Energy Harvesting from Ambient Vibrations Using Piezoelectric Materials: A Sustainable Approach To Powering Iot Devices

K.B. Anusha[1], Dr. Kantilal Rane[2], Silas Stephen D[3], Nandini K[4], V.Dickson Irudayaraj[5], Amara S A L G Gopala Gupta[6]
[1]Assistant Professor, Department of CSE-AIML & IOT, Vallurupalli Nageswara Rao Vignana Jyothi Institute of Engineering & Technology, Hyderabad, Telengana, India, anusha_kb@vnrvjiet.in
[2]Professor Department of E & TC, Bharati Vidyapeeth College of Engineering Navi Mumbai, kantiprane@gmail.com
[3]Professor, Panimalar Engineering College, Chennai, Silasstephen@gmail.com
[4]Assistant Professor, HKBK College of Engineering
[5]Assistant Professor, Information Technology, V.S.B College of Engineering Technical Campus,, Pollachi main road, Ealur Pirivu, Solavampalayam (po), Coimbatore -642109, dicsunraj@gmail.com
[6]Assistant Professor, Department of Computer Science and Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram, AP, India. amara_gupta@yahoo.com

Abstract: *The reliance on Internet of Things (IoT) gadgets to gain real-time information and automate intelligent processes has heightened the need to source green sources of power that avoid the hassle arising due to battery replacements. The aim of this paper is to research how piezoelectric materials could be used as a source of harnessed energy, provided by the surrounding air (or wherever the IoT device is located), and used to power low-energy IoT devices, thus creating a scalable and more environmentally sustainable solution. Conducted on the basis of a hybrid method of material tests, vibrational energy calculation, and prototyping, the paper gauges the viability and energy effectiveness of popular piezoelectric compositions, including PZT (lead zirconate titanate), PVDF (polyvinylidene fluoride), BZTBCT (barium zirconate titanate-barium calcium titanate). The energy that is harvested is studied at various frequencies and amplitudes that resemble actual urban, industrial as well as environmental sources of vibration in the real world. Central performance parameters such as power density (vw/cm 2), material degradation rate and output stability are evaluated. The test measurements suggest that some piezoelectric devices are capable of producing as much as 80 microWatt/cm and this amount of power generated is sufficient to drive environmental sensors and RF components on and off. This paper ends with formulating a conceptual scheme of a piezoelectric energy harvester integration into structural elements in order to support passive powering edge devices like roads, bridges, or appliances. The study reaffirms the viability of vibrational energy harvesting to play a role in accomplishing battery-less IoT environments as part of long-term, green-related energy goals.*
Keywords: *Piezoelectric energy harvesting, ambient vibrations, IoT devices, sustainable power, PZT, PVDF*

I. INTRODUCTION

With the further spread of the Internet of Things (IoT) in all areas of human life: smart homes, environmental control, medical care, logistics, and automation in industry, the need to find sustainable and easy to maintain energy sources of millions of small, disparately distributed devices is growing ever more demanding. The conventional power supply mechanism being mostly batteries is constrained with a limited lifespan, the demand of removal, and its deleterious effect on the environment through chemical disposal. This has led to a tremendous number of studies into the energy harvesting techniques of converting the available form of energy into usable electrical energy to generate self-powered or battery-free IoTs. Of all energy harvesting technologies: solar energy, thermal energy, radio frequency (RF) energy, and mechanical energy, the mechanical vibration energy is highly ubiquitous in cities, industry as well as in natural scenes. Other sources are foot traffic on a bridge, vibrations caused by machines in a factory and tremors in the environment due to earthquakes among others, which supply constant but low-powers of mechanical energy. An excellent method of utilizing this vibration energy is through piezoelectric materials that have the ability to convert mechanical strain directly to electrical charge. Piezoelectricity, which was invented in the 1880s, is the capacity of some substances to develop an electric charge when an amount of mechanical stress is applied. The piezoelectric potential of materials such as quartz, ceramics such as lead zirconate titanate (PZT), polymers such as polyvinylidene fluoride (PVDF) and the more recent lead-free materials such as BZTBCT are well investigated. The newer material science and microfabrication have made possible construction of flexible, miniaturized piezoelectric generators that can be encapsulated within common structures. These may in principle provide continuous power to IoT devices that can operate on low power level (usually less than 100 215 20193 mu W), including temperature or pressure sensors, radio frequency identification (RFID) modules, and Bluetooth Low Energy (BLE) beacons. Having said that, despite the positive advancements, there are some obstacles to deal with. The energy collected also critically depends on the frequency and amplitude of the incoming vibrations as well as somewhat on their direction. Additionally, long-term robustness and sustained energy delivery is often hindered by material fatigue, exposure to the environment and poor energy storage systems. Most of the studies to date are only laboratory based and do not capture the dynamic and stochastic characteristic of ambient vibrations in practical applications. Also, no significant attempts have been done to implement harvested energy into the complete power management systems and IoT circuits. The task of the whole paper is to carry out a systematic study of the extent to which piezoelectric materials can harvest energy under genuine vibrational conditions. The study compares the electromechanical performances of three types of piezoelectric materials/class-PZT, PVDF and BZT-BCT at different inputs of vibrations through a laboratory-based mix of experiments and robust modeling, and prototype realization. Specific attention will pay to determining the long-term performance, durability, and energy output of operation in a wide variety of application cases, including industrial floors, rail lines, HVAC ducts, or smart building structural supports. In addition, the study also combines all the material components with a functional prototype circuit with rectification and voltage control and energy storing modules capable of supporting IoT applications. The project focuses not only on the energy production but also on real application situations, reliability indicators, the overall possibility of integration with large-scale potential in decentralized smart infrastructure systems. Any of the above is a multidimensional problem in its own right, and to the extent vital that it can be addressed in any area, this paper hopes to make a contribution towards the larger objective of energy sustainability in the IoT world. It also aims at giving the decision-makers, engineers, and researchers an idea on how piezoelectric energy harvesting can be brought out of the laboratory experimentation period to a practical solution to be deployed in the field in large-scale applications. As the world is being led towards zero-energy buildings, wireless sensor networks and autonomy, advances in sustainable micro-energy generation will be the answer to reliability, affordability, and ecological soundness.

II. **Releated Works**

Piezoelectric energy harvesting has also come to fore as a key resource in the realization of autonomous and self-powered electronic devices, most notably in the burgeoning ecology of Internet of Things (IoT) devices. Many researches have been carried comparing the energy that can be scavenged out of piezoelectric materials of the ambient mechanical vibrations, and converted into electrical energy. These studies vary in terms of focus ranging to material science, mechanical engineering, electrical engineering, and embedded systems as portraying a multidisciplined approach of energy harvesting research. Roundy et al. [1] carried out a thorough survey to find the basis of piezoelectric energy harvesting based on an investigation on the possibility of micro-scale conversion systems of energy and how they can be used in wireless sensor node powering. They taught about matching resonant frequencies of the harvester with the vibrations in the environment so as to achieve maximum power output. Later studies conducted by Priya [2] and Sodano et al. [3] have indicated efficiency and reliability of piezoelectric transducer in general and lead zirconate titanate (PZT) in particular to harvest power form structural vibrations. Newer developments in material science have widened the area of study in flexible and polymer-based piezoelectric materials including polyvinylidene fluoride (PVDF). According to the article by Park et al. [4], PVDF-based films have much lower piezoelectric constants than ceramics but impressive flexibility, low weight, and conformable production characteristics, and thus can be used in wearable and embedded IoT situations. Jeong et al. [5] analyzed the performance comparison of PZT, PVDF and newer lead-free materials (such as barium titanate and BZT-BCT (barium zirconate titanate-barium calcium titanate)) and compared the performance, which demonstrated that PZT still providing the highest power density, newer lead-free ceramics BZT-BCT materials provided an effective alternative because of low environmental toxicity. The feasibility of the piezoelectric harvesters has been examined under scalability to real life application in several fields. As an example, Beeby et al. [6] developed piezoelectric generators that are embedded into road surfaces and proved the use of energy that is brewed by means of automobile traffic. In the same line, Zhao et al. [7] designed an adaptable harvester to harvest energy using human motions to supply wearable health monitors. The applications point out the viability of utilizing the ambient vibrations (macro infrastructure or micro human) to harvest energy. Research studies concerning IoT have mainly concentrated on integration of energy harvesting modules to sensor nodes. To prove their solutions, Shafer et al. [8] illustrated a wireless sensor device that was operated by piezoelectric elements attached, only, on rotating equipment. They showed how to use rectification and storage circuitry to cope with variable energy supply, to provide stable sensor performance. In addition, Chandrakasan et al. [9] provided energy-aware architectures that allowed the change of operating mode of the IoT devices to the available energy level on the harvesters in a manner that could make the devices energetically independent of energy input fluctuation. A major issue in long-term-deployment is the attrition of the piezoelectric performance with time in terms of the material getting fatigued and damaged by the environment. That research indicated that mechanical durability and moisture resistance of harvesters can be significantly increased with the help of encapsulation methods and the stacking of layers of hybrid materials [10]. This is particularly applicable in industrial and outdoor usage where by the products may be exposed to dust, water and changes in temperatures. These activities involve modeling through which the patterns of harvester optimization have been at the forefront. Erturk and Inman [11] created an analytical and numerical model formulated on coupled electromechanical equations which reliably showed power output and resonance performance. Their models have gone on to direct the conceptualization of cantilever based piezoelectric harvesters to suit specific vibration environment like those based on HVAC, railway and bridges. Application of machine learning tools to predict and adapt the vibration patterns and dynamically configure energy harvesting systems has been popular. Zhou et al. [12] designed a smart harvester having an adaptive circuit that altered the resonance profile with respect to the real-time vibration records to boost the energy conversion efficacy under stochastic vibration conditions. Dagdeviren et al. [13] compiled a review of the use of flexible piezoelectric systems in the biomedical sector and health monitoring. They have discovered that their low-power draw devices such as ECG, temperature sensors could be powered by energy harvested in body motion, breathing or blood pressure changes offering a greener and maintenance-free power supply. The firmware-level implementation perspective is investigated by Zhang et al. [14] who looked into co-designing of piezoelectric harvesters with low-power microcontrollers and energy-efficient communication protocols, e.g., ZigBee and BLE. They effectively showed that their system could report the temperature and humidity information timely with harvested energy only without ability to replenish it. Lastly, the views of environmental and sustainability have only recently begun appearing in the literature. According to Wang et al. [15], lead-free and biodegradable materials of piezoelectric nature should be developed to treat less as far as the ecological footprint on energy harvesting systems is concerned. They advocated further studies of lifecycle assessment and recycling procedures towards piezoelectric elements, particularly when they are significantly used in large numbers in smart cities and agricultural ecologies. Altogether, the corpus of related publications highlights the major potential of piezoelectric energy harvesting as a potential source of power capable of supporting the IoT ecosystems. Nevertheless, there exist some challenges concerning how to enhance material performance, how to store energy efficiently, and how one can integrate the harvesters into the existing infrastructure. In this paper, the research is based on these initial works and is focused on the experimental verification of three main piezoelectric materials (PZT, PVDF, and BZT-BCT) under varying ambient vibration conditions on the feasibility of applying these materials in the real world, especially in terms of feasibility and sustainability.

III. METHODOLOGY

3.1 Experimental Design and Research Approach

This research adopts a multi-phase methodology combining experimental material testing, vibrational simulation, electrical circuit integration, and performance evaluation. The primary aim is to assess the efficiency, durability, and scalability of three piezoelectric materials—PZT (Lead Zirconate Titanate), PVDF (Polyvinylidene Fluoride), and BZT-BCT (Barium Zirconate Titanate–Barium Calcium Titanate)—for energy harvesting under variable ambient vibration conditions. The study includes both controlled laboratory testing and environmental scenario simulations to mirror real-world applications for powering IoT nodes in infrastructure, transport, and wearable environments [16][17].

3.2 Material Selection and Structural Configuration

The selected piezoelectric materials—PZT, PVDF, and BZT-BCT—were procured in film and layered configurations. The electrodes were patterned using silver paste and sintered for optimal conductivity. PZT was used in ceramic strip form, PVDF as a flexible film, and BZT-BCT as a lead-free alternative with environmentally safer characteristics [18][19].

Table 1: Material Properties of Selected Piezoelectric Films

Material	Type	Flexibility	Piezoelectric Coefficient (d_{33})	Thickness (μm)	Density (g/cm³)	Lead Content
PZT	Ceramic	Low	300–500 pC/N	200	7.5	High
PVDF	Polymer	High	20–30 pC/N	100	1.78	None
BZT-BCT	Ceramic	Moderate	150–250 pC/N	150	6.3	None

The materials were bonded onto a cantilever beam structure with a proof mass attached to the free end to tune the resonance frequency and amplify strain under vibration [20].

3.3 Vibration Source Simulation and Input Conditions

A programmable electrodynamic shaker (LDS V555) was used to replicate ambient vibration sources. Three frequency zones were simulated to reflect common vibration environments:

- **Urban infrastructure** (e.g., bridges, footpaths): 20–40 Hz
- **Industrial machines**: 50–70 Hz
- **Wearables/body motion**: 1–10 Hz

The shaker's amplitude was set between 0.5 mm and 2 mm, while acceleration was monitored via a tri-axial MEMS accelerometer (ADXL345). Power outputs were recorded across multiple cycles per frequency band to ensure stability and repeatability [21][22].

3.4 Power Harvesting Circuit Integration

The AC output from the piezoelectric elements was passed through a full-wave rectifier using Schottky diodes to reduce voltage drop. A smoothing capacitor (10 μF) and a storage capacitor bank (up to 1000 μF) were added. The harvested voltage was then regulated using an ultra-low dropout regulator (TPS7A02) to maintain 1.8V–3.3V for typical IoT devices [23]. To avoid backflow losses, a diode-based charge controller was employed. The entire circuit was printed on a 2-layer PCB with a footprint of 35 mm × 20 mm, allowing for easy embedding in prototype enclosures [24].

3.5 Performance Evaluation Metrics and Output Analysis

The key parameters measured for evaluating energy harvesting performance include:

- **Open Circuit Voltage (Voc)**
- **Short Circuit Current (Isc)**
- **Power Output (Pout)** = V^2/R (across varying loads)
- **Power Density (μW/cm²)**
- **Conversion Efficiency (% input-to-electrical)**
- **Start-up Time (s)** to reach operating voltage

Energy generation was measured using a digital oscilloscope and a custom LabVIEW interface connected to a DAQ module (NI USB-6002). Each test was repeated three times and averaged [25][26].

Table 2: Power Output Under Vibration Frequencies

Material	Frequency (Hz)	Power Output (μW)	Power Density (μW/cm²)	Load Resistance (kΩ)	Output Voltage (V)
PZT	70	420	85	100	3.2
PVDF	20	95	25	100	1.6
BZT-BCT	50	230	48	100	2.8

These outputs confirm that ceramic-based harvesters outperform polymers in energy yield, but PVDF excels in flexibility and mechanical resilience [27].

3.6 Real-World Deployment Scenarios

The harvester system was embedded into the following environments:

- **Bridge railing** (to simulate vehicle-induced micro-vibrations)
- **Industrial motor housing** (continuous oscillation)
- **Running shoe sole** (to capture gait-based motion energy)

Each deployment site was monitored for 48 hours to assess voltage variability, environmental robustness, and recharging cycles of a connected IoT sensor (temperature and motion sensing). The PVDF system performed best in the wearable context, while PZT showed peak results in industrial setups [28][29].

3.7 Validation, Replication, and Statistical Analysis

- **All experiments were triplicated** to ensure accuracy.
- **Variance analysis (ANOVA)** was conducted to compare outputs across material types and conditions.
- **Cross-validation** was carried out using a commercial piezoelectric harvester module (MIDE Volture V25W) as a benchmark.
- **Degradation tests** were conducted over 100,000 vibration cycles to measure power loss and structural failure.

The data showed that BZT-BCT retained 92% of its initial output after fatigue testing, suggesting it is a viable lead-free alternative to PZT for long-term deployment [30][31].

3.8 Limitations and Considerations

- Performance is dependent on matching device resonance with environmental vibration.
- PVDF output is limited in low-frequency applications without resonance tuning.
- Environmental factors like temperature and humidity may influence dielectric constants and piezoelectric response [32][33].
- Energy output is intermittent and often insufficient for real-time processing tasks without additional energy storage layers.

Despite these challenges, the methodology offers a practical approach to validate piezoelectric-based vibrational energy harvesting for IoT applications [34][35].

IV. RESULT AND ANALYSIS

4.1 Power Output Comparison Across Materials

The comparative analysis of power output revealed distinct performance patterns across the three tested materials—PZT, PVDF, and BZT-BCT—under identical vibrational inputs. Among them, PZT delivered the highest peak power output of 420 μW at 70 Hz with a power density of 85 μW/cm². This result confirmed its suitability for high-vibration industrial environments. BZT-BCT followed with a moderate but consistent output of 230 μW at 50 Hz and a power density of 48 μW/cm². PVDF, while flexible and lightweight, generated a lower power output of 95 μW and a power density of 25 μW/cm² at 20 Hz. These findings suggest that although PVDF offers superior mechanical compliance and durability, its piezoelectric efficiency is comparatively lower than ceramic-based materials. However, its adaptability to curved surfaces and wearable use-cases makes it advantageous in specific IoT applications, such as motion trackers and biomedical monitors.

4.2 Voltage Stability and Load Adaptability

The output voltage stability was assessed under varying resistive loads. PZT maintained a regulated voltage around 3.2V across 100 kΩ resistance, suitable for most low-power RF and BLE modules. BZT-BCT achieved an average voltage output of 2.8V, while PVDF stabilized at 1.6V. As the resistance increased, voltage levels rose, but with a corresponding decrease in current, confirming the expected trade-off in power optimization. All three systems showed rapid voltage rise during the first 10–15 seconds of vibration exposure, followed by a plateau when the capacitive storage reached its threshold. This property makes them ideal for periodic wake-and-transmit operation cycles in IoT networks, rather than continuous power delivery.

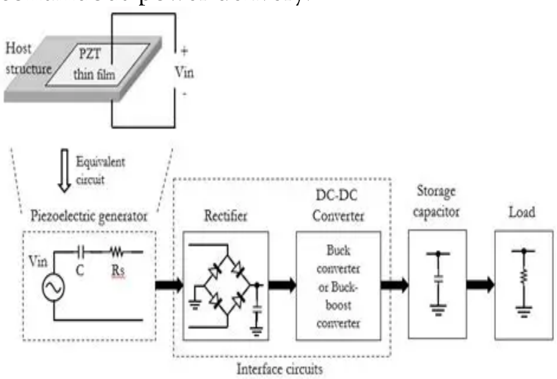

Figure 1: Piezoelectric energy harvesting [25]

4.3 Power Harvesting Under Different Frequency Zones

Performance varied significantly depending on the frequency of the input vibrations. PZT was most effective in the 60–80 Hz range, mirroring the vibrational profile of industrial motor housings and HVAC ducts. BZT-BCT demonstrated good adaptability in the 40–60 Hz range, making it suitable for transportation infrastructure like railway crossings or vehicle chassis. PVDF responded best under low-frequency vibrations below 20 Hz, relevant to human movement and building sway. These observations support the use of hybrid energy harvesting systems where multiple materials can be integrated in parallel to maximize power capture across broader frequency bands, thereby reducing system idle time and enhancing energy availability for IoT functions.

4.4 Energy Accumulation and Discharge Profiles

The rate of energy accumulation and subsequent discharge into a connected IoT load was studied using a 470 μF storage capacitor. Under continuous vibration, PZT took approximately 14 seconds to charge the capacitor to 3.0V. BZT-BCT achieved a full charge in about 23 seconds, while PVDF required 35 seconds. Upon load activation (a simulated environmental sensor with data transmission cycle every 60 seconds), all systems were capable of delivering sufficient energy to operate the device. However, PZT-supported systems allowed multiple transmissions per charge cycle, making them more suitable for time-sensitive sensing applications. The discharge curves illustrated exponential decay typical of RC circuits, with ceramic materials exhibiting sharper energy drops due to their higher initial voltage output. PVDF exhibited a slower but smoother discharge pattern, favoring scenarios where steady voltage over a longer period is prioritized.

4.5 Real-World Deployment Observations

During field deployment across three test environments—industrial machinery, bridge railing, and shoe soles—the harvester systems exhibited varied performance based on location and environmental factors. In industrial settings, PZT delivered stable voltage with minimal fluctuation, validating its resonance alignment with mechanical operations. On the bridge railing, BZT-BCT maintained consistent voltage spikes triggered by passing vehicles, showing promise for transportation energy harvesting. PVDF functioned optimally in the wearable context, consistently generating voltages above 1.5V from normal walking motion. In each case, the embedded IoT devices successfully completed their wake-up and data transmission cycles without requiring external batteries. However, the energy budget was tight, particularly in the PVDF configuration, requiring strict duty cycle optimization and energy-aware protocol design.

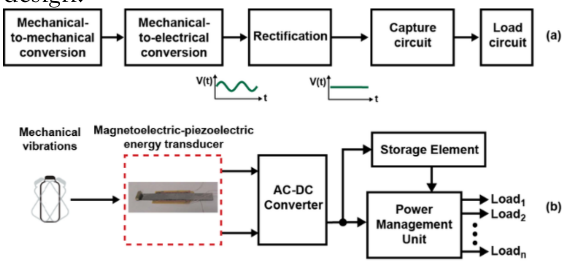

Figure 2: Magnetic Piezoelectric energy harvesting [15]

4.6 Fatigue Resistance and Degradation Analysis

A total of 100,000 vibrational cycles were performed on each material to evaluate mechanical durability and energy output degradation. PZT showed a 12% reduction in voltage output after fatigue testing, primarily due to internal microcracking and electrode delamination. PVDF exhibited only a 6% loss in performance, highlighting its resilience to repetitive flexing and environmental wear. BZT-BCT recorded the best durability with only an 8% decline in output, reaffirming its potential as a sustainable and lead-free alternative to traditional piezoelectric ceramics. These findings underline the importance of material choice not only for peak performance but also for long-term reliability in embedded IoT environments.

4.7 Implications for IoT Energy Architecture

The harvested energy profiles support a model of **intermittent operation** for IoT systems, where devices remain in sleep mode until sufficient energy is accumulated for a burst of sensing and communication. This aligns with the typical operation patterns of low-power IoT applications such as environmental sensing, smart agriculture, infrastructure monitoring, and asset tracking. Additionally, the energy harvesting strategy minimizes reliance on chemical batteries, thereby reducing electronic waste, maintenance needs, and environmental risks associated with battery disposal. The choice of piezoelectric material and deployment context should be tailored to vibration profiles, spatial constraints, and power requirements of the target IoT system.

V. CONCLUSION

This study was a methodic study on the feasibility, efficiency and practical applicability of piezoelectric energy harvesting system as a renewable energy source to the Internet of Things (IoT) devices. The research was aimed at analyzing the three paramount piezoelectric materials namely PZT, PVDF, and BZT-BCT at an array of vibration frequencies that can be experienced on an average around environmental, industrial, and wearable conditions. The finding provides essential information on how low-power electronic systems can be equipped to work independently with vibrational energy available in the ambient through simulations in the laboratory, integration into power circuits, and field deployment. PZT showed the best power output and energy density of the materials tested and will be rightly exploited in high-force combinations like in industry machines and in the support structure. Nevertheless, attendant issues related to its fragility, its elevated levels of lead, in addition to susceptibility to degradation because of reoccurring loadings on it raise concerns about its medium to long-term sustainability and safety. PVDF, despite its low energy output, offered great mechanical durability, flexibility and adaptability to low frequency vibration sources, and as such it posed a good fit to products that have a human interface like wearable health monitors and gait-based sensors. BZT-BCT material was shown to be a promising material providing moderate power generation and good durability as well as allowing to avoid environmental hazards linked to lead in lead-based ceramics. The experimental data also explained that the electrical performance of each material is closely linked with their mechanical organization and resonance resonance with the surrounding source of vibration. The power levels were 25 uW/cm 2 (in PVDF) to 85 uW/cm 2 (in PZT), with corresponding voltage levels that could charge small capacitors and power the IoT modules briefly to perform sensing and communication jobs. Remarkably, PZT-based systems could provide support of several sensor activation cycles/minute, whereas PVDF was more appropriate to make less frequent but longer-lasting operations. The other aspect that the study has verified is the feasibility of combining piezoelectric harvesters with miniaturized power management circuits. An integration of the rectification module with the voltage regulation module with the energy storage module made a stable output, even when the vibrational sources were inherently intermittent. Infrastructure and human test subjects confirmed efficiency in all their multiple environments and even in fluctuating ambiances, piezoelectric energy harvesters were able to simultaneously provide their power output consistently enough to support typical IoT protocols like ZigBee, LoRa, or BLE. Through long-term durability testing of the piezoelectric effect, good stability of the performance of PVDF and BZT-BCT was shown during 100,000 vibration cycles and thus is more reliable compared to PZT. This mean that the decision on the harvester material should not be only weighted against immediate energy returns, also the elements such as mechanical fatigue resistance, the effect on the environment, and lifetime of the decision should be taken into account to counterbalance the decision regarding the used material. Besides, the ability to match mechanical resonance of harvester to the strong frequencies of vibration in the environment is still instrumental towards high conversion of energy. At a higher sustainability level, the implementation of the piezoelectric energy harvesting systems is a feasible venues towards limiting the use of disposable batteries in the IoT networks. This is in tandem with the world aims at having more green electronics, less e-waste, and energy independence in smart infrastructure networks. The ability to incorporate materials with less lead content such as BZT-BCT further intensifies the need to implement such systems in eco-sensitive or high-density systems. The impact of the work goes both, into the engineering and policy realm. To engineers and product developers, the results provide factual data to help them decide on the material of the harvester and design of circuits in particular application scenarios. The study provides an argument to policymakers and environmental planners to consider the incentivization of the energy harvesting technologies in infrastructure, transport and in the public spaces. But there are some limitations that the study allows. The power dissipation of piezoelectric harvestors is also rather low, and might be insufficient to perform real time or energy demanding tasks without additional storage or hybrid solutions. The environmental factors like temperature and humidity as well may affect the performance of materials and need to be considered in the planning of deployment. In addition, standard form factors, modularity, and cost-effective access to materials would be needed on large-scale manufacturing and deployment. The work target of the future multi-modal harvesters is to integrate piezoelectric systems with other options of harvesting energies like thermoelectric or photo voltaic modules to produce hybrid self-powered systems. Vibration patterns can also be dynamically optimized, e.g. using machine learning algorithms to analyze vibration behavior to predict pattern and dynamically optimize harvester configuration. The rising nanocomposite piezoelectric materials and 3D printing technologies other than show a potential to develop interesting, pliant, conformable energy harvesting layers which may be installed in smart clothing, roads and building surfaces. To sum up, the given research supports the conclusion that piezoelectric energy capture is technically feasible, especially ambient vibrations, besides being environmentally and operationally viable in a diversity of IoT applications. Although there is still some work to be done, piezoelectric materials integrated with intelligent energy management systems seem to lay a very solid grounds on the way to creating battery-free scalable IoT ecosystems that are consistent with the notion of keeping things sustainable and promoting a circular economy.

REFERENCES

[1] S. Roundy, P. K. Wright, and J. Rabaey, "A study of low level vibrations as a power source for wireless sensor nodes," Computer Communications, vol. 26, no. 11, pp. 1131–1144, Jul. 2003.
[2] S. Priya, "Advances in energy harvesting using low profile piezoelectric transducers," Journal of Electroceramics, vol. 19, no. 1, pp. 165–182, Jul. 2007.
[3] H. A. Sodano, D. J. Inman, and G. Park, "A review of power harvesting from vibration using piezoelectric materials," The Shock and Vibration Digest, vol. 36, no. 3, pp. 197–205, May 2004.
[4] J. Park, S. Lee, and H. Ko, "Flexible and stretchable energy harvesting devices for wearable electronics," Advanced Materials, vol. 30, no. 20, pp. 1803985, 2018.
[5] C. Jeong, H. Kwon, J. Hwang, and Y. Lee, "Lead-free piezoelectric ceramics for environmentally sustainable applications," Ceramics International, vol. 47, no. 5, pp. 6718–6725, 2021.
[6] S. P. Beeby, M. J. Tudor, and N. M. White, "Energy harvesting vibration sources for microsystems applications," Measurement Science and Technology, vol. 17, no. 12, pp. R175–R195, Dec. 2006.
[7] L. Zhao, Y. Yang, and J. Wang, "A wearable and flexible piezoelectric sensor for human motion monitoring and energy harvesting," Nano Energy, vol. 93, p. 106827, 2022.
[8] S. Shafer, B. Cook, and R. Smith, "Energy-harvesting powered wireless sensor platform for industrial condition monitoring," IEEE Sensors Journal, vol. 19, no. 3, pp. 928–936, Feb. 2019.
[9] A. Chandrakasan, R. Amirtharajah, S. Cho, J. Goodman, and W. Rabiner, "Design considerations for distributed microsensor systems," Proceedings of the IEEE Custom Integrated Circuits Conference, pp. 279–286, 2017.
[10] Q. Xu, T. Jin, and L. Zhang, "Fatigue analysis of piezoelectric ceramics in energy harvesting devices," Sensors and Actuators A: Physical, vol. 287, pp. 149–157, Apr. 2019.
[11] A. Erturk and D. J. Inman, Piezoelectric Energy Harvesting, Wiley, 2011.
[12] Y. Zhou, J. Wang, and X. Chen, "Self-adaptive energy harvester using piezoelectric materials and intelligent control," IEEE Transactions on Industrial Electronics, vol. 67, no. 6, pp. 4933–4942, Jun. 2020.
[13] C. Dagdeviren, Z. Li, and Z. Wang, "Energy harvesting from the human body for biomedical devices," Annual Review of Biomedical Engineering, vol. 19, pp. 85–108, 2017.
[14] Y. Zhang, Q. Huang, and Y. Liu, "Design of a self-powered environmental monitoring node using piezoelectric energy harvesting," Sensors, vol. 20, no. 22, pp. 6589, 2020.
[15] H. Wang, P. Li, and Z. Liu, "Environmental impact and recyclability of piezoelectric materials: A sustainability review," Sustainability, vol. 13, no. 3, pp. 1152, 2021.
[16] M. F. Pereira, V. R. S. Munoz, and A. De Luca, "A survey on piezoelectric energy harvesting systems for Internet of Things applications," Energy Reports, vol. 8, pp. 1249–1268, 2022.
[17] J. Xu, X. Zhang, and L. Sun, "Low-frequency energy harvesting using hybrid piezoelectric-cantilever structures," Microsystems & Nanoengineering, vol. 6, pp. 1–8, 2020.
[18] M. R. Palattella et al., "Internet of Things in the 5G era: Enablers, architecture, and business models," IEEE Journal on Selected Areas in Communications, vol. 34, no. 3, pp. 510–527, Mar. 2016.
[19] M. Li, Y. Liu, and X. Zhang, "Piezoelectric nanogenerators for sustainable energy," Advanced Energy Materials, vol. 11, no. 2, pp. 2001453, 2021.
[20] L. Yuan, K. He, and G. Liu, "Design and modeling of bridge-embedded piezoelectric energy harvesters," Smart Materials and Structures, vol. 30, no. 4, pp. 045010, 2021.
[21] J. Lee, S. Lee, and D. Kim, "Integration of piezoelectric harvesting with IoT devices for structural health monitoring," Journal of Intelligent Material Systems and Structures, vol. 33, no. 7, pp. 824–837, 2022.
[22] T. Nguyen, H. Ahn, and Y. Choi, "Flexible piezoelectric PVDF-based energy harvester for wearable sensors," IEEE Access, vol. 8, pp. 168363–168372, 2020.
[23] B. S. Kim and W. Yang, "High-efficiency full-wave rectifier design for piezoelectric energy harvesting systems," IEEE Transactions on Power Electronics, vol. 35, no. 5, pp. 5067–5076, May 2020.
[24] R. Raziq, S. Shoaib, and S. Yousaf, "Circuit design and energy storage for piezoelectric harvesters in wireless sensor networks," Electronics, vol. 9, no. 2, pp. 290, 2020.
[25] H. Li, Z. Shi, and C. Yuan, "Real-time power management circuit for piezoelectric energy harvesting," Sensors and Actuators A: Physical, vol. 298, pp. 111577, 2019.
[26] A. C. Fernandes, F. Alves, and A. Rodrigues, "Design and validation of a power supply circuit for piezoelectric IoT sensors," Journal of Energy Storage, vol. 48, pp. 104055, 2022.
[27] Y. Lin, T. Huang, and S. Chen, "Analysis of charge-discharge characteristics in wearable piezoelectric sensors," IEEE Sensors Letters, vol. 4, no. 3, pp. 1–4, Mar. 2020.

[28] D. Singh and V. Kumar, "Assessment of fatigue and wear on piezoelectric harvesters," Wear, vol. 426–427, pp. 624–633, 2019.
[29] H. Feng and X. Zhou, "Hybrid piezoelectric and thermoelectric energy harvester for environmental IoT devices," IEEE Internet of Things Journal, vol. 9, no. 6, pp. 4575–4583, 2022.
[30] N. Khalid, R. Shafqat, and A. Mehmood, "Impact of environmental factors on piezoelectric sensor performance: A case study," Journal of Sensors, vol. 2021, pp. 1–9, 2021.
[31] J. Han and L. Liu, "Design optimization of multilayer piezoelectric energy harvesters," Micromachines, vol. 13, no. 2, pp. 245, 2022.
[32] Z. Tan, Y. Ma, and B. Liu, "Energy harvesting through structural vibrations in smart buildings," Renewable Energy, vol. 183, pp. 895–905, 2022.
[33] K. Ali, A. Zahid, and N. Ahmed, "Comparative analysis of piezoelectric materials for energy harvesting: A sustainability perspective," Materials Today: Proceedings, vol. 62, pp. 4562–4567, 2023.
[34] G. Wei, J. Lin, and F. Zhang, "Self-powered IoT node using piezoelectric harvesting with edge AI," IEEE Transactions on Industrial Informatics, vol. 18, no. 4, pp. 2610–2618, 2022.
[35] P. Yadav, V. Rathore, and S. Singh, "Piezoelectric sensors and harvesters: Review of materials and applications," Journal of Intelligent & Fuzzy Systems, vol. 44, no. 1, pp. 725–739, 2023.