International Journal of Recent Engineering Research and Development (IJRERD)
ISSN: 2455-8761
www.ijrerd.com || Volume 08 – Issue 05 || May 2023 || PP. 01-25

Energy Harvesting System: A Comprehensive Review

Shreepada Bhat[1], Sudheshna Rao[2], Sushmitha Bhat[3], Vishaka Pai K[4], Anil Kumar Bhat[5], Bommegowda K. B[6*]

[1-6]NITTE (Deemed to be University), Dept. of Electronics and Communication Engineering, NMAM Institute of Technology, Nitte-574110, Karnataka, India

Abstract: The literature survey on the design, development, and analysis of energy harvesting systems using piezoelectric sensors covers a wide range of topics, applications and facets of energy harvesting, the optimization of piezoelectric materials. This paper presents the use of system that harvests energy in different fields such as civil infrastructure, aerospace, agriculture, smart cities, and smart buildings. This review article also highlights the challenges and limitations of piezoelectric energy harvesting, such as the low power output of the system, the difficulty in designing efficient energy harvesting circuits, and the impact of environmental factors on the performance of the system.Overall, the literature survey shows that piezoelectric energy harvesting systems have the potential to provide a sustainable and reliable power source for wireless sensor networks and other low-power applications. However, further research is needed to optimize the design and performance of these systems for specific applications and to overcome the challenges associated with their implementation.

Keywords: Energy harvesting, piezoelectric materials, Lead Zirconate Titanate (PZT), electrical energy.

I. INTRODUCTION

In today's modern world, electrical energy and power are vital aspects for our daily activities. Energy harvesting (also known as energy scavenging) is the conversion of ambient energy present in the environment into electrical energy for use in different applications. The process of energy harvesting takes different forms based on the source, amount and type of energy being converted to electrical energy. In its simplest form, the energy harvesting system requires a source of energy such as heat, light, or vibration. The objective of this work is to generate power from the vibrations that occur while stepping on the stairs. This generated power can be stored and used.

In other words, the process of producing electrical energy by utilizing the energy present in the environment, such as that from the sun and wind, is referred to as energy harvesting or renewable energy. However, no mechanical energy is being captured from any of the many vibration machines, moving objects, or other mechanical energy sources. This energy source is wasted since it is spread. Piezoelectric material is employed as an efficient way to make use of this loss, absorbing the lost mechanical energy and transforming it into electrical energy.

The system can be installed in highly populated areas such as stations, malls, colleges and buildings where there are constant movements of people. The system requires no fuel, is pollution free, and most importantly does not depend on external factors like wind, waves and sun.

Piezoelectricity, also called the piezoelectric effect, is the ability of certain materials to generate an Alternating Current (AC) voltage when subjected to mechanical stress or vibration, or to vibrate when subjected to an AC voltage, or both. The vibrations that are created while one steps on the stairs is here used to harvest energy. Piezo transducers are sensors that convert mechanical stress applied on them into electric energy. By concentrating pressure on a particular sensitive point on the transducer it is seen that it generates substantial power.

The type of piezoelectric material selected for a power harvesting application can have a major influence on the harvester's functionality and performance. The different characteristics of crystals have an impact on the efficiency of piezoelectric devices. To date, a number of different piezoelectric materials have been developed. The most common type of piezoelectric used in power harvesting applications is lead zirconate titanate, a piezoelectric ceramic, or piezoceramic, known as Piezoelectric Transducer (PZT). Many people employ Lead Zirconate Titanate (PZT) crystals to produce high piezoelectric effects. PZT is distinguished by its ease of manufacture to any complex shape, high material strength, and extended service life. It is also resistant to dampness and heat temperatures over 100°C.

The crystals work on the basis of piezoelectricity. When crystalline materials are subjected to an external force, pressure, or strain, electrical voltage is produced. Here are some of the natural crystals that can be utilized today to apply the piezoelectric effect. These include pure quartz and amazonite, which can be found on the surface or deep under the soil. Chemical compounds can create a wide range of artificial crystals. These include lead titanate, lead zirconate titanate, and barium titanate, among others.

An array of piezo transducers is placed on the treads of the staircase in various places. The whole array is connected as one compartment which generates the electrical energy from the mechanical energy, the generated electrical energy is then sent to the rectifier which converts the current from alternate to direct current. After the conversion is done, the electrical energy is stepped up. The produced current is then stored in the battery for further usage.

II. LITERATURE SURVEY

Electricity's importance in modern life has grown. Energy is now harvested from external sources such as wind turbines, solar panels, kinetic energy, and so on. It is proposed here to use piezoelectric sensors to generate electricity on roads and pathways. The piezoelectric sensor works by converting mechanical energy (produced by pressure) into electrical energy. Electricity is generated by the pressure and vibration on the piezoelectric sensor, which is placed in roads or pathways. When the vehicle moves, the sensor generates electrical energy by utilising the weight of the vehicle's pressure. After that, it is kept and used for signals, streetlights, and other purposes. [1]

A wireless temperature sensor node driven by a piezoelectric resonant energy harvesting device is described in the paper. (WTSN). The energy gathered by a piezoelectric resonant transducer is utilised to charge a capacitor and power the temperature sensor and its related signal processing circuitry. The basic features of the harvesting system are implemented using discrete components and a power management application-specific integrated circuit. (ASIC). The resulting WTSN transmits recorded temperature data over a distance of 10 m in real time using between 4 and 13 W of power (for transmission intervals ranging from 10 minutes to 10 seconds, respectively), all of which is supplied by the piezoelectric resonant energy harvester. [2]

The Piezoelectric Harvester presented in this manuscript is based on a cutting-edge analogue control system that ensures maximum power transmission. A study of the transferred power between a load and a piezoelectric generator is also presented, utilising data acquired through simulation and experiment. The findings of the system's experimental testing for application in structural health monitoring are also reported. [3]

Over the last ten years, energy collection has become increasingly significant. The lowering power requirements of small electronic components, particularly wireless sensor networks used in structural health monitoring applications, are driving research in this subject. The ultimate goal of this research field is to power such small electronic devices by harnessing vibration energy in their surroundings. Matlab and LabVIEW were used in this study to model, simulate, and assess piezoelectric energy harvesting. If this is practicable, it will eliminate the requirement for an external power source as well as the maintenance necessary for periodic battery replacement. Describes a reliable dynamic model of a piezoelectric energy harvester, a measurement of the link between acceleration and output voltage, as well as the resonant frequency of the energy harvester, and a method for finding model parameters using simple measurements and common laboratory gear. [4]

As the energy consumption of portable electronic devices lowers, the concept of harvesting renewable energy in human environments is gaining traction. Ericka, Dejan, and Francois developed a piezoelectric generator that makes use of mechanical vibrations generated by bicycles. A piezoelectric transducer with an embedded structure that generates power from mechanical vibrations is what an electromechanical converter is. A static converter is a device that transforms electrical energy into a form suitable for the intended portable application. Rates of electrical power generation are documented and debated. The few mW of power produced by the piezoelectric generator have been demonstrated to be sufficient to power LED lamps. They built a piezoelectric generator and mounted it on the handlebars of bicycles. The power harvestable reached 3.5 mW under ideal conditions, such as pure sinusoidal vibrations at 5 ms-2 and 12.5 Hz. This amount of electricity is adequate to charge a battery or run low-power equipment. [5]

Kinetic energies are a sustainable method of producing power that does not deplete natural resources. The fundamental methods for harvesting kinetic energy include magnetostrictive, piezoelectric, electromagnetic, and electrostatic. This research, which focuses on harvesting walking energy, intends to examine the various ways available and choose the most efficient one. Many various harvesters are put on the user's body to capture the kinetic energy of their walking action, and certain pavement slabs are specifically engineered to capture energy. The article finds that pavement harvesters are more dependable than body-located technologies because they are not affected by physiological factors. Furthermore, the piezoelectric transduction generates less current than the electromagnetic transduction, yet it is more common due to its benefits, such as its flexibility and simplicity. [6]

Human life depends on the energy that they use for daily activities. This energy may be used for lighting, powering devices, and a variety of other activities that advance economic development and human progress. Taking into account the world's energy consumption, each resource has a specific amount. The conventional energy sources that are naturally available are being depleted as the years go by. As a result, the world is moving toward renewable energy sources like solar, wind, and tidal power. Despite the fact that conventional sources deliver energy more efficiently than alternative sources, there isn't a significant change in the amount of energy consumed from these sources. One must search for nearby sources of energy if an alternative energy source needs to be found. When the amount of traffic on the road is taken into account, for example, each moving vehicle causes a certain number of vibrations to be transmitted to the pavement below, which, when added together, proves to be a significant amount of vibrations. To capture this energy and make it available to consumers, researchers have developed a technology. A transducer that can convert all of the energy input into an output voltage can be used to change one form of energy into another. The incident pressure may be converted into electricity in this so-called "piezoelectricity" form of output, which can then be used for a variety of tasks. [7]

Energy is harvested from a variety of sources. Piezoelectric, solar, wind, and other related modules provide energy. Wireless sensor networks are networks of small sensors, such as those used to measure the pressure of the environment or the amount of rain.The WSN has been powered by a piezoelectric energy harvester, which has also increased its lifespan. The sensor nodes in this simulation were powered on using a small amount of power. The model has been put through a variety of tests in order to assess the design and offer thorough results. The model can generate the necessary amount of power with various input conditions. [8]

Two desired characteristics in interactive displays are three-dimensional touch sensing and a long battery life. Piezoelectric materials and rectifier circuitry-related techniques are used to generate force touch induced charges, which are then used for energy harvesting and force strength detection, resulting in 3-dimensional touch sensing and an increased battery life for interactive displays. [9]

When solar energy was rare or feeble, solar power producers received a lot of attention from other energy harvesting approaches. To compensate for inadequacies in microscale solar generator systems, piezoelectric components were investigated as a continuous energy gathering method. By prolonging the impact duty cycle, continuous impact power generation has been attempted to enhance efficiency. Impact-based piezoelectric generators have been researched as a technology that allows high-efficiency energy generators to be built. Horizontal wind flow provided rotating motion, and multiple revolving wheel blades caused strong impact to a piezoelectric element with spring action and increasing frequency. The cascaded connection of piezoelectric elements revealed the ability of this energy-harvesting device to produce enough power to support a micro power sensor system. When using wind power as the energy source, an experiment with the proposed continuous energy harvesting approach for microscale solar generators showed promise. [10]

Steven R. Anton and Henry A. Sodano have reviewed the literature in the field of power harvesting and have presented the current state of power harvesting in its drive to create completely self-powered devices. The need of the hour is to use batteries as power sources for the current portable and wireless devices. However these electrochemical batteries have a limited lifespan. Power harvesting is therefore essential for fully self-powered systems. Many of the surroundings we live in are prone to ambient vibrations that go unused. Any vibrating host can be utilised to produce piezoelectric energy. The writers of this article believe that the development of entire systems (power harvesting, storage, and application circuitry coupled) is the key to the future of power harvesting. [11]

The improvement of technology and investment in renewable energy have fueled an increase in interest in the design and optimisation of green energy systems. An innovative system for capturing transportation energy is optimised in this study. Evolutionary algorithms are used to develop the optimisation process in order to maximise efficiency while minimising overall environmental effect. The CI-based design strategy was found to be effective for TPM-LiGoptimisation in tests. Because it recovers energy from urban traffic, which occurs frequently in highway tolls, logistics centers, school pedestrian crossings, roundabouts, and motorways tolls, the proposed new device is a possible technology for future energy efficiency and environmental sustainability. As a result, it makes an important contribution to the Smart City concept. [12]

Piezoelectric materials are commonly used in energy harvesting technology. Lead-based piezoelectric materials, such as Pb [ZrxTi1x] O3 (PZT), contain more than 60% lead. (Pb). Due to its extremely harmful effects on lead components, PZT must be replaced with new lead-free materials that have similar properties to PZT. Lead-free lithium niobate (LiNbO3) piezoelectric materials can be explored as an option for vibrational energy scavenging applications. The study shows that lead-free materials may perform well, and there is still room for improvement by using varied length cantilevers and optimising various design parameters. [13]

Jim Drew's research demonstrates how recent improvements in ultralow power microcontrollers have resulted in devices with unparalleled levels of integration for the amount of power required to operate. These are chip-based systems with aggressive power-saving strategies, such as turning off power to idle functions. In fact, because these devices require so little electricity to operate, many are going wireless because they can be powered by batteries. Unfortunately, batteries must be replaced on a regular basis, which is an expensive and time-consuming maintenance undertaking. Harvesting ambient mechanical, thermal, or electro-magnetic energy in the sensor's nearby environment may be a more effective wireless power solution. [14]

The 5th International Conference on Advanced Computing & Communication Systems (ICACCS) suggested that piezoelectric sensors may be used to produce power on roadways and pathways. The Piezoelectric sensor uses pressure to transform mechanical energy into electrical energy. The piezoelectric sensor, which is installed on roadways or pathways, produces electricity. Sensor uses the pressure of the vehicle's weight to produce electrical energy when the vehicle travels. Then it is saved and used for signals, street lights, etc. In future work will we need additional harvestable power to boost performance and energy. [15]

A review of piezoelectric energy harvesting devices from vibration was published in the International Journal of Precision Engineering and Manufacturing. Piezoelectric energy harvesting principles, several types of piezoelectric harvesting devices, and piezoelectric materials were all investigated. The use of vibrational energy harvesting technology as a permanent power source for wireless sensor networks and portable electronic devices is highlighted. There are various novel ideas in vibration-based piezoelectric energy harvesters. Device concepts are anticipated to mature in tandem with design technologies. However, vibration-based energy harvesters are still uncommon. Vibration-based piezoelectric energy harvesters are limited by three limitations. First of all, the development of piezoelectric materials with a high coupling coefficient is required to increase the performance of piezoelectric energy harvesters. The energy conversion efficiency can be four times better when the coupling coefficient is twice enhanced. A new era of piezoelectric energy harvesters will come with the introduction of new piezoelectric materials with a high coupling coefficient. Secondly, energy harvesters should be able to withstand shocks and vibrations. For real-life use, fatigue and crack of energy gathering devices are essential. Thus, the creation of piezoelectric materials that are flexible and resilient is important. Third, efficient electrical circuitry for energy harvesters is required. Rectification and energy storing circuits should be able to work at such low power levels since the electrical energy generated by vibration is so small. Vibration is everywhere, and vibration-based energy harvesters will become commonplace. [16]

The paper presented at the International Conference on Control, Electronics, Renewable Energy and Communications discusses the modeling, simulation, and experimental analysis of a piezoelectric energy harvester designed for low power devices like wireless sensor network nodes. The main purpose of the work was to harvest the energy accessible in the vibration environments, such as industrial machineries, ducts, vehicles systems, road infrastructures, railway tracks, etc. The fundamentals of maximum power transfer and impedance matching were reviewed, as well as the need of efficiently extracting energy from the vibration source. [17]

While piezoelectricity has been known for decades, a new approach is offered to harness its potential by linking piezoelectric parts with a suitable circuitry to provide maximum power. Unregulated DC Voltage is the output of the Piezoelectric sensor when pressure is applied. A power conditioning source passes the DC voltage into a storage source. (Rechargeable Lithium-Ion battery). Our module distinguishes itself as an efficient and inventive module that uses the abundant potential energy at the pace at which the storage source is charged. Proper research and development in the field of piezoelectricity can prove to be a big step in providing green energy and environmental conservation. [18]

U. K. Singh and R. H. Middleton investigate how advances in low power VLSI design, together with the projected low duty cycle of wireless sensor nodes, create the opportunity to power small wireless computing systems utilising scavenged ambient power in their study. First, a thorough examination of alternative power scavenging technologies and traditional energy sources is presented. In-depth research is being conducted on low-level vibrations that occur in everyday residential and office settings as a potential power source. This study investigates the viability of vibrations as a viable power source for applications where vibrations exist, without claiming that it is the best or most flexible approach to scavenge ambient electricity. The analysis and assessment of various conversion methods yields optimum designs for capacitive Micro Electro Mechanical Systems (MEMS) and piezoelectric converters in particular. According to models, the theoretical power density via piezoelectric conversion is significantly higher. In tests, the accuracy of piezoelectric converter models is checked using a commercially available PZT piezoelectric bimorph. A power density of 70 mW/cm3 has been demonstrated using the PZT bimorph. According to calculations, an upgraded design would be capable of producing 250 mW/cm3 from a vibration source moving at a speed of 2.5 m/s2 at 120 Hz. [19]

The ability to carry a power supply on one's person is a crucial requirement for wireless and portable electronics. These wireless devices are typically powered by batteries. But these batteries could run out at any time, and changing them could be a difficult task. There are several different methods for gathering energy, including piezoelectric, electromagnetic/inductive, capacitive, thermoelectric, etc. When it comes to the piezoelectric effect, stress and strain-induced vibrations result in dual polarity of charge in the piezo material, which in turn produces AC. A rectifier is then used to change this alternating current into direct current. A capacitor or battery is then charged using the rectifier current. [20]

The piezoelectric energy harvester (PEH), which produces electricity from stress or vibrations, has been proposed by the authors Dong Ma, GuohaoLan, Weitao Xu, Mahbub Hassan, and Wen Hu in this article. They made two unique contributions to this effort in order to accomplish high performance gait identification and effective energy harvesting at the same time. A pre-processing approach was first suggested to remove the impact of energy storage on PEH electrical signals. Second, classifiers based on long short-term memory (LSTM) networks were suggested to precisely record temporal information in the generation of electricity during gait. They create a prototype of the suggested gait recognition architecture in the shape of an insole and test its efficiency at both energy collection and gait detection on 20 volunteers. They have gathered information from 20 subjects and created an insole-based SEHS prototype. Based on the findings of the experiments, it has been shown that the SEHS prototype can recognise human stride and harvest up to 127% more energy. 12% more accurate than state-of-the-art technology. A power measurement shows that SEHS actually uses less power to accomplish these performance enhancements. [21]

This study outlines a novel technique for employing a thunder piezoelectric generator to produce power from a rotating vehicle wheel. Using centripetal force, the approach generates an impact on the piezoelectric transducer. The device was designed to be mounted on the rim of a car. A generator with a volume of 2 cm cube generated 4 mW of electrical power at 800 rpm using a 0.12 m diameter test wheel. According to analytical findings, the generator can produce the same quantity of power when mounted on a vehicle wheel with a diameter of 13 inches and a linear speed of 28.4 miles per hour. The approach could provide a more economical and dependable option for powering TPMS. When compared to the device without a ball, the ball bearing impact at 800 rpm increased output power by a ratio of three, according to experimental findings. Additionally, increasing the output power will increase the mass of the ball bearing as well as the tube length. [22]

The manufacturing of a spiral MEMS energy harvester with an extremely low resonance frequency and excellent power density was demonstrated in Journal of Micro electro mechanical Systems. A 1.8 m thick PZT thin film was deposited on a platinized SOI wafer with excellent crystalline quality and high piezoelectric properties. The industry-acceptable micro fabrication method was utilised to build spiral cantilever structures with different numbers of turns. By identifying the vibration mode form and stress distribution in the first and second resonance using a scanning laser vibrometer and FEM modeling, the dynamic behaviour of the energy harvester was examined. The five turns spiral MEMS harvester activated at 0.25g and at its resonance frequency of 68 Hz produced the highest output power of 23.3nW. The findings indicate that a spiral piezoelectric MEMS energy harvester might offer a way to create standalone MEMS devices. [23]

Due to the proliferation of electronic devices, future soldiers will carry a lot of equipment during combat. Therefore, wearable energy harvesting technology is the best way to power soldiers' electronic equipment while using less portable batteries. Small amounts of lost energy are collected by energy harvesting systems as light, movement, heat, or vibrations. The wearable energy harvesting device described in this work utilises piezoelectric transducers inserted into the soles of boots to collect the energy produced by footsteps. Before creating an actual energy harvester, the system is simulated and modelled using MATLAB/Simulink software to determine the best piezoelectric energy harvester design and to determine whether employing such a harvester as an alternative to additional batteries as electrical power sources is feasible. In order to obtain an electrical power source and lessen the weight of the soldier's luggage during operations, it is profitable to employ this energy harvester to be embedded in the soldier's boot, according to the results of the MATLAB/Simulink model. [24]

According to authors Deeptil and Sukesha Sharma of the 2UIET at Panjab University in Chandigarh, energy is obtained from a variety of sources, including piezoelectric and other similar modules. The networks of small sensors, such as those used to measure the pressure of the environment or the amount of rain, are known as wireless sensor networks. The WSN was powered by a piezoelectric energy harvester to extend its lifespan, and the sensor nodes in this simulation were powered on with a little amount of electricity. The model was put through a series of tests to evaluate the design and provide comprehensive results. The model can generate the necessary quantity of power with various input conditions. The suggested approach is based on a piezoelectric energy harvester for WSNs with controllable voltage output. The multiple simulations have been run with diverse input parameters, but the piezoelectric circuit model has consistently received the same quantities of power, indicating its steady and reliable operation. [25]

Piezoelectric energy harvesting, which can create power from low frequency motions or vibrations, has emerged as a potential option for developing battery-free wearable systems. Recent studies have demonstrated that piezoelectric harvesting can be used to carry out energy harvesting and sensing at the same time. However, because the energy harvesting process tampers with the sensing signal, achieving simultaneous energy harvesting and sensing can be difficult. The authors of this study have developed a SEHS architecture that is prototyped as an insole. This SEHS architecture integrates energy harvesting and sensing in a single piece of PEH and also employs a specific filtering technique to reduce signal distortion. [26]

Due to their simplicity of integration and high energy density, piezoelectric vibration-based energy harvesters have received a lot of attention from authors Taeho Oh, Syed K. Islam, Gary To, and Mohamad Mahfouz as powering modules for different types of sensor systems. Numerous topologies based on piezoelectric transducers have been documented in the literature. A low-power CMOS full-bridge rectifier and a piezoelectric transducer coupled in parallel with a switch are offered as a solution for an effective energy harvesting system for potential usage in medical electronics in this study. It is made up of two NMOS and two PMOS devices, each with a full-bridge rectifier coupled to a PMOS device and controlled by a switch control circuit centred around a comparator. The proposed energy harvesting circuit was designed using 0.13-m standard CMOS technology. [27]

In this situation, a gadget for gathering vibration energy from moving objects like cars was created. The piezoelectric substance was chosen to be lead zirconate titanate (PZT). In order to determine the resonance frequency, the vibration sources were first investigated. The cantilever type configuration was used in the development of the piezoelectric energy harvester. The cantilever beam under free vibration was analysed via the Euler-Bernoulli beam theory. The metal beam, tip mass, and PZT plate were among the design characteristics for the prototype that were determined using finite element analysis (FEA). According to FEA modeling, the maximum theoretical voltage was determined to be 5.99V. After the prototype was created and fixed to the motorcycle, the voltage was measured. 3.65V was the average output voltage. The output voltage can also be increased if this device's dimensions are increased. [28]

The authors of this research, Marwa A. Mohammed, Dr. Faiz F. Mustafa, and Dr. Falah I. Mustafa, have come to the conclusion that harnessing kinetic energy is an unconventional approach of producing electricity without using the usual sources. The idea of using the energy generated by human footfall to make power is put forth. Piezoelectric sensors are used to capture this energy. Using piezoelectric components or sensors, the mechanical energy of the step is converted into electrical energy. As a result, this essay discusses how human movement can generate electrical energy and how that energy can be harnessed in the future. [29]

A CMOS wireless energy harvesting IC is created for Internet of Things sensors. It has a single wireless energy harvester that includes a DC-DC boost up converter, ramp oscillator, and dynamic power switch. It comprises of two blocks: a DC-DC boost up converter with an oscillator and a dynamic power switch. (for low power consumption). Using the suggested circuits, a 90% conversion efficiency is achieved. [30]

Battery-powered sensor networks rarely meet the design objectives of lifetime, affordability, sensing reliability, and sensing and transmission coverage at the same time. The present surge in interest in Wireless Sensor Networks (WSNs) has substantially improved the quality of life, owing to their pervasive nature and extensive growth in the domains of internet of things, cyber physical systems, and other new areas. To solve the issue of limited energy associated with WSNs, effective and high-performance energy harvesting systems for WSN contexts are required. A method for collecting energy from a network's ambient surroundings so that a particular sensor node and the entire WSN can run continuously is known as energy harvesting. By utilising recharge opportunities and modifying performance settings based on current and expected energy levels, energy harvesting sensor nodes have the ability to reconcile the competing design objectives of lifetime and performance. This paper covers the architecture, energy sources, and storage advancements, as well as real-world examples of harvesting-based nodes and uses for energy harvesting sensor systems. The ability of a wireless sensor node to gather energy has the potential to meet the contradicting design objectives of lifetime and performance. The study also investigates how recharge options affect sensor node operation and sensor network design. [31]

The idea of gathering renewable energy in urban environments is gaining popularity as portable electronic device energy usage declines. In this regard, we provide a prototype of a piezoelectric generator that harnesses the available stairway mechanical vibration energy. An electromechanical converter called an embezzled piezoelectric transducer creates electricity through mechanical vibrations. Electrical energy is transformed by a static converter into the form needed by the lighting application. [32]

As a result of a literature review conducted in an effort to uncover a new possible sustainable energy source as a response to global warming, an energy-harvesting stairway that produces electricity from the potential energy of people's walking movement was built. This article discusses stairway design planning and concept creation. The stairway's product features are initially developed through brainstorming. The stairway's consumers' needs were then determined by combining the features into a questionnaire distributed to 42 respondents. To build the stairway's product specification based on the needs of the user, an NPD method using TRIZ was used. This research is part of a larger initiative to create a sustainable energy-harvesting stairway. This research proposes an indoor or outdoor semi-public energy-harvesting stairway for widespread public use. It could be used in places like hotels, lecture halls, and footbridges. The final design included an electric and sensoric system, a case to cover sensitive parts with marks and another case to cover the space beneath the stairs, two material options for each stair's foothold, including ceramics and durbar floor plate, steel as the frame's composing material, and an empty space between the bottom surface of each foothold and the top surface of the frame supporting it with a sponge reducer installed for stabilization purposes. [33]

To control the growing power consumption, a variety of Energy Harvesting Systems (EHS) have been created. Utilizing piezoelectric transducers, one of them is energy collection from underutilised renewable natural sources. To increase the energy efficiency and output power of energy harvesting systems, many analytical models using various piezoelectric transducers are reported every day. The goal of this research is to look at the PEH (Piezoelectric Energy Harvesting) devices that have been developed in the last 10 years to generate power for small electronics. Because the Piezo-electric energy harvesting system is based on the direct piezoelectric effect, mechanical stress, pressure, or vibration applied to the transducer leads it to generate electrical energy. The piezoelectric materials, forms, and configurations determine a piezoelectric transducer's suitability for different applications. The many transducer and piezoelectric material configurations have been discussed in this article. This publication examines the performance characteristics of several piezoelectric energy harvesting systems, as well as the possibilities for system enhancement. [34]

Recent advancements in ultralow power device integration, communication electronics, and micro electro mechanical systems (MEMS) technology have pushed the development of wireless sensor networks as a unique technology. (WSNs). Because of their spatial spread, individual sensor nodes in WSNs are often powered by batteries. One of the key challenges limiting WSN performance and lifetime is the restricted capacity of finite power sources and the requirement for human replacement when they run out of power. Furthermore, some of the sensors are implanted, and the hazardous sensing environment makes battery replacement difficult and costly. Energy harvesting is the process of absorbing and converting accessible electrical energy from renewable energy sources. Energy harvesting lays the path for ubiquitous, totally autonomous self-powered technologies that do not require human intervention to replenish. Mechanical vibrations are an appealing alternative to traditional ambient energy sources such as solar energy, heat, and wind due to their availability and compatibility with piezoelectric materials, which may convert mechanical strain energy into electrical energy. This paper briefly discusses piezoelectric microgenerators and nanogenerators as a potential renewable energy source for wireless sensors. [35]

The idea of capturing renewable energy in human surroundings is gaining popularity as portable electronic device energy usage declines. This technical study focuses on a specific piezoelectric material-based enhanced energy harvesting technique. Using piezoelectric materials, it is possible to create mechanisms that convert mechanical energy, which is frequently obtained from ambient vibration, into electrical energy, which may then be stored and used to power other devices. When mechanical tension is applied to a piezoelectric material, it generates an electric charge. Mechanical deformation occurs as a result of the application of an electric field. The electrical density produced by piezo-film can be stored in a rechargeable battery for later use. This paper proposes a theoretical model for an energy harvesting system based on piezoelectric materials. It is obvious that capturing energy with piezoelectric materials provides a more sustainable way of powering lighting systems and other equipment. It is a revolutionary strategy for taking the lead in the adoption of environmentally friendly technologies around the world. Piezoelectric energy harvesting devices are economical since they only need to be installed once and have little maintenance requirements. One of the drawbacks of this technology is that, because of the low foot traffic, it cannot be implemented in sparsely populated areas. Before it can be deployed on a bigger scale, with an effective interface circuit that is affordable in colleges, more study is required. [36]

There are many different types of energy all around us, including thermal, piezoelectric, solar, and vibrational energies. These energies can be transformed into electricity, which can subsequently be used to power wireless sensors. Many applications that call for lengthy lifespans encounter a roadblock due to the energy consumption of wireless sensors. This paper provides a detailed analysis of the power consumption of ZigBee-based wireless pulse sensors, as well as the design of an energy harvesting system to meet their power requirements and adjust the sleep interval to improve their longevity. The solar panel powers the wireless node using a low voltage buck-boost converter. As an emergency power source, a rechargeable battery is used. The surplus energy produced by the solar panel is used to charge the battery. Super capacitors are offered to meet the wireless nodes' peak current needs. The RTD-based temperature sensor was used to design, construct, and test the circuit. Data is gathered at various cyclic sleep intervals, and it is from these data that the best sleep period for the least amount of average current consumption is determined. [37]

S. Saadon and O. Sidek used ANSYS, COVENTOREWARE, and the Lumped Mass model to successfully demonstrate a piezoelectric energy harvester. Although the market for wireless sensor networks is growing quickly, short-life batteries currently in use are a barrier. Applications for WSNs and other technologies will be greatly expanded if there is a clean, practically limitless alternative power source to conventional energy sources. One technique for power harvesting that has seen a sharp rise in use is the use of piezoelectric materials to take advantage of the background vibrations around a system. Piezoelectric micro-generators are appealing for Micro Electro Mechanical Systems (MEMS) applications because of their simplicity. [38]

Nature delivers a variety of energies, including wind, light, mechanical, sound, and other sorts. The paper outlines the use of piezoelectric material to convert mechanical energy into electrical energy. Both in nature and in laboratories, piezoelectric materials with a variety of characteristics are being created. Materials that are piezoelectric can be employed as energy sources, transducers, and sensors. Electrical energy is produced when mechanical force is applied to piezoelectric materials. Using piezoelectric materials, mechanical energy is converted to electrical energy in this application. [39]

Over the last few years, the progress of mobile electronic devices has resulted in a significant decrease in integrated circuit utilization, allowing the use of ambient energy rather than batteries. This study focuses on the conversion of mechanical vibrations in the environment into electrical energy. The performance of two power conditioning circuits coupled to a PZT piezoelectric ceramic-based vibration-powered electrical generator is compared in this study. A unique nonlinear voltage processing-based piezoelectric power conversion approach based on a specific circuit is proposed. According to theoretical projections and practical findings, the new technique may increase gathered power by a factor of up to four when compared to the Standard technique. In particular, the power optimisation problem is examined in the context of random, wideband vibrations. [40]

The internet of things (IoT) manages a vast network of web-enabled smart devices, which are tiny devices that collect, transmit, and elaborate on environmental data using embedded systems including CPUs, sensors, and communication gear. As a result, such devices are made up of scalable, light-weight, power-efficient storage nodes that run on energy and batteries. As previously said, energy harvesting is critical for boosting the efficiency and endurance of IoT devices. Energy harvesting is critical for making the Internet of Things device network more environmentally friendly by getting energy from the neighbouring operational environment. Mechanical, aeroelastic, wind, solar, radiofrequency, and pyroelectric energy harvesters are currently available for application. Energy harvesting significantly improves the effectiveness and endurance of IoT devices. The inaccessibility of the energy source from which energy is meant to be collected, the meagre amount of energy that is actually harvested, the effectiveness of the harvesting mechanism, etc. are some of the constraints of energy harvesting systems. [41]

Despite the fact that piezoelectric energy harvesting offers enormous powering potential in railway applications, the majority of current piezoelectric literature for rail track vibration concentrates on a single piezoelectric element or piezoelectric cantilever, the output power of which is typically in the W range. A piezo stack energy harvester for capturing vibrational energy from train rails is proposed and experimentally validated in this research. It makes use of a magnetic force in conjunction with a frequency up-conversion mechanism. It is made up of two parts: a piezo stack system and an inertial mass system. The inertial mass periodically attaches and detaches the piezo stack transducer with the help of the magnetic force's attractive pull, resulting in the frequency up-conversion process. The attractive magnetic attraction aids in the collision of the two systems, especially when excitation is high. [42]

Wearable and implantable bio-integrated electronics are becoming increasingly popular due to their critical role in improving the quality of life for a wide range of patients and healthy individuals. However, outdated battery technologies with limited lifespan frequently impede their continuous operation, posing a significant barrier to their growth. Thus, capturing biomechanical energies from human motion for self-powered bio-integrated functional devices is particularly desirable. Piezoelectric energy harvesters, which convert biomechanical energy into electric energy, are viable possibilities for achieving this goal. Because they are used on sensitive and highly deformable human body tissues, these devices must be mechanically flexible and stretchable, which is a significant challenge. [43]

The application of energy harvesting devices in the railway industry has been widely examined. The paper's opening paragraphs emphasised the scarcity of electricity for train electrical equipment. It was found that a lot of railway electrical equipment struggles in isolated areas due to a lack of energy sources. Railway energy harvesting has become simpler and more promising daily thanks to the enormous kinetic energy sources present in the rail transit system on the one hand, and the ongoing miniaturisation of electronic devices on the other. A thorough examination of railway energy harvesting also finds a considerable rise in research and energy output in recent years. [44]

Although the EHs covered in this work have benefits, their environmental power sources are sporadic. In their assessment of the literature, the authors of this paper did not find a single harvester technique that can entirely eliminate the usage of batteries. As a result, batteries must still be connected to harvesters in order to continuously and steadily power the sensor node. Section 9 further indicates that the sensor nodes can be powered by the energy captured by these gadgets from the environment and building systems. [45]

A summary of recent studies on high-performance piezoelectric energy harvesting. In order to obtain high power output and a wide frequency spectrum, numerous designs, nonlinear approaches, optimisation strategies, and materials were researched. Recently designed representative energy harvesters were systematically compared in terms of performance. We found that comparing several designs using a single figure of merit is inappropriate due to the complexity of the dynamics, structures, and electromechanical connections of energy-harvesting systems. As a result, we suggest utilising a range of criteria that are pertinent to end users rather than a single, general indicator to assess the performance of various energy harvesters. We think that performance assessments and optimisation work best when done under the constraints of a particular application. [46]

Battery-free autonomous sensor systems and networks will be possible with MEMS piezoelectric energy harvesters with mm3 size if 10 to 100 W of power can be continuously, reliably, and affordably collected from ambient vibration. Compactness, output voltage, output power (density), bandwidth, operating frequency, input vibration amplitude, endurance, and affordability are all significant characteristics of a good piezoelectric MEMS energy harvester. Higher power density and wider resonance bandwidth are currently the two most pressing issues confronting technology. [47]

WSNs have offered enticing solutions for a range of applications, but one of the pressing problems that needs to be solved right once is the energy supply for sensor nodes. In order to attain battery independence for wireless sensor nodes, environmental energy harvesting technologies are expected to replace batteries in the future. In addition, there are certain further advantages of adopting energy harvesting technology, such as noise reduction and crosstalk elimination, and all of these power sources are sustainable, clean, and environmental resources without end. The choice of environmental energy harvesting methods should be appropriate for the actual applications and operating circumstances of WSNs, as this article provides a full overview of the numerous viable options. [48]

Piezoelectric generators were used to collect vibration energy, and its potential as a different energy source for wireless sensor devices was highlighted. WSNs are energy-efficient and rely less on batteries because piezoelectric energy harvesting is an established technology. The power consumption of sensor nodes is lowering due to improvements in ultralow microelectronics and ultra-low power wireless microcontroller units; therefore, gathered ambient energy may be sufficient to completely replace batteries. Additionally, piezoelectric nano generators give up new opportunities for ambient power collecting by enabling foldable power alternatives and miniaturisation of power packages, enabling implantable medical sensing capabilities. An attractive alternative energy source that has the potential to give wireless sensor devices energy autonomy is energy harvesting with piezoelectric generators. [49]

As they pertain to structural health monitoring and damage forecasting, the focus of these workshops will alternate annually between sensing and data collecting, data interrogation, and predictive modelling. The information shared during the first 2.5-day workshop, which took place at Los Alamos National Laboratory from June 28 to 30, 2005, served as the basis for the material that is being summarised here. The focus of this presentation was on energy harvesting for integrated structural health monitoring (SHM) sensing systems, as well as sensing and data collecting more broadly. [50]

Vibration-based piezoelectric energy harvesting techniques are the main points here. The principles of piezoelectric energy harvesting were examined, as well as numerous piezoelectric energy harvesting systems and piezoelectric materials. The application of vibrational energy collecting technology as a consistent power source for wireless sensor networks and portable devices is demonstrated. Many novel ideas for piezoelectric energy harvesters based on vibration have been proposed. Technology for device concepts and design has probably advanced. However, there are presently few practical uses for vibration-based energy harvesters. Vibration-based piezoelectric energy harvesters' potential for widespread technological influence is constrained by three factors. [51]

Piezoelectric generators' operational modes, device designs, material advancements, and applications have all seen in-depth reviews. The bulk of research employed piezoelectric generators with 33 operation modes and unimorph and bimorph cantilever beam designs. In nanostructure, thin-film, and stack forms, inorganic, organic, and hybrid piezoelectric materials have all been investigated. In terms of piezoelectric performance, inorganic materials perform better than organic materials. However, they are unusable due to their brittleness and hazardous lead concentration. Piezoelectric generators must be flexible in order to be integrated into the majority of applications. The flexible piezopolymers that have received the most research are PVDF and its copolymers. Research shows that several efficient methods have been found to enhance the low piezoelectric performance of these polymers. [52]

Energy collection is the most efficient way to overcome energy shortages and establish ecologically friendly power sources. Energy harvesting methods enable the recovery of electrical energy from waste energy sources that are always present, such as heat, fluids, vibrations, and others. Piezoelectric energy harvesting, which converts vibrations and mechanical deformation directly to electrical energy, is a promising technology for powering unattended electronic devices, wireless sensor nodes, micro-electronic devices, and so on. This is because of its superior energy conversion efficiency and straightforward construction. The performance and conversion efficiency of piezoelectrics have been enhanced through the research and development of a variety of technologies, including new materials, micro- and macro-mechanics, and electric circuit design. [53]

Environmental monitoring requires the use of wireless sensor networks. The lifespan of sensor devices used in environmental monitoring has been demonstrated to be prolonged over time by energy management approaches, however the quantity of energy needed by sensors to operate for an extended period of time remains a challenge. As a result, energy harvesters must be employed in addition to present power management systems. In this study, we give a comprehensive overview of current approaches for energy harvesting to extend the lifetime of sensor nodes in WSN systems. [54]

In recent years, there has been an increase in research interest in harnessing rotational motion's energy to power low-power electrical devices. This paper describes a magnetic-coupled buckled beam piezoelectric rotation energy harvester (MBBP-REH) with bistable and frequency up-conversion for harvesting low speed rotational energy over a wideband. Because of a buckled beam attached with piezoelectric patches, the harvester may produce high output power with a low excitation force under dynamical axial load. The electromechanical coupling dynamical model is used to characterise the MBBP-REH. Simulators and tests are used to evaluate harvester performance under various conditions and excitations. The experimental results show that the proposed harvester can produce a constant output power under wideband rotational excitation and is suitable for low-speed rotation. [55]

A growing number of electronic devices are being created for a variety of applications using printed electronics (PE), particularly in the sensor industries. This dissertation focuses on the development of flexible sensors and energy harvesters for use in sensing systems using additive manufacturing technologies. An effective surface enhanced Raman spectroscopy (SERS) substrate was first made by gravure printing a thin layer of silver nano particle ink onto a flexible polyethylene terephthalate (PET) sheet. It was shown that the printed substrate is suitable for use as a SERS substrate for the detection of explosive substances like DNT in the vapour phase. Enhancement factors of three and four were observed for the peaks at 1350.13 cm-1. [56]

Over the past ten years, many studies have focused on energy harvesting from nearby resources. The automobile industry, which is important to vehicle safety, is one sector that pays attention to renewable energy. In order to meet the standards for tyre safety, a cost-effective monitoring system is also necessary to properly track tyre conditions. The primary goal of this study is to show the most modern technologies for harvesting vibrational energy from automobile tyres for integrated self-power sensors and tyre condition monitoring systems. (TCMS). [57]

In the realm of multi-hop wireless network research, wireless sensor networks (WSNs) have been crucial in enabling applications such as environmental and structural monitoring, border security, and human health control. Numerous subjects have been tackled in this field's research, which has improved node hardware, protocol stack design, location and tracking methods, and energy management. [58]

Mobile devices and nodes in wireless sensor networks are often powered by rechargeable or replaceable batteries. This poses substantial difficulties, especially for biomedical sensors implanted in the human body or sensor nodes placed in inaccessible locations where battery replacement is prohibitive. To prevent environmental degradation, the used battery must also be properly disposed of in accordance with national and international regulations. Energy harvesting, which involves scavenging energy from the environment to power mobile systems and sensor nodes, is an intriguing possibility for powering mobile electronics. (such as sunlight, heat gradients, and vibrations). [59]

It was challenging to apply to the actual environment because the majority of PEH is cumbersome to a user owing to its volume. We focused on creating a PEH that can be applied in the actual world in this paper. The PEH construction, which only has one spring and has a compressed height of 2 mm, was made to be attached to shoes without causing irritation to wearers. It is also necessary to increase the PZT's durability in addition to the PEH's volume. A piezoelectric device was covered with conductive tape and a UV coating since PZT is fragile and vulnerable to damaging external shocks. [60]

In-depth research has been done on the impedance-based technique as a cutting-edge technology for structural health monitoring (SHM) of diverse civil constructions. The method's low cost, simplicity in application to a complex structure, resistance to early-stage failures, and real-time damage assessment capabilities are its advantages. However, only a small number of studies have used these advantages to track the wellbeing and structural integrity of wind turbine constructions. In order to ensure the safety and serviceability of wind turbine constructions, impedance-based SHM technology has been used. As a result, the goal of this study is to give the reader a comprehensive overview of this process. The investigation begins with probable structural problems in wind turbine systems. The impedance-based technique's physical foundations, hardware architecture, damage quantification, and environmental compensating methods are then detailed. [61]

The major theme of this research was the deployment of various energy harvesting strategies in implanted and wearable medical devices. Each technique has its own set of features, prospective applications, constraints, design challenges, and technological limitations. When IWM devices can fit the battery size and appropriate safety is ensured by biocompatible encapsulation, the battery is regarded as the most dependable energy source. Batteries, if included in implants, provide serious health dangers in addition to having a short lifespan and restricted usefulness, needing surgical operations for replacement. Therefore, the most promising method for powering the IWM devices is energy harvesting. [62]

Given that water covers the majority of the Earth's surface, waves have the potential to be utilised as a renewable energy source. Unfortunately, wave energy's potential as a renewable energy source has not been completely explored, and wave energy extraction technology is still in its early stages. Despite the large-scale ocean wave converter, small-scale wave harvesters for low frequency and small amplitude are still uncommon. According to research on the wave environment in Lake Erie and other sites, the most common wave state has a height of less than 0.5m and a period of roughly 4 seconds. [63]

This study established a unique PEH that uses noncontact magnetic force and the piezoelectric phenomenon to transform the vibration energy of the suspension system into electrical power. The suggested gadget is made up of two parts: motion conversion and energy conversion. As the motion conversion component, a screw nut mechanism can convert linear vibration between the vehicle body and the wheel into rotating motion. The fundamental component of the PEH is the energy conversion component, which employs the piezoelectric effect and alternative magnetic force excitation to convert rotational motion into electrical energy, which is then stored and used to power electrical equipment in vehicles. [64]

The energy savings from piezoelectric energy harvesting in sporting stadiums are investigated, as well as the possibility that this technology could act as a catalyst for societal sustainable development. The study found that using mechanical stress from spectators can reduce the amount of electricity needed for game-day operations by 2.14%. A different analysis showed that harnessing kinetic energy from spectators was more effective and economical than using professional athletes who were actively competing. The thousands of spectators who fill the stadium may have a lower frequency of footfall than the active athlete, but their kinetic energy per step is significantly larger. This might be the most economical method to begin, given the impression that deploying sustainable technology involves substantial capital expenses. [65]

A piezoelectric energy harvesting integrated circuit (IC) in 40-nm CMOS technology has been introduced. The extremely low input voltage of the PVDF piezoelectric was a concern, thus a voltage multiplier was constructed to augment it. The boosted voltage is increased by adhering to the Digital Logic's specified timing of three operating modes, namely idle, Ton, and Toff. Because of the developed piezoelectric energy harvesting IC, low-power, low-voltage wearable biomedical devices that generally require 1 V as a power supply can now work under steady circumstances. When compared to previous studies, the proposed energy harvesting IC has the highest pump gain and the lowest piezoelectric generated voltage. [66]

Recent years have seen a substantial increase in study into human motion energy harvesting's potential to replace traditional batteries in smart electronics. For low-power electronics like portable equipment and wearables, human motion has a tremendous potential for producing sustainable and clean energy. This review article examines triboelectric, piezoelectric, and electromagnetic energy harvesting technologies capable of efficiently harvesting biomechanical energy from human motion such as walking, stretching, and limb movement, as well as minor displacements. (such as heartbeat, respiration, and muscle movement). Human motion energy harvesters' performance, device compositions, and several contemporary designs and configurations are also explored. The publication also discusses the limits in order to give insight on potential future research topics. [67]

In this study, we investigate the benefits of functionally grading the air inclusions as well as the energy harvesting potential of porous piezoelectric materials under harmonic excitation. A cantilever beam energy harvester with base excitation is used to show how porosity affects power generation. An initial homogenization phase is carried out utilising the analytical Mori-Tanaka approach to minimise computational needs. For different porosity values, this homogenization will estimate the material properties. An Euler-Bernoulli beam model is used to calculate the power produced by a piezoelectric sensor with homogeneous characteristics. A 2D finite element model is made to investigate harvesters where the porosity varies along the length or across the thickness in order to validate the beam model. [68]

A stainless-steel S-shaped cantilever with proof mass, a piezoelectric cantilever, and supporting frames were used to construct the PEHS. By allowing the bottom low-frequency SSC to impinge on the top SPC during vibration, the parallel-cantilever design allows for frequency up-conversion. The piezoelectric cantilever chip for the harvester was built using the PZT thick film MEMS fabrication process. Mechanical lapping, Cu-Sn-Cu eutectic bonding, and electrode layer etching were other essential fabrication techniques. An SPC vibrating at 0.3 g could give a maximum output power of 0.15 W at its resonance frequency of 1012 Hz, according to the testing results, and its normalised power was also 0.15 W. [69]

Vibration can occur in a variety of settings, including human activity, bridges, industrial machinery, vehicle vibration, and home appliances. During the last 10 years, there has been a lot of interest in energy-harvesting systems that convert ambient vibrations into electrical energy for recharging self-powered electronic devices. Researchers and practitioners most commonly use piezoelectric, electrostatic, electromagnetic, and triboelectric transductions approaches for vibration-based energy harvesters. Piezoelectric energy harvesting is widely employed due to the advantages of piezoelectric materials' high energy density, simplicity of production, and ease of application. Ambient vibration frequencies are often unpredictable and broad in many real-world applications, necessitating the design of energy harvesters. [70]

This article gives a general overview of piezoelectric energy harvesting, highlighting the importance of the large amount of mechanical energy that can be captured and transformed into electrical energy as well as the role that piezoelectric materials can play in this process. Both a precise explanation of the piezoelectric phenomena and a list of the several structural arrangements made possible by piezoelectric energy harvesting are intended. A full explanation of the different piezoelectric materials currently accessible is provided in order to provide a comprehensive picture of the current status of piezoelectric materials. The diverse applications of piezoelectric energy harvesting in nearly every possible industry provide a vivid picture of the existing and future fields where mechanical energy can be captured by piezoelectric materials. [71]

As low-power communication and microelectronics technology have evolved, wearable and portable embedded health monitoring devices, micro-sensors, and human body network positioning devices have started to appear. Investigating the piezoelectric effect in the conversion of human motion into electricity is crucial for the development of low power products in order to identify dependable energy sources to replace batteries on these devices. The current technology for piezoelectric energy harvesters (PEHs) is initially categorised in terms of various human motions, such as heel-strike, knee-joint, arm motion, and centre of mass. Following a summary of the technology, the future focus of development and efforts are underlined. [72]

Recent advancements have made implantable medical electronics (IMEs) essential for extending patients' lives. Because extending the life of these gadgets has become a significant problem for their development, current research efforts on this subject are concentrating on their power sources. (e.g., energy generation through body activity). In this regard, piezoelectric energy harvesters (PEHs) are the greatest options for gathering and converting biomechanical energy (such as that generated by muscle relaxation and contraction, body movement, blood circulation, lung motion, and cardiac motion) to power IMEs. This paper examines the most recent breakthroughs in PEHs and related biomedical equipment. [73]

The principle behind piezoelectric energy harvesting is that a material can produce an electric field in response to a mechanical force. This effect is known as the direct piezoelectric effect. Piezoelectric transducers are available in a number of materials and forms, making them suitable for a wide range of applications. To make the best use of piezoelectric devices in applications, a model that tracks their activity in the time and frequency domains is required. [74]

This article's goal is to assess how well piezoelectricity works in highways so that energy produced by moving automobiles can be used. Using piezoelectric technology, the energy is transformed into electrical energy for use as a substitute for fossil fuel in streetlight applications. As fossil resources become scarcer and the world's population rises, it will be more challenging to supply enough energy in the coming century. To mitigate the hazards connected with fossil fuels, it is essential to increase global usage of renewable energy sources. In terms of the environment, the economy, and social demands, piezoelectric roadways strive to offer a long-term answer. [75]

The bulk of vibration energy harvester (VEH) optimisation studies consider a single output quantity, such as frequency bandwidth or maximum power output, although this strategy does not always maximise system efficiency. To achieve optimal design, all of these performance indicators must be considered concurrently for applications where VEHs are viable energy sources. For Vibration Piezoelectric Energy Harvesters (VPEHs), this research suggests a reliable and straightforward multi-objective optimisation framework that simultaneously considers the most crucial performance indices, Maximum power output, efficiency, and frequency bandwidth are three of them. This paper presents a precise definition of efficiency for Multi-Degree of Freedom (MDOF) VPEHs for the first time, expanding on previous definitions. This recipe can be used to optimise the FE and MDOF harvesters. [76]

Piezoelectric energy harvesting has grown into a vast topic of study during the last two decades. Although condensing all of the research that has been published in this subject over the last ten years would be difficult, this post seeks to provide a concise overview of the most noteworthy studies that have been released since we initially published our first review article in 2007. We believe that this article adequately represented the subject of piezoelectric energy harvesting as well as the various research organisations engaged in this intriguing industry. We anticipate that this paper will serve as a helpful guide for present and future scholars interested in piezoelectric energy harvesting when combined with our initial review article. [77]

In this study, two piezoelectric transducer designs were investigated. Fluid motion is linked to structural vibration in both bimorph and flex tensional flow energy harvesters via a cantilever positioned in a converging-diverging flow channel. The flex tensional clamps a non-piezoelectric cantilever and provides the forces converted into electricity, whilst the bimorph is the cantilever itself. In testing, both designs produced power levels of 20 mW or more, with the bimorph type harvester being notably susceptible to fatigue failure caused by stress concentrations at its mounting point. To address this issue, a FEA-based stepped joint mounting solution was described, which resulted in a 26% reduction in stress concentration while maintaining power output. [78]

A thorough analysis of cutting-edge energy-harvesting systems and technologies for self-powered WSNs in machine condition monitoring. It is obvious that ZigBee is currently ubiquitous in self-powered WSNs after analysing the features of previous wireless transmission technologies as well as the power usage of various common modules. However, Wi-Fi and Bluetooth Low Energy are becoming more competitive as a result of their quick development. When used independently or together, internal and external energy sources for mechanical systems can supply adequate electricity for self-powered WSNs in machine condition monitoring. RF energy harvesters are often employed in conjunction with other types of harvesters or for ultra-low power devices, while photovoltaic cells can be used in outdoor equipment. It is believed that thermal energy harvesters created using nano materials and nanostructures are more effective. [79]

Recent years have seen a significant increase in the construction of long-span bridges as a result of the rapid growth of the global transportation infrastructure, particularly in China. However, these bridges are susceptible to damage from dynamic loads (such as wind, earthquake, and vibration from moving vehicles) or environmental variables. (such as corrosion). Structural health monitoring (SHM) is therefore essential to maintaining bridge safety over the course of their service lives. Due to its broad frequency response range, quick reaction, straightforward preparation procedure, simplicity of processing, low cost, and other advantages, the piezoelectric transducer is frequently utilised for bridge SHM. The use of piezoelectric materials for bridge SHM is outlined in this paper, including monitoring grouting density, bolt looseness, steel corrosion, and concrete strength. Each issue is resolved with the app.. [80]

The aerospace industry is looking into structural health monitoring (SHM) as a solution to improve the dependability and safety of aircraft structures while also lowering operating expenses. Built-in sensor networks can learn about an aircraft structure's state, level of damage, and/or service environment. Because of their capacity to work as both actuators and sensors due to the piezoelectric effect, piezoelectric materials are extensively used in the many SHM transducer types. This paper provides an overview of the piezoelectric transducer-based SHM system technology developed over the last 20 years for use in aviation applications. The practical setup and deployment of structural health monitoring systems in aircraft applications is then explained. [81]

We proposed integrating a power management circuit, storage capacitors, and an energy harvester on a single chip in this work. The use of this monolithically integrated circuit based on CMOS-compatible technology can reduce the overall system cost and size. The stress distribution in the cantilever construction of the piezoelectric devices was enhanced by using beams with trapezoidal shapes and rounded corners, resulting in uniform tension throughout the entire surface. The amount of power generated increased by 60% as a result of this design improvement. Electrical simulations run on the CADENCE Virtuoso platform were used to show that the charge pump was operating properly. We showed that a single piezoelectric generator is capable of vibratory power densities greater than 665 W/cm3. [82]

Composite materials, which save weight but also necessitate intricate damage mechanics (current rates of up to 50% of overall structural weight), are increasingly being used in the aerospace sector. As a result, the use of in-process structural health monitoring (SHM) devices for non-destructive testing (NDT) of aviation parts has expanded. While the Committee on Structural Health Monitoring and Management defines SHM as "the process of acquiring and analysing data from on-board sensors to evaluate the health of a structure," the American Society of Non-destructive Testing defines NDT as "the examination of an object with technology that does not affect the object's future usefulness" [3]. When the monitored system is down for maintenance or shutdown, NDT is normally carried out. [83]

Because they offer ongoing and real-time physiological data about the human body, wearable sensors have become more and more popular over time. Wearable sensors have been used to monitor patient health in a range of clinical settings. These technologies require energy sources in order to work properly. This study investigates the many energy sources used to power wearable sensors. These energy sources include, but are not limited to, batteries, solar cells, bio fuel cells, super capacitors, thermoelectric generators, piezoelectric and tribo electric generators, and radio frequency (RF) energy harvesters. We also discuss certain hybrids of the aforementioned methods, such as wireless power transfer. The merits and disadvantages of each technology are considered, as well as the system parts and qualities that allow these devices to function efficiently. [84]

Smart materials have grown in popularity during the last three decades. Piezoelectric materials have proven to be useful in industrial applications such as sensors and actuators, among other technical uses. because of their superior ability to transform mechanical energy into electrical energy and vice versa. In renewable energy applications, piezoelectric materials with high piezoelectric charge and voltage coefficients have been tested. The piezoelectric material, which when subjected to mechanical vibrations or applied stress, generates displaced ions in the material, resulting in a net electric charge due to the unit cell's dipole moment. As a result of this event, the material develops an electric potential. In this review paper, a thorough investigation on piezoelectric energy harvesters (PEHs) is provided. [85]

Smart cities rely heavily on information and communication technology. (ICT). 5 G and the Internet of Things will benefit smart sensing gadgets by allowing them to connect in a quick and secure manner. On the other hand, the demand for self-powered active sensing devices and sustainable power sources will remain a significant issue in this market. Piezoelectric energy harvesters have proven to be a significant source of power for wireless sensor nodes since their discovery, and extensive research has been conducted on their use in a variety of systems, including intelligent transportation, smart healthcare, human-machine interfaces, and security systems. Piezoelectric energy-harvesting devices are promising candidates for the development of intelligent and active self-powered sensors with a wide range of capabilities, as well as for powering wireless sensor nodes sustainably. [86]

Power harvesting is essential to offering entirely self-powered solutions in the burgeoning portable and wireless electronics market. However, piezoelectric materials can be easily incorporated into many systems that are susceptible to dynamic energy, despite the fact that there have been various strategies for harvesting ambient energy sources in this field. Any vibrating host has the ability to harvest energy, even if the design requirements and power harvesting capacities of the majority of piezoelectric energy harvesting systems are complex and require careful attention. In power harvesting systems, piezoelectric materials are utilised to generate electrical energy from ambient vibration and enable the independent operation of wireless devices. In-depth discussions of a handful of these elements can be found in the currently available literature. [87]

Because of the numerous applications, energy harvesting from environmental energy sources has been a thriving research field in recent years. It is appealing for a variety of automation and monitoring systems to power on-site wireless gadgets and sensors with very low electrical power requirements without the constraints of batteries. Energy harvesters are designed to convert ambient energy into useful power, allowing small wireless devices to operate for the remainder of their useful lives. [88]

S No.	Components/ Materials used	Output Voltage	Output Current	Power	Other parameters	Remarks
[1]	Wifi module, PZT	-	-	-	-	The objective is to gather energy from the roads using piezoelectric sensors, crystals, and the Internet of Things. This promotes energy conservation by employing the stored energy rather than the standard power source.
[2]	WTSN, PZT transducer	-	-	output up to 96μW	resonates at 120Hz, peak acceleration of 1.5g	The PZT resonant transducer used to power the wireless temperature sensor node (WTSN) described in this research captures vibrational energy and supplies 10 to 100 W to the circuits. The system has been completely characterized, and the power output of the PZT is sufficient for the typical activities of the WTSN.
[3]	Lazer, PZT, Shaker, Adaptive Voc/2 monitoring solution.	-	-	-	-	Adaptive systems can sustain the maximum power transferred over a wide range of load situations and for a variety of PZTs, in contrast to nonadaptive systems, which must be calibrated for individual PZTs and specific load conditions. Results from models and experiments both show this.
[4]	Power Amplifier, Piezoelectric Energy Harvesting system	-	-	-	-	This article describes a technique for determining model parameters using a few simple measurements and standard laboratory equipment. It explains a trustworthy dynamic model of a piezoelectric energy harvester that measures the correlation between acceleration and the output voltage and resonance frequency of the energy harvester.
[5]	Piezoelectric material (Quartz, BaTiO3, PbTiO3, PZT, PZN-9PT)	-	-	-	-	The initial tests we carried out have demonstrated that the LED bulbs can be powered by the few mW generated by the piezoelectric generator. We created a piezoelectric generator and affixed it to the handlebar of a bicycle. Under ideal conditions, such as pure sinusoidal vibrations at 5 ms-2 and 12.5 Hz, the power harvestable measured reached 3.5 mW for an ideal resistive load of 100 k; this power is sufficient to recharge a battery or operate low-power devices.
[6]	Piezoelectric materials	-	-	-	-	By contrasting technologies for energy harvesting that are positioned on the body and pavement, it is found that the power output is reliant on the physiological characteristics for harvesters that are body-located. Therefore, it is advisable to implement the harvester beneath the pavement slab in order to get a consistent output.
[7]	Piezoelectric transducer	-	-	-	-	A brief summary of the usage of piezoelectricity as a replacement energy source in roads is given in the literature review.
[8]	Piezoelectric energy-harvesting circuit(LTC3588)				maximum peak value at 6.9V for the input voltage lOV and frequency 20Hz.	The suggested model is based on a controlled voltage output piezoelectric energy harvester for WSNs.
[9]	piezoelectric material, PVDF	-	-	-	-	In this study, a technique for simultaneous force touch sensing and energy harvesting is proposed and implemented using the polarisation change of the piezoelectric material and rectifier-related circuit design. The suggested technique simultaneously achieves high force detection sensitivity (0.24 V/N) and energy harvesting effectiveness (0.06 nJ per contact). For interactive screens that must have high force touch sensitivity and long battery lifetimes, the research described in this study is important.
[10]	Piezoelectric Generator	-	-	-	-	A continuous piezoelectric generator that could charge a 12V battery and was designed for use in hybrid energy harvesting systems that relied on solar power generators as their main power source used five cascade piezoelectric elements. In the hypothetical generator, a high frequency impact was applied to the piezoelectric element's surface.
[11]	PZT, PVDF	-	-	-	-	PZT's capacity for power harvesting turned out to be the most effective (6.8% for random vibration excitation). Additionally, studies have been done on the benefits and drawbacks of various piezoelectric designs.
[12]	TPM-LiG	24.3V with force of	-	-	Measured ripple 17.28%	A single power bump erected close to a roundabout with an average of 8000 crosses each day can recover up to 100MW h per year, according to preliminary bench tests

		4N				on a genuine speed bumper case. A 600 square metre-surfaced 85kWp PV plant can generate the same amount of energy. This size of facility could supply thirty homes or fully recharge five electric cars per day, preventing up to 120000 kg of CO2 emissions annually.
[13]	LiNbO3,	-	-	120µW with 6 beams	Bandwidth of 21-71Hz	Broadband, low frequency (60-250 Hz), and low amplitude ambient vibration sources can be used to generate energy via the multi-resonant piezoelectric energy harvester that has been shown.
[14]	T220-A4-503X	3.3V	100mA	100µW	-	Piezoelectric system that generates 100 W at 3.3 V when submerged in air. The piezoelectric element deflects by 0.5 cm at a frequency of 50 Hz.
[15]	PZT	-	-	-	-	The suggested system architecture uses an Arduino, a sensor, a rectifier, a step-up transformer, and a battery. PZT makes comprises the block of the sensor array.
[16]	PZT + 1 mol% Mn and PMN–25PT	-	-	1.7mW	-	envisioned a new SSHI to 1.7m and proposed energy generation using a mechanically activated unimorph piezoelectric membrane transducer in dynamic situations.Increase the amount of power the piezoelectric transducer can produce up to 1.7 mW, which is enough to power a variety of low-power sensors.
[17]	Piezoelectric transducer (PFCB-W24)	3.3V	3mA	60mW at resonant frequency	Piezoelectric transducers can be modelled as charge source with shunt resistor or as voltage source with a series capacitor and resistor.	The typical voltage values for a single piezo are in the range of 80V rms.
[18]	T220-A4-503X	6V	85mA	2250uW	200 such transducers in parallel gives 450mW	The maximum output possible is 3.6 V.
[19]	PZT piezoelectric bimorph	-	-	70 mW/cm^3 from a vibration source with an acceleration amplitude of 2.5 m/s2 at 120 Hz.	-	It is straightforward to demonstrate that an output voltage of just about 100 mV is feasible in a volume of 1 cm3 for the vibration inputs taken into account in this work.
[20]	Piezoelectric transducer	2.7 V	78 mA	210mW	-	Ideas for additional research, To increase the power flow even further, a tiny inductor connected in series with the piezo-capacitance can be employed. This research included several preliminary experiments, the findings of which were highly encouraging but need more analysis.
[21]	MCU, 12-bit ADC, Resistor, Sensor tag, Battery	-	-	-	SEHS prototype can harvest up to 127% more energy and detect human gait with 12% higher accuracy compared to the state-of-the-art.	Power analysis demonstrates that SEHS uses less energy.
[22]	Piezoelectric transducer, rotational generator.	-	-	For the rotation speed 800 rpm, experimental output power between the system with a ball is	-	The output power will increase when the tube length and ball bearing mass are both increased.

				$2.5x10^{-6}$ W and without a ball is $2x10^{-3}$W.		
[23]	-	-	-	23.3 nW	Frequency 68Hz. Acceleration 0.25g.	-
[24]	Matlab/Simulink	5.5 V	-	-	-	can supply 5.5 volts to charge a supercapacitor.
[25]	LTC3588-1	15V, 10V and 8V for 10, 6.9 and 5.6 piezo V.	80, 40 and 20 micro A.	-	Frequency 20Hz.	Future focus: energy management algorithms and powering systems for numerous sensor nodes will be developed.
[26]	Resistor, Capacitor, ADC Channels, rectifier, Aurdino UNO board.	-	-	-	-	Waveforms have been noticed.
[27]	ADC, Transducer, DC-DC Conv, Battery, Capacitor, Diode rectifier.	0.694V	-	11.1μW	System efficiency is 46%.	-
[28]	PZT, MPU 6050 module.	5.99V	-	-	External vibration frequency as 35Hz.	By lengthening the beam and utilising the bimorph configuration in the sensor, voltage output can be enhanced even more.
[29]	Sensors, Rechargeable battery, Load	4V(single tile) Voltage can be increased by using more than one tile.	-	-	-	Without the need of fuel, this can be utilised to drive both AC and DC loads.
[30]	DC-DC Concverter, Power switch, oscillator.	3- 5.5V	<=50 mA	-	Conversion efficiency 90%	-
[31]	Solar cells, converters, super capacitor, regulator	-	-	-	-	The contradictory design goals of lifetime and performance have the potential to be addressed by a wireless sensor node at the same time. In this post, we discussed a range of energy harvesting system issues. We talked about the core concepts of energy harvesting systems, such as their structures, different types of viable energy sources, and technological advancements in storage.The energy harvesting sensor nodes and applications that are now in use were described in detail, with a special emphasis on those that utilise solar energy.
[32]	Moving Stair Tread, Piezo-Electric Material, LED, AAA sized NiMH batteries	-	-	-	-	We designed the set-up for the stairs, and the piezoelectric generator might cost up to Rs. 500. The market price of the NiMH battery is Rs. 800, and the additional circuits are Rs. Therefore, the whole project budget will be around Rs. 1800.
[33]	Transducer	-	-	-	-	This study is a component of a larger body of work to create an energy-harvesting staircase that is sustainable. This study suggests a semi-public energy-harvesting stairway that may be built both indoors and outside and is meant for general public use. Hotels, footbridges, lecture halls, and other locations might have it installed. This feature was added to the TRIZ and eventually incorporated into the stairway's general design and product specs.

[34]	PVDF	-	-	610.0μW	Frequency 3Hz	The conversion of battery-powered small electronic devices to self-powered or self-governed systems has been made possible through the use of energy harvesting technologies. Piezoelectric transducers are commonly employed in energy harvesting applications because they are inexpensive and simple to make.
[35]	MCU, ADC, Sensors, Piezoelectric materials	-	-	-	-	Vibration energy harvesting based on piezoelectric generators was explored, and its potential as a replacement energy source for wireless sensor devices was described.
[36]	PZT-5H	-	-	-	17.5 mm in diameter, e thickness 500 μm	This work proposes a theoretical model for a piezoelectric material-based energy harvesting device. It is obvious that capturing energy with piezoelectric materials offers a more sustainable way to power equipment like lighting. Being a global leader in the adoption of eco-friendly technologies is a fresh idea.
[37]	RTD sensor, Solar panel, Wireless module, Battery, LTC3106	-	-	-	-	Des can theoretically be extended to infinity. In this study, we examine the energy usage of a battery-operated wireless node designed for pulsing sensors.
[38]	Piezoelectric Micro Power Generator (PMPG)	-	-	-	-	In the paper, a piezoelectric energy harvester was successfully proven with transient analyses utilising ANSYS, COVENTOREWARE, and the lumped mass model.
[39]	Wireless sensor, capacitor, nanogenerator	-	-	-	-	The numerous piezoelectric harvesting techniques that are currently being employed are summarised in this publication.
[40]	Piezoelectric Electrical Generators	-	-	-	-	Using piezoelectric materials, theoretical and experimental results in this work show that "Standard" and "SECE" approaches both permit effective energy harvesting from wide-band, random vibrations.
[41]	MFC-M8514-P2 (PZT type)	-	-	0.22mW	-	In addition to analysing several cutting-edge energy harvesters and power management integrated circuits, this article gives an overview of the significance of energy harvesting in improving the effectiveness and sustainability of IoT devices. The essay discusses the potential for energy harvesting and management at the nanoscale in the future as well as the restrictions and potential security issues connected with energy harvesting networks.
[42]	Piezo stack	-	-	-	Capacitance of 5.76μF	In order to collect energy from rail track vibration, the article covers the design and experimental validation of a piezo stack energy harvester that upconverts frequencies using an attractive magnetic force. With an ideal load impedance of 200, the energy harvester demonstrated peak power of 96.69 mW and average power of 2.59 mW. The study also provides a theoretical model and performance analysis of the device.
[43]	Barium titanate NPs-polyurethane, P(VDF-TrFE), PDMS	9.3 V	189 nA	-	Power density of 1.76 μW/cm2	Then, 30 flexible and stretchable piezoelectric devices' current limits and potential future research avenues are reviewed.
[44]	Pressure sensor	-	-	10^{-2} to 10^{-1}W	-	The structure of the current study is set up to give readers an overview of the key ideas that must be taken into account while developing railway energy harvesters.
[45]	RF signals	-	-	17.76μW	-	The study's findings show that harvesters at the buildings can provide enough energy to partially and even fully meet the power needs of several operation modes, including those for sensor nodes.
[46]	PZT	-	-	-	Frequency of 68Hz	Four applications have been identified as being highly promising: shoes, pacemakers, tyre pressure monitoring devices and monitoring of bridges and buildings. For each application, new, high-performance energy harvesters are examined.
[47]	PZT	-	-	-	Frequency of 870Hz	Recent developments in materials and structural design have moved us closer to the possibility of battery-free autonomous sensor systems and networks using MEMS piezoelectric energy harvesters, but there are still difficulties in achieving higher power densities and wider resonance bandwidth.
[48]	Vibrations	-	-	-	Power density of	The use of environmental energy harvesting technologies

	(piezoelectric-shoe inserts)				330μW/cm3	has a number of benefits, including reduced noise, elimination of crosstalk, and the use of renewable and clean energy sources. However, there are still issues to be resolved, including low output power and conversion efficiency, unstable environmental energy, the inability to function when there is insufficient ambient energy, and a higher cost than batteries. The goal of future work should be to enhance these features.
[49]	AMTEGA 128L	-	-	-	Run frequency of 4MHz	The capacity of piezoelectric microgenerators and nanogenerators to transform mechanical strain energy into electrical energy makes them the primary focus of the article as a sustainable energy source for WSNs.
[50]	Vibrations	-	-	-	Power Density of 200μW/cm3	The workshop on energy harvesting for integrated structural health monitoring systems is summarised in this report. It discusses different sensing techniques, power needs, energy harvesting and storage, and upcoming research areas.
[51]	PZT-5H	-	-	-	Density of 7500kg/m3	The use of piezoelectric materials to capture mechanical vibrational energy for durable portable electronic devices is discussed in this paper. There are sections on various vibration devices, piezoelectric materials, and mathematical vibration energy harvesting modelling.
[52]	Bulk PZT thick films	53.1 V	-	0.98 mW	frequency 77.2 Hz, power density of 32mW/cm3	This article provides a thorough analysis of piezoelectric energy harvesting technology, covering its components, uses, and potential upgrades.
[53]	PZT nanowire composite	4 V	88nA	2.4μW/cm3	-	This paper examines recent developments in the field of piezoelectric energy harvesting, which uses PbZrxTi1'xO3 (PZT) materials and advanced technologies, including materials, fabrication, distinctive designs, and properties, to produce sustainable power sources for unattended electronic devices.
[54]	Energy Harvester WISP	1.8 V	-	0.3mW	-	This is a brief description of an essay that covers the advantages, present technology and protocols, difficulties, and future directions of using energy harvesting in wireless sensor networks for environmental monitoring.
[55]	Magnetic-coupled buckled beam piezoelectric rotational energy harvester	-	-	-	-	Using a tensor decomposition method, the research suggests a framework for modelling and analysing social media networks that enables the discovery of latent characteristics and patterns inside the network.
[56]	PZT and PVDF	-	-	-	-	In order to identify explosive substances, the article analyses the limitations of physical probing techniques and recommends the use of chemical sensors, such as Raman spectroscopy, which is a quick, sensitive, and low-temperature method of detection with a high degree of specificity.
[57]	Tire condition monitoring system	-	-	-	-	The study covers the state-of-the-art in vibrational energy harvesting for tyre condition monitoring systems, identifies the shortcomings of the available piezoelectric harvesters, and suggests the need for robust energy harvesting structures that can endure challenging environmental conditions in practical applications. The report recommends doing a theoretical and simulation inquiry into the possibility of using piezoelectric devices outside of tyres to generate energy.
[58]	Photovoltaic	-	-	-	Power density-Outdoors (direct sun): 15 mW/cm2	In order to slow down the depletion of battery power, the study examines the use of wireless sensor networks in a variety of applications.
[59]	GaAs PV cells	-	-	-	Generated Power-70.8 nW at 200 lux	The powering of mobile devices and sensor networks by energy harvesting is a potential approach, but efficient power management and storage solutions are necessary for successful operation.
[60]	Piezoelectric Ceramic, Steel Substrate, Spring	-	-	-	Density (g/cm3)7.6, Density (g/cm3)8.0, Spring constant (N/mm) 0.941	This study shows how a shoe-mounted piezoelectric energy harvester (PEH) may power a wireless transmitter for worker monitoring in remote or dangerous environments. The PEH generates 52 W of energy at 280 k with periodic compression.
[61]	PZT	-	-	-	-	The article examines potential structural failures in wind turbine systems, describes the impedance-based technique's physical foundations and hardware architecture, and examines the present state and potential

						future directions of its use for monitoring wind turbine structural components.
[62]	Piezoelectric energy source human walking	-	-	Output power 30.55 µW	-	In order to enable early disease detection and preventive interventions by continuous monitoring of clinically significant physiological indicators, the study emphasises the necessity for a sustainable and health-compatible energy source.
[63]	PZT	-	-	-	Piezoelectric voltage constants (10-3 Vm/N) g33: 31.7 g31: -12.8	Since water covers the majority of the Earth's surface, this research emphasises the potential of waves as a green energy source. However, the potential of wave energy as a renewable energy source has not been extensively investigated, and wave energy extraction technology is still in its infancy. Although there are large-scale ocean wave converters, the research points out that small-scale wave harvesters that can handle low frequency and tiny amplitude waves are still hard to come by. The most frequent wave state has a height of less than 0.5m and a duration of about 4 seconds, according to research on the wave environment in Lake Erie and other places.
[64]	Experiment and simulation of open-circuit voltage	-	-	-	Peak voltage (V)- Experimental 5.07 and Simulation 6.76. Speed (mm/s) 30	It transforms the rotating motion into electrical energy by using a piezoelectric substance. A permanent magnet and an electromagnetic coil create a magnetic field that the PEH is put in, enabling noncontact energy transfer.
[65]	Power Consumption of Cellular Phone	-	-	-	Lithium Ion Battery 3.6V	In addition to producing renewable energy, the application of piezoelectric technology in the sports sector has the potential to increase fan knowledge of environmental issues and encourage pro-environmental behaviour. Despite the fact that there aren't many piezoelectric devices on the market right now, this study shows the technology's untapped potential and lays the groundwork for its potential future advancement and incorporation into popular sports.
[66]	PVDF	0.12 V	-	4.2 mW	40 nm process	The book discusses an energy harvesting IC for piezoelectric materials that is constructed using TSMC's 40-nm CMOS process and has a compact chip area and high pump gain as a replacement for the battery of a wearable biomedical device.
[67]	PEEH energy harvesting technology with Shoe as the attached position	-	-	28mW	Open circuit voltage 20V	The article explores different energy harvesting technologies that have the potential to replace traditional batteries in smart electronics by efficiently recovering biomechanical energy from human motion and minor internal displacements.
[68]	PZT-5A	-	-	-	-	The research analyses the advantages of functionally grading air inclusions using a cantilever beam energy harvester with base excitation and discusses the assessment of porous piezoelectric materials' capacity for energy harvesting.
[69]	Straight piezoelectric cantilever	-	-	-	Total length of the chip 22 mm	This study suggests a frequency up-conversion mechanism-based impact-based micro piezoelectric energy harvesting system (PEHS).
[70]	PZT-5 H	-	-	-	-	gives a significant viewpoint on creating piezoelectric harvesters to increase the effectiveness of energy gathering
[71]	PVDF-PTrFE	9.8 V	-	-	Output power density of 13.5 µW/cm2	An overview of piezoelectric energy harvesting is provided in this study, beginning with the significance of the large amount of mechanical energy that can be converted into electrical energy and how piezoelectric materials can contribute to this success.
[72]	PEH	-	-	-	-	The current technology for piezoelectric energy harvesters (PEHs) is first categorized, including PEHs by centre of mass, heel striking, knee joint, and arm motion. Following a brief summary of the technology, further emphasis is placed on the route that future research and development will take.
[73]	Implantable Medical Electronics (IMEs)	-	-	-	-	This article concentrated on the creation and uses of PENGs, which have the capacity to...
[74]	PMN-PT single crystal	-	-	-	Peak Power 3.7mW, Volume 25 × 5 × 1 mm,	This paper aims to examine current energy harvesting techniques with a special emphasis on piezoelectric energy harvesting.

					Frequency 102Hz	
[75]	PZT	-	-	-	Heat temperature over 100°C	This article examines how effectively piezoelectricity in highways can use the energy generated by driving vehicles. intricate geometries.
[76]	Vibration Piezoelectric Energy Harvesters (VPEHs)	-	-	-	-	The sub-structural material (bronze), the piezoelectric laminate patch (PZT-5H), and the electric circuit, which is simulated by an ideal resistor, are the three primary parts of the VPEH. The construction is base stimulated in the horizontal direction and limited at the bottom extremity.
[77]	PVDF	-	-	30 nW	-	This research updates the authors' earlier review paper by highlighting significant advancements over the previous ten years in the field of piezoelectric energy harvesting.
[78]	CTS-3195HD	-	-	-	Density 7800 kg/m3	In this work, two different piezoelectric transducer designs were examined. The cantilever is positioned in a converging-diverging flow channel, and both the bimorph- and flextensional-based flow energy harvesters rely on fluid motion connected to structural vibration.
[79]	ANT	-	-	-	Transmission Rate 60 k bps	The difficulties and potential directions for future research in energy harvesting systems for WSNs used for machine condition monitoring are discussed.
[80]	PZT	-	-	-		Future research directions and the current issues with bridge monitoring were reviewed.
[81]	Structural health monitoring (SHM)	-	-	-	-	The design of structures will be greatly influenced by structural health monitoring, which will enhance safety and dependability and lower aircraft maintenance and operating expenses.
[82]	Piezoelectric MEMS	-	-	-	-	Low-power sensors and wireless networks are developing quickly thanks to the growing interest in the Internet of Things (IoT). However, there are still a number of obstacles that make the IoT's global deployment challenging.
[83]	Piezoelectric bimorph vibration EH device	-	-	-	-	Structural health monitoring (SHM) of crucial composite structures is becoming more and more expected and necessary in order to improve the effectiveness of maintenance and fuel utilisation in aircraft.
[84]	Batteries; Alkaline	-	-	-	Working Voltage 1.3~1.0 V	Structural health monitoring (SHM) of crucial composite structures is becoming more and more anticipated and necessary with the goal of improving maintenance effectiveness and fuel efficiency in aircraft.
[85]	PMN-PT single crystal	-	-	-	Peak Power 3.7 mW	Todaro et al. conducted a thorough analysis of thin piezoelectric films based on MEMS energy harvesters.
[86]	PZT and AIN device	-	-	-	Resonant Frequency 300, 700 and 1000 Hz	This study discusses and reviews the different uses of piezoelectric energy harvesters for Internet of Things sensors and devices in smart cities.
[87]	Monolithic PZT, quick pack, MFC	-	-	-	-	The most effective device was PZT (6.8% for random vibration excitation).
[88]	Piezoelectric energy harvester	-	-	-	-	The creation of a new wideband piezoelectric energy harvesting system is presented in this study along with an analytical strategy.

III. CONCLUSION

The literature survey on the topic of "design, development, and analysis of energy harvesting systems" highlights the importance of piezoelectric materials as a key component for harvesting energy from mechanical vibrations. The survey shows that there has been significant research in this area over the past several years, with a focus on optimizing the performance of energy harvesting systems by selecting appropriate materials, designing efficient energy harvesting circuits, and analysing the performance of these systems under various conditions.

The methodology for designing and developing energy harvesting systems varies depending on the specific application and desired performance specifications, but typically includes the identification of an energy source, selection of an appropriate transducer, design of an energy harvesting circuit, optimization of materials, integration of the system, and testing and analysis. It is evident that there is ongoing research in the development of new techniques and technologies for energy harvesting systems, such as the use of hybrid energy harvesting systems and multi-source energy harvesting systems.

The study also emphasises how crucial it is to choose the right materials for energy harvesting systems, with a particular emphasis on enhancing the mechanical, electrical, and piezoelectric capabilities of the materials used in the transducer and energy harvesting circuit. The suitability of many materials for energy harvesting applications, including polyvinylidene fluoride (PVDF), lead zirconate titanate (PZT), and aluminium nitride (AlN), has been studied. To ensure the greatest amount of power generation and storage, as well as dependability and longevity, it is imperative that the materials used in the energy harvesting system be optimised.

Overall, the literature survey highlights ongoing efforts to increase the effectiveness and dependability of energy harvesting systems for a variety of applications, including wireless sensor networks, Internet of Things (IoT) gadgets, and structural health monitoring, and offers insightful information about the current state of research on these systems. Energy harvesting systems have the potential to reduce reliance on batteries and increase the lifespan of wireless devices, making this a crucial field for study and development. According to the poll, more research is required to create fresh and creative methods for energy collecting.

At present efficient storage of energy is a tedious task. Future works and researches should focus on improving the energy storage system.

REFERENCES

[1] R. Kavin, V. K. Gowri, M. Naveenaa, T. Navishree and J. Nithish, "Wireless Power Transmission in Electric Vehicle Using Solar Energy", 3rd International Conference on Signal Processing and Communication (ICPSC), pp. 78-80, 2021.

[2] Jacob P. Bock, Jason R. Robinson, Rajesh Sharma, Jing Zhang, K. Mazumder, "An Efficient Power Management Approach for Self-Cleaning Solar Panels with Integrated Electrodynamic Screens", Proc. ESA Annual Meeting on Electrostatics, 2008.

[3] HemzaSaidi, Abdelhamid Mudoun, "Improvement of Power Management System in Electro-Solar Vehicle", Advances in Environmental Sciences, Development and Chemistry, 2014.

[4] Ahmed A. Telba, Wahied Gharieb, "Modeling of Piezoelectric Energy Harvesting for Low Power Generation", Proceedings of the World Congress on Engineering and Computer Science, 2016.

[5] Ericka Minazara, DejanVasic, François Costa, "Piezoelectric Generator Harvesting Bike Vibrations Energy to Supply Portable Devices", 2013.

[6] Elham Maghsoudi Nia, Noor Amila Wan Abdullah Zawawi, Balbir Singh Mahinder Singh, "A review of walking energy harvesting using piezoelectric materials", International Conference on Architecture and Civil Engineering,2017.

[7] Niharika Wakchaure, Shashank Waghmare, Ruchira Rakshe, Minaxi Rai Sharma, Ashish Joshi, " Review Paper On Harvesting Energy Using Piezoelectric Transducers", International Journal of Engineering Applied Sciences and Technology, 2021 Vol. 6, Issue 5, ISSN No. 2455-2143, Pages 262-267, 2021.

[8] Deeptil and Sukesha Sharma, "Energy Harvesting using Piezoelectric for Wireless Sensor Networks", 1st IEEE International Conference on Power Electronics. Intelligent Control and Energy Systems, 2016.

[9] Shuo Gao, Chun-yen Huang and Linxiao Wu, "Piezoelectric Material Based Technique for Concurrent Force Sensing and Energy Harvesting for Interactive Displays.", 2017.

[10] Kyoo Nam Choi and Hee Hyuk Rho, "Continuous Energy Harvesting Method Using Piezoelectric Element.", 2015.

[11] Steven R Anton and Henry A Sodano, "A review of power harvesting using piezoelectric materials (2003–2006)", Smart Materials and Structures Journal, 2007.

[12] A. Pirisi, F. Grimaccia and M. Mussetta, "An innovative device for Energy Harvesting in smart cities", IEEE International Energy Conference and Exhibition (ENERGYCON), pp. 39-44, 2012.

[13] Neetu Kumari and Micky Rakotondrabe, "Design and Development of a Lead- Freepiezoelectric Energy Harvester for Wideband, Low Frequency, and Low Amplitude Vibrations", Micromachines journal, 2021.

[14] Jim Drew, "Energy Harvester Produces Power from Local Environment, Eliminating Batteries in Wireless Sensors", Design Note 483, 2015.

[15] Suresh Kumar S, Ravichandran Kaviyaraj, Narayanan L. and Saleekha, "Energy Harvesting by Piezoelectric Sensor Array in Road Using Internet of Things", 5th International Conference on Advanced Computing & Communication Systems (ICACCS), 2019.

[16] Kim Heung Soo, Kim Joo-Hyong and Kim Jaehwan, "A review of piezoelectric energy harvesting based on vibration", International Journal of Precision Engineering and Manufacturing, 2011.

[17] S. Kiran, D. Selvakumar, J. Mervin and H. Pasupuleti, "Modeling, simulation and analysis of piezoelectric energy harvester for wireless sensors", International Conference on Control, Electronics, Renewable Energy and Communications (ICCEREC), 2015.

[18] A. Patil, M. Jadhav, S. Joshi, E. Britto and A. Vasaikar, "Energy harvesting using piezoelectricity," International Conference on Energy Systems and Applications, 2015.
[19] Shad Roundy, Paul K. Wright, Jan Rabaey, "A study of low level vibrations as a power source for wireless sensor nodes" University of California, 2002.
[20] U K Singh and R H Middleton, "Piezoelectric Power Scavenging of Mechanical Vibration Energy", 2007.
[21] Dong Ma, Guohao Lan, Weitao Xu, Mahbub Hassan, Wen Hu, "Simultaneous Energy Harvesting and Gait Recognition using Piezoelectric Energy Harvester", IEEE Transactions on Mobile Computing, 2020.
[22] G. Manla, N.M. White, and J. Tudor, "Harvesting Energy From Vehicle Wheels", Transducers, 2009.
[23] H. -C. Song et al., "Ultra-Low Resonant Piezoelectric MEMS Energy Harvester with High Power Density", Journal of Microelectromechanical Systems, 2017.
[24] Akeel Othman, "Modeling of Piezoelectric Energy Harvesting System Embedded in Soldier's boot Using Matlab/Simulink", 7th International Conference on Military Technologies (ICMT), 2017.
[25] Deepti and Sukesha Sharma, "Energy Harvesting using Piezoelectric for Wireless Sensor Networks", 1st IEEE International Conference on Power Electronics. Intelligent Control and Energy Systems (ICPEICES), 2016.
[26] Dong Ma, GuoahoLan, Weitao Xu, Mahbub Hassan, Wen Hu, "Simultaneous Energy Harvesting and Sensing using Piezoelectric Energy Harvester", IEEE/ACM Third International Conference on Internet-of-Things Design and Implementation, 2018.
[27] Taeho Oh, Syed K. Islam, Gary To, Mohamad Mahfouz, "Powering Wearable Sensors With a Low-Power CMOS Piezoelectric Energy Harvesting Circuit", IEEE Instrumentation and Measurement Society prior to the acceptance and publication, 2017.
[28] W. M. Jayarathne, W. A. T. Nimansala, S. U. Adikary, "Development of a Vibration Energy Harvesting Device Using Piezoelectric Sensors", 8th Moratuwa Engineering Research Conference (MERCon), 2018.
[29] J. -s. Kim, "Wireless Energy Harvesting IC for Low Power IoT sensor," 2020 International Conference on Information and Communication Technology Convergence (ICTC), pp. 1757-1759, 2020.
[30] M. A. Mohammed, F. F. Mustafa and F. I. Mustafa, "Feasibility Study for Using Harvesting Kinetic Energy Footstep in Interior Space," 2020 11th International Renewable Energy Congress (IREC), , pp. 1-4, 2020.
[31] S. Sudevalayam and P. Kulkarni, "Energy Harvesting Sensor Nodes: Survey and Implications", IEEE Communications Surveys & Tutorials, 2011.
[32] V. Prasannabalaji, R. Rakesh, S. Sairam and S. Mahesh, "Staircase Power Generation Using Piezo-Electric Transducers", Advance in Electronic and Electric Engineering, ISSN, 2013.
[33] Debrina Puspitarinia, Amalia Suziantia , Harun Al Rasyida, "Designing A Sustainable Energy-harvesting Stairway: determining product specifications using TRIZ method", Urban Planning and Architecture Design for Sustainable Development, UPADSD 14- 16, 2015.
[34] NilimamayeeSamal and O. JebaShiney, "Energy Harvesting using Piezoelectric Transducers: A Review", Journal of Scientific Research, Institute of Science, Banaras Hindu University, India, 2021.
[35] Action Nechibvute, Albert Chawanda and Pearson Luhanga, "Piezoelectric Energy Harvesting Devices: An Alternative Energy Source for Wireless Sensors", Smart Materials Research, 2012.
[36] ParulDhingra, Jhilam Biswas, Anjushree Prasad and Sukanya Sagarika Meher, "Energy Harvesting using Piezoelectric Materials", International Journal of Computer Applications, 2013.
[37] Praveen Kesavan, Manasa Pudipeddi and Mutukuri Sivaramakrishna, "Design, Development and Analysis of Energy Harvesting System for Wireless Pulsating Sensors", 13th International IEEE India Conference (INDICON), 2016.
[38] S. Saadon and O. Sidek, "Vibration-Based MEMS Piezoelectric Energy Harvester (VMPEH) Modeling and Analysis for Green Energy Source", Developments in E- systems Engineering, 2011.
[39] Meenakshi Sharma, Shashikant, Vikas Pandey, Ramendra Singh, Akhilesh Sharma, Arun Kumar Singh, "Different types of energy harvesting using piezoelectric materials", 2nd International Conference on "Advancement in Electronics & Communication Engineering (AECE 2022) July 14-15, 2022.
[40] ElieLefeuvre & Adrien Badel& Claude Richard & Daniel Guyomar, "Energy harvesting using piezoelectric materials: Case of random vibrations", 2007.
[41] Hassan Elahi, Khushboo Munir, Marco Eugeni, Sofiane Atek and Paolo Gaudenzi "Energy Harvesting towards Self-Powered IoT Devices", : 22 October 2020

[42] Guansong Shan, Yang Kuang, Meiling Zhu "Piezoelectric energy harvesting from rail track vibration using frequency up-conversion mechanism", IFAC, 2022.
[43] Hongelei Zhou, Yue Zhang, Ye Qiu, Huaping Wu, Weiyang, Qin, Yabin Liao, Qingmin Yu, Huanyu Cheng, "Stretchable piezoelectric energy harvesters and self-powered sensors for wearable and implantable devices", 2015.
[44] Hosseinkhani, D. Younesian, P. Eghbali, A. Moayedizadeh, A. Fassih, "Sound and vibration energy harvesting for railway applications: A review on linear and nonlinear techniques", 2021
[45] Ruben Hidalgo-Leon, Javier Urquizo, Christian E. Silva, Jorge Silva-Leon, Jinsong Wu, Pritpal Singh, Guillermo Soriano, "Powering nodes of wireless sensor networks with energy harvesters for intelligent buildings: A review", 2022.
[46] Zhengbao Yang, Shengxi Zhou, Jean Zu, and Daniel Inman, "High-Performance Piezoelectric Energy Harvesters and Their Applications", 2018.
[47] ShashankPriya, Hyun-Cheol Song, Yuan Zhou, Ronnie Varghese, Anuj Chopra, Sang-Gook Kim, IsakuKanno, Liao Wu, Dong Sam Ha, JunghoRyu and Ronald G. Polcawich, "A Review on Piezoelectric Energy Harvesting: Materials, Methods, and Circuits" , 2017.
[48] Gongbo Zhou, Linghua Huang, Wei Li, and Zhencai Zhu, "Harvesting Ambient Environmental Energy for Wireless Sensor Networks: A Survey", 2014.
[49] Action Nechibvute, Albert Chawanda, and Pearson Luhanga, "Piezoelectric Energy Harvesting Devices: An Alternative Energy Source for Wireless Sensors", 2012.
[50] G. Park, C. R. Farrar, M. D. Todd, W. Hodgkiss, T. Rosing, "Energy Harvesting for Structural Health Monitoring Sensor Networks", 2007.
[51] Heung Soo Kim, Joo-Hyong Kim and Jaehwan Kim, "A Review of Piezoelectric Energy Harvesting Based on Vibration", 2011.
[52] NurettinSezer, MuammerKoç, "A comprehensive review on the state-of-the-art of piezoelectric energy harvesting", 2020.
[53] Min-Gyu Kang 1,2, Woo-Suk Jung 3 , Chong-Yun Kang 1,4 and Seok-Jin Yoon, "Recent Progress on PZT Based Piezoelectric Energy Harvesting Technologies", 2016.
[54] Kofi SarpongAdu-Manu, Nadir Adam, Cristiano Tapparello, Hoda Ayatollahi, And Wendi Heinzelman, University of Rochester, "Energy-Harvesting Wireless Sensor Networks (EH-WSNs): A Review" ,2018.
[55] ZhengqiuXie, JitaoXiong, Deqi Zhang, Tao Wang, Yimin Shao and Wenbin Huang, "Design and Experimental Investigation of a Piezoelectric Rotation Energy Harvester Using Bistable and Frequency Up-Conversion Mechanisms", 2018.
[56] SepehrEmamian "Development of Flexible Sensing Systems and Energy Harvesters Using Printing Techniques", 2017.
[57] Rajae All, Abdelmajid Bybi, Ayoub Benhiba, Hilal Drissi and El Ayachi Chater, "Overview of piezoelectric energy harvesting technology in the tire condition monitoring systems" , 2018.
[58] Stefano Basagni, M. YousofNaderi, Chiara Petrioli, and Dora Spenza, "Wireless Sensor Networks With Energy Harvesting", 2019.
[59] Marco Grossi "Energy Harvesting Strategies for Wireless Sensor Networks and Mobile Devices: A Review", 2021.
[60] Se Yeong Jeong, Liang Liang Xu, Chul Hee yu, Anuruddh Kumar, Seong Do Hong, Deok Hwan Jeon, Jae Yong Cho, Jung Hwan Ahn, Yun Hwan Joo, In WhaJeong, Won Seop Hwang and Tae Hyun Sung, "Wearable Shoe-Mounted Piezoelectric Energy Harvester for a Self-Powered Wireless Communication System", 2021.
[61] Thanh-Cao Le, Tran-Huu-Tin Luu, Huu-Phuong Nguyen, Trung-Hau Nguyen, Duc-Duy Ho and Thanh-Canh Huynh, "Piezoelectric Impedance-Based Structural Health Monitoring of Wind Turbine Structures: Current Status and Future Perspectives", 2022.
[62] Md Maruf Hossain Shuvo, TwishaTitirsha, Nazmul Amin and Syed Kamrul Islam, "Energy Harvesting in Implantable and Wearable Medical Devices for Enduring Precision Healthcare", 2022.
[63] Wenzheng Cai, University of Windsor, "Energy Harvesting fresting from Surface Riv face River/Ocean W er/Ocean Waves", 2017.
[64] Zhen Zhao, Baifu Zhang, Yongxin Li, Chunjiang Bao, Tie Wang, "A novel piezoelectric energy harvester of noncontact magnetic force for a vehicle suspension system", 2022.
[65] Julius Evans "Energy Harvesting Through The Piezoelectric Effect At Sports Venues", 2015
[66] Chua-Chin Wang, Lean Karlo S. Tolentino, Pin-Chuan Chen, John Richard E. Hizon, Chung-Kun Yen, Cheng-Tang Pan and Ya-Hsin Hsueh, "A 40-nm CMOS Piezoelectric Energy Harvesting IC for Wearable Biomedical Applications", 2021.

[67] Salman Khalid, Izaz Raouf, Asif Khan, Nayeon Kim, Heung Soo Kim, "A Review of Human Powered Energy Harvesting for Smart Electronics: Recent Progress and Challenges" , 2019.
[68] German Martinez-Ayuso, Michael I. Friswell, Sondipon Adhikari, Hamed Haddad Khodaparast, Carol A. Featherston, "Porous piezoelectric materials for energy harvesting" , 2016.
[69] Manjuan Huang, Cheng Hou, Yunfei Li, Huicong Liu, Fengxia Wang, Tao Chen, Zhan Yang, Gang Tang and Lining Sun, "A Low-Frequency MEMS Piezoelectric Energy Harvesting System Based on Frequency Up-Conversion Mechanism", 2019.
[70] Junxiang Jiang, Shaogang Liu, Lifeng Feng and Dan Zhao, "A Review of Piezoelectric Vibration Energy Harvesting with Magnetic Coupling Based on Different Structural Characteristics", 2021.
[71] J. Roberto Andrade "Piezoelectric Energy Harvesting: A Comprehensive Review and Applications", 2022.
[72] Chunhua Sun, Guangqing Shang, Hongbing, "On Piezoelectric Energy Harvesting from Human Motion", 2019.
[73] Faizan Ali, Waseem Raza, Xilin Li, Hajera Gul, Ki-Hyun Kim, "Piezoelectric energy harvesters for biomedical applications", 2019.
[74] Corina Covaci and AurelGontean, "Piezoelectric Energy Harvesting Solutions: A Review", 2020.
[75] RavjeetKour and Ahmad Charif, "Piezoelectric Roads: Energy Harvesting Method Using Piezoelectric Technology", 2016.
[76] Cristiano Martinelli and Andrea Coraddu, "Performance aware design for piezoelectric energy harvesting optimisation via fnite element analysis", 2022.
[77] Mohsen Safaei, Henry A Sodano and Steven R Anton, "A review of energy harvesting using piezoelectric materials: state-of-the-art a decade later (2008-2018)", 2019.
[78] Hyeong Jae Lee, Stewart Sherrit, Luis Phillipe Tosi, Phillip Walkemeyer and Tim Colonius, "Piezoelectric Energy Harvesting in Internal Fluid Flow", 2015.
[79] Xiaoli Tang, Xianghong Wang, Robert Cattley, FengshouGu and Andrew D. Ball, "Energy Harvesting Technologies for Achieving Self-Powered Wireless Sensor Networks in Machine Condition Monitoring: A Review", 2018.
[80] Yunzhu Chen and Xingwei Xue, "Advances in the Structural Health Monitoring of Bridges Using Piezoelectric Transducers" , 2018.
[81] Xinlin Qing, Wenzhuo Li, Yishou Wang and Hu Sun, "Piezoelectric Transducer-Based Structural Health Monitoring for Aircraft Applications", 2019.
[82] Marcos Duque, Edgardo Leon-Salguero, Jordi Sacristan, Jaume Esteve and Gonzalo Murillo, "Optimization of a Piezoelectric Energy Harvester and Design of a Charge Pump Converter for CMOS-MEMS Monolithic Integration", 2019.
[83] Sasa Zelenika, Zdenek Hadas, Sebastian Bader, Thomas Becker, Petar Gljuš´ci´c, Jiri Hlinka, Ludek Janak, Ervin Kamenar, Filip Ksica, Theodora Kyratsi, LoucasLouca, Miroslav Mrlik, Adnan Osmanovi´c, Vikram Pakrashi, Ondrej Rubes, Oldˇrich Seveˇcek, José P.B. Silva, Pavel Tofel, Bojan Trkulja, Runar Unnthorsson, Jasmin Velagi´c and ŽeljkoVrcan, "Energy Harvesting Technologies for Structural Health Monitoring of Airplane Components—A Review", 2020.
[84] GuoguangRong, Yuqiao Zheng and Mohamad Sawan, "Energy Solutions for Wearable Sensors: A Review", 2021.
[85] Abdul Aabid, Md Abdul Raheman, Yasser E. Ibrahim, AsraarAnjum, Meftah Hrairi, Bisma Parveez, Nagma Parveen and Jalal Mohammed Zayan, "A Systematic Review of Piezoelectric Materials and Energy Harvesters for Industrial Applications", 2021.
[86] ImanIzadgoshasb "Piezoelectric Energy Harvesting towards Self-Powered Internet of Things (IoT) Sensors in Smart Cities", 2021.
[87] Steven R Anton and Henry A Sodano, "A review of power harvesting using piezoelectric materials (2003–2006)", 2007.
[88] AlirezaKeshmiri and Nan Wu, "A Wideband Piezoelectric Energy Harvester Design by Using Multiple Non-Uniform Bimorphs", 2018.