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REVIEW ARTICLE

A Review of the Generation of Electrical Energy with Renewable Energy Sourced Piezoelectric Material

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HIGHLIGHTS

> This article presents information about the use of piezoelectric materials in energy harvesting from renewable energy sources and their preferability in the near future with particular reference to their performance characteristics.

> Examining the studies reported in the literature, the use of piezoelectric in renewable energy applications was concluded to have the potential to reduce cost as well as to provide a cleaner energy generation.

> The meticulous scrutiny of data and deficiencies in the articles addressed herein is thought to serve as a guide for the researchers to study on this subject.

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ABSTRACT

Today, obtaining energy from renewable energy sources plays an important role in meeting the ever-increasing energy demand. Since renewable energy sources are clean energy sources, they include many research topics that are studied and open to development. Despite these advantages, the high investment costs of renewable energy sources enable cheaper, simple and space-saving alternative energy sources such as piezoelectric materials to be included in the solution of energy needs. Piezoelectric crystals are materials that release electrical energy when they are deformed. The use of different piezoelectric materials that will maximize the amount of energy to be obtained is an area open to development. In this study, in order to emphasize the renewable application areas of piezoelectric materials, a literature review was made by examining many experimental studies. In the studies reviewed, the vibration, motion, and pressure phenomena required to generate electricity from piezoelectricity were derived from renewable energy sources such as wind, rain, waves, tides, light, and so on. The studies examined reveal that piezoelectric materials are open to development in maximizing energy production with various methodologies and mechanisms. It has been emphasized that piezoelectric materials can be redesigned with changes to be made in systems designed for renewable energy sources, and their dimensions and installation costs will reach significantly optimum results and can be used in an environmentally friendly manner.

Contents

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1. Introduction

Energy has been a sensitive issue in human society for many years. The phenomenon of electric energy is a very important consideration to ensure that community structures on a country-by-country basis can achieve quality living standards. Because it determines the development, production, and consumption of the mentioned social structures in the economic context, socio-cultural context, scientific field, the various amounts of energy they undertake. In the modern world, the demand is to bring voltage levels closer to more reasonable economic values at high rates and to offer energy in a way that does not harm the nature of our planet.

Especially in recent years, human migrations, increases in the human population in societies, and rapid increases in production and consumption in industrialization in parallel with this situation have caused more energy production. This need for energy production is provided by ahigh proportion of fossil fuels and their derivatives, which again serve this purpose. But fossil fuels were in danger of extinction due to the inability to regenerate, which led to a shortage of resources. At the same time, CO_2 emissions resulting from consumption reactions of fossil fuels cause serious damage to the atmosphere, nature, and indirectly to man. Increasing the use of renewable energies and sustainable approaches are recommended since non-renewable energy sources are gradually depleted, contribute to greenhouse gas emissions and cause climate change significantly [1]. Non-renewable energy sources (coal, oil, natural gas, etc.) are expected to be the most important consumed energy sources in the next 30-40 years [2]. All these reasons have led to the use of resources such as solar, wind, wave, hydro and geothermal energy, which are environmentally friendly and have the potential to be renewable.

2. Overview of Piezoelectric

The word *piezo* is derived from the Greek word for pressure or press [1]. Piezoelectricity, discovered in 1880 by French physicists Pierre Curie and Jacques, can convert mechanical energy into electricity or vice versa, electrical energy into mechanical energy [3]. Quartz (SIO_2), Rochelle salt and tourmaline are naturally occurring piezoelectric materials [4]. But PZT (lead zirconate titanate), which is found as a synthetically favorite material in nature, has taken its place in many application areas for both its strong structure and affordable costs [3]. The piezoelectric property is divided into two types. The first property is the generation of electrical energy from mechanical energy called direct piezo event (generator work) and the second property is the generation of mechanical energy from electrical energy called reverse piezo event (motor work). The production of voltage by the effect of mechanical pressure, the formation of mechanical vibration when voltage is applied, are important features of piezo crystal and piezo ceramic materials (Figure 1).

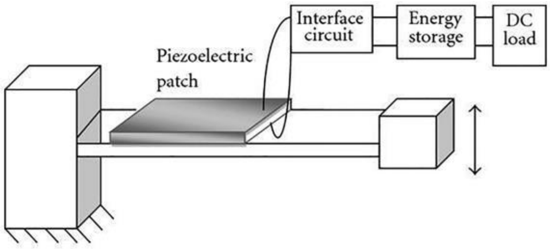

Figure 1 Block diagram Piezoelectric Energy Harvesters [3].

A clean, environmentally friendly renewable energy conversion is achieved by converting the mechanical energy that occurs spontaneously in nature into electrical energy with piezoelectric materials. Energy harvesting; vibration, light, heat, temperature, airflow, etc. can be obtained from different energy sources such as. And it also enables the conversion of ambient energy into usable electrical energy.

2.1. Piezoelectric Harvesting of Wind Energy

The fact that piezoelectric material is a promising option in clean energy production and that wind energy is renewable has recently become a topic that attracts researchers' attention.

Zheng et al [5] introduced a new power supply system to collect wind energy insidethe subway tunnels and for tunnel wireless sensor network (WSN) nodes. They have designed tunnels to allow wireless sensor network nodes to self-collect power. The system is fixed upon the inner walls of a subway tunnel to collect wind energy from the tunnel and convert the energy. A wind wheel was used to collect wind energy from the tunnel; electrical energy is generated by electromagnetic and piezoelectric wind energy modules and stored in super-capacitors (Figure 2). Electromagnetic modules can recover more wind energy at high wind speeds, while piezoelectric modules provide greater voltages at low wind speeds to improve the energy conversion rate [5].

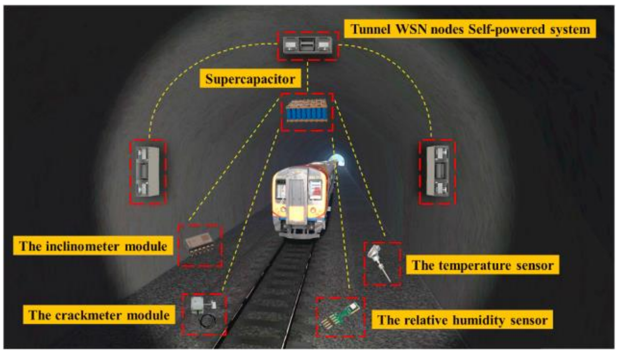

Figure 2 Application of the Tunnel WSN nodes Self-powered system [5].

Wang et al. [6] proposed a dynamic multi-stable configuration composed of a piezoelectric beam and a rectangular plate for harvesting the energy of variable-speed wind. The harvester jumps between two static balance positions at low wind speeds. At high wind speeds, however, it may jump between an emerging neutral equilibrium position and three equilibrium positions. They made a theoretical analysis, produced a prototype for verification, and connected a piezoelectric material to the beam. They carried out the related experiment by increasing the wind speed from 1.5 to 7.5 m/s. They proved with experimental results that the harvester they proposed could produce a large output in the speed range. They noted that at low wind speeds, the harvester jumps between two static equilibrium positions; at high wind speeds, with the resulting neutral equilibrium position, the harvester can jump between three equilibrium positions. They noted that dynamic stability helps to sustain a passing motion for variable speed wind, and in particular, passing motion can achieve consistency resonance within a wind speed range. In this way, they proved that the system can perform a sudden movement in a variable speed wind environment and create high pulse voltages to hold a largeoutput (Figure 3).

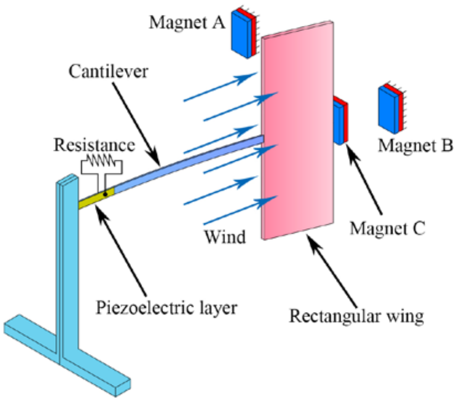

Figure 3 Schematic of the proposed dynamic-stable flutter energy harvester (DFEH) [6].

Tan et al. [7] studied the effects of atmospheric temperature and airflow rate of the piezoelectric energy collector depending on the seasons and region of the harvester. As a result of the experiments, they observed that combined frequency and electrical damping decrease as the temperature increases, and optimal electrical damping is almost unaffected bytemperature (Figure 4).

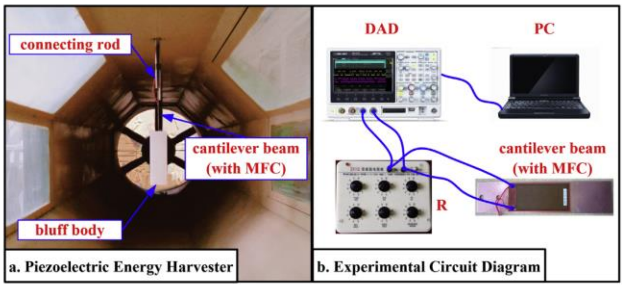

Figure 4 (a) Energy harvester inside the testing section of the wind tunnel and (b) testing setup [7].

Yang et al. [8] investigated the performance of the double beam piezo- magneto-elastic wind energy harvesting machine (DBPME-WEH) when demonstrating a galloping energy harvesting regime under wind stimulation. They explained the DBPME-WEH structure as a structure containing two piezoelectric beams, each supporting an embedded prism bluff body with a magnet at its end. They directed the magnets to repel each other to provide a double-balanced non-linear state. They conducted wind tunnel tests to compare the performance of DBPME-WEH and the double beam piezoelectric wind energy collector (DBP-WEH), which does not contain magnet-welded non-linear properties (Figure 5).

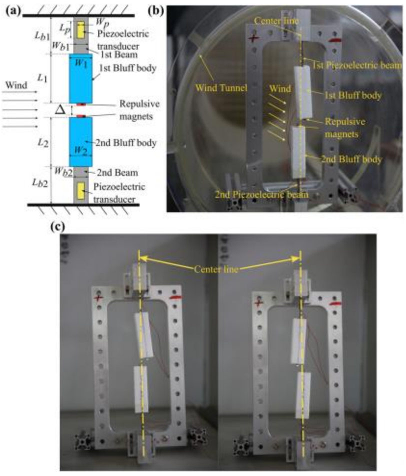

Figure 5 (a) The schematic of the DBPME-WEH, (b) the photo of the experimental setup, and (c) the bistable static equilibrium positions of each beam [8].

Büyükkeskin et al. [9] used two different wind stem prototypes with a 3d printer. These structures installed in the wind tunnel have been tested for different wind speeds and high turbulent situations (Figure 6).

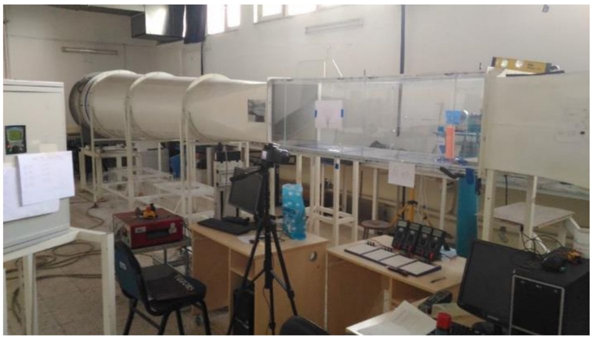

Figure 6 The wind tunnel where the experiments are performed [9].

Usta [10] has designed a wind-based piezoelectric generator and has targeted vibration-based energy production from piezoelectric crystals. He basically based on the piezoelectric vibration energy cards placed on the vertical axis of the wind blades in the helical structure and generating electrical energy by creating vibrations by utilizing the wind speed. The electrical energy generated in the system he built has performed the correct voltage generation on the occasionof the correct voltage harvest card he designed, and it has prevented the loss of energy in AC-DC transformations after that. In his tests and experiments, the maximum power got because of electricity generation in piezoelectric vibration generators was 408.79 µW at a wind speed of 36 m/s. Based on the technical documentation of the piezoelectric vibration generators he used, he stated that the maximum power he could achieve should be at 12mW level, and theefficiency he received from the generated power was at 3.4% levels. The current level, whichshould rise to 1 mA levels, could see levels of 16.90 µA. During the Test, he added trapezoidal Springs and neodymium magnets to increase the resonance value, contributing 12% to the efficiency he has already achieved. He found that changes in wind speed and pressure on piezoelectric generators in the wind tunnel he used led to large changes in the resonance value (Figure 7).

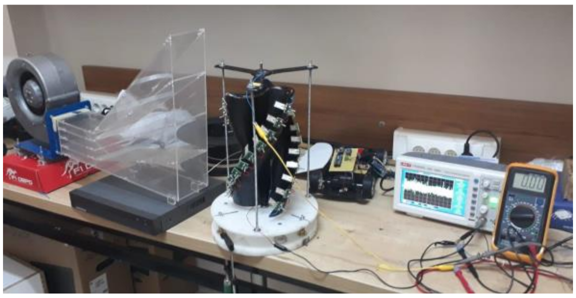

Figure 7 Experiment setup used in wind tests [10].

He made shortening operations to prevent current drops that would arise from the wiring and cable distances he made and tried cables with different internal resistance, but he concluded that there was no change in the current level that he got. But he used super-capacitors in the payload circuit he deployed to the experimental Assembly. He found that voltage drops experienced during charging and discharging do not occur after waiting 15-20 seconds before charging in the step-down DC-DC voltage-reduced circuit using the super-capacitors. He observed that under the current value measured after the step-down operation, mA-level current will also be generated. Using the resulting amount of voltage at load with two parallel red LEDs after the storage process has proven that the amount of energy they produce is at a usable level. It determined that the time to access the capacity from the charging state took 2-2.5 minutes and that the discharge process with two LEDs completed in 10-12 minutes [10].

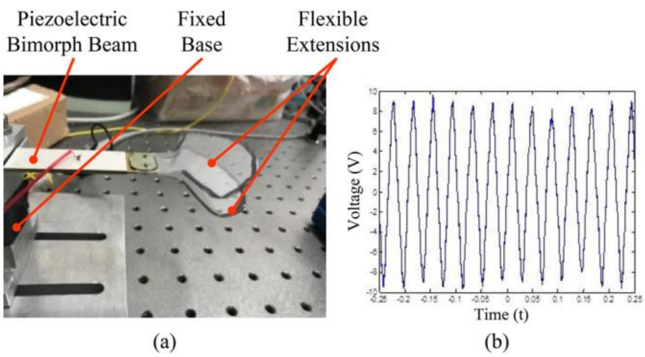

Figure 8 (a) Assembled energy harvester prototype in the experiment. Note that the oscilloscope and the wind source are not shown here and that the fixed base is not fully shown. (b) One of the typical voltage output measured. Note that the time coordinate is just shown for a reference and does not indicate any actual measurement time in the experiment [11].

Zhou et al. [11] inspired by the ripple of leaves in the wind, introduced a new wind energy collection device comprising piezoelectric bimorph beams and flexible extensions. Because of the data they got, they showed that performing the device is greatly affected by the flexible extension (Figure 8).

Ödemiş [12] designed and manufactured a different piezoelectric energy harvesting (PEH) mechanism by placing drum-type harvesters on the savonius turbine body in order to generate energy from wind-based mechanical vibrations (Figure 9).

Figure 9 Test setup for energy performance analysis [12].

Materials used and design a prototype of piezoelectric energy conversion system has been manufactured, manufactured a prototype of the energy output, efficiency, and usability in terms of the evaluation done in the literature, together with information on the use of alternative energy sources and aims to contribute to developments in this field offer a different perspective. Having designed and manufactured the system, Ödemiş [12] has conducted a wind tunnel test under 7 m/s wind-speed, taking measurements with Arduino, and 5 Volts, 1.16 W instantaneous power output values were achieved after the system became stable. The average power output of the system was determined to be 0.62 W. Considering these values, 60 drum-type harvester system, in groups of 15, is required to charge for 64 hours in order for a 220-volts 40W bulb to light up for 1 hour and at 7 m/s average wind speed the total energy production a year was found to be 5434.92 Wh. The theoretical calculations revealed that the yield of the harvesting system was 8.5% [12].

Sun et al. [13] proposed a new piezoelectric energy collector based on a gallop that can adapt to external wind speed (GPEHAW). While they achieved a significant power density improvement rate in a high wind speed regime, the galloping phenomenon is more helpful because we can easily start it in a low wind speed regime by reducing the critical wind speed for galloping. In the experiment, when the turbine was rotating at a higher speed, they could not keep the turbine speed at the set-point, as it could not produce the baking torque in such a case because it operated well below the rated speed of the corresponding generator (Figure 10).

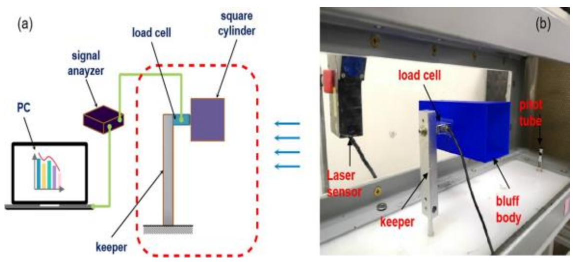

Figure 10 (a) Schematic of experimental setup for drag force measurement. (b) Actual experimental platform installed in a wind tunnel [13].

The circuits used to make wind energy and piezoelectric energy production more efficient have been improved and have been a promising way to generate more energy.

Chen et al. [14] have proposed a self-powered SECE integrated circuit for the micro wind effect type Piezoelectric Energy Harvester (PEH). When they compared the pulse-type Peh to the traditional type, they predicted it was better suited for micro-wind conversion, as it could generate more energy at various wind speeds. Having three modes of the circuit they proposed, they explained the circuit can operate reasonably so that it can benefit to improve energy collection efficiency and applicability (Figure 11).

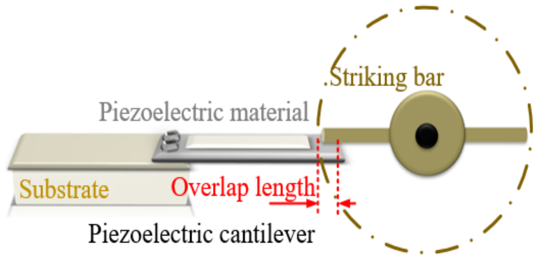

Figure 11 Schematic diagram of the impact-type PEH [14].

Interface circuits are needed for the AC - DC conversion of the piezoelectric power generation device. In the standard interface circuit, the output power is limited and varies with the load. Wang et al. [15] conducted experiments and proposed P-SSHI and S- SSHI circuits, and they think that energy harvesting efficiency improving. They stated that adding an indicator and switch to the S-SSHI circuit will reverse the voltage on the piezoelectric material at the turning point, producing a higher output voltage (Figure 12).

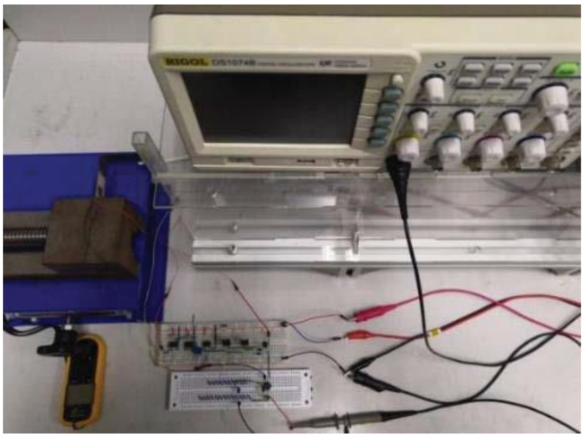

Figure 12 Experimental setup of the prototype tests [15].

Chatterjee [16] offered a device capable of generating energy from both the sun and wind. The device is also a terrain device that can work in dual weather. In normal weather, the winding voltage is dominant if the sun is in stormy weather. It has a quartz and polypropylene bar positioned end-to-end to take advantage of solar energy. Quartz and polypropylene rods increase the temperature of polypropylene when exposed to radiation in the sun, while the temperature change is not observed because quartz is thermally insulating. Because of the thermal pressure occurring in polypropylene, as the rotor mill rotates, spring compression causes mechanical pressure to form in Quartz. This pressure creates a piezoelectric potential difference in the quartz bar (Figure 13).

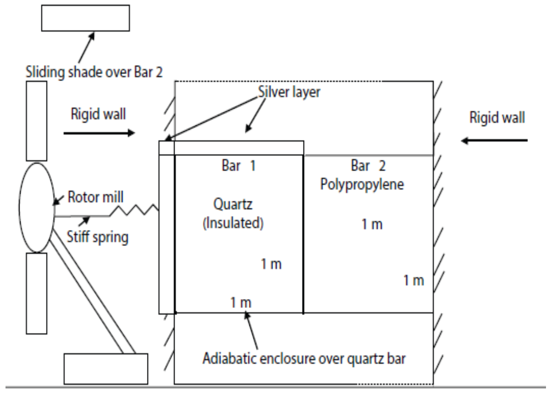

Figure 13 The experimental setup [16].

Instead of mechanical vibration, flowing water or wind is used as a source of excitation to make piezoelectric materials work. Zhou et al. [17] designed a wind source energy harvester with a pull strip to collect wind energy using the Karman vortex theory. They used running water or wind instead of mechanical vibration as a source of excitation to make piezoelectric materials work. They conducted investigations on the piezoelectric bimorph to prevent voltage distribution and damage to the material. According to the structure they designed; They proved that the model with a turning radius of 775 mm can easily reach 10 V and 1 MW, respectively, if the generated voltage and power exceed 140 rpm with a mounting angle of 30 ° and the rotation speed (Figure 14).

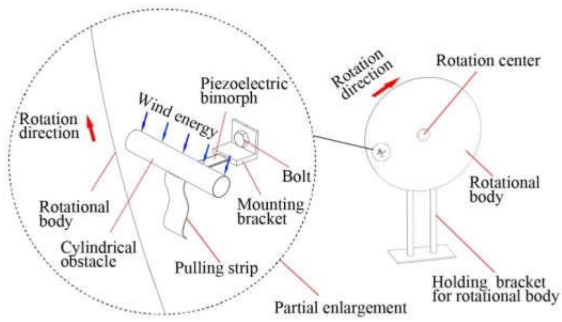

Figure 14 Schematic illustration for the structure of the wind-induced energy Harvester [17].

2.2. Piezoelectric Harvesting of Wave Energy

Ocean climate detectors have the option to take advantage of the ocean by using tidal energyor wave energy, and wind flow can charge bridge safety monitors to suit local conditions.

Therefore, the ubiquitous flow energy thinking provides a good energy-gathering option to attract self-powered systems (Figure 15). If ocean energy can use effectively, the world's energy problem will be eased. For all kinds of military, ecological and environmental detectors, in the ocean or river, charging or replacing batteries is much less economical and workable than harvestingthe surrounding energy [18].

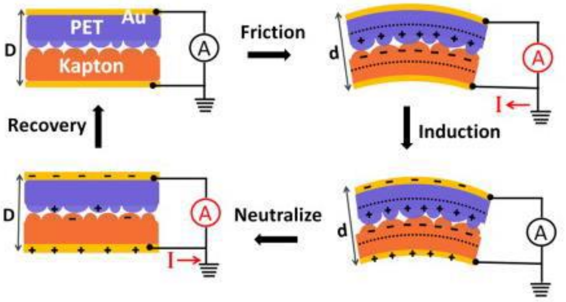

Figure 15 Schematic diagram of triboelectric nano-generators [19].

Erdoğan [20] designed a system in which small amplitude and wavelengths can transform electrical energy from the mechanical energy of waves (Figure 16). She aimed to examine the piezoelectric materials that can harvest energy from small pressure effects and the energy harvesting systems created by these materials.

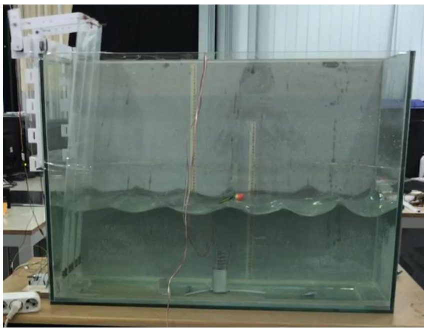

Figure 16 General view of the experiment setup [20].

To examine the effects of waves on the piezoelectric energy harvester, Erdoğan [20] placed 3 differently-designed energy harvesters in the wave tank and carried out experimental studies by changing the distance of the harvester from the water level and from the wave generator. To determine the situation where the energy harvester reaches the highest efficiency, she tried 24 configurations measuring the current and voltage values and made several evaluations. Considering the data obtained, he determined the highest power value at 2.26 (µV) and provided this value from its configuration number 16. In the given configuration, it deployed the energy harvester perpendicular to the surface of the free water and 50 cm away from the wave generator. However, 2 cm wave height and 0.29 SEC. it has reached these data in line with the effect of periodic waves. The yield value measured in this configuration is the value with the highest yield ratio under the configurations it has made. She got the efficiency by dividing the amount of power he got by the power he had because of the height of the wave. She calculated the energy and power potential of the wave based on general equations [20].

Zou et al. [21] presented a magnetically coupled, two-state piezoelectric energy harvesting approach for underwater applications (Figure 17). They stated that the flexible-sized piezoelectric transducer will collect the fluid-induced vibration energy by magnetic coupling, and because it transfers non-contact mechanical energy, it can pack sensitive key components without affecting the normal process. However, they noted that the magnetically connected system is a case of having nonlinear two-state properties, which is useful for improving the performance of the flow energy harvester. They noted that the magnetic excitation force is upgradeable and can be applied uniformly to the piezoelectric layer through its flexible dimensional structure, thereby exhibiting a higher equivalent piezoelectric coefficient and improved reliability.

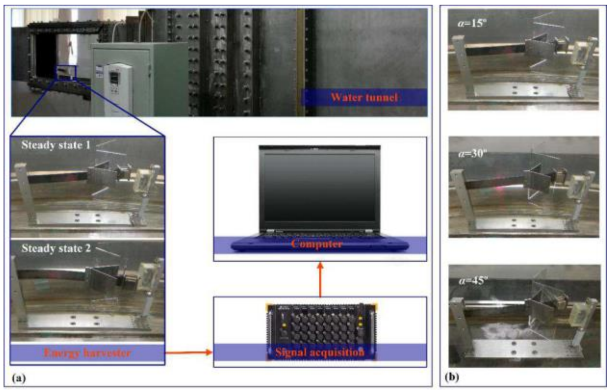

Figure 17 (a) The experimental setup, (b) Prototypes with different wing angles [21].

They successfully developed an underwater vibration energy collection approach using a magnetically coupled flexible transducer. They characterized the underwater energy collection system with a model of electromechanical coupling dynamics. They summarized the main results of the study as below:

i. Experimental results, using the proposed approach confirms the strength of the magnetic clutch and stretching mechanism underwater, a toggle magnetically mounted piezoelectric energy harvester, 144 hours in the water (in a working state time of approximately 50%) demonstrate stable performance power output, magnetic coupling and the flexible mechanisms under-reported in harsh environments such as water has a great potential for energy harvesting.

ii. Again, they found that experimental results significantly improved the performance of the piezoelectric energy harvester, to which the wings are magnetically connected underwater. They determined that it saturated the prototype at 450.5 µW at 4 m/s water flow. They concluded that a larger surface perpendicular to the water flow was necessary to excite the cantilever beam at low flow. At a large flow, they reported that a larger surface perpendicular to the flow of water will also increase resistance.

iii. They found that the simulation results were basically consistent with the experimental results. However, they stated that the structure they established was a simplified model and that the model should characterize the underwater energy harvester [21].

Durgun [22] has designed and manufactured a system that can transform electrical energy from kinetic energy using the kinetic energy of sea waves in his work. He has studied the effects of wave height and wave period change in shallow water on generating electricity (Figure 18).

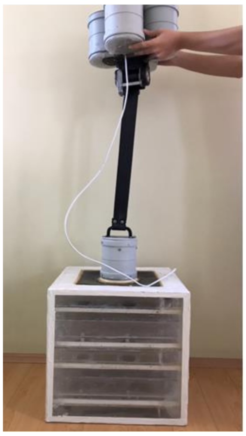

Figure 18 Piezoelectric energy harvesting system [22].

Using his preference as a generator in favor of piezoelectric materials, Durgun [22] tried to reveal the conversion of electrical energy through piezoelectric materials, the kinetic energy that occurs in the oscillating motion of the float. He made voltage, current, and power measurements of the design he created with Arduino Uno.

He calculated the yield and unit cost of the piezoelectric harvesting system that he designed considering the data obtained using Arduino Uno. When he compared the yield of the harvesting system that he designed with other studies in terms of power density; he achieved 300% more power.

In his experimental work, he tested the voltage, current, and power values got because of his experiments with the piezoelectric energy harvesting system, which he designed and manufactured for shallow waters with a depth of 1 - 3 meters, according to the change in wave height. During this time period, he calculated the power density of the system as 508 ($\mu W/\mu^3$). It found that the average wave power entering the system was P=300.243 (W/m), and the average electric power obtained from the system was Pport = 0.998 mW. According to these power values, between 16:00 and 19:30 hours, the efficiency of the system was 3.32x10 above -6% [22]. Because of all these experiments, he concluded that the system has a very low efficiency when he compared the electrical energy produced by the system against the wave power applied to the piezoelectric harvesting system. Designs and manufactures piezoelectric energy harvesting system using piezoelectric material in the same format as other low-power system power densities when compared concerning producing approximately 300% more power you saw you could get. He concluded that the harvesting system, which he tried as a unique design from this point of view, was efficient compared to its counterparts.

Sun et al. [13] established piecemeal distributed parameter models for piezoelectric energy harvesting from low-speed water flow leading to VIV and gallop. They proposed a piecemeal distributed parameter model for the piezoelectric cantilever beam with three types of Bluff bodies. They created the van Der Pol model, which they changed, to simulate the VIV force for the cylinder bluff body and used the semi-constant hypothesis to get the hydrodynamic force that gallops for the three prisms and semi-cylinder bluff bodies. Hydrodynamic forces have considered both the Viv and galloping forces. They introduced the extended Hamiltonian principle and Gauss law to establish electromechanical unified management equations. It derived approximate solutions using the Galerkin approach, the equivalent dynamic representation, and the harmonic equilibrium method. They derived approximate analytical solutions of harvested power for the Viv and galloping models. They conducted experiments on the circulating water channel and confirmed theoretical models (Figure 19).

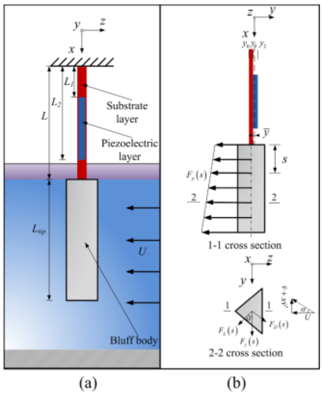

Figure 19 A schematic of the water flow energy harvester [13].

They found that the maximum power of the Viv harvester with a cylinder bluff body was U = 0.48 m/s at the optimum flow rate. They calculated the maximum RMS power and energy density of the harvest at 1.064 mW and 1.949 mW/cm^3, respectively. They found that the power of the galloping harvest with three prisms and half cylinders increased with the flow rate. They found that the maximum experimental RMS power and power density was 2.37 mW and 4,286 mW/cm^3 for the Tri-prism harvester and 4.14 mW and 7.582 mW/cm^3 for the semi-cylinder harvester if the flow rate was 0.54 m/s. They said that for the galloping condition, the starting speed is inversely proportional to the hydrodynamic coefficient a1. They stated that the magnitude of absolute a_1/a_3 rises in direct proportion to the magnitude of the energy got. They determined that the coefficient of the Tri-prism Harvester a1 and the absolute a_1/a_3 were lower than that of the semi-cylinder Harvester. When they compared it to the three-prism combine, they found that the half-cylinder had a lower initial speed, but collected more power. With VIV, they found that the starting speed is almost independent of the load resistance; with the galloping, the starting speed varies with the load resistance. At optimal VIV speed, they believed that the power harvested from a half-cylinder gallop quadruples the power harvested from a VIV, which is almost twice the power harvested from a three-prism gallop.

2.3. Hybrid Piezoelectric Harvesting Systems

Puri et al. [23] developed an Internet of Things (IoT) - based system to generate electrical energy from multiple sensors for home appliances and industrial areas. They used different sensors, namely piezoelectric sensors, body temperature, and solar panels for electrical converters. After processing the data they send to the cloud processor for electrical power generation, they connected it to the power storage circuit. They said that the stress caused by body weight can be transferred to the control system after storing electricity from renewable energy sources, such as the heat produced by the human body and the movements of the body, by measuring it with different sensors. For verification, they have developed 4 models from a data set they collect in real-time.

They noted that two different Artificial Intelligence (AI) models, such as the artificial neural network (YSA) and the network-based fuzzy inference system (ANFIS), can adapt to the total power generated from renewable energy sources. They performed the verification process through statistical parameters such as root-mean-square error (RMSE) and R_2 correlation coefficient (Figure 20).

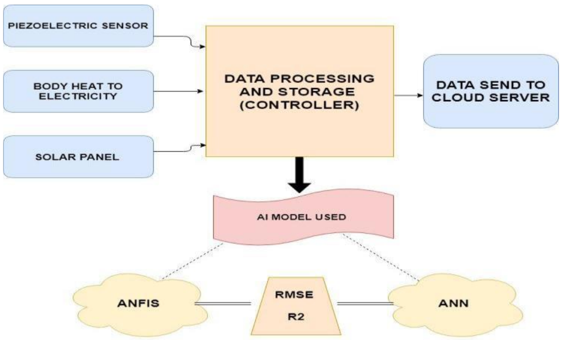

Figure 20 Proposed IoT model [23].

Kumar et al. [24] have fabricated flexible hybrid device by combining of the piezoelectric nano-generator (PVDF-ZnO), thermoelectric generator (n-leg and p-leg made of $Bi2Te_3$-RGO (Reduced Graphene Oxide) and $Sb2Te_3$-RGO, respectively) by using simple chemical solution method. The focus of their research has been on integrating thermoelectric and piezoelectricity into a small flexible device to collect electrical energy from both thermal and mechanical energies. They found the output power of the 4K temperature-aware thermoelectric generator (1 x 1 array) ~1.8 nW (Figure 21).

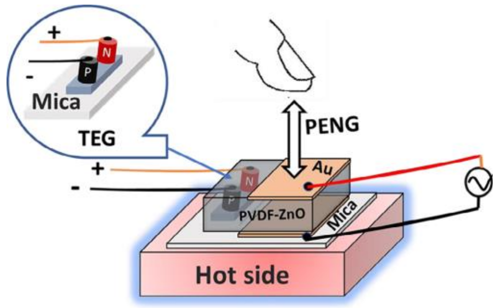

Figure 21 Schematic of hybrid device consisting of a thermoelectric generator (TEG) and piezoelectric nano-generator (PENG) [24].

Chen et al. [25] have developed a micro-stable piezoelectric energy collector. They mounted the Combine on a micro-Stable Plate with mass blocks placed in four corners, fixed from the center and without quadrangles. Considering the thermal electromechanical coupling effect, they created a nonlinear oscillation differential equation with the Hamiltonian principle. They applied strain gradient theory to consider the size effect and used Karman theory to consider the large deformation effect. They investigated the piezoelectric layer's slab position and the effects of its field on energy capture efficiency. They studied the voltage-frequency response of the nonlinear system and reported that the passing behavior of the double-balanced plate results in energy harvesting reaching the ideal extended frequency range before the resonance region (Figure 22).

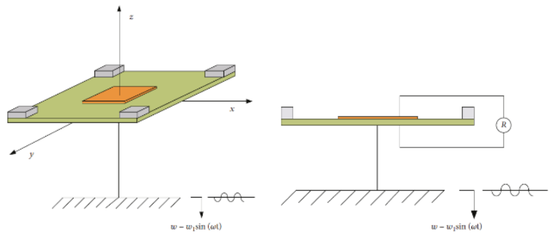

Figure 22 The energy harvesting structure diagram [25].

3. Discussion

When the renewable energy harvest from wind energy by piezoelectric studies are examined;

In the study of Zheng et al. [5], as a result of the experiment, the power of the piezoelectric module and the electromagnetic module was positively correlated with the wind speed. When the wind speed reaches a maximum of 7 m/s, the output power of the system reaches its maximum: the output power of the piezoelectric module is 6.5 mW, the output power of the electromagnetic module is 52.81 mW, and the total output power is 59.31 mW.

Wang et al. [6] believe that this harvester can be applied directly to the real environment after improvement due to its simple structure and cheap material, stated that in practice, the size of the structure can be reduced to adapt to the environment without affecting its performance. However, they explained that the storage circuit for electrical energy needs more design and research and that the connections between the components need to be improved.

Tan et al. [7] found that the designed galloping piezoelectric energy harvester, by adjusting the load resistance at each airflow velocity, exhibits excellent environmental adaptability at an atmospheric temperature from -40◦C to 50◦C and airflow rate from breeze to storm.

Yang et al. [8] from experimental results, concluded that DBPME-WEH performed significantly better than the dual-beam piezoelectric wind energy collector (DBP-WEH), which lacked the ability to be magnet- induced non-linear. That is 1 of DBPME-WEH. beam and 2. they reported that the critical wind speed would be reduced by 25% and 41.9%, respectively, for the galloping vibrations of its beam (the harder beam) to act. They reported that experimental studies also revealed that the greater the distance between the two magnets, which achieves the weak bistable nonlinearity is favorable for the performance of the DBPME-WEH in reducing the critical wind speed and enhancing the output voltage. For these reasons, they declared that the results confirm the significant performance improvement of DBPME- WEH.

Büyükkeskin et al. [9] found that as a result of the experiments, the maximum power obtained at a wind speed of 17 m/s is 380.73 73μW/cm^2. This value should be 15.3 mW/cm^2 according to technical data. Therefore, the efficiency of the piezoelectric material is 2.5% from the experimental results. According to these results, it is possible to generate more energy using more piezoelectric generators. The fact that wind STEM can also use in turbulence flows shows that it provides more advantages than wind bleachers. It has also been concluded that piezoelectric material can be used in multilayer.

Usta [10] concluded that the amount of current produced by the experimental Assembly is higher than the current drawn by two parallel-connected LEDs and that it can also store this increased energy.

Zhou et al. [11] got unexpected results, showing that we need to investigate further the interaction and collision between the flexible extension.

Ödemiş [12] evaluated the efficiency of the system by comparing it with the studies in the literature, in the calculations made according to the equations used for power and performance analysis in the savonius turbine, he calculated the total power generated at constant wind speed (vT=7 [m/s]) to be $Ptop$=7.33 [W]. Accordingly, Efficiency ηs was found to be 0.0846 when compared with the electrical power output of the system (Pc=0.62 [W]) in the experimental study. These results showed that the system had an energy output of about 8.5%.

Sun et al. [13] accounted that this performance decline could be suppressed by replacing the generator with one with a nominal speed of about 750 rpm. They planned to include regenerative breakage during turbine deceleration to generate and store electrical energy to provide a microcontroller and Control Board, which would allow the proposed approach to vibrate itself [13].

Chen et al. [14] proved the peak efficiency of 86.1% in self-executing SECE simulations and wind speed of 2.05 m/s.

Wang et al. [15] found that the optimum output power of the P-SSHI and S-SSHI circuits for wind speeds below 6 m/s is three-quarter of the standard circuit, while the optimum loads are one-quarter and one-third of the standard circuit. They stated that the P-SSHI interface circuit provides a higher output power increase under the higher load resistance range, and simultaneously, the output power of the S-SSHI interface circuit can be increased under the lower load resistance range.

In the study of Chatterjee [16] offered experiment results 1K temperature increase in polypropylene Rod creates a voltage of 11.754 kV in Quartz Rod, piezoelectric voltage technique at thermal pressures shows that high voltage can produce up to 255.08 kV. The device will reduce its carbon footprint and be suitable for regions (desert, coastal, rugged areas) where electricity transmission is difficult because of geophysics.

Zou et al. [17], as a result of their findings; reported that the most important factors affecting the power generation capacity were the rotation speed and the selection of the appropriate placement angle when the cylindrical barrier diameter is small.

When renewable energy harvesting from ocean-wave energy by piezoelectric studies are examined:

Network-based triboelectric Nano-generator (TENG's) provide an alternative solution for large-scale blue energy harvesting but still face other challenges in terms of durability, water resistance, energy transmission, and pollution controls. More efficiency can achieve it addressed if this problem [18].

Erdoğan [20] showed that a good efficiency can be obtained in the use of the energies of waves with small amplitudes and wavelengths, which are sensitive mechanical energy sources in piezoelectric materials. It founds that the efficiency rate of configuration 16 with the highest efficiency was 21.04%.

Zhou et al. [21] produced the prototypes to confirm the design's advantages and subjected them to a series of tests in a water tunnel. At a flow rate of 4 m/s, they found the top-to-top voltage and maximum power of the 390 kΩ load resistance at 26 V and 450.5 µW, respectively. They found that the magnetically coupled two-state piezoelectric energy collector exhibited stable power output performance after 144 hours in water (approximately 50% of the time in operation).

Durgun [22], as a result of all these experiments he conducted, when he compared the wave power applied to the piezoelectric harvesting system against the electrical energy produced by the system, he came to the conclusion that the system had a very low efficiency. When he compared the power densities of the piezoelectric energy harvesting system, which he designed and manufactured, using the same format piezoelectric material, he saw that it could obtain approximately 300% more power. In this respect, he concluded that the harvesting system, which he tried as a different design, was more efficient than its counterparts.

Sun et al. [13] explained that the pressure and velocity differences of the semicircular cylinder are also more important than the other two cases. They found that the phenomena they mentioned were consistent with analytical and experimental results. As a result, they showed that galloping energy harvesting is superior to VIV energy harvesting.

When renewable energy harvesting from hybrid energy with piezoelectric studies are examined:

Puri et al. [23] estimate the total output power generation as output in the AI models, a total of 3 input modules such as piezoelectric, solar energy and body-heat energy have been considered. In the results they obtained from this model, they stated that training and testing of all models through ANFIS and ANN was good, but ANF performance was better than ANFIS. They reported that their proposed study will be useful for estimating electricity generation from renewable sources.

Kumar et al. [24] noted that efficiency can be improved if more thermoelectric elements were integrated in series into the thermoelectric generator device. From the piezoelectric nano-generators, they determined that an open-circuit voltage of 4 4 V will be obtained while obtaining a short-circuit current of 75 75 nA. They found that 1,2 1.2 µW of output power achieving. They explained that this single-module device can be effectively used in the exhaust pipe of engines where both thermal energy and mechanical vibrations are present to usefully convert it into electrical energy.

Chen et al. [25], as a result, considering the dimension effect, extended the strain gradient theory to the nonlinear problem of micro-stable piezoelectric energy harvesting. Based on the dynamic model they created in this paper, they got a microbicide table energy collector structure by theoretical analysis. They found that with the increased ambient vibration frequency, the snap-through phenomenon for the micro-scale double-balanced energy collector arose. They also investigated the effect of snap-through behavior on energy efficiency capture and achieved the goal of capturing more energy across several wide frequency ranges away from the resonance region [25].

4. Conclusion

In response to the increasing energy need, one of the primary targets of environmentally friendly and renewable system designs that will meet this need is their cost. In this study, the designs and studies made using piezoelectric crystals are especially hybrid applications with renewable energy sources. The studies addressed in this study were examined under three categories according to the energy source they rely on, i.e. wind energy systems, ocean-wave energy systems and hybrid systems and piezoelectric material designs were examined separately. Studies using piezoelectric crystals are available in a wide variety of fields.

The piezoelectric energy harvesting method generates electricity from the vibrational energy of energy. The use of different piezoelectric materials that will maximize the amount of energy to be obtained is an area open to development. In this review, based on the data of 24 studies examined with 3 different renewable energy sources, some regulation proposals to increase efficiency were examined. In general, it has been determined that the tests to be carried out under laboratory conditions before each study and the test to be carried out in the field will contribute to the determination and elimination of some possible design errors. In terms of energy type, mass production is at the forefront in the selection of the piezoelectric material used for wave power, which brings less cost to the fore. It has been emphasized that in the design of piezoelectric materials, mechanisms that will increase the trigger frequency in order to increase the efficiency of the systems should be developed in every study.

In terms of wind energy, one of the biggest advantages of using piezoelectric materials is to achieve the energy conversion rate efficiently at low wind speeds. Electromagnetic modules can recover more wind energy at high wind speeds, while piezoelectric modules provide larger voltages at low wind speeds to improve the energy conversion rate. It has been emphasized that the system can operate in variable speed wind environments, is not affected by temperature changes in the environment, and can be used in terms of cost and efficiency when necessary arrangements are made regarding the design dimensions.

As a result of the studies, we observed that the experiments with the piezoelectric materials mostly gave positive results, but they should be improved. Today, the development trend of electronics is to minimize the size of devices, to reduce power consumption, and to improve device flexibility and integrability. When the literature studies are examined in general, it is concluded that the production processes of piezoelectric materials should be developed and they should be easily integrated into renewable energy sources. In addition, the proliferation of designs that will provide maximum output power will further reveal the importance of piezoelectric materials in the current and future periods.

Declaration of Conflict of Interest

The authors declare no conflict of interest.

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