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The Major Mechanisms for Efficient Hybrid Energy Harvesting: Overview and Recent Developments

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***Abstract* - Devastating environmental issues and the cost of replacement of batteries in autonomous low-powered electrical, electronic, and mechatronic systems, the interest in ambient energy harvesting has witnessed steady growth recently. The maximization and utilization of these eco-friendly energies have given rise to efficient hybrid energy harvesting, which involves the combination of two or more standalone energy harvesting mechanisms such as Vibrational, thermoelectric, pyroelectric, photovoltaic, etc. The comparison of the recent development, applications, and challenges of the major standalone and hybrid harvesting mechanisms in both large and small-scale mechanisms are the main emphasis of this article. Also, this review holistically discussed the latest optimal techniques utilized in hybrid energy harvesting mechanisms for the effective performance of systems and to guarantee stable power to autonomous electronics and wireless sensor networks. The study will help research scholars to understand and focus on the high-potential techniques to achieve maximum power from hybrid harvesters.**

***Keywords:* Efficient, Energy Harvesting, Mechanisms, Ambient, Standalone, Hybrid**

I. INTRODUCTION

With increasing innovation in the electronic and information technology (IT) systems, the need for greater energy generation has increased, despite the efforts to reduce the energy input of these devices. This demand has led to seeking and sourcing power from human locomotion, automobile exhaust, wind, etc. In the recent past, energy storage has improved significantly, and this progress has not been able to keep up with the development of microprocessors, memory storage, and wireless technology applications [1]. Modern and sophisticated technologies such as battery-powered sensors, and wireless sensor networks (WSN) have a long-life expectancy in use. However, replacement of this source of power for a large-scale network consisting of hundreds or even thousands of sensor nodes may be difficult if not impossible. Ambient energy resources are the best option for energy sources but due to the instability of this source, [2] reported super capacitors as a better alternative to batteries in low-cost electronics, WSNs, and micro-energy harvesting (MEH) systems. According to [3], ambient energy sources have the potential to replace batteries, thereby minimizing the maintenance and operation cost. Energy harvesting may enable autonomous and wireless electronic devices to be completely self-sustaining, and hence, battery/replacement maintenance can be eliminated.

Natural and artificial sources of energy can co-exist to generate energy continuously [4]. For instance, solar energy generated in the daily sunlight can be hybridized with mechanical energy (vibrations) from automobile or industrial operations, and thermal energy from waste heat to increase the output performance of the energy scavenging devices. This is illustrated in figure 1.

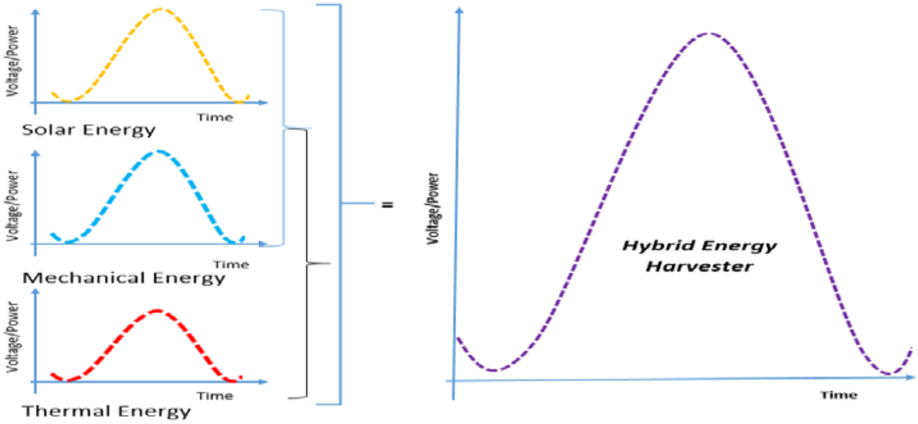


Fig. 1 A schematic illustration of hybrid energy harvesting from standalone mechanisms

When compared with batteries, capacitors, and other energy storage elements, the environment has unlimited availability of energy sources [5]. Single harvesters or harvesting of single power sources are currently insufficient for energy demands in many systems like biosensors, humans, electronic devices, structure and machine health monitoring, and wireless sensor nodes. To overcome this limitation, the hybridization of harvesters is utilized to increase the insufficient energy generation of individual energy harvesters.

Based on the configurations, the study of hybrid energy harvesting (HEH) can be categorized as fixed-frequency broadband which includes linear, nonlinear, tunable HEHs; multimode, and multisource powered configurations. Sometimes, HEH is investigated as two, three, or four-multisource power generation at large, meso, and microscale. It has been proven that HEH produces larger power outputs than standalone components. The 315mW harvested from a novel four-source powered HEH in mesoscale, the 215µW by tunable broadband classic HEH in microscale, and the 440kW h/day by partially three sources HEH in large scale are few most promising power and energy harvesting systems [6]. In addition to the increase in the power outputs and densities of HEHs, the numerous configurations of these systems are known to enable maximum power source harnessing. Efficient energy harvesters take advantage of mechanical nonlinearities (and nonlinear compliance) to ensure a maximization of the input energy [7].

With the development of different mechanisms with high potential for optimal performance, a detailed review of the recent breakthroughs in this field is presented. This review will highlight the latest development in techniques and mechanisms utilized, especially at Microscale. Ways of improving hybrid energy harvesting mechanisms for WSN will be discussed.

A. Motivation for Efficient Hybrid Energy Harvesting Mechanisms

Different Energy harvesting mechanisms have been seen as prominent research fields, and the benefits keep growing rapidly. In other words, the applications of energy harvesters are enormous, including recharging the batteries of large systems, and monitoring embedded and implanting sensor nodes for medical applications [8]. Self-discharging, energy density, life cycles, and cost were identified by [2] as the disadvantages of current energy storage systems (batteries, super capacitors, and batteries). Some of these challenges are peculiar to standalone harvesters.

According to [9], over 40% of all energy consumed in the world today is in the form of electrical energy, this amount is projected to be 60% in the next 20 years as stated by the International Energy Agency [IEA] [10]. As emerging electronics became reduced in size, enabling modern wireless and mobile application explosions [11], the power requirements of components of modern devices keep decreasing with time.

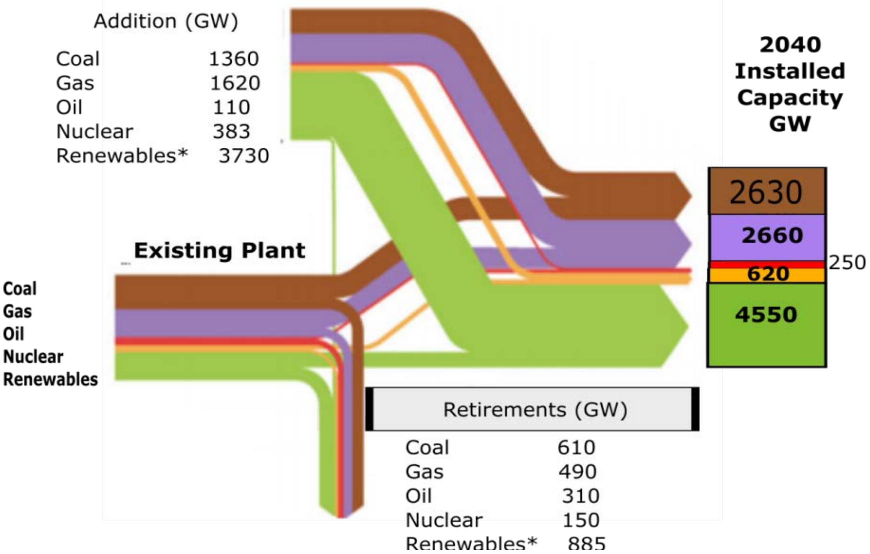


Fig. 2 Power generation capacity flow by the source from 2014 to 2040 projected by [10]

From figure 2, in the year 2040, the power generation capacity is expected to attain 10700GW compared to 5952GW in 2014. Electrical energy obtained from renewables such as wind power and photovoltaics cannot be connected to the power grid without power electronic-based conversion systems [9]. The maximum utilization of energy-efficient systems is crucial in the reduction of CO_2 emissions and eco-unfriendly pollutants in the environs.

The rest of this paper is organized as follows: Section 2 describes the different methodologies and techniques of energy harvesting. Section 3 highlights the recent breakthroughs in the development of efficient and effective hybrid mechanisms, and finally, conclusions and recommendations are presented in Section 4.

II. MATERIALS AND METHODS

There are several sophisticated modern methodologies used to harvest existing ambient energy. Although some of these energy harvesting options have yielded tangible results and have been implemented in many low-powered autonomous systems, the rise on the internet of things (IoT) has led to the study of hybrid of these mechanisms. In this section, a brief discussion of efficient energy harvesting mechanisms is presented.

A. Vibrational Mechanism

Vibrational energy is available in various environments as an alternative form of waste energy [12]. Piezoelectric, electrostatic, and electromagnetic energy harvesting mechanisms are the four main forms of vibrational energy harvesting. Research has shown that piezoelectric energy conversion produces relatively higher voltage and power density levels than the electromagnetic system.

1. Piezoelectric Energy Harvesting (PEH)

The piezoelectric effect occurs in some materials (mostly ceramic and crystals), these materials can generate electrical energy when subjected to mechanical stress. This effect was discovered by Pierre and Jacques curre in 1880. High power densities and easy means of application are the advantages of Piezoelectric materials compared to the other means of energy transduction [12].

Piezoelectric energy harvesting (PEH) involves scavenging electric potential from ambient energy sources, using a piezoelectric energy harvester. This energy harvesting mechanism has high energy density and alternating current (AC) can be produced in response to applied strain, hence, it is the most preferred energy harvesting mechanism among the VEH [13]. This mechanism has been mainly considered as a cantilever beam coupled with a proof mass. Generally, piezoelectric materials are strained to convert mechanical energy to electrical energy. This straining process generates charge separation across the material (see figure 3), and consequently, an electric field is produced [14].

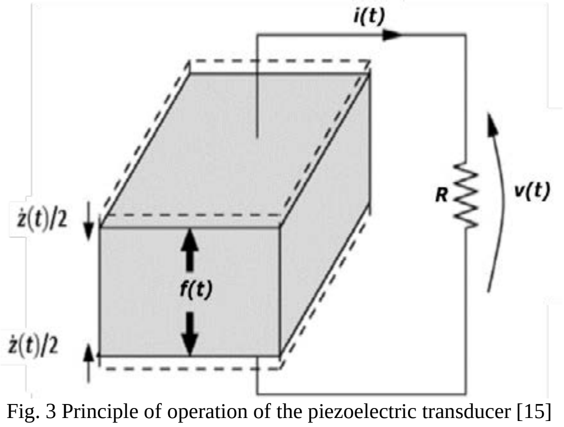


Fig. 3 Principle of operation of the piezoelectric transducer [15]

Some of its bottlenecks include energy loss due to clamping conditions, the additional space requirement for the clamping device and proof mass, and failure due to excess strains. To address some of these challenges, [16], proposed a design paradigm of the cantilever beam, known as piezoelectric energy harvesting skin (PEH), which can be attached directly to the surface of a vibrating system and thus eliminates proof mass and clamping.

Fundamentally, piezoelectricity is an interaction between the electrical and mechanical behavior of materials [17]. It has two effects: the direct and converse effects. In the direct effect, piezo materials generate electric polarization due to mechanical deformation, whereas the converse effect produces mechanical strain when an electric potential is applied to the materials. Energy harvesting and piezoelectric transductions are examples of the direct piezoelectric effect.

According to IEEE standards on piezoelectricity (1998), the constitutive equation for piezoelectricity is expressed as Eq. (1)

$$\left.\begin{aligned} \mathrm{D} &= \varepsilon^{s}E + eS\ (electricalequation) \\ \mathrm{T} &= C^{E}S - e^{t}E\ \ (mechanicalequation) \end{aligned}\right\} \qquad (1)$$

The variables D, T, S, and E are electric displacement, mechanical stress, strain, and electric field respectively, and C and ε are elastic constant and dielectric permittivity respectively. The properties of piezoelectric material include high piezoelectric and dielectric constant, high flexibility, and low electromechanical coupling. Lead zirconate titanate (PZT), polyvinylidene difluoride (PVDF), zinc oxide (ZnO), lead magnesium niobate lead titanate (PMN-PT), and propylene polymer are some of the piezo materials.

Piezoelectricity in some elements takes the form of separation of electric charge within a crystal lattice and if this is not short-circuited, the applied mechanical stress induces a voltage across the material [18]. The electric cigarette lighter is one of the many applications of piezoelectric materials. In this system, pushing the button causes a spring-loaded hammer to hit a piezoelectric crystal, and the voltage that is produced injects the gas slowly as the current jumps across a small spark gap, and with this idea, portable sparkers used to light gas grills, gas stoves, and a variety of gas burners have built-in piezoelectric based ignition systems [19].

The schematic of the piezoelectric microgenerator is shown in figure 4.This diagram shows that backward coupling greatly affects the previous stage and hence the global performance of the harvester [20]. Thus, when designing an efficient piezoelectric harvester, the global chain should be considered rather than the separate optimization of each stage.

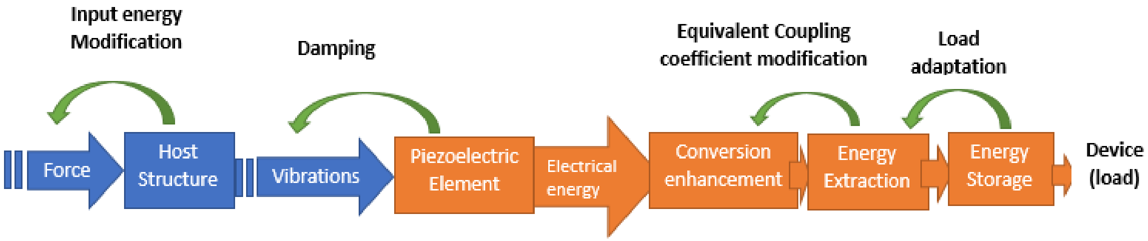


Fig. 4 Basic block diagram of the piezoelectric energy harvester [20]

Materials used in PEH could be classified as inorganic and organic matters. Currently, piezoelectric single crystals and polycrystalline are the common inorganic piezoelectric materials. A well-known Organic piezoelectric material is polyvinylidene fluoride (PVDF) [21]. Other organic nanostructures discovered in recent years through special processing are nanowires [22], nanotubes [23], and nanoparticles [24].

Nanostructures with a high effective piezoelectric constant are used for energy harvesting in nanoscale PEHs and reports have shown high conversion efficiency in nanoscale PEHs [25]. Also, nanostructures are lead-free and hence do not cause pollution of the environment. A major difference between piezoelectric ceramics and polymer at large scale PEHs is that ceramics is the largest material group for piezoelectric devices, whereas a piezoelectric polymer has fastest the growth because of its small size and lightweight. Furthermore, the dielectric constant and piezoelectricity of the single crystal are lower than that of ceramics, despite the disadvantages of the piezoelectric polymer such as low impedance, and low density, it should be noted that its piezoelectric constant is also relatively low. Other merits of piezoelectric ceramics over polymer are the plasticity of the shape is higher, and the material composition is easy to be controlled. The development of environmentally friendly piezoelectric ceramic (lead-free) is ongoing. In [26], $K_{0.5}Na_{0.5}TiO_3$ and $NaNbO_3$were reported as lead-free materials, but the sintering process of these materials is tasking. Guo *et al.*, 2005 examined $(Na_{0.5}K_{0.5})$ NbO_3-$LiTaO_3$ using mixed oxide and revealed that it was a good lead-free ceramic material.

2. Electromagnetic Energy Harvesting (EMEH)

This is another form of vibrational energy harvesting where electromagnetic motors are often used, especially when the vibration magnitude is large. The coil, proof mass, magnet, and spring are the main features of EMEH [27]. The electromagnetic motor can act as an actuator and a harvester at the same time, capable of bi-directional power flow [28]. When an electromagnetic motor is modeled and used as a voltage source in serial connection with the resistor and inductance of the motor [29], electrical energy is dissipated as heat waste, and [30] remarked that resistance load approximates the potential amount of energy harvesting system. [31, 32] used an electromagnetic transducer as a passive vibration damper, the performance of the vibration can be improved by shunting the damper with a resistor, inductor, and capacitor [33], and rather than losing the electric energy in form of heat waste [34]. This analysis applies to linear electromagnetic motors, and similar relations can be obtained for the rotational electromagnetic motors with permanent magnets ([28]). An example is Energy recovery from vehicle suspension. Instead of the dissipation of the vibrations into heat waste using shock absorbers, the energy can be harvested, thus reducing the vibration [35, 30, 36].

The principle of the Electromagnetic energy harvesting mechanism is based on Faraday's law of electromagnetic induction which states that an electric current is induced in any closed circuit whenever a magnetic flux passes through a surface bounded by the conductor change. Applying a permanent magnet and coil is the most effective way of achieving this for energy harvesting in EMEH. In Electromagnetic harvesting, kinetic energy is transformed into electricity by moving a coil across the field [37, 38], thereby inducing a voltage. This mechanism is difficult to manufacture at the microscale, despite being simple and rugged [39], whereas Macro-scale devices are bulky due to their large magnetic components [40]. According to [41], the advantage of this mechanism includes the low cost of production, no maintenance required, and the ability to harvest energy in a wide range of frequencies. Some formulations and principles of electromagnetic vibration harvesting are reported in ([42, 43]. Permanent magnets and coils generate a very strong field and are mostly used in EMEH. The coils normally perform as a conductor or are composed with a permanent magnet act to fix to the frame, though the other attaches to the inertial mass [28].

A recent application of EMEH is the ball-screw mechanism. It was used by [44] to design an electromagnetic transducer for energy harvesting from large scale civil structures, while [41] presented a prototype of an electromechanical actuator consisting of a rotational electromagnetic motor and ball-screw mechanism. The ball-screw mechanism converts the translational motion into rotary motion, which drives the motor. Also, using this mechanism, a vehicle’s vibration performance experiment and potential for energy scavenging were examined [45].

The vibrational power generator and investigation of the optimum condition for electromagnetic damping and local resistance were modeled by [43]. Also, they verified the optimum condition by using measurements on two macro-generators. From their analysis, the parasite damping is always greater than electromagnetic damping, and this power is maximized for a load resistance equal to the coil resistance. A novel micro energy harvester of size 9.5 × 8 × 6 mm^3, which employed an array of perylene cantilevers was proposed [46]. This harvester generated voltage under the relative motion between the stationary magnet and the coils. These values can be improved considerably by increasing the coil turns and the natural frequency of the cantilevers. [47] developed a mini-scale electromagnetic energy harvester prototype that consists of a coil and a silicon wafer cantilever beam, with four pole magnets as its proof mass. The experimental investigation achieved its aim of demonstrating the possibility for a device of 0.15cm^3, shown in figure 5, to generate efficient power from 0.59m/s^2 of the ambient vibration.

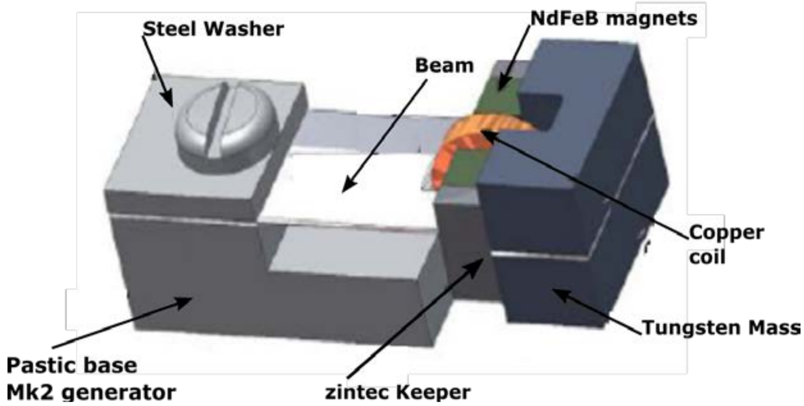


Fig. 5 Microcantilever generator [47]

In a combined theoretical and experimental study presented by [48], an EMEH was configured to utilize the movement of a levitated hand-magnetic element to generate power in both transient and steady-state of the harvester. This investigation utilized a predictive model which gave an insight into the mechanism of energy transduction and geometric optimization for smart design of energy mechanisms. Further, it was established by [49], that the main limitation of EMEHs is their non-linear behavior. Thus, performance maximization is currently a difficult task. This can be achieved by topology optimization, modeling, and evaluating their energy transduction mechanisms in both large-scale and small-scale application. This would ensure the design of smart EMEHs with negligible energy loss.

3. Comparison between PEH and EMH

EMH generates power based on faraday’s law of induction, which equates the time derivative of the flux to the electromotive force. Apart from the fabrication boundaries of coil diameters and turns, theoretically, EM harvesters are bound to be limited at the low speed [50], Thus EM harvesters perform better at high frequencies, and piezoelectric energy harvesters outperform at low frequencies [51]. Generally, at the microscale, EMH output voltage remains lower than the need for power devices [52]. Hence, piezoelectric, and electrostatic harvesters are more suitable for microscale applications, while electrostatic systems are more advantageous due to the ease of integration to microelectromechanical (MEMS) [53]. Both EMHs and PE harvesters do not require voltage sources whereas electrostatic harvesters require distinct voltage sources and are more difficult in practice, and in contrast to EMHs, PEHs produce adequate output voltage but low current level [51, 54, 53]. Among these 3 mechanisms, the simplest one in terms of required size, components and directly transducing mechanical energy to voltage output is the piezoelectric generator [55]. In addition to PEH at a microscopic level, EMHs also provide simplicity in production, geometry, and design. PEHs are applicable for micro-, meso-, and large- scales, while EMHs are easily manufactured and although they perform better at mesoscale, they can also be integrated into MEMS.

4. Triboelectric Energy Harvesting

Triboelectric energy harvesting occurs when two dissimilar materials contact each other through friction. According to [56], bonds are formed between the parts of the two surfaces having opposite tendencies i.e., to gain and lose electrons [57], [58]. For instance, Aluminum materials tend to lose electrons when it meets a less positive triboelectric material such as polydimethylsiloxane (PDMS) [59], [60]. Molecules, ions, and electrons are believed to be the charges transferred in the mechanisms. In general, the advantages of triboelectricity mechanisms include higher power output, low-cost materials, and a simple fabrication process.

Based on principle, five modes of TENG have been invented as highlighted in figure 6. Utilizing biomechanical energy generated by the daily actions of humans in many small electronics and sensors which are being converted from battery powered to self-powered are giving rise to new triboelectric mechanisms. This new effective energy harvesting technique is widely used in automatic and biosensors [61]. The attribute of high performance at low frequencies of this mechanism makes it suitable for biomedical application when harvesting energy produced by heartbeat [62]and motion of the respiratory system [63], the human movement for implantable and wearable devices [64][65]. This mechanism has been combined with other harvesting mechanisms as can be found in [66],[67][68]. The performance of triboelectric energy harvesters under random excitation is the focus of [69]. They reported a maximum peak power density of 7Mw/m^2 at 1.4g with an optimal resistance of 4mΩ and noticed that a large gap between the triboelectric layers results in higher output voltage for low excitation amplitudes but lower bandwidth. Less positive triboelectric material can be used to examine this random excitation. The triboelectric transduction mechanism work cycle is shown in Fig. 7. The last four processes repeat during the work cycle.

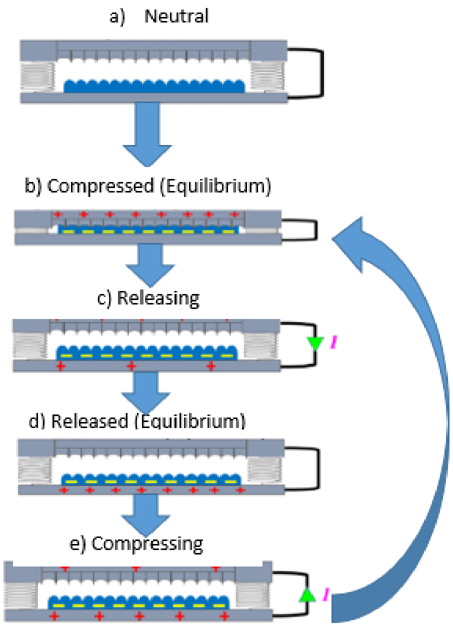


Fig. 6 The triboelectric energy harvesting cycle

Devising new tools to accurately measure the surface density and its relation to dielectric properties [70] and surface morphology of the material would ensure a better understanding of the triboelectric effect and performance optimization of harvesters based on this mechanism. Some challenges faced by the hybridization of standalone energy mechanisms include coupling the output powers from TENG and EMG, and high friction lateral sliding of TENG for real-life applications.

5. Electrostatic Energy Harvesting

An electrostatic harvester harnesses the work ambient vibrations exert on the electrostatic force of a variable capacitor [71]. This utilizes the force between charges stored on electrodes to convert the mechanical energy into electrical energy. As shown in figure 7, when the charge is placed on the capacitor, and the plates are moved apart, mechanical energy is converted into electrical energy which can be stored and utilized by a load.

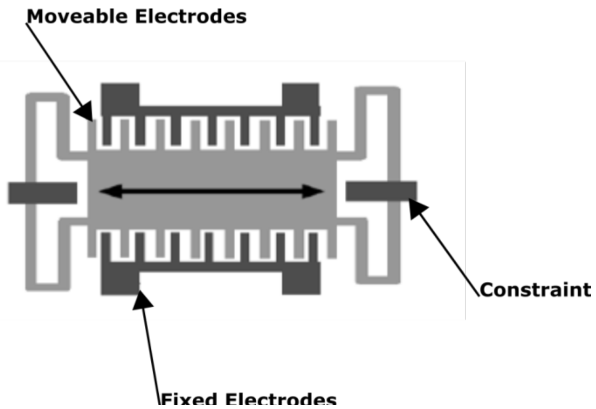


Fig. 7 Schematic of a typical electrostatic harvester vibrating horizontally [72]

An electrostatic generator that employs a variable micromachined capacitor was presented by [73]. Fundamentally, vibrations cause the gap and/or surface area of a parallel-plate capacitor to vary with a net effect, under constant charge or voltage conditions, of producing electrical energy [74]. Also, this energy scavenging mechanism harvesting does not require smart materials and could be used in microelectromechanical systems. Due to a capacitive-based device, this harvester generates a relatively high voltage of 2~10 V and results in a limited current-supplying capacity due to its capacitive property [72]. To improve the amount of energy harvested and the output power density of this mechanism, an optimized electrostatic harvester was reported in [72]

Presently, piezoelectric, or PZT, is the most common material due to its compatibility with MEMS (Micro-Electro-Mechanical System) and compact configuration, but its challenges such as brittleness, aging, depolarization, and high output impedance limit its applications in real wireless sensor networks (WSN).

B. Thermal Energy Harvesting

Thermal energy is another form of energy that is readily available in the environment. Some notable sources of Thermal energy harvesting are man, machine, animal, and other natural resources. The search for an efficient way to convert thermal into useful electrical energy has been ongoing for decades. Thermal energy is commonly present in the ambient as temperature gradient and/or temperature time-variation. The electrical energy generation effects corresponding to these two variations are the thermoelectric effect and pyroelectric effect.

1. Thermoelectric Energy Harvesting

This power harvesting mechanism utilizes the well-known thermoelectric effects which incorporate the Seebeck, Peltier, and Thomson effects. These effects are reversible thermodynamically. In the Seebeck effect, two dissimilar metals whose junctions are at different temperatures are connected in a series circuit, as shown in Figure 8.

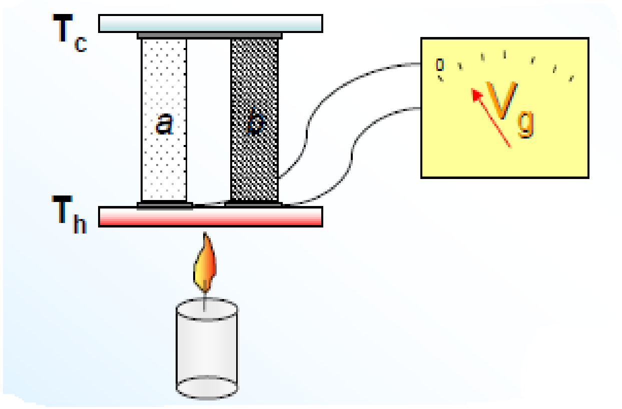


Fig. 8 Representation of thermoelectric device [75]

Both energy harvesting and cooling occur in this mechanism. A thermoelectric device generates a potential when a temperature difference occurs on each side. Whereas, when a voltage is applied to this device, it produces a temperature difference.

The components of thermoelectric systems are doped semiconducting elements arranged thermally in parallel and electronically in series as shown in Figure 9**.** If heat is flowing between the top and bottom of the thermoelectric device (forming a temperature gradient) a voltage will be produced and hence an electric current will flow.

A thermoelectric harvester is a heat engine and like all heat engines, it obeys the laws of thermodynamics. The efficiency of this heat engine when it operates as an ideal generator (without heat losses) is defined as the ratio of the electrical power supplied to the load to the heat absorbed at the hot junction [71]. For a given temperature difference, the conversion efficiency (η) is limited by the properties of the material, and the expression for this parameter is given in [76].

$$\eta = \frac{\theta_2-\theta_1}{\theta_2}\frac{\sqrt{ZT+1}-1}{\sqrt{ZT+1}+\frac{\theta_2}{\theta_1}} \qquad (2)$$

In Eq. 2, θ1 and θ2 denote the temperatures at the cold and hot sides of the converter, and ZT represents the figure of merit.

Generally, the applications of thermoelectric technology have steadily increased for recovering ambient energy in wide areas. A waste-heat thermoelectric generator concept was initiated by [77]. They established that a reversible heat engine is important in the performance of thermoelectric harvesters.

There are many attempts to increase the electric power factor of thermoelectric, which would expand the application of these devices. The synthesis of intermediate valence compound $YbAl_3$ examined by [78] showed that at temperatures below 100 K, the electrical resistivity and Seebeck coefficient reveal temperature dependence, and when huge Seebeck coefficient and low resistivity of crystal $YbAl_3$ are combined at 80K, it yields significant power factor of 340 × 10-6 W cm-1K−2. A small thermoelectric harvester based on thin-film thermoelectric materials was developed by [79].This device at a temperature differential of 10°C generated power of 15 µW/cm2.

Microscale air vehicles powered by thermoelectric generators (TEG) were examined by [80]. The goal of the investigation was to recover the engine's waste heat in form of electric power by integrating the TEG in the assembly. A 380mW of electric power was recovered from the exhaust system of the combustion engine when a TEG was mounted on the system. There are numerous research on waste heat recovery from the exhaust of automobiles using thermoelectric harvesters. A novel thermoelectric device was designed and tested by [81]. This device was able to recover an electric power greater than 20Kw when mounted on a diesel engine. And with 5% efficiency, the device can enable the generation of 750W of power. Also, a TEG was embedded in the exhaust by [82], and from the experimental evaluation, the electric power of 58W was recovered.

Another exhaust system was developed by [83], using about ten modules of TEG and a heat exchanger, the system produced 266W of power. A little greenhouse device that recuperated thermal energy from solar by maximizing the radiation captured was presented by [14].

Micro and nanogenerators are now available due to the fast advancement in formulating new thermoelectric materials of good performance. The miniaturization of n-legs and p-legs of thermoelectric in the micro-devices has been the focus of some reported research. In both micrometer and nanometer scales, the properties of the thermoelectric material are the same as that in large size. Theoretically and experimentally, it has been established that the nanowires of thermoelectric material should have an enhanced figure of merit due to the quantum-size effects [71]. Similarly, a one-dimensional n-type and p-type Bi2Te3 nanowire has been successfully prepared by Wang et al. Based on those works, there are different emanating micro and nano harvesters comprised of n-type and p-type nanowire arrays were designed. These miniature harvesters are sometimes used independently as power generators and often combined with electrical devices to scavenge electric power from waste heat.

A novel development process for this mechanism was suggested by [84]. The ten-step scheme, illustrated in figure 9, provides support to the developer of the thermoelectric energy harvesting systems (EHS).

An analysis of low-temperature thermoelectric energy harvester by [29], focused on energy conversion efficiency improvement from thermoelectric generator (TEG) design. An application of a thermoelectric energy harvester in building energy management (BEM) investigated by [85] is presented in figure 10, as the layout and key parameters of a thermoelectric generator.

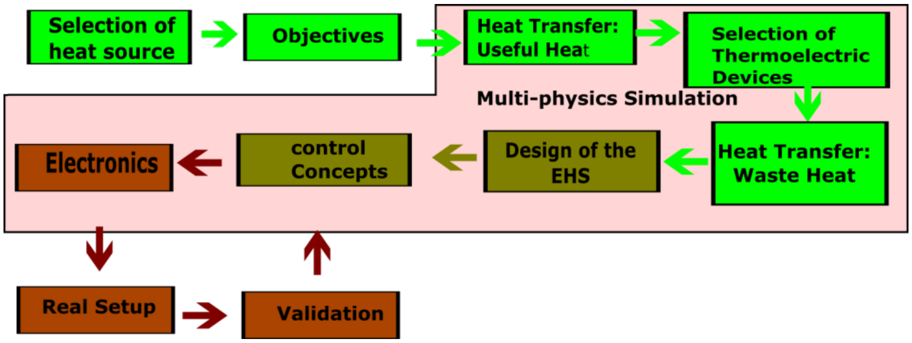


Fig. 9 The model-based development process for thermoelectric energy harvesting systems [86]

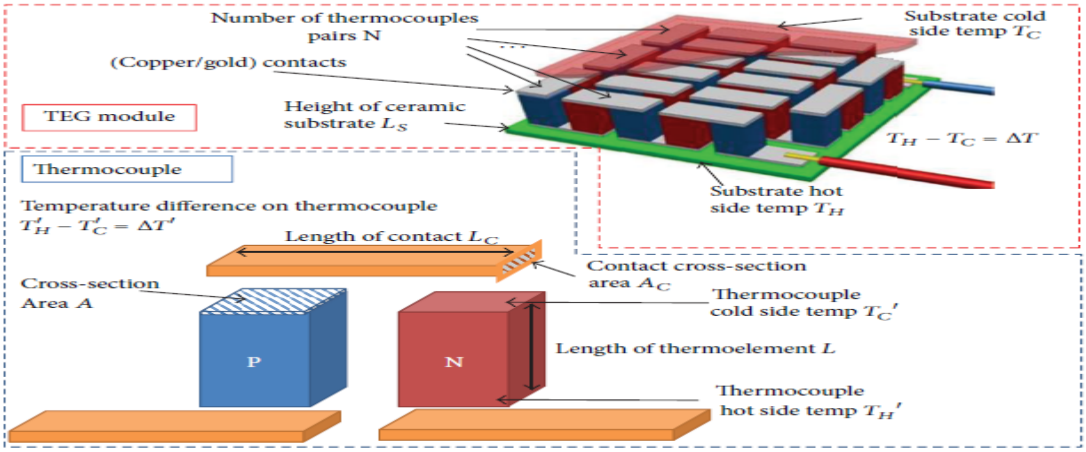


Fig. 10 The thermoelectric generator layout and key parameters [85]

2. Pyroelectric Energy Harvesting

Pyroelectricity can be defined as the capacity of certain materials to produce an electrical charge when heated. Pyroelectric energy conversion offers a novel and direct solution to convert waste heat into electricity by alternatively heating and cooling a pyroelectric material resulting in electricity generation. Contrary to the thermoelectric generator, pyroelectric materials do not need a temperature gradient, but time temperature fluctuations, thus the application targets are quite different. The pyroelectric coefficient at constant stress σ can be defined using scalar notation [23, 71]

$$\frac{\partial D}{\partial \theta}_{E,\sigma} = \left(\frac{\partial D}{\partial \theta}\right)_{E,e} + \left(\frac{\partial D}{\partial e}\right)_{E,\theta}\left(\frac{\partial e}{\partial \theta}\right)_{E,\sigma} \qquad (3)$$

Where E, e D, and θ denote the electric field, electric displacement, strain, and temperature of the pyroelectric material respectively. In Eq. (3), the primary pyroelectric material effect, or the first term in the equation corresponds to the charges produced owing to the change in polarization with temperature when the pyroelectric materials are constant [71].

The benefits of pyroelectric energy harvesting are no need for high source temperatures, unlike thermoelectric energy scavenging. Secondly, it has the potential for reliable and long-lasting power generation. But, there is the need for pyroelectric current to be rectified using a full-wave bridge rectifier or Schenkeldoubler.

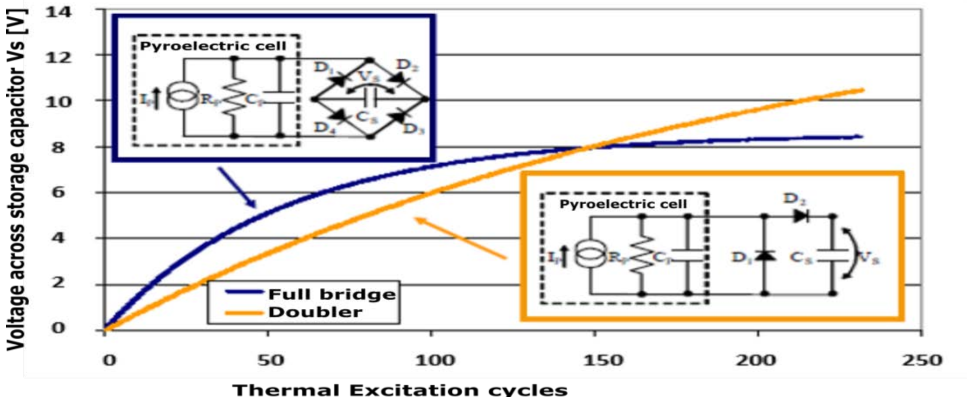


Fig. 11 Voltage across capacitor against excitation cycles [75]

A characterization of pyroelectric samples was studied by [75], and the experimental results highlighted in figure 11 demonstrate the harvested energy can be compatible with use in autonomous sensors.

From Eq.3, the maximum power harvested in the pyroelectric mechanism can be expressed as

$$P_{max} = \frac{\sigma^2\theta^2}{2\pi\varepsilon_{33}^{\theta}} f \qquad (4)$$

In Eq. (4), $\varepsilon_{33}^{\theta}$ and f are the dielectric permittivity of the pyroelectric material and frequency respectively.

Hence, according to [71], the FOM is represented as Eq. (5).

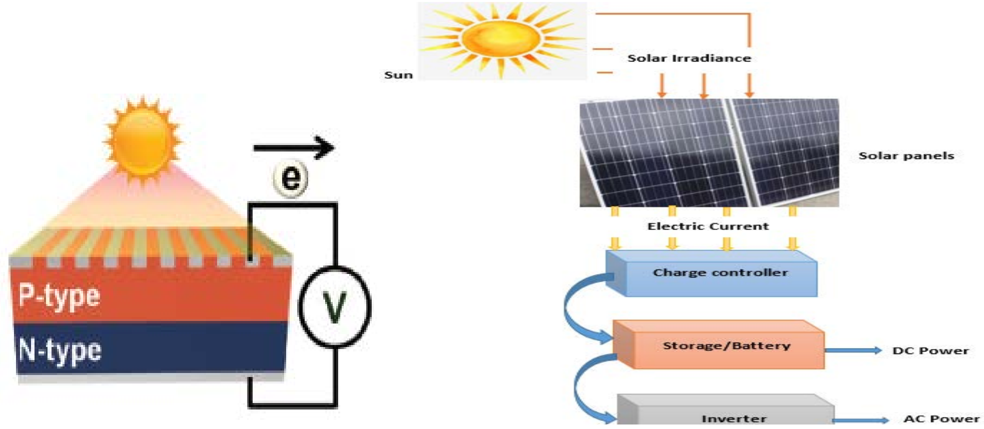
$$FOM = \frac{\theta^2}{\varepsilon_{33}^{\theta}} \qquad (5)$$

Improving the FOM of the pyroelectric energy mechanism increases the efficiency of the harvester.

3. Photovoltaic Harvesting

This energy harvesting mechanism generates electrical energy from the light energy in solar radiation using photovoltaic cells. A photovoltaic (solar) cell is one of the promising green energy harvestings converting solar energy into useful electricity by photovoltaic effect [4]. The solar energy that reaches the earth has been estimated at around $173 \times 10^{12} Kw$, and exceeds by far humankind's needs [87]. Such as geothermic or tidal energy, nuclear power, and fossil fuels [88].

The principle of this energy harvesting mechanism involves each cell which consists of a reverse-biased pn$^+$ junction, in which the light crosses with the heavily conservative and narrow n+ region [19]. Within the depletion region, photons are absorbed, and this action generates electron-hole pairs. Each pair is instantly separated by the built-in electric field of the junction. Holes and electrons are accumulated at the P and n+ regions respectively (see figure 12a). Subsequently, an open circuit is established. As illustrated in figure 12 b, solar irradiance is converted to direct current and linked to the charge controller to avoid possible reversal of the power to the solar panels. The battery stores the electric power which can be used at night when sunlight is not available. The inverter connected to the battery or storage system converts the direct current (DC) electricity into alternating current (AC).



(a) (b)

Fig. 12 Schematic illustrations of energy harvesting systems based on photovoltaic effect [4], (b) Detailed connection of solar energy harvesting

When a load is connected, the stored electrons travel through the load and recombine with holes at the p-side, producing a photocurrent that is proportional to the light intensity. Several research efforts have been conducted so far have demonstrated that solar cells can produce sufficient power, and the efficiency of these mechanisms can be significantly increased by exposing the internal surface area of the device [89].

The energy harvested from this mechanism is both renewable and sustainable. The harnessing and utilization of photovoltaic energy have increased greatly in the last two decades, reducing/eliminating the dependence on power generation through conventional means, and ensuring that renewable energy is adequately available in homes and other establishments.

According to [88], based on the mode of capturing, conversion, and distribution, we have two broad characterizations of solar energy harvesting mechanisms i.e., passive and active. The use of photovoltaic solar panels, fans, and pumps in converting energy from sunlight into useful potentials is known as active characterization while the passive method involves the selection of favorable thermal materials, creating a vacuum that permits the natural circulation of air, and the position referencing of a building to the sun [90, 88]. The development of this energy mechanism will enhance the sustainability of countries' energy security through dependence on inexhaustible energy sources [10]. This is because the total energy market share of solar is small and below 1% of the total consumption, compared with roughly 85% from coal, oil, and natural gas [91] The thermal (pyroelectric) energy harvesting figure of merit (FOM) is used to quantify and check the effectiveness of this energy harvesting mechanism. For the heat exchange on the outer surfaces, it has been shown that FOM does not express the performance of a thermoelectric harvester [92].

Overall, this energy conversion is an eminent energy harvesting mechanism capable of generating higher power output levels, when compared with the other energy-harvesting mechanisms [19]. But its scavenged power strongly relies on solar intensity; in other words, varying environmental conditions.

III. THE FUTURE - EFFICIENT AND EFFECTIVE HYBRID ENERGY HARVESTERS

As the principle of the major standalone harvesters has been described, this section aims to present the various hybrid energy harvesters that have been reported in the literature and discuss their performances. The scope of hybrid energy harvesters is vast; hence we are mostly concerned with the efficient performance of hybrid VEH in this review, especially at the microscale level for self-powered WSNs.

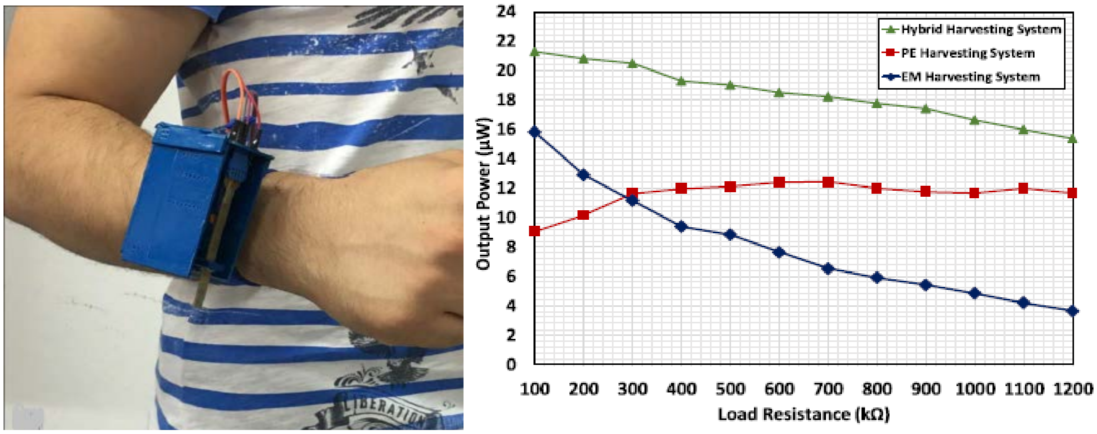
With the application of the first law of thermodynamics, conservation of energy implies that the existing and dissipated power sources can be scavenged and transduced into another form of usable energy [93]. Traditionally, energy harvesting was only important in the use of electronic devices, humans, biosensors, health monitoring, and wireless sensors [94, 95, 51, 55]. Single or individual power harvesting generates low power output compared to the energy supplied to the system. To eliminate this low power output and meet the increasing energy requirements of traditional and modern systems, hybridization of the standalone energy harvesting systems is employed [96, 97, 98, 99, 100, 101, 102, 103, 54, 104][105, 106, 107]. The combination or harnessing of multiple power sources for energy extraction in a single component is called multimodal or hybrid energy harvesting [108, 109, 110, 53].

To support the low input and continuous flow of energy, an ultra-low-power hybrid inputs of thermal and vibration micro-energy harvester (HMEH) was presented by [111], the HMEH system achieved an output power of 1.6 and 1.182mW for simulation and hardware part respectively. A similar hybrid architecture aimed at extending the lifetime of semi-active Radio frequency identification (RFID) tags was proposed by [112].

Hybrid inputs of RF, thermal, and vibration were simultaneously harvested, and 6.5mW of output power and 90% of efficiency were expected in the system. A comparative study between thermoelectric and pyroelectric energy harvesting presented by [113], stated that both mechanisms are complementary and even though pyroelectric energy harvesting outputs little energy, it has greater efficiency. Also, thermoelectric materials typically possess large heat conductivities, which decrease efficiency. For this reason, they are difficult to implement.

A synergistic hybrid energy harvesting that interfaced scavenge power obtained from piezoelectric (PE) and electromagnetic (EM) sources and which drove a single load was investigated by [114]. The prototype of a wearable energy harvester attached to the wrist of a jogger is presented in figure 13(a), and experimentally, the fundamental frequencies between 2 and 3Hz were mounted on the base and operated around 20Hz damping frequency.

The power extracted from the standalone and the hybrid harvesting circuits for different loading conditions are highlighted in figure 13(b). In the individual operation, the power output of the PE harvesting system is low at small load resistance, and increased with increasing load resistance, signifying that the losses decreased [114]. Also, the Electromagnetic system generates more power at a lower resistive load, as the resistive load approaches the internal resistance of the EM harvesting system. The recent and most effective HEH is presented in table I.



(a) (b)

Fig. 13 (a) The hybrid system placed on a human's wrist [114]. (b) Experimentally extracted power [114]

TABLE I SOME RECENT HEH MECHANISMS

Properties	**[114]**	**[115]**	**[116]**	**[117]**	**[118]**	**[119]**	**[120]**
Sources	PE EM	PV TEG, PE	PE EM, TEG	GBFC TEG	PE	PE	TEG RF
Excitation Frequencies	PE:20-500Hz EM: 2-10Hz	TEG:DC PV:DV PE:NA	PE:282Hz EM:2-3Hz TEG:DC	GBFC:DC TEG:DC	200 Hz	NA	TEG:DC RF:NA
Minimum Input power	PE:<0.7 μW EM:1 μW	PV:150μW TEG:90μW PZT:45 μW	PE:4.2μW EM:1 μW TEG:NA	GBFC:0.5μW TEG:0.5 μW	20 μW	33 μW	TEG:70μW RF:NA
Output Voltage	1.1-3.41V	1.9V	0.8-1.25V	1.9 V	1.8-6.3 V	1-8V	1.75-4.3V
Maximum Conversion Efficiency	90% at 100 μW	NA	29% at 68 μW	85.5% at 56.4 μW	NA	80% at 5 mW	78% NA

Based on the size of the efficient hybrid harvesting mechanism, 400 μW power output in micro-scale by [114] is the greatest, while at mesoscale, the most promising mechanism yielded 200mW, as reported by [119]. The peak power achieved by [117] is considered the most efficient at a large scale among the reviewed mechanisms.

A new framework proposed by [121] adopted lightning search algorithms (LSA) to maximize the PEH converter using a controller board as the proportional-integral voltage controller (PIVC). This controller outperformed two other controllers investigated and increased the voltage from the range of 150-250mV at 30Hz A.C. to 7.05V DC. Similarly, to improve this system, [122] utilized a hybrid optimization technique to reduce the power loss of this converter during hardware implementation and obtained 85% on both simulation and experimental validation of the system.

Multiple natural energy sources can be harnessed in a single EMEH transducer. This has been demonstrated in a study aimed at suggesting a smart low-voltage electronic circuit for low-powered sensors and unmanned systems [27]. A detailed analysis of the major recent breakthroughs in the hybrid of electromagnetic-triboelectric VEH based on various architectures such as linear, rotational, sliding, pendulum, cantilever, multidimensional, magneto-electric, etc. was conducted by [70], they concluded that energy scavenging capacities of TENGs are still not enough to ensure steady power of most conventional electronic devices, and the creation of hybrid cells to simultaneously harvest energy from multiple ambient sources are recommended.

Abbreviations

The following abbreviations are used in this paper.

BEM	Building energy management
FOM	Figure of Merit
EM	Electromagnetic
EMEH	Electromagnetic energy harvesting
EMGs	Electromagnetic generators
GBFC	Glucose biofuel cell
HEH	Hybrid energy harvesting
IEA	International Energy Agency
IoT	Internet of things
MEMS	Microelectromechanical systems
PE	piezoelectric
PEH	Piezoelectric energy harvesting
PZT	Lead zirconate titanate
PVDF	polyvinylidene difluoride
PMN-PT	lead magnesium niobate-lead titanate
PV	Photovoltaic
RF	Radiofrequency
TEG	Thermoelectric Generator
TENG	Triboelectric Nanogenerator
RFID	Radio frequency identification
WSN	Wireless sensor Network
ZnO	Zinc oxide

IV. CONCLUSION AND RECOMMENDATIONS

Most developed standalone energy harvesting has yielded poor power outputs despite huge power input requirements. This paper summarized the recent developments of efficient hybridized-single energy harvesting mechanisms from ambient sources such as machine vibration, wind, solar, automobile noise, and waste heat. The introduction emphasized the world energy demand and the motives behind energy harvesting, thereafter, different standalone harvesting mechanisms, specifically, piezoelectric, electromagnetic, electrostatic, thermoelectric, pyroelectric, and photovoltaic mechanisms were highlighted, and, the efficient hybridized mechanisms were outlined based on excitation frequencies, minimum input power, output voltage, and maximum conversion efficiency. Despite the remarkable improvement of the mechanisms in the last decade, more experimental research outputs are recommended to improve the harvested energy in hybrid form as well as standalone mechanisms.

1. Monitoring performance and extraction power of mechanical vibration mechanism using piezoelectric or capacitive effects.
2. Development of an analytical model that would predict accurately, the efficiency of hybrid energy conversions.
3. Dimensional optimization to obtain higher energy efficiency of the suitable for autonomous micro-devices.

Finally, the development and improvement of the existing major standalone energy harvesters enable the generation of maximum power in hybridized architecture which would sustain the operations of low-powered autonomous systems. Control algorithms presented in [123] and [124] are recommended for the optimization of hybrid systems.

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