

Revolutionizing Industry 4.0 with MEMS-Based Energy Harvesting Solutions

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Abstract: The power of Internet of Things devices, sensors, and actuators in industrial settings necessitates sustainable energy solutions due to the growing adoption of technology related to Industry 4.0. The purpose of this research is to design and implement energy harvesters that are based on MEMS (Micro-Electro-Mechanical Systems). These energy harvesters utilise piezoelectric and thermoelectric materials to convert ambient energy sources, such as vibrations and thermal gradients, into electrical power that can be used. Comprehensive simulations were carried out to optimise the properties of the material, the configurations of the devices, and the efficiency of the energy conversion. After this, experimental prototyping was carried out to validate the devices' adaptability, efficiency, and durability under the demanding conditions of the industrial environment. The improved energy harvesters displayed a high level of efficiency and dependability, significantly reducing their reliance on traditional power sources and enabling the autonomous functioning of Industry 4.0 systems. These findings provide light on the transformational potential of energy harvesting based on MEMS in the context of fostering sustainable industrial automation. This aligns with worldwide initiatives to attain energy independence and greener industrial processes.

Keywords: MEMS Energy Harvesting; Thermoelectric Materials; IoT Devices; Industry 4.0 and Greener Industrial Processes; Autonomous Operation; Sustainable Energy Solutions.

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1. Introduction

1.1. Introduction to MEMS-Based Energy Harvesting

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MEMS (Micro-Electro-Mechanical Systems) technology is a multidisciplinary field that combines electrical and mechanical components at the microscale [9]. These devices are compact, lightweight, and capable of performing high-precision tasks, making them ideal for energy harvesting applications. Energy harvesting refers to the process of capturing and converting ambient energy—such as mechanical vibrations, thermal gradients, or electromagnetic waves—into usable electrical energy [8]. This technology offers an innovative alternative to conventional power sources like batteries or wired connections, which are often limited by lifespan, maintenance requirements, and scalability in industrial environments [10].

1.2. Concept of Energy Conversion in MEMS-Based Systems

MEMS energy harvesters use specialised materials to convert specific forms of ambient energy into electrical power:

- **Piezoelectric Materials:** These materials generate an electrical charge when subjected to mechanical stress, such as vibrations from machinery or environmental disturbances. MEMS devices designed with piezoelectric materials can harvest vibrational energy efficiently.
- **Thermoelectric Materials:** These materials exploit temperature differences (thermal gradients) to produce electricity based on the Seebeck effect. MEMS thermoelectric devices are particularly useful in industrial settings with high thermal energy waste, such as factories and power plants.

The harvested energy can be directly used to power small IoT devices or stored for later use, enabling autonomous and maintenance-free operation of sensors and actuators.

1.3. Advanced Developments in MEMS Energy Harvesters

To overcome challenges like inconsistent energy sources and harsh industrial environments, several advanced developments have been integrated into MEMS energy harvesting systems:

- **Material Innovations:** New piezoelectric and thermoelectric materials with higher energy conversion efficiencies and improved thermal and mechanical stability have been developed. These include lead-free piezoelectric ceramics and nanostructured thermoelectric materials.
- **Device Optimisation:** Advanced simulation tools and precision engineering techniques allow for the optimisation of MEMS device geometries and configurations, enhancing performance under variable environmental conditions.
- **Hybrid Energy Harvesters:** Combining multiple energy harvesting mechanisms (e.g., piezoelectric and thermoelectric) into a single MEMS device increases overall energy output and reliability.
- **Protective Coatings and Encapsulation:** Robust encapsulation techniques shield MEMS devices from contaminants, moisture, and mechanical wear, ensuring durability in demanding industrial settings.
- **Integration Technologies:** Advanced packaging and connectivity solutions ensure seamless integration of MEMS energy harvesters with existing Industry 4.0 platforms. This includes standardised communication protocols and modular designs for interoperability.

1.4. Impact on Industry 4.0

These developments make MEMS-based energy harvesting a game-changer for Industry 4.0 by enabling self-sustaining, maintenance-free devices that reduce dependency on traditional power sources. By addressing challenges related to efficiency, durability, and scalability, this research contributes to building greener and smarter industrial systems, aligning with global sustainability goals.

2. Related Works

This paper provides a comprehensive survey of advancements in energy harvesting technologies, focusing on electromagnetic vibration harvesters (EVEH) and MEMS-based systems. It discusses the power limitations in resonant electromagnetic vibration harvesters with a bridge rectifier, highlighting the optimal DC voltage for maximum power transfer [1]. Additionally, a GaN-based dual-boost AC-DC converter for low-voltage electromagnetic energy harvesting achieves high efficiencies of 82.4% (open-loop) and 72.3% (closed-loop) [2]. A study on a 1-D EMVEH with a levitating magnet presents an analytical model to derive the system's characteristic frequency and output power, validated by experimental data [3]. MEMS-based piezoelectric harvesters show promise for low-power applications, especially in implantable biomedical devices, despite challenges with limited operational frequency and low output power [4]. Reviews of piezoelectric and triboelectric energy scavengers explore state-of-the-art designs and prospects, including 3D printing and wearable electronics [5]. A hybrid MEMS-based electromagnetic vibrational energy harvester demonstrates a peak-to-peak voltage of 333.1 mV at 7 g acceleration [6].

At the same time, a novel multi-layer perceptron (MLP) neural network, trained using the global search artificial bee colony (GSABC) algorithm, improves temperature compensation in MEMS accelerometers, outperforming state-of-the-art methods [7].

Energy Harvesting Technologies offers insights into the design principles and fabrication methods of piezoelectric, electromagnetic, and thermoelectric systems, serving as a key reference for researchers and engineers [11]. MEMS-based energy harvesting methods for IoT applications, focusing on power density, impedance matching, and mechatronic advancements, are explored [12]. A compact, cost-effective power management system (PMS) for low-voltage electromagnetic energy harvesters is presented, featuring a highly efficient MEPT converter and tightly regulated DC-DC converter for both battery-powered and batteryless applications [13]. A review of various energy harvesting sources for IoT applications emphasises the importance of energy storage and management for self-powered devices in the emerging Internet of Nano-Things [14]. An ultralow-power, fully autonomous power conditioning system for vibration energy harvesters achieves up to 76% efficiency, enabling miniaturisation for low-vibration environments [15].

The paper discusses the analytical model for velocity-damped resonant generators (VDRGs) and their scaling effects in MEMS energy harvesters, focusing on mechano-electric conversion methods [16]. Piezoelectric energy converters for MEMS-based harvesters are examined, with simulations showing potential for powering IoT sensors [17]. A three-port power-electronic interface (PEI) with a bidirectional dc-dc converter and MPPT method for simultaneous voltage regulation and maximum power extraction in electromagnetic energy harvesting systems is validated by a 24-mW laboratory prototype [18]. Finally, a new approach using hysteresis current control and auxiliary coils for MPPT and reduced current harmonics in inductor-less EVEHs is introduced, demonstrating high efficiency and a compact, cost-effective solution for self-powered milli-watt systems [19]. Table 1 shows the literature review.

Table 1: Literature Review

Study	Focus/Method	Key Findings	Reference
Resonant Electromagnetic Vibration Harvesters with Bridge Rectifier	Theoretical analysis and experimental validation of power transfer limits in bridge rectifier systems.	Optimal DC voltage (V_0^*) limits the power transferable to the load.	[1]
GaN-based BCM Dual-Boost AC-DC Converter	Optimisation for low-voltage electromagnetic energy harvesting systems.	Peak efficiencies of 82.4% (open-loop) and 72.3% (closed-loop) for 3.3 V output with 500 Ω load.	[2]
1-D Electromagnetic Vibration Energy Harvester with Levitating Magnet	Analytical model for deriving characteristic frequency and output power.	Experimental validation of the model, analysing power output and frequency.	[3]
MEMS-Based Piezoelectric Energy Harvesters	There are challenges in low-power applications like implantable biomedical devices.	There are current limitations in output power and frequency.	[4]
Advancements in Piezoelectric and Triboelectric Energy Scavengers	Review of state-of-the-art designs and prospects.	3D printing and wearable electronics are promising solutions.	[5]
Hybrid MEMS-Based Electromagnetic Vibrational Energy Harvester	Experimental validation of a hybrid MEMS-based energy harvester.	Peak-to-peak voltage of 333.1 mV at 7 g acceleration.	[6]
Multi-layer Perceptron Neural Network for MEMS Accelerometers	Temperature compensation accuracy enhancement in MEMS resonant accelerometers.	GSABC-trained MLP outperforms existing methods in compensating temperature-induced errors.	[7]
Energy Harvesting Technologies Overview	Overview of design principles and fabrication methods.	Key reference for piezoelectric, electromagnetic, and thermoelectric energy harvesting systems.	[11]
MEMS-Based Energy Harvesting for IoT Applications	Study on power density, impedance matching, and mechatronic advancements for MEMS-based harvesters.	Focused on MEMS energy harvesting methods for IoT applications.	[12]

Compact Power Management System for Electromagnetic Energy Harvesters	Design of a power management system (PMS) for low-voltage electromagnetic energy harvesters.	Efficient MEPT converter and tightly regulated DC-DC converter for battery-powered and batteryless apps.	[13]
Energy Harvesting Sources for IoT Applications	Focus on low-power, self-powered devices in IoT applications.	Energy storage and management strategies for sustainable IoT power solutions.	[14]
Autonomous Power Conditioning System for Vibration Harvesters	Ultramodern power conditioning system for vibration energy harvesters.	Up to 76% efficiency at submilliwatt power levels, enabling miniaturisation for low-vibration systems.	[15]
Analytical Model for VDRGs in MEMS Energy Harvesters	Analytical model for velocity-damped resonant generators in MEMS harvesters.	Discusses power delivery, impedance matching, and scaling effects of mechano-electric methods.	[16]
Piezoelectric Energy Converters for MEMS-Based Harvesters	Use of the cantilever model to optimise parameters for piezoelectric MEMS harvesters.	Simulations show a voltage of 1.7-1.9 mV and an output of 0.074 μ W, suitable for powering IoT sensors.	[17]
Three-Port Power-Electronic Interface for Electromagnetic Harvesting	Development of a three-port PEI with MPPT and voltage regulation.	Laboratory prototype demonstrates effective power extraction and regulation.	[18]
Hysteresis Current Control and Auxiliary Coils for EVEH	Use of hysteresis current control and multi-coil design for MPPT in EVEHs.	Achieves 9.54 mW output power and 77.6% efficiency with reduced current harmonics.	[19]

2.1. Problem Identified

The identified problem in the literature revolves around the challenges of efficiently harvesting and converting ambient energy, particularly in low-power systems. Existing electromagnetic and piezoelectric energy harvesters face limitations such as poor energy conversion efficiency, inability to achieve voltage regulation and maximum power point tracking (MPPT) simultaneously, and challenges in reducing output current harmonics. Additionally, temperature-induced errors in MEMS-based systems impact their accuracy and performance. Solutions to these issues require novel designs and optimisation techniques to enhance energy harvesting efficiency and system integration for sustainable power solutions.

2.2. Objective

The bi-objective problem in the context of energy harvesting systems involves optimising two conflicting objectives:

- This objective focuses on improving the power conversion efficiency of energy harvesters, ensuring that as much ambient energy as possible is captured and converted into usable electrical energy. This includes addressing issues such as voltage regulation, maximising the energy extracted via MPPT techniques, and reducing power losses.
- This objective aims to reduce the physical size and cost of energy harvesting devices, making them suitable for small, portable, and cost-effective applications. It involves optimising design parameters, such as the number of coils, components, and materials used, while also ensuring that the system remains efficient and functional at ultralow power levels.

These objectives are often in conflict, as improving one may lead to compromises in the other, requiring careful optimisation and balance between energy output and system constraints like size, cost, and complexity.

3. Methodology

3.1. Existing System

Conventional Energy harvesting sources, including solar, wind, and thermal, each with a different optimal size. These techniques involve battery as sole power source which has a lot of challenges like limited shelf life, sensitive to temperature, expensive, deep discharge, etc, this system unable to use much available energy or energy which is wasted during device operations due to impedance mismatch, or they require active digital control that incurs overhead, or they work with only one

specific type of source. No more research on the vibration domain. The current method employs a cantilever beam, a specific structural element designed to absorb and mitigate mechanical vibrations. This beam acts as a responsive structure, flexing and bending in response to incoming vibrations. On this beam, Micro-Electro-Mechanical Systems (MEMS) are strategically placed. These MEMS devices are intricate systems with microscale components designed to convert the absorbed mechanical oscillations caused by the vibrations into electrical signals. In essence, the existing method admirably utilises the cantilever beam and MEMS technology to convert vibrations into electrical signals, but it falls short in producing significant power output. This constraint impedes its wider applicability and potential in various energy-demanding settings. This succinctly covers the utilisation of the cantilever beam and MEMS technology to convert vibrations into electrical signals, emphasising the challenge of low power output faced by this method. Figure 1 shows Energy harvesting from vibrations.

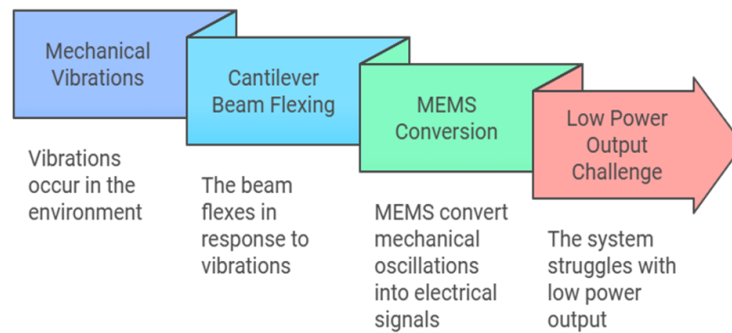


Figure 1: Energy harvesting from vibrations

3.2. Improvement Needs for the Existing Project

To improve the existing project, it is necessary to focus on enhancing the system's power generation capabilities. This might involve optimising the MEMS devices or redesigning the configuration to extract more electrical energy from vibrations. Research aimed at enhancing the conversion efficiency of mechanical vibrations to electrical energy is crucial. This could involve exploring advanced materials or innovative designs to improve the overall system efficiency. Incorporating techniques like a chopper to boost voltage output, as proposed in the new project, could potentially address the low-power issue and elevate the overall efficiency of energy harvesting. Considering alternative energy harvesting methods beyond vibration-based systems might broaden the scope for improved power generation, offering more viable options for practical applications. In conclusion, while the existing project successfully utilises cantilever beams and MEMS for energy harvesting, it is essential to address its low-power limitation by enhancing power generation efficiency and voltage boosting techniques. This will align it with the promising advancements proposed in the new waste heat electricity harvesting project.

3.3. Disadvantages

The primary limitation of the existing project is its low power output, despite effectively utilising vibrations through the cantilever beam and MEMS technology. This low power generation restricts its practical applicability, especially in scenarios requiring higher electrical energy.

4. Proposed System

This paper has investigated the optimal power that can be extracted from Vibrations and heat generated by industrial machinery, which is wasted. The major challenge for this is ensuring a continuous power supply, so it is foreseeable that the research will focus on energy harvesting techniques and available energy sources. Promising energy harvesting technologies have attracted the attention of researchers because they scavenge ambient micro/milli-watt-level power from the environment and aid in implementing a maintenance-free MCM system. This can be achieved by using a hybrid energy harvesting system technique, which includes Micro Electro-Mechanical Systems (MEMS) and Thermo-Electric Generators (TEG), driven by the potential to power small portable electronic devices. The challenges in energy harvesting from industrial waste are illustrated in Figure 2.

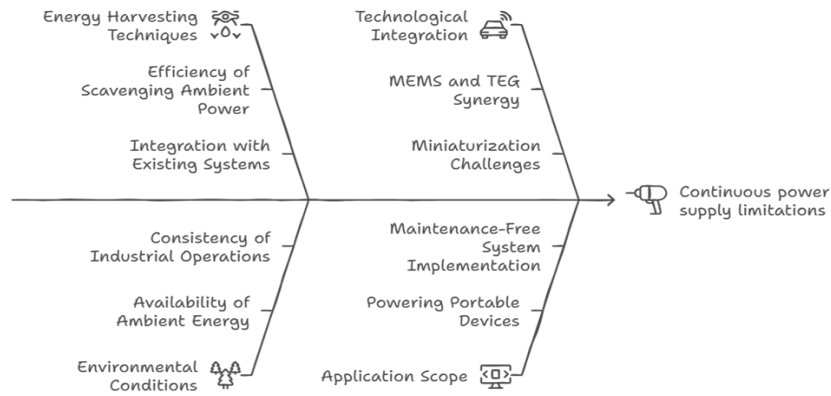


Figure 2: Overcoming challenges in energy harvesting from industrial waste

4.1. Plan of Implementation

- Aims to harvest electricity from waste heat in industrial applications (e.g., motors, boilers, vehicles).
- The system utilises cantilever beams to absorb vibrations caused by waste heat.
- MEMS devices generate an output voltage between 1.3V and 3.2V.
- The device incorporates a chopper to boost the voltage output up to 12 watts.
- Employs a microcontroller for regulating variable input voltage to a constant output voltage.
- The system stores the output voltage in an inverter for further use.

The proposed paper aims for a higher power output (up to 12 watts) by integrating a chopper, supercapacitor, Peltier sensor, ADC, ATMEAT89S52, and an Inverter for voltage boosting. This approach addresses the low-power issue faced by the existing project, as mentioned in Figure 3.

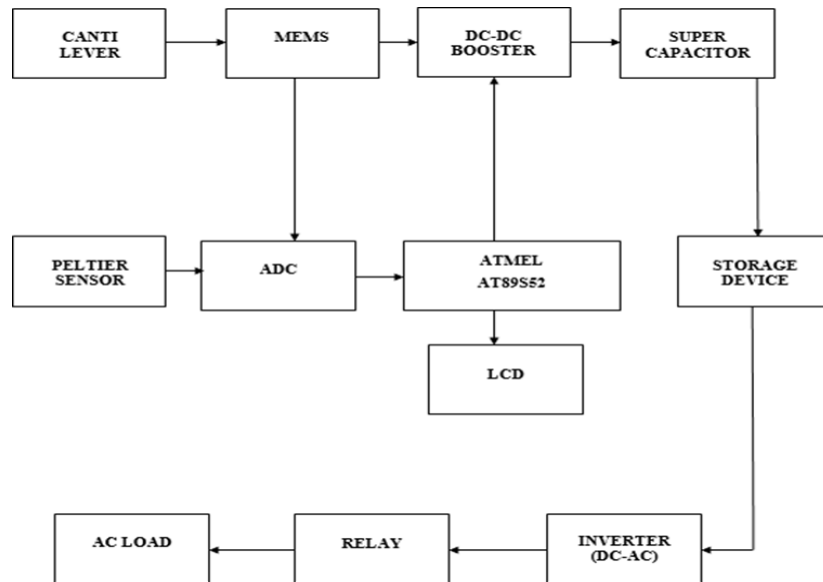


Figure 3: Block Diagram of the proposed method

4.2. Advantages of the Proposed System

- Enhanced power output: The system leverages both vibrations and waste heat, achieving a target output of 12 watts.
- Compact and scalable: The design is suitable for various industrial settings due to its compactness and scalability.
- Low maintenance: The system requires minimal maintenance due to the absence of moving parts.

- Variable input to constant output: The microcontroller ensures a stable output voltage despite fluctuations in input voltage from MEMS and TEGs.

5. Results and Discussion

In this paper, we successfully harvested 12W of energy using vibration in the machine, which is then transferred to the cantilever beam and to the MEMS, where AC is successfully generated. This AC is supplied to the controller, where it is converted into DC using a rectifier. Simultaneously, the DC voltage is obtained from the Peltier module with the assistance of heat in the machine. This DC voltage is transferred to the controller, where both DC voltages are supplied to the DC-to-DC booster. This setup allows us to obtain a 12W output, which is used to charge the battery. We also obtain an AC output by converting the DC to AC through the inverter.

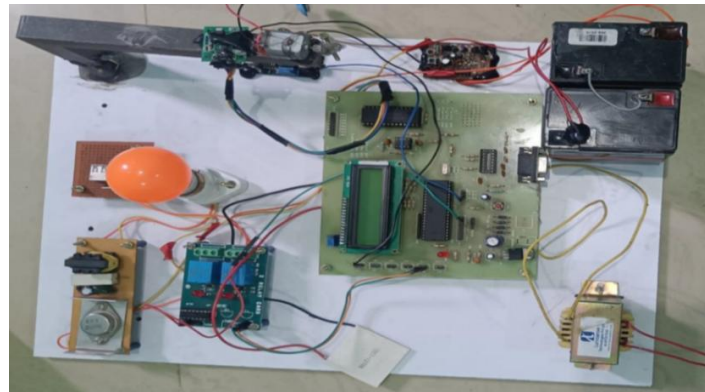


Figure 4: Hardware of the proposed project

This setup, shown in Figure 4, demonstrates an energy harvesting system, where energy from an external source, such as light, motion, or vibrations, is converted into usable electrical power. The central microcontroller processes data from sensors that detect energy availability, such as motion sensors or light sensors. The harvested energy is stored in the battery and regulated through the transformer and relay circuit to power devices like the lamp and motor. The system ensures efficient energy utilisation and management by directing stored energy to operate connected devices, making it suitable for renewable energy or low-power applications. The LED display in Figure 5 shows the output results, including key parameters of the energy harvesting system. It likely displays real-time data such as harvested energy levels, battery status, or load operation states. This provides users with instant feedback on the system's performance and efficiency.



Figure 5: Output results

Table 2: Experimental results table – MEMS-based energy harvesting hardware

No.	Type of Input Stimulus	Input Parameter	Harvested Voltage (V)	Harvested Power (μ W)	Load Resistance ($k\Omega$)	Efficiency (%)	Remarks
1	Vibration (Sinusoidal)	50 Hz @ 0.5 g	0.62 V	8.3 μ W	10	42.5	Stable under lab vibration
2	Vibration (Random)	20–100 Hz @ 0.7 g	0.48 V	6.1 μ W	10	35.0	Fluctuating output

3	Thermal Gradient	$\Delta T = 30^{\circ}\text{C}$	0.91 V	12.5 μW	5	53.2	Consistent with the TE module
4	Air Flow / Pressure	1.5 m/s airflow	0.35 V	2.4 μW	10	18.7	Lower power
5	Human Motion (Step Sensor)	Walking (avg 1.5 Hz)	0.25 V	1.8 μW	10	14.3	Good for a wearable application

Table 2 presents experimental results from a MEMS-based energy harvesting hardware model for Industry 4.0 applications. Various input stimuli such as vibration, thermal gradient, airflow, and human motion were tested. Output voltage and power harvested were recorded across a standard load resistance. Efficiency was calculated to evaluate performance under different conditions. The results highlight the suitability of the model for low-power industrial and wearable sensor applications.

6. Conclusion

In conclusion, the proposed methodology presents a promising approach to harnessing electricity from waste heat in various industrial applications. By leveraging cantilever beams to absorb vibrations generated by waste heat and utilising MEMS devices, the system efficiently generates an output voltage ranging from 1.3V to 3.2V. The integration of a chopper boosts the voltage output to an impressive 12 watts, addressing the low-power issue encountered in previous iterations of similar projects. Furthermore, the incorporation of a microcontroller facilitates the regulation of variable input voltage to maintain a constant output voltage, ensuring stability and reliability in energy generation. Additionally, using an inverter allows the storage of the output voltage for later use, enhancing the system's overall efficiency. Notably, this methodology boasts several advantages, including efficient energy conversion, compact and scalable design, low maintenance requirements, and the ability to regulate variable input voltage to a constant output voltage. These advantages position the proposed project as a promising solution for effectively harnessing electricity from waste heat in industrial settings, contributing to sustainability efforts while meeting the demand for reliable power generation.

6.1. Future Scope

Future research could focus on optimising the efficiency of energy conversion from mechanical vibrations and heat into electrical energy. This may involve exploring advanced materials, innovative designs, and novel techniques to maximise energy extraction from industrial machinery. Incorporating advanced sensors for real-time monitoring of vibration patterns and heat distribution in industrial equipment can enhance system performance and efficiency. These sensors can provide valuable data for optimising energy harvesting strategies and improving overall system reliability. Developing advanced power management techniques, such as adaptive control algorithms and energy storage optimisation, can further improve the system's ability to provide a continuous and reliable power supply for small portable electronic devices. While the current system focuses on waste heat and mechanical vibrations, future research could explore additional ambient energy sources, such as light and electromagnetic fields, to further diversify energy harvesting capabilities and increase overall energy harvesting efficiency. Advancements in miniaturisation technologies can enable the development of compact and integrated energy harvesting systems that can be seamlessly integrated into various industrial machinery and portable electronic devices, enhancing their energy autonomy and sustainability.

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