Advancements in Energy Harvesting Technologies: A Comparative Study of Various Techniques and Materials

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Abstract – Energy harvesting refers to gathering and transforming mechanical energy into electrical energy. Energy harvesting is a viable approach for a wide array of tiny devices and systems capable of self-powering. Examples of such systems include Bluetooth headsets, wireless sensors, watches, structure-embedded equipment, calculators, biological implants, remote weather stations, and military monitoring devices. This article examines many methodologies for energy harvesting, including mechanical vibration devices, wind turbines, thermoelectric generators, and solar cells. The study examines the projected capacity and challenges linked to diverse ambient energy sources, presenting a broad spectrum of potential methods for capturing and preserving energy from distinct sources. The paper also highlights the significance of considering electrical attributes, physical features, environmental traits, operational and maintenance qualities, and operational and maintenance qualities when assessing the performance and durability of portable energy suppliers. The text highlights the need for exercise while using energy harvesters in integrated systems to advance system durability and performance.

Keywords – Energy Harvesting, Thermoelectric Generators, Mechanical Vibration Devices, Wind Turbines, Solar Cells, Portable Energy Suppliers.

I. INTRODUCTION

The number of research studies on energy harvesting has consistently grown over the last decade, indicating the growing interest in this subject in recent years. The objective of this article is to provide researchers with a concise summary of the latest advancements in energy harvesting via the use of vibration, heat, and radio frequency (RF) waves. Priya and Inman [1] presents the fundamental concept of energy harvesting techniques. The recognition of producing power from renewable sources was first documented in 1826. Thomas Seebeck observed that when two distinct metals are sustained at varying atmospheres, a closed circuit may be formed, enabling the flow of electric current. During the next thirty years, scientists extensively studied the basic principles of thermoelectric phenomena, acquired a comprehensive knowledge of them at a larger scale, and finally recognized their potential applications in thermometry, power generation, and refrigeration. In 1839, Edmund Becquerel made the discovery of the photovoltaic phenomenon while conducting experiments with a two-metal electrode electrolytic cell [2]. In 1894, Charles Fritts created the first big area solar cell by applying a thin layer of gold on selenium.

Edmund Becquerel was the first observer of the photovoltaic effect, but its entire comprehension did not occur until the early 1900s, when the solid and light state physics` quantum theory were established [3]. In 1831, Michael Faraday and Joseph Henry independently made the discovery of electromagnetic induction (EI), which is the technique of producing electricity from magnetism [4]. Faraday's first direct-current generator, developed in October of that year [5], included the rotation of copper plates between two magnetic poles. The use of charging as a method of collecting energy was first seen in the year 1880. The application of mechanical stress (MS) induces the manifestation of a surface charge in certain crystals, a phenomenon that was predicted and empirically verified by Bazant, Kilic, Storey, and Ajdari [6]. The word "piezoelectricity" was used by Newnham, Skinner, and Cross [7] to explain this phenomenon.

Wireless sensor networks have made significant progress, and certain applications need sensor nodes to have a prolonged lifespan. Due to their need on human intervention for replacement, conventional batteries may not always be the optimal choice. Hence, the acquisition of energy to power these devices is a significant challenge. We must consider an alternative types of energy generation beyond conventional batteries. These devices may be powered by harnessing the existing thermal, mechanical, or light energy in the habitat. By employing this approach, it assures that the electronic tool will have an uninterrupted and unlimited supply of energy during its entire time of use. In case an individual wants to obtain electrical energy from the neighborhoods, they might participate in energy harvesting, or power scavenging. The four major forms of environmental energy are thermal. Mechanical, wind, and solar energy. The sources of energy harvesting (EH) have the capabilities to prolong the lifespan of operations of a specific device and boost its functionality when utilized in conjunction with or as battery substitute.

Energy harvesting (EH) might be utilized in distant environments to collect fundamental data on structural and operational issues. Recent research efforts have shown a significant surge in research on EH [8]. This research focusses on a discussion of the different technologies and methods of energy harvesting. To effectively ascertain the most efficient and reliable approaches for collecting and storing energy, scholars should undertake comparable research of projected power generation, and the related challenges linked to various sources of ambient energy. The rest of the article is arranged as follows: Section II discusses the various sources of harvesting energy. In Section III, a discussion of mechanical vibration and elements such as piezoelectric materials, electrostatic energy harvesting, and electromagnetic energy harvesting, has been presented. Section IV focusses on defining photovoltaic cells, while Section V further discusses thermoelectric generators. Lastly, Section VI presents a summary of the discussion on the advancements of energy harvesting.

II. SOURCES OF ENERGY HARVESTING

Energy Harvesters (EHs) may be classified based on the specific energy source used for power generation. One example is the use of piezoelectric harvesting devices to transform mechanical energy (ME) into electrical energy (EE) that may be used. Electromagnetic harmonics (EH) may arise from several sources such as mechanical vibration devices, wind turbines, thermoelectric generators (TEGs), solar cells, and electromagnetic and piezoelectric devices. As shown in **Table 1**, Pearce [9] conducted research that examines the estimated power and limitations associated with different ambient energy sources. The data in the table was derived from a diverse range of sources, including published research, experiments conducted by authors, theoretical investigations, and often referenced material in textbooks. The origin of the data for each strategy is indicated in the third column of the table.

Table 1. A comparison of the power density of several energy harvesting devices

Source of Energy	Power Performance & Density
Heel strike	7W/cm2
Hand generators	30W/kg
Shoe Inserts	330µW/cm2
Push buttons	50_J/N
Airflow	1µW/cm2
Vibrations (Piezoelectric)	200µW/cm3
micro generator (Vibration)	Human motion-Hz (4_W/cm3) Machines-kHz (800_W/cm3)
Thermoelectric	60_W/cm2
Ambient Light	Direct sun (100mW/cm2) Illuminated office (100_W/cm2)
Ambient Radio frequency	1µW/cm2
Temperature Variation	10µW/cm3
Acoustic Noise	0.003µW/cm3 @75 Db 0.96µW/cm3 @100 Db

While not exhaustive, this comparison offers a wide range of possible techniques for gathering and storing energy from various environmental sources. The viability of light as a substantial energy source is contingent upon the specific application and operational conditions of the device. Due to the scarcity of temperature gradients inside a chip, the amount of thermal energy is restricted. According to Furtenbacher, Császár, and Tennyson [10], the presence of vibration energy (VE) differs based on the specific use case.

When discussing a portable energy provider, it is crucial to consider the fundamental characteristics specified by Veiga et al. [11]. The list comprises physical attributes such as dimensions, shape, and mass; environmental factors like operational temperature range and water resilience; electrical properties like current, maximum voltage, and power density; and operational and maintenance features. To effectively enhance the efficiency and quality of a system, it is important to exercise caution while using EH.

III. MECHANICAL VIBRATION

Indoor operation settings may allow for the collection of ambient energy via the use of consistent and dependable mechanical vibrations. Indoor machinery sensors, often used in industrial settings, generally contain a significant quantity of mechanical vibration energy that may be consistently monitored and utilized. VE harvesting devices may be categorized as either piezoelectric or electromechanical. Electromechanical harvesting systems are the subject of more extensive study and are more often used. According to Liu et al. [12], the extraction of energy from vibrations may be achieved by the displacement of a mass attached to a spring in relation to its supporting frame.

Vibrations provide mechanical acceleration, which then induces movement and oscillation in the mass component. The displacement of this object relative to its original position results in the application of opposing forces of friction and damping on the mass, leading to a gradual decrease and final cessation of the oscillations. The energy of the damping force may be transformed into EE by the use of strain on a piezoelectric material, magnetic field (electromagnetic), or electric field (electrostatic). When a gadget experiences vibration, movement may be generated by using an inertial mass. Electrical energy may be generated from this movement via three mechanisms: piezoelectric, electromagnetic, and electrostatic. The energy being used in this context is mechanical energy.

Piezoelectric Materials

These materials transform ME derived from force, or pressure into electrical energy. They may produce an electric charge when subjected to mechanical force. Researchers explore this characteristic of piezoelectric materials to produce a range of piezoelectric harvesters for powering diverse applications. Piezoelectric materials have become a practical source of energy scavenging due to their natural capacity to sense vibrations. Let's look at the transverse piezoelectric effect's influence on a piezoceramic plate's longitudinal mechanical vibration. This example, shown in **Fig 1**, aims to demonstrate that the vigorous combination factor k at resonance is equivalent to the static coupling factor.

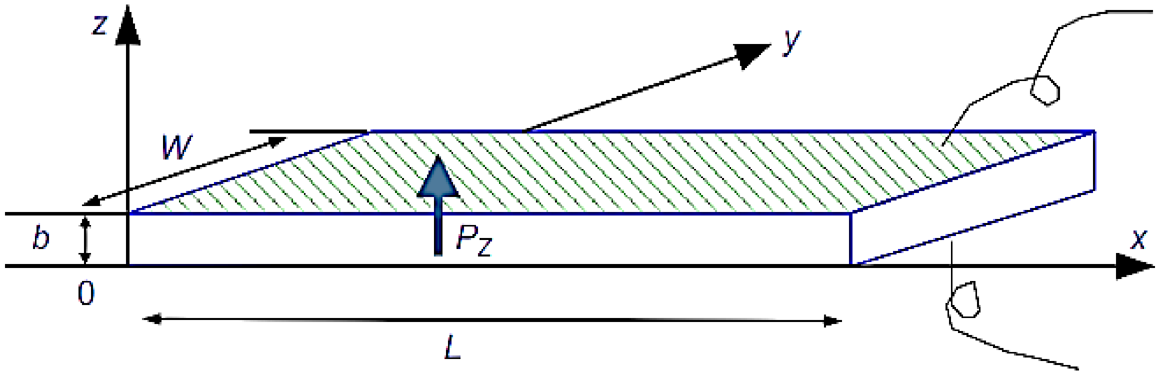

Fig 1. The diagonal piezoelectric effect (d31) induces longitudinal vibration in a rectangular plate with dimensions L, W, and b.

The following dynamic equation may be used to explain the extensional tremor in the x direction if the polarization is aligned in the x-y planes and the z-direction corresponds to the electrode planes. It is worth noting that when L is significantly greater than 5 times the thickness of b or the width w, we can neglect the coupling mode involving width or thickness vibrations.

$$\left(\frac{\partial^2 u}{\partial t^2}\right) = F = \left(\frac{\partial X_{11}}{\partial x}\right) + \left(\frac{\partial X_{12}}{\partial y}\right) + \left(\frac{\partial X_{13}}{\partial z}\right), \quad (1)$$

Let u represent the shifting of the tiny capacity component within the ceramic plate along the x-axis. The relationships between electric fields (with just Ez present due to the electrodes), stress, and the resulting strain are described by the equations below:

$$x_1 = S_{11}E_{X_1} + S_{12}E_{X_2} + S_{13}E_{X_3} + d_{31}E_3$$

$$x_2 = S_{12}E_{X_1} + S_{11}E_{X_2} + S_{13}E_{X_3} + d_{31}E_3,$$

$$x_3 = S_{13}E_{X_1} + S_{13}E_{X_2} + S_{33}E_{X_3} + d_{33}E_3,$$

$$x_4 = S_{44}E_{X_4},$$

$$x_5 = S_{44}E_{X_5},$$

$$x_6 = 2\left(S_{11^E} - S_{12^E}\right)X_6. \quad (2)$$

In order to harness energy using piezoelectric materials (PM), it is necessary to have a means of storing the energy that is produced. This implies that they have the option to either a circuit designed to use the captured energy to generate further energy or create a circuit designed to store the gathered energy. Instead of using capacitors for energy storage, the captured energy may be stored in rechargeable batteries. The rapid discharge characteristic of ordinary capacitors renders them unsuitable for use as devices for energy storage in computational electronics. Guan and Liao [13] used a piezo-alternator consisting of a viaduct and a condenser for energy storage. The outcome yielded an efficiency of 35%, which was thrice more than the electricity generated by solar cells. Chew, Ruan, and Zhu [14] developed a mechanical strain energy sensor capable of generating electrical energy from applied mechanical strain. In order to demonstrate this concept, a simple beam bending experiment was carried out. A piezofilm sensor is used to produce an electrical warning by attaching it to a beam.

Nozariasbmarz et al. [15] are now working on the creation of an enhanced energy-harvesting system. This gadget is created by applying a substantial coating of piezoelectric material over a slender steel beam. The resonance of the beam causes the PM to change shape, resulting in the production of electrical energy. The power generation capacity might potentially be enhanced by the modification of the employed material. The group is now doing thorough research in this field and is on the verge of finishing a comprehensive study that will assess the efficacy of magnet-coil and piezoelectric generators, as well as their potential uses. One of the first uses of piezoelectric transducers for structural health monitoring included capturing the force exerted by a descending steel ball bearing. Subsequently, the energy was stored in either a a battery or capacitor. In their latest study, Calautit, Nasir, and Hughes [16] examined the energy generation achieved by using a nickel package to precisely apply mechanical force onto a piezoelectric panel.

Rocha et al. [17] conducted research on the use of piezoelectric materials to generate electrical energy from human movement. An instance involves affixing a piezoelectric substance, such as polyvinylidene fluoride (PVDF), to the back of the shoe. Upon impact with the ground, the shoe converts the generated energy into electric charge via the use of piezoelectric material. This fee is applicable to some luxury shoe styles. Callaway and Edgar's book on Wireless Sensor Networks also explores a commercial application including the application of a piezoelectric generator in a switch for wireless lighting. The electricity supplied by flipping the switch is applied in a convert-only wireless node (WN). This node establishes communication with a WN that can only receive signals. The WN is energized by the mains and is connected to the light. Currently, a research is being conducted to investigate the possibility of producing electricity by incorporating piezoelectric devices into orthopedic implants.

According to Rashmi, Sairam, and Suresh [18], the present research on energy harvesting using piezoelectric technology may be categorized into two main categories. One is engaged in the enhancement of energy harvesting structures that are optimized for maximum efficiency, while the other is focused on the design of electrical circuits that can efficiently store the charge created. The study conducted at The Pittsburgh University concentrates on the initial domain, aiming to develop compact and lightweight devices that effectively connect to mechanical stimulation and generate practical EE. This team is focused on building efficient devices that can transform the existing mechanical energy in the environment into EE. Recently, a unique circuit for power conditioning of devices that scavenge piezoelectric energy has been proposed.

Anastasopoulos et al. [19] provides a significantly enhanced efficiency compared to current systems when subjected to sinusoidal shaking motion. This circuit employs a step-down converter and yielded an energy harvest that exceeded fourfold the power obtained by the same circuit without the converter. The new technology was able to capture over 70 mW of power, which is enough to provide power to a transpacific detector NN, even while it is constantly receiving data. Subsequently, a streamlined converter was used to enhance power generation. This study represents a significant advancement in the use of energy derived from the application of piezoelectric materials. Piezoelectric materials exhibit age-dependent, stress-induced, and temperature-sensitive characteristics. Piezoelectric materials provide the potential benefits of directly generating the necessary voltage without requiring an external voltage source. These alternators are unanimous with Microelectromechanical Systems (MEMs). These alternators are the most basic and may be used in applications involving impact and force harvesting. One drawback is that piezoelectric materials have a brittle character and may sometimes experience charge leakage.

Electrostatic (Capacitive) Energy Harvesting

A variable capacitor and an energy transfer circuit are combined in an electrostatic energy harvester, as seen in **Fig 2**. The electrostatic phenomenon occurs between the parallel plates of the capacitor, where electrical charge is accumulated. To harvest electrical energy, one of the plates is fixed while the other is moved using an external mechanical motion. This motion changes one of the parameters (P) of the variable capacitor, either the plate area or the plate spacing. Electrostatics enables the mechanical movement conversion into electrical energy. The electrostatic energy conversion concept is discussed in full.

This harvesting method relies on the fluctuating capacitance of varactors that are sensitive to vibrations. The plates of a varactor, which is a variable capacitor, are separated by vibrations, resulting in the conversion of mechanical energy into EE. Electrostatic generators (EG) are mechanical apparatuses that generate electricity by the use of human force. Crovetto, Wang, and Hansen [20] offer a clear explanation of the fundamental working concept, which involves using the gathered energy to do work against the electrostatic tension between the capacitor`s plates. Ahmed and Kakkar [21] provide a comprehensive explanation of the categorization of electrostatic generators into three distinct types: out-of-plane gap closing, in-plane gap closure, and in-plane overlap.

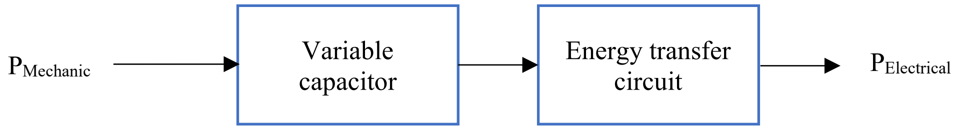

Fig 2. Electrostatic harvester schematic diagram

The numerous forms of EG are examined in several articles. The research conducted by Jefimenko and Walker [22] focuses on the study of electrostatic generators that use charged electrets. An important benefit of using electrostatic converters (EC) is their capacity to seamlessly interact with capacitors and resistors without requiring any intelligent materials. An inherent drawback of EC is their need for an auxiliary source of voltage to first charge the capacitor.

Electromagnetic Energy Harvesting(EEH)

The EEH may be accomplished by the concept of EI. EI refers to the phenomenon where a conductor produces an electric potential difference when the magnetic field around it is altered. An efficient method for generating EI for energy harvesting involves the use of a resonant cantilever beam, a coil, and permanent magnets. El-Hami et al. [23] provide a description of an electromechanical power generator that utilizes vibrations. The generator is composed of a pair of magnets and a cantilever beam. Doolittle and Brevik [24] have recognized the ways used to produce electricity from electromagnetic resources since the late 1990s. The developed electromagnetic generators has the benefit of being enclosed, hence enabling protection from external environmental factors. Electromagnetic induction has the benefits of enhanced dependability and less mechanical resistance due to the absence of any physical contact between elements. Additionally, it eliminates the need for a separate voltage source. Nevertheless, electromagnetic materials exhibit a large physical volume and pose challenges when it comes to integrating them with MEMs.

Fig 3 displays the diagrammatic design of a vibration-based EE harvester, which utilizes three sets of magnets and coils. The gadget has an acrylic beam that is compatible, three sets of copper coils arranged in two layers, and three stationary magnets. The coils are fabricated using traditional PCB technology, using thin fire-resistant 4 (FR4) substrates. On the other hand, the acrylic beam is produced by laser scribing. As the magnets oscillate and get closer to the coils, the coils will generate an induced voltage following the principle of Faraday's law of induction. The vortex arrangements of coils on both sides of a FR4 substratum are designed to enable a current to flow in opposing directions on each side, while maintaining the same magnetic flux direction. By using this method, the renumeration of the produced current from both sides is prevented.

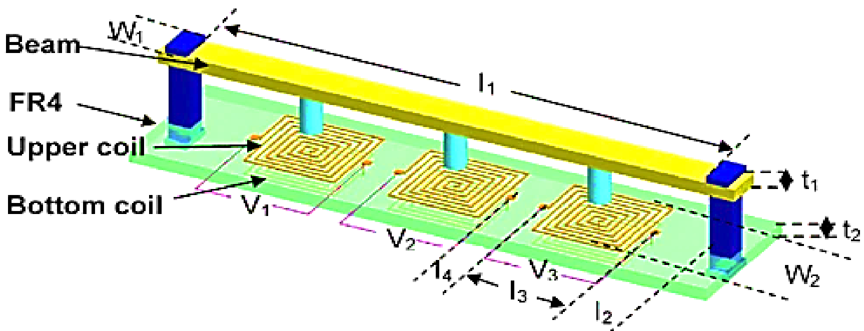

Fig 3. Illustration depicting the FR4 energy harvester

Energy harvesting (EH) using Magneto-strictive Materials (MsM) was the main emphasis of Niazi, Kazemzadeh-Parsi, and Mohammadi [25]. MsM are used to build sensors and actuators due to their ability to convert magnetic energy into kinetic energy. Because of their remarkable adaptability, resonance at high frequencies, and capacity to evade these limitations, these materials outperform other vibrational sources. Wang and Fang [26] detail the use of MsM for energy harvesting to power wireless sensors in structural health monitoring. It is hard to use these products with MEMs. The greatest voltage that piezoelectric and electrostatic harvesters have potential of generating ranges from 2 to 10V, in contrast to the 0.1V that electromagnetic harvesters are capable of producing. A big bonus when trying to gather energy from mechanical vibrations is that they are the most frequent sort of source of energy in various regions.

IV. PHOTOVOLTAIC CELLS

A photovoltaic cell (PVC) is a gadget that transforms the power from light into electricity. The power used is often in the form of light energy, primarily derived from sunshine. In places where a consistent supply of light is assured and the use of batteries and other forms of energy generation is impractical or costly, the use of photovoltaic cells is a practical alternative. Some examples of such settings include marine environments and road signage. When designing solar energy sources, it is important to consider conditions like the availability of daylight, periods of heavy snow and cloud cover, the effects of operating at maximum latitudes, the features of the PVC being used, the intensity of the supply of power and the incoming light requirements.

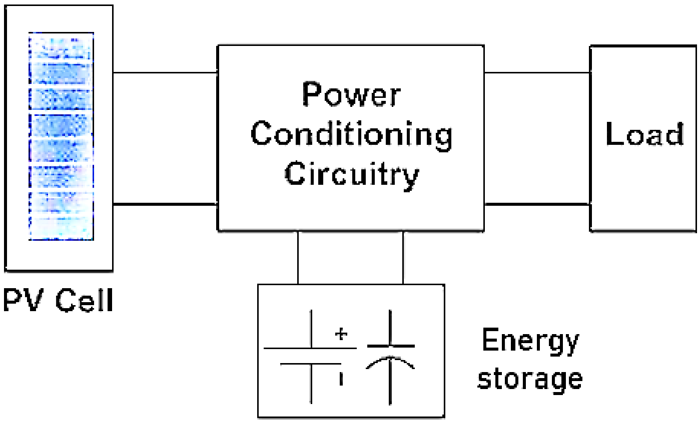

Fig 4. Layout of the photovoltaic cell-based indoor EH system

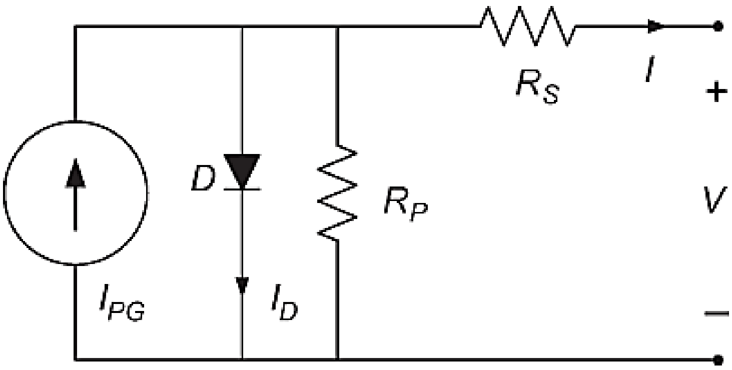

Fig 5. Typical PV cell comparable circuit

A photovoltaic (PV) cell operates as a current source with a restricted voltage range, unlike a battery which functions as a voltage source. The power collected from the cell is maximum at an ideal operating point, characterized by precise current and voltage values. The short circuit current varies due to the fluctuating quantity of incoming solar radiation in outdoor situations. Nevertheless, the value of the open circuit voltage stays almost constant. Because the solar panel behaves as a current source, it is not advisable to directly power the target system from it. This is because the supply voltage would be influenced by the changing the light energy presence and load impedance. Hence, it is essential to use a power storage component, such as ultracapacitor or a battery, to store the power obtained by the board and offer a consistent electric pressure to the method. The light energy emitted by regularly used 34-W fluorescent lamps is very useful for many interior applications. Prior to constructing an indoor PV circuit of harvesting energy, it is important to use an effective energy-scavenging method. Therefore, it is essential to have a very effective method for storing the collected power.

The method must also efficiently transmit the power accumulated to the load (control and sensor circuit). Hence, it is essential to implement an intelligent power management approach that is energy-efficient and promotes the longevity of the device for energy storage. By directly connecting PV frameworks to the terminals of a storage element, the output electric pressure of the PV modules is set to the storage elements` voltage. Hence, the system is unable to consistently function at the precise optimal operating point. Hence, in cases where the operating point of the PV harvesting system fluctuates throughout the day or due to variations in temperature, it becomes imperative to incorporate a dc-dc converter (DCDCC) between the storage elements and the PV modules. This ensures that the system consistently operates at the most efficient point of operation. The DCDCC ensures a consistent and uninterrupted power supply to the intended system.

The electric potential range of the chosen supply voltage and storage component level required by the target system are factors that influence the choice of DCDCC. When the supply voltage is within the storage component`s electric pressure range, a buck-boost converter (BBC) [27] is needed since the storage element's electric pressure must be modified up or down relying on its condition. If the supplied voltage exceeds the voltage range of a battery, a boost-buck converter (BBC) may be used to raise the voltage, or voltage can be reduced using a voltage regulator. Regardless of the scenario, the EH efficacy is greatly enhanced. **Fig 4** depicts the arrangement of a standard EH system using a photovoltaic PVC. As will be further explained in subsequent segments, this is true for a method with a maximum power rating (PR). When dealing with a system that has a PR in the milliwatt range, the DCDCC will not be efficient since it consumes power itself and adds extra expense and complexity.

The primary component of the EH module is the management circuit of power, often equipped with a microprocessor. This circuit extracts power from the PVC oversees the storage of energy, and controls the distribution of power to the load. Hence, while developing the harvesting module, it is essential to include power management choices that are cognizant of the harvesting process. Specifically, the harvesting module need to possess the ability to monitor energy. Typically, depleted battery detector integrated circuits (ICs) may be used for this purpose. However, most of these ICs are specifically intended to control charging at much larger currents than the little amount of milliamperes generated by a small PV cell. As a result, they are not efficient when operating at such low voltage. **Fig 5** illustrates the fundamental equal circuit of a PVC. The equation governing the cells` output current is as follows:

$$I = I_{PG} - I_O\left(e^{\frac{V+R_{SI}}{Vt}} - 1\right) - \frac{V + R_{SI}}{R_P} \tag{3}$$

The variables in question are IPG, which represents the photo-established current, IO, which represents the RP, RS, and dark drenching current, which represent the shunt cell aversion, and series, and Vt, which represents the junction terminal voltage. The P vary throughout various working conditions, including factors like ambient temperature and light intensity. The P are determined by using five established factors of the PVC. This article disregards the usage of RP and instead utilizes four distinct working circumstances, namely short circuit, maximum power point (MPP), open circuit, to ascertain the P.

V. THERMOELECTRIC GENERATORS

Thermoelectric generators (TEG) use the concept of TE to generate the necessary EE. Thermoelectricity refers to the phenomenon of generating electric potential via an atmosphere differential, as well as the reverse process. In this process, the thermal energy is harvested in order to generate EE for the purpose of operating electronic equipment. TE devices are mostly utilized in both space and terrestrial applications.

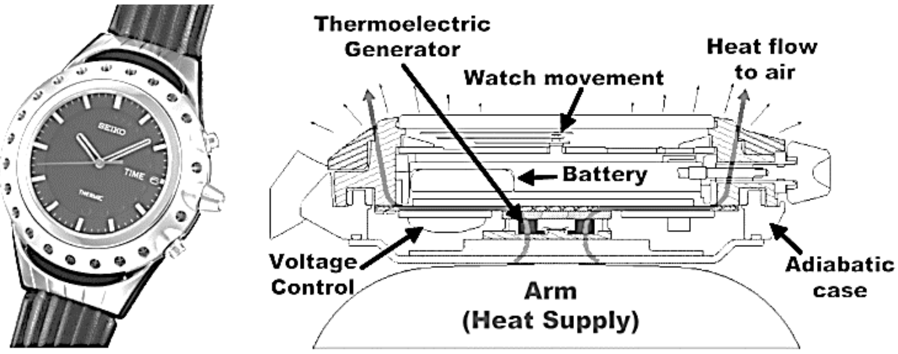

Fig 6. Seiko Thermic, a timepiece that operates by harnessing body heat using a thermoelectric EH. The watch is on the left, while the cross-sectional schematic is on the right

In order to be considered viable, energy harvesting systems must surpass battery solutions in terms of cost, power density, and energy density. The energy harvesting niche mostly caters to applications with extended lifespans, where energy density plays a crucial role and regular maintenance, such as battery replacement, is not feasible. An energy harvester is often used to recharge a battery. In this scenario, the battery provides a substantial amount of power (measured in milliwatts or watts) for a brief duration (such as a few seconds or milliseconds) for tasks like sensing and communication. However, for the remainder of the time, the battery is charged slowly by an energy harvester at a much lower power level (measured in microwatts). Heat, while a kind of energy, is limited in its ability to do productive work by the Carnot factor.

$$\eta_{Carnot} = \frac{\Delta T}{T_h} \tag{4}$$

The temperature differential across the TE is represented by ΔT, which is calculated as Th – Tc. EH is at a significant challenge compared to other techniques of EH that are not restricted by the Carnot limit. Visible light has a significant amount of useable energy, allowing photovoltaic systems to surpass thermoelectric systems in situations when there is sunshine or strong illumination. Photovoltaics may provide an output of 100 milliwatts per square centimeter in direct sunlight and around 100 microwatts per square centimeter in a regularly lighted workplace. This is much more than the power output of the timepiece shown in **Fig 6**.

A thermoelectric generator is a device that transforms heat (Q) into electrical power (P) with a certain level of efficiency, denoted by η.

$$P = \eta Q \tag{5}$$

The thermoelectric converter's maximum efficiency is significantly influenced by the temperature differential ΔTTE throughout the device. This is due to the fact that—as with other heat engines—the TEG efficiency cannot exceed that of a Carnot cycle (Eq. 4).

$$\eta = \Delta T_{TE} \frac{\eta_r}{T_h} \tag{6}$$

ηr represents the decreased efficiency, which is the efficiency ('E') compared to the Carnot efficiency. The efficiency of TE materials is influenced by several factors, making it a complicated phenomenon. However, by assuming that certain parameters such as the thermal conductivity, electrical conductivity, and Seebeck coefficient remain constant regardless of temperature, a simplified equation for ('E') may be derived.

$$\eta = \frac{\Delta T}{T_h} \cdot \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_c}{T_h}} \tag{7}$$

ZT represents the value of merit for thermoelectric devices. **Fig 7** demonstrates that this is a very accurate representation of a common thermoelectric device used in commercial applications, which is composed of bismuth telluride alloys. The ('E') of a practical TE device is typically about 90% of the theoretical value, mostly owing to losses incurred by electrical and thermal contact resistances, electrical interconnects, and other thermal losses.

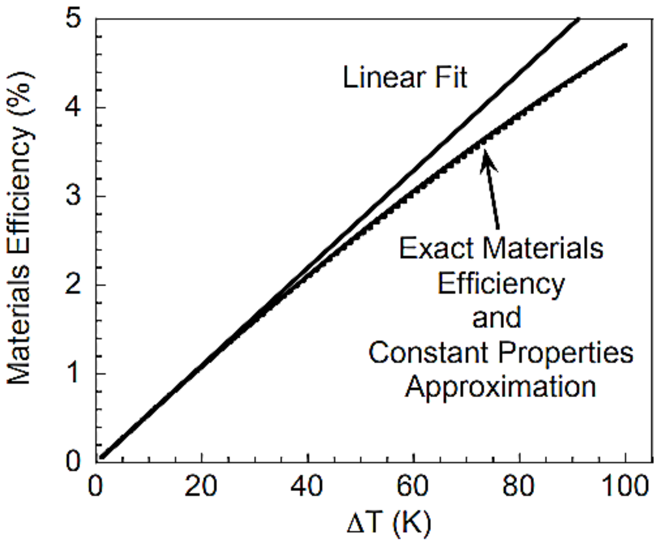

Fig 7. The ('E') of a thermoelectric module based on bismuth telluride is being evaluated, with the cold side temperature set at 300K and supposing no further losses.

$$\eta = \eta_1 \cdot \Delta T$$

$$\eta_1 \approx 0.05\%/K \tag{8}$$

The thermoelectric generator's efficiency has a roughly linear relationship with the temperature difference, as seen in **Fig 7**. This suggests that the ratio ηr/Th, as defined in Equation 4, remains relatively constant. In energy harvesting applications with a small temperature differential ΔT, the efficiency is almost directly proportional to the ΔT across the thermoelectric device. The efficiency of bismuth telluride devices increases by roughly 0.04% for every 1 K increase in ΔT.

VI. CONCLUSION

Energy harvesting has great potential as a technique for gathering and transforming mechanical energy into electrical energy. Diverse methods, including mechanical vibration devices, wind turbines, thermoelectric generators, and solar cells, provide distinct benefits and obstacles. Scientists have conducted a comparative analysis of the projected capacity and challenges linked to distinct ambient energy sources, offering a diverse array of potential methods for collecting and preserving energy from different sources. When evaluating the performance and durability of their goods, portable energy suppliers should take into account the electrical properties, physical features, environmental factors, as well as maintenance and operational aspects. Prudence should be used while using EHs in embedded systems to augment system efficiency and durability. Additional investigation is required to enhance the EH performance structures and develop effective electrical circuits for the storage of electric charges. In general, energy harvesting technologies has the capacity to fundamentally transform the methods by which we produce and use electrical energy.

Data Availability
No data was used to support this study.

Conflicts of Interests
The author(s) declare(s) that they have no conflicts of interest.

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Competing Interests
There are no competing interests.

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