stainless-steel parts, no deformation or corrosion was detected. However, slight corrosion at some solder joints was found after a few months where the rubber-coating around the piezo elements did not seal the soldering sufficiently. The applied combination of silicone buffers and setscrews effectively allowed for good relaxation while limiting the degree of deflection of the piezo elements. The vinyl flooring was damaged one time when some students had exercised high impact, but it could be fixed very easily.

Fig. 7 depicts the total number of steps and energy amount as well as energy yield per step for this demonstrator recorded during the entire period of service from Sep. 2021 to Aug. 2022 (**Fig. 7a**), and during one representative week in Oct. 2021 from 10/18 to 10/25 (**Fig. 7b**). During the entire test period, a total number of 78,311 steps were captured which yielded 22.5 mJ or 6.3 μWh of energy. Note that from mid of Nov. 2021 to mid of Jan. 2022 the harvester had to be removed to make space for a traditional Christmas tree. For the entire period, the average voltage generated per step was 1.97 V, and the maximum voltage was measured at 18.4 V, corresponding to energy amounts of 288 nJ and 9.1 μJ, respectively. Extrapolation of the data to a full one-year period results in an energy amount of ~ 25 mJ generated using this device.

A one-week breakdown of the data recorded is displayed in **Fig. 7b** where for every day the step count and energy harvested is indicated. According to this data, traffic activity was not only during workdays, but also on Saturday and Sunday, obviously by citizens from Munich who walked across the campus at the weekend and tested the energy harvester. Within this specific week, a total of ~ 5,000 steps were recorded and ~ 2.8 mJ of energy were harvested.

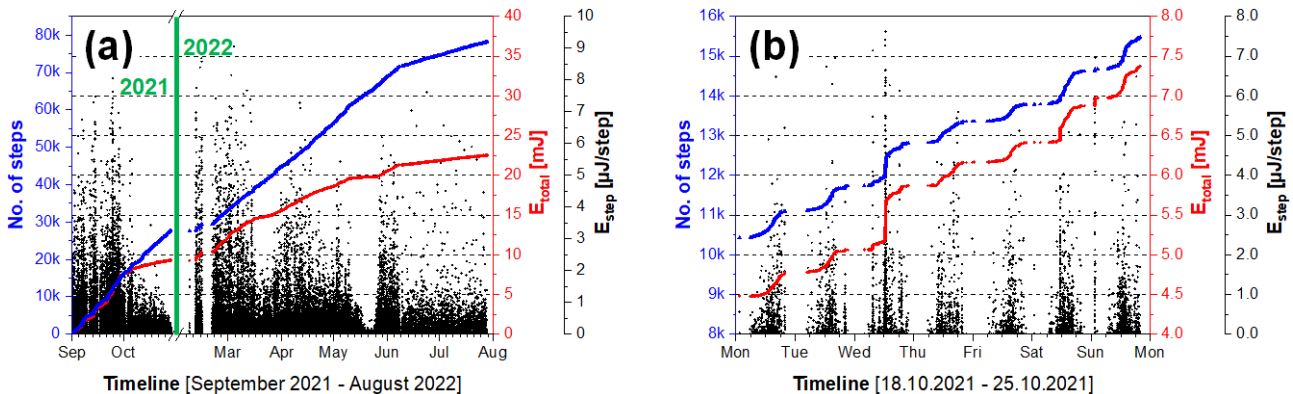


Fig. 7 (a) Data recording from the energy harvester over the entire service period (09/2021 – 08/2022); (b) breakdown of steps and energy data captured during one week in October 2021 (10/18 – 10/25).

This energy harvesting device has been in continuous operation without any need for repair or maintenance (except for the minor damage on the vinyl flooring) and generated significant interest among students and citizens. Even though the amount of energy harvested seems rather low and was not directly stored in a battery for further use, the feasibility of this concept and design of this model floor tile has been proven. The use of more efficient piezoelectric materials could significantly increase the yield of the energy generated. Moreover, in highly crowded areas and countries with dense population the electricity output of such energy harvester can be expected to be multiple times higher.

VI. CONCLUSION

This study aimed to demonstrate the potential of an energy harvester based on a relatively simple floor tile design using the piezoelectric effect which converts mechanical stress into electrical energy. Moreover, the practical aspects of design, installation and durability of such device were evaluated. During an 11-month exposure test, a total energy amount of 22.5 mJ were generated by ~ 78,000 steps, without any substantial need for maintenance or repair work. Placement of the floor tile was relatively simple, and different cantilever-type elements made from piezoelectric materials other than the PZT ceramics used in this harvester which yield a higher energy output could be placed in this way. The PZT-based piezoelectric ceramics used in this harvester are inexpensive, but yield a relatively low amount of energy per step. Significant optimization is possible by installing more efficient materials. Apart from the electrical energy generated emission-free, a positive effect of the experiment was the generation of public awareness of the problem of energy supply in general and rising consumption by our society. According to the feedback received from the people who tested the harvester it inspired them to save energy where possible. At present, global anthropogenic greenhouse gas emissions still are increasing as a consequence of growing population, ongoing industrialization and higher standard of living. Thus, application of piezoelectric energy harvesting devices which – once installed – operate without any noticeable CO₂ emission e.g. in train or underground stations, highways or railways can contribute to control the ongoing climate change.

REFERENCES

- [1] *International Energy Outlook 2021 Narrative, with Projections to 2050*, U.S. Energy Information and Administration (EIA), Independent Statistics and Analysis, U. S. Department of Energy, Washington, DC, **2021**, available from: <https://www.eia.gov/outlooks/aeo/> [accessed 30.05.2023].
- [2] R. A. Rohde: *Global Temperature Report for 2022*, Berkeley Earth, **2023**, available from: <https://berkeleyearth.org/global-temperature-report-for-2022/> [accessed 30.05.2023].
- [3] M. Pawan: Impact of Global Warming on Environment. *Int. Res. J. Environment Sci.* **2014**, 3 (3), 72–78.
- [4] K. Calautit, D. S. Nasir, B. R. Hughes: Low power energy harvesting systems: State of the art and future challenges. *Renewable and Sustainable Energy Reviews* **2021**, 147, 111230, <https://doi.org/10.1016/j.rser.2021.111230>.
- [5] B. Jaffe, W. R. Cook, H. L. Jaffe: *Piezoelectric ceramics*, Academic Press, London, **1971**, ISBN: 9780323155687.
- [6] T. Ikeda: *Fundamentals of piezoelectricity*, Oxford University Press, Oxford, **1996**, ISBN: 0198564600.

- [7] M. Kimura, A. Ando, D. Maurya, S. Priya: Lead Zirconate Titanate-Based Piezoceramics. In: *Advanced Piezoelectric Materials*, Elsevier, **2017**, 95–126, <https://doi.org/10.1016/B978-0-08-102135-4.00002-3>.
- [8] S. Stølen, E. Bakken, C. E. Mohn: Oxygen-deficient perovskites: linking structure, energetics and ion transport. *Phys. Chem. Chem. Phys.* **2006**, 8 (4), 429–447, <https://doi.org/10.1039/B512271F>.
- [9] S.-E. Park, T. R. Shrout: Ultrahigh strain and piezoelectric behavior in relaxor based ferroelectric single crystals. *J. Appl. Phys.* **1997**, 82 (4), 1804–1811, <https://doi.org/10.1063/1.365983>.
- [10] S. H. Wright: MIT duo sees people-powered "Crowd Farm". Plan would harvest energy of human movement, MIT News, available from: <https://news.mit.edu/2007/crowdfarm-0725> [accessed 03.06.2023].
- [11] J. Ryall: Japan harnesses energy from footsteps. Train stations in Tokyo are harnessing the energy of legions of commuters to power advertising hoardings and ticket machines, The Telegraph, available from: <https://www.telegraph.co.uk/news/earth/energy/3721841/Japan-harnesses-energy-from-footsteps.html> [accessed 03.06.2023].
- [12] R. Shreesayana, L. Raghavendra, V. G. Manjunath: Piezoelectric Energy Harvesting using PZT in Floor Tile Design. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE)* **2017**, 6 (12), 8872–8879, <https://doi.org/10.15662/IJAREEIE.2017.0612018>.
- [13] R. R. Moussa, W. S. Ismael, M. M. Solban: Energy generation in public buildings using piezoelectric flooring tiles; A case study of a metro station. *Sustainable Cities and Society* **2022**, 77, 103555, <https://doi.org/10.1016/j.scs.2021.103555>.
- [14] P. Thainirarnit, S. Jayasvasti, P. Yingyong, S. Nandrakwang, D. Isarakorn: Triboelectric Energy-Harvesting Floor Tile. *Materials (Basel, Switzerland)* **2022**, 15 (24), <https://doi.org/10.3390/ma15248853>.
- [15] X. Li, V. Strezov: Modelling piezoelectric energy harvesting potential in an educational building. *Energy Conversion and Management* **2014**, 85, 435–442, <https://doi.org/10.1016/j.enconman.2014.05.096>.
- [16] L. Guo, Q. Lu: Potentials of piezoelectric and thermoelectric technologies for harvesting energy from pavements. *Renewable and Sustainable Energy Reviews* **2017**, 72, 761–773, <https://doi.org/10.1016/j.rser.2017.01.090>.
- [17] S. D. Hong, K.-B. Kim, W. Hwang, Y. S. Song, J. Y. Cho, S. Yeong Jeong, J. H. Ahn, G.-H. Kim, H. Cheong, T. H. Sung: Enhanced energy-generation performance of a landfilled road-capable piezoelectric harvester to scavenge energy from passing vehicles. *Energy Conversion and Management* **2020**, 215, 112900, <https://doi.org/10.1016/j.enconman.2020.112900>.



Impact Factor: 8.423



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

 9940 572 462  6381 907 438  ijirset@gmail.com



www.ijirset.com

Scan to save the contact details