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# A REVIEW ON ENERGY HARVESTING FROM VARIOUS NON-CONVENTIONAL SOURCES

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## ABSTRACT

At present, scarcity of energy is an imperative problem where traditional energy sources are contracting progressively. So men have been rushing for renewable energy sources and researchers have come up with the idea of energy harvesting from our immediate environment. Sunbeams, wind, heat, mechanical stress, RF waves are readily available in the nature and energy is being extracted from these and put into use. This paper principally portrays different schemes of obtaining energy from ambient nature along with their operating principle, pros and cons, usages and impending possibilities. Apart from the above mentioned sources, energy harvesting from human power and other sources viz. Nano materials, Biological Parasitic, Atomic Particle motion are also taken into consideration in this text. This document explores different aspects of modern technologies like Wireless Sensor Nodes (WSNs), Micro Electro-Mechanical Systems (MEMS) which needs to be supplied limitless energy. Existing batteries are not suitable to provide the required power for the lifetime of these systems. Energy is available everywhere and if this energy is harnessed and channelized properly, this will help to provide limitless power to these device.

**KEYWORDS:** Piezoelectric, Solar, Electromagnetic, Electrostatic, Radio-Frequency, Thermal, Wind.

## INTRODUCTION

With the progression of technologies, the use of sophisticated gadgets has increased and also new sets of efficient devices are being produced day by day [1, 4]. Those gadgets, microprocessors [1], sensors [2, 7], transmitters/receivers [2] are battery-powered and we need those to last for a long period of time. Also the Wireless Sensor Nodes employs various sensor nodes which are connected together in wireless manner and used for target tracking, monitoring human structure and health issues, examining environmental activities [17, 21] etc. These devices use conventional batteries for power source. However, batteries have low lifespan and are expensive [1, 4, 5, 7-10] and they need to be recharged or replaced after a specific time.

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But if WSNs are employed in inaccessible locations where human involvement is not possible frequently, then the replacement of battery will be a great issue. Nowadays sustainable energy consumption is also a serious matter due to limited amount of natural resources. So a self-powered source is required. Obeying the first law of thermodynamics, conservation of energy implies that the existing and dissipated power sources can be scavenged and transduced into usable electrical energy [12]. After due consideration, scientists are researching for energy harvesting from ambient nature [1, 4, 7] and it is emerging as a self-powered source [15-19]. Energy harvesting is the procedure of trapping and accumulating easily available energy from ambient nature and storing it for using as electrical power later on. [8, 10, 15-21] It is also termed as 'Energy Scavenging' [8, 13, 15-17, 19, 20], 'Parasitic Energy', 'Micro-Generators' [20]. It is the most optimistic way to solve the finite lifespan problems like batteries have [1, 4-8]. As energy is scavenged from vicinity of surroundings, we can get lifetime supply of free energy with better efficiency [1-6]. Unlike batteries, these renewable energy supplies need low maintenance and hence cost is reduced [1-6, 8, 9]. Harvesting energy from human power will let the people experience more undisrupted service of the gadget, sensors they are using inside or outside their body [26, 28]. The growth of energy harvesting is significant over previous few years with the increased desire of developing wireless and portable devices. These devices include- Micro Electro Mechanical System (MEMS) [8, 9, 12, 15, 19, 20], Wireless Sensor Nodes (WSN) [2, 8, 9, 12, 15-19, 21], Biomedical sensors [7, 26], Chemical sensors [26] etc. Biosensors can be implemented in human brain to detect the brain impulses of the people having blindness, deafness, epilepsy, Parkinson's disease, paralysis etc. so that their mobility can be restricted properly [26]. Chemical sensors can also be used to detect health status but the main constraint is biocompatibility and power consumption [26]. Researchers have been pondering over the prime sources of energy harvesting. Findings say that solar energy is the most developed and economically sound solution for this [4, 8-10]. Beside this, wind energy harvesting through windmills has now emerged and are used in various applications [3-6, 8, 10]. New trend of RF energy along with thermal [8-11], mechanical energy (Electrostatic Converters [22], Piezoelectric Effect [8, 25]) harvesting is bubbling up beside those previously mentioned resources [3-6, 8, 25]. Nowadays RF energy (more the frequency, higher is the power) is being used everywhere for communication purpose and it can be harvested to power up low power equipment. In that case battery-free devices can be designed, so that freedom of charging can be achieved. These efforts will replace battery in different field in future [10, 11, 23, 27]. In addition to these, scientists have proved some body fluid [4], chemical or biological sources [8], exploiting human movements can also be used for energy harvesting. Cellulose nanomaterial is the biopolymer generated by the bacteria *Acetobacterxylinum.* They have various distinctive properties, for instance, sustainability, high strength, flexibility, limpidity and low thermal expansion. They can be implemented in electronic devices, storage devices and energy harvesting devices by means of sensors etc. The plus point is that this type of devices also includes biodegradable ones. Using any one of the methods, the lifetime and efficiency of the wireless, low power, portable devices can be extended and improved [15-17, 19]. WSNs comprised of a sizeable sensor nodes are capable of wireless communication and make it viable to trace sensor nodes in isolated and sometimes unrecoverable places. Routing is important for WSNs. It is the method of communication of data between sensor and base station. If there is any problem in routing then with the increase in energy consumption, lifetime will decrease. So the correct routing protocol must be employed to

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decrease the energy consumption which can be done by energy harvesting techniques [21].

## LITERATURE SURVEY

Erdogan reported about piezoelectric energy scavenging by assorted methods and explained the functioning principle of piezoelectric energy harvesting.

Chalasani *et al*. reviewed the variation of energy scavenging sources for embedded systems. The required physical, electrical, environmental properties that an energy harvester should possess, was also mentioned by them. Piezo materials, varactors, electromagnetic energy harvesters cantilever beam were introduced as a source of energy harvesters from mechanical vibration.

Mitcheson *et al.* reported on various motion-based energy harvesting practices viz. direct force generators, electromagnetic inertial generators, electrostatic inertial generators, piezoelectric inertial generators etc., and also about air flow energy harvesting. They also tabulated different system parameters of various proposed energy harvesting devices and stressed on the size of devices thoroughly.

Yildiz reported about various ambient sources for energy harvesting and clarified its future in replacing batteries.

Tan *et al.* reported about sustainable Wireless Sensor Network and its various applications, researches, challenges etc. They included energy harvesting from ambient nature as a remedy to the power supply challenge. Then they discussed different methods to harvest energy.

Paulo *et al.* reviewed and predicted the future direction of the energy harvesting mechanisms for mobile medical gadgets. First they discussed the different mechanisms of energy harvesting. Then they mentioned the application of those mechanisms in the industry and medical field. In the future scope, they mentioned that the energy can be harvested from the body and the movement of the human being to power up the mobile medical devices. [11]

The paper by The Energy Harvesting Network (An EPSRC funded network) deals with the energy harnessing from human power. This paper discussed the approaches to harvest energy outside as well as inside the human body. The paper also discussed the scopes and the limitations of energy harvesting.

Olivo*et al*. discussed about different energy harvesting techniques like kinetic energy harvesters, low frequency magnetic field harvesters, inductive links, emerging techniques, their advantages, disadvantages and also discussed whether these techniques are directly applicable to the field of the implanted biosensors or not. They focused on the Inductive Links to power up implanted biosensors, calculated several parameters and compared this technique to all the others techniques. The predicted that inductive link is the most eligible technique to be implemented.

Cottone reviewed the vibration energy harvesting technique. Different types of vibration energy harvesting like electromagnetic, electrostatic, piezoelectric and magnetostrictive were discussed in detail along with their basic operating principle.

Kim *et al.* discussed about the methodology of energy extraction using mechanical stress or vibration. Energy extracting utilizing piezoceramics and piezopolymers were explicated in this paper. The basic principle of piezoelectric energy harvesting was elaborated in this paper along with some energy harvesters incorporating piezo materials were highlighted.

Dierks *et al.* reported that engineering educators should be concerned about the particular field of energy harvesting. They also informed about the different energy harvesting sources, such as, solar

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energy, air flow energy, vibrational energy etc. They explained Piezoelectric Vertical Axis Wind Turbine concept experimentally by designing the actual device.

Nechivute *et al.* reported about usage of piezoelectric energy as a valuable substitution of energy source for Wireless Sensor Networks. They compared various other energy sources and showed that vibration energy is more efficient in generating power than any other ambient sources of energy.

Matak *et al.* discussed the various non-conventional as well as green energy sources. Then the paper focused on different types of mechanical energy and their harvesting mechanisms, its working principle and the construction of these energy harvesters. They also discussed the FEM (Finite Element Method) simulated energy harvester modules. [10]

Sharma *et al*. discussed on several processes of energy harvesting like Electromagnetic Energy Harvesting, Photovoltaic Cells, Mechanical Vibration Harvesting, Mechanical Vibration Harvesting, Thermo-electric Generators. Then they discussed the paths in which the future research on energy harvesting may take place. The paper concentrated on Radio Frequency (RF) energy harvesting due to proliferating use of mobile and computing devices in our standard of living, nowadays.

Singh *et al.* introduced MEMS piezoelectric power generators. This paper discussed cantilever beam structure for energy harvesters. They provided basic equations to understand the operation of cantilever and mentioned unimorph and bimorph configuration of cantilever beam for power generation at low frequencies.

Calio *et al.* reported about detailed theory of piezoelectric energy harvesting methods and its applications. Also they compared different types of modes of piezoelectric energy harvesting and explained a particular mode for Micro Electro-Mechanical Systems' power supply.

Singh *et al.* discussed vibration energy scavenging technology as a stable power supply of portable electronic gadgets and Wireless Sensor Nodes. Piezoceramics of cantilever type, cymbal type, stack-type, shell type and piezopolymers for energy scavenging were elaborately discussed in this paper.

Prabha *et al.* reported that piezoelectric energy harvesting technique can be used in railway traffic signals, lighting a bulb or LED and also as a power supply. Also the charge level of battery will be updated through a message in the controller's mobile phone.

Nwogu reported about future of Internet of Things and also the energy harvesting as an alternative main source for its power supply. Also he compared vibrational data of different freight cars and showed that that can be converted into sufficient power that can drive sensors.

Panda *et al.* discussed on the use of Wireless Power Transmission (WPT) in various applications. Categorization of wireless power transfer and classification of WPT are based on the coupling between the transmitter and the receiver. Energy harnessing from RF is used in wireless transmission.

The paper discussed the problems associated with current approaches in WPT and the constraints to be removed in the future researches. They concluded that WPT will reduce the dependency on batteries as well as more improved transmission in future.

Sabo *et al.* reviewed on Cellulose Nano Fiber (CNF) substrate modification, production of flexible electronics on CNF substrate , use of CNFs as substrates for light-emitting diodes and displays, application of CNFs in LCDs(Liquid Crystal Display) and others optoelectronic devices, fabrication of energy harvesting and

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storage application using CNFs, utilization of cellulose nanomaterial as sensors and stimuli-sensitive functional substances. Then they discussed on piezoelectric and electro active effect in cellulose nanomaterial, magnetic cellulose Nano composites in aero gels and Nano paper, magnetostrictive cellulose Nano composites for actuation and sensing. They concluded that CNFs are economical and can be improved more, so these can be used in various functional devices commercially.

Ahmed *et al.* discussed various energy extracting methods and their niftiness in wearable health monitoring applications. They commented on solar, wind, radio frequency, thermal, vibrational sources. For health monitoring purpose, hybrid i.e. blending of different sources appeared to be helpful.

Chaware *et al.* reviewed on the energy harvesting from piezoelectric materials.

Abdulhasan *et al.* reviewed the improvement of antenna characteristics by energy harvesting. For harvesting applications, phase control on micro-strip patch array antenna, bandwidth improvement of slot antenna, gain enhancement of reflector patch antenna and coupled E-patch antenna with bandwidth and efficiency improvement could be achieved. Dual-port antennas, SIWs etc. are discussed as e-harvesting techniques of communication applications.

Sil *et al.* elaborately discussed mechanical and thermal sources of harvesting. The applications of harvesting techniques included in the paper were biomedical, wireless networks and various other fields.

Aljadiri *et al*. reviewed on Electrostatic Energy Harvesting. This paper discussed the use of variable capacitors like variable area capacitors, variable gap capacitors and variable dielectric constant capacitors for energy harvesting. They discussed on electrostatic harvester conversion mechanisms and compared several conversion mechanisms and the different capacitor structures. The paper concluded that electrostatic harvesters are simple in structure and their energy density can be increased by only changing the used capacitor's structure.

Rakholiya reviewed on several routing protocols for energy harnessing in wireless sensor networks.

Gure *et al.* discussed about Hybrid Energy Harvesters (HEH) vividly. They also described several types of multisource powered HEHs and draw comparison among them.

## SOLAR ENERGY HARVESTING

Solar energy is the most abundant and inherent natural energy source for energy harvesting. This source provides the maximum power density (theoretically 100 mW/cm$^2$, practically 3750 µW/cm$^2$) with respect to all the other energy harvesting sources like wind energy, vibration energy etc. [2] For solar energy harvesting solar cells i.e. photovoltaic cells is used. A photovoltaic cell is a unique form of semiconductor diode which transforms the light energy into DC electricity by the photovoltaic effect. The output power of photovoltaic cell can be given as,

$$P = EA_{cell}$$

Where $P$is the power output (Watt) of the cell, is the efficiency of the cell, $E$is the solar radiation (W/m$^2$), and $A_{cell}$is the area of the photovoltaic cell [2].

Several types of solar cells are being used. Those are Non-Silicon Thin film solar cell, Amorphous Silicon Thin Film solar cell, Polycrystalline Silicon solar cell, Mono-crystalline Silicon solar cell etc. [3]

### ADVANTAGES

The solar energy causes no environmental effluence. Solar energy is a renewable source of energy.

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## DISADVANTAGES

Solar panels require regular cleaning as well as maintenance so that those can work properly [2]. Direct sunlight is required to be incident on the solar panels so that we can get the maximum output from the panels. So solar panels can't be used in the region where direct sunlight is not frequently available [2].

Figure (a) shows the basic operation of photovoltaic cell.

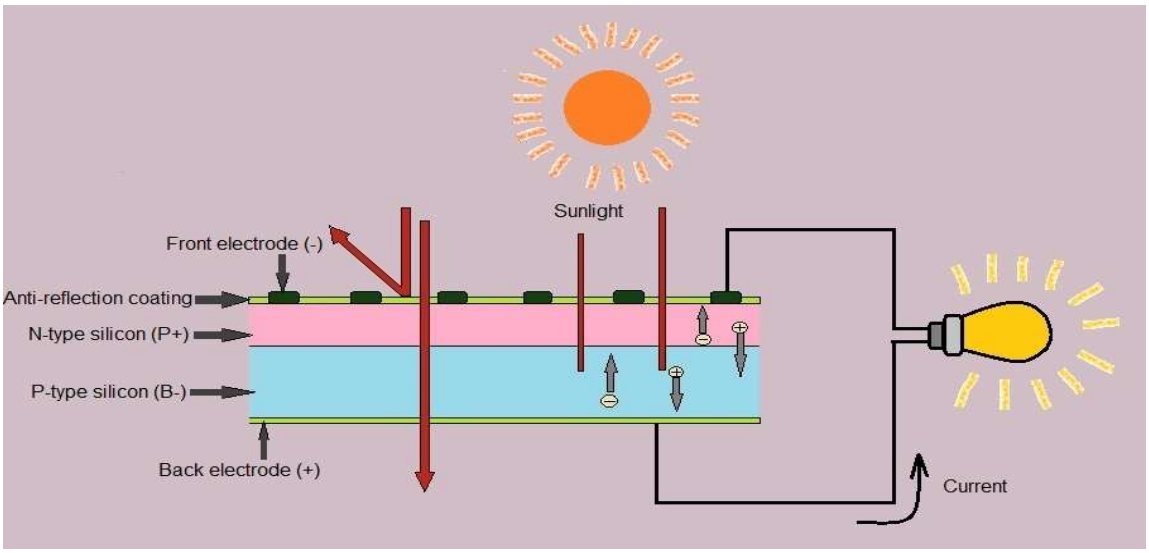


**Figure a.Schematic Diagram of Photovoltaic Cell:http://thesolarcell.blogspot.com/2008/06/most-commonly-known-solar-cell-is.html dated: 31/03/2018 [Ref. 29]**

**Figure b.Solar Panel: https://erfolconter.pt/2017/05/10/empresa-de-energia-solar-termica/ dated: 26/03/2018[Ref. 30]**

**Figure c.Solar Panel: https://www.indiamart.com/proddetail/solar-cell-panel-16291135248.html dated: 26/03/2018 [Ref. 31]**

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## APPLICATIONS

Solar energy, harvested from the solar panels, can be used for mobile devices [27]. Stored energy of the solar panels can be used to power up the lights, fans at low voltage. If more number of panels is used, more power will be generated, so high power equipment can be powered up. Typical solar panels are shown in the Figures (b) & (c).

## FUTURE SCOPES

Researchers are going on so that we can charge the mobile phones using solar energy but there is space as well as time constraint [27]. The solar nantenna is the latest concept which will be able to receive the solar radiation just similar to the radio waves. Further studies must go on to make the nantenna in reality [2].

## WIND ENERGY HARVESTING

One of the various energy sources that are considered to be natural as well as non-polluting is Wind Energy [17]. For wind based energy scavenging, wind turbines are used wherein dynamic energy of the wind is transformed to mechanical power [2, 17]. Further generators are used to harvest electricity from this mechanical power. Wind turbine consists of propellers which spin the rotor. The rotor is attached to the main shaft which in turn is rotated [17]. This rotation results into electro-magnetic induction and thus this induction is converted into electrical energy. There are two types of turbines- Micro or Small-scale Turbines and Macro or Large-scale Turbines [2]. The relationship between the output power from the turbine and dynamic energy of the wind is given by

$$P = \frac{1}{2}\rho S v_1^3 C_p$$

Where $P$ is the output power in Watt, $\rho$is the density of air (Kg/m$^3$), $S$ is the operative cross-sectional area of the turbine (m$^2$), $v_1$is the initial velocity of the inflowing air to the turbine (m/s), and $C_p$is the efficiency ofthe system. The efficiency of large-scale turbines is usually 30-50%, whereas for small-scale turbines, it reduces to 5-10%. Standard wind farms have the capacity factor in the limit 20-40% [2]. Rotational turbines are of two categories viz. Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT). HAWTs spin about axes parallel to the air flow and VAWTs rotate about axes perpendicular to the wind flow. HAWTs are unidirectional but VAWTs are omni directional but in contrast they are less efficient. Still VAWTs are preferred as they can be incorporated irrespective of the wind direction [2]. Figure (d) shows some commercially available turbines.

## ADVANTAGES

There are lots of advantages of using wind energy. Wind is open and renewable source of energy. It is easily obtainable. The wind turbines employed in this regard does not harm at all. Moreover this method of generating energy is clean and non-polluting. Wind energy harvesting is far more eco-friendly and it does not release any greenhouse gases. Also the advantage lies in the fact that the wind turbines can be placed anywhere necessary preferably unpopulated areas, so off-shore turbines are utilized in this regard [32].

## DISADVANTAGES

Proper maintenance of the turbines is required. The exposed rotating parts of the turbines can be easily damaged. The availability of wind power varies from one location to another. So there is a necessity of measuring wind speed using anemometer on the location where a turbine is placed. For scattered wind encountered in any location, ducting is used for proper channeling of wind which yields unidirectional behavior of the turbine [2]. Also lack of advancement of technology can lead to increase the cost of harvesting energy from wind power [32].

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**Figure d.Some Commercially Available Wind Turbines: Dierks*et* al. [Ref. 2]**

**Figure e.Bladeless Turbine: http://www.abzu2.com/2017/03/15/ vortex-bladeless-wind-generator/ dated:31/03/2018 [Ref. 42]**

## APPLICATIONS

In remote wireless sensors, wind energy harvesting technique is used [16].

## FUTURE SCOPES

New innovation can be made by using bladeless wind turbines. This creates a vortex like motion which can be used to harvest energy. Theoretical results of experts say that this will cost 40% less than the cost of present standard windmills [42]. A structure of bladeless windmill is shown below.

## MECHANICAL ENERGY HARVESTING

Mechanical vibration, pressure can be obtained by human power or machines can provide it. Exploiting these physical parameters, we can generate electrical energy by applying some basics laws of science. Here the basic law establishes relation between the mass and frequency of impact of the vibrating element. The essential relationship which shows us the theoretical power generated from vibrating energy harvesting system at mechanical resonance is given by:

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$$P = \frac{m\zeta_E a^2}{4\omega(\zeta_E + \zeta_M)^2}$$

where, $P$ is the output power of the system, $m$ is the mass of vibrating element, $a$ is the magnitude of acceleration of the vibrating mass, $\omega$ is the frequency of vibration and $\zeta_M$ and $\zeta_E$ are the mechanical and electrical damping coefficients respectively. By the equation, we can infer that by increasing the mass and acceleration of the vibrating element along and decreasing frequency and mechanical damping, we can obtain a sufficient amount of power output [2]. Mechanical energy can be extracted by three major techniques- a) Piezoelectric, b) Electromagnetic, c) Electrostatic. A typical model of vibrational energy harnessing system is illustrated in Figure (f).

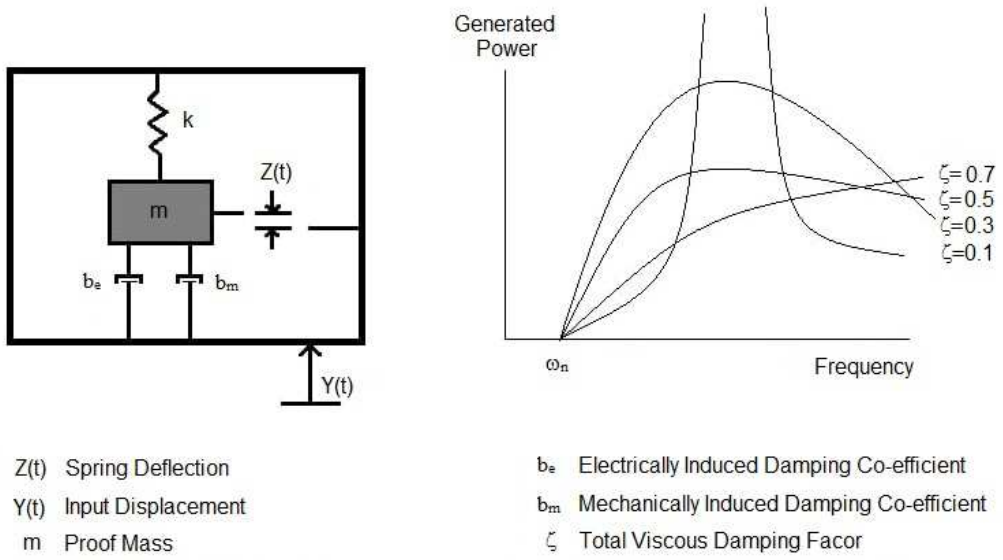


**Figure f.A Typical Model for a Vibrational Energy Converter: GurkanErdogan [Ref. 13]**

## PIEZOELECTRIC ENERGY HARVESTING

Piezoelectric energy is harvested from mechanical pressure or stress. There are some crystals like tourmaline, quartz, Rochelle salt, barium titanate generate voltage across itself when they undergo mechanical strain [8]. When mechanical strain is applied, one part of work done is stored as strain energy within the material and another part generates electric field which causes the polarization of material [4]. This polarization results in generating electromotive force across the material. This effect is called direct piezoelectric effect. Also these crystals undergo physical deformation when subjected to electric field. This is known as converse piezoelectric effect. The behavior of such stuffs is managed by the subsequent equations.

Direct piezoelectric effect,

$$D_i = e_{ij}^{\sigma} + d_{im}^{d}\sigma_m$$

Converse piezoelectric effect,

$$\varepsilon_k = d_{jk}^{c}E_j + S_{km}^{E}\sigma_m$$

where, $D_i$ is the dielectric displacement in N/mV or C/m$^2$, $\varepsilon_k$ is the strain vector, $E_j$ is the applied electric field vector in V/m, $\sigma_m$ is he stress vector in N/m$^2$. $d_{jk}^{c}$, $d_{im}^{d}$ are piezoelectric coefficients in m/V or C/N, $e_{ij}^{\sigma}$ is the dielectric permittivity in N/V$^2$ and $S_{km}^{E}$ is the elastic compliance matrix in m$^2$/N. The superscripts $d$ and $c$ are for direct and converse effects respectively. Also superscripts$E$ and $\sigma$ indicate that the quantity is evaluated at constant electric field and stress respectively [8].

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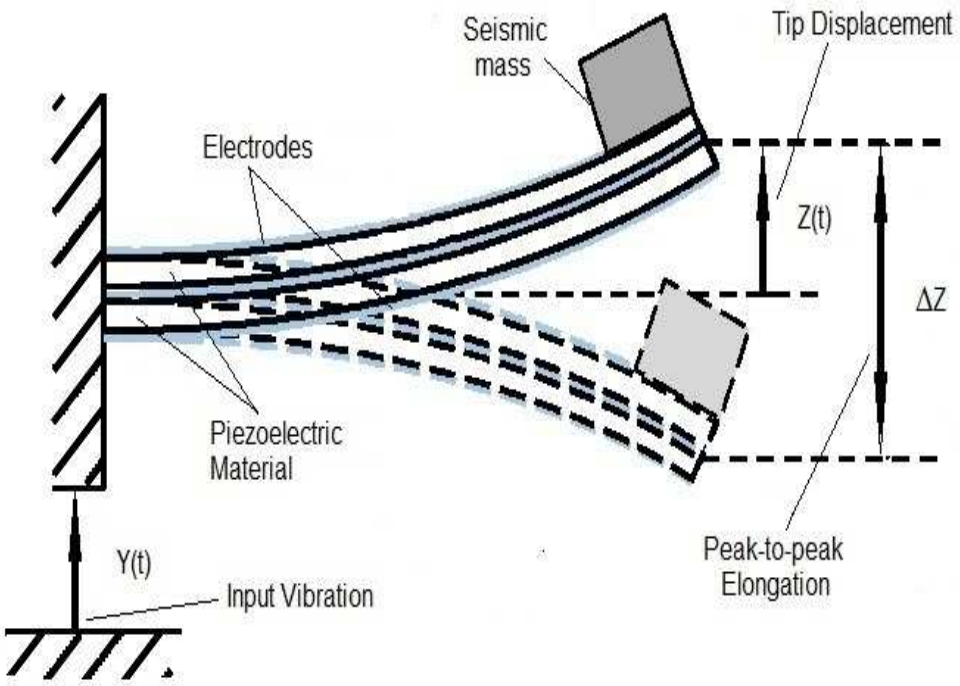


**Figure g.Structure of Piezoelectric Bimorph Cantilever Beam: https://www.researchgate.net/figure/Structure-of-a-piezoelectric-bimorph-cantilever-beam-with-a-tip-mass-for-harvesting_fig1_254046423 dated: 30/03/2018 [Ref. 41]**

In majority of the cases, a cantilever beam structure with a proof mass at the loose end of the beam is used. The piezoelectric material is placed in layer form inside the beam. Figure (g) shows the cantilever beam configuration. This typical configuration provides higher strain for a given input. This particular structure gives both the expansion and compression of the piezoelectric material at the same time and thereby produces high AC voltage [5].

## ADVANTAGES

Piezoceramics and piezopolymers are easily available as the source of piezoelectric energy harvesting. So there is no need of smart materials and cost is reduced. These substances have high electro-mechanical coupling constants which provides high energy transformation rate [8]. Also this process can give high output voltage and high value of capacitance [3]. There is no need of applying external voltage source for starting the operation. The size is considerably reduced, so it is compact [9].

## DISADVANTAGES

Piezoelectric materials leak charges. These crystals offer high output impedance [9] which in turn results in low output current [3]. Also materials like PZT are very much brittle [10]. Piezoelectric crystals lose its property of generating voltage when subjected to high temperature [19]. This cannot be used for static measurement [39].

## APPLICATIONS

Piezoelectric energy harvesting techniques are used in sensors to check pressure or vibrations. Piezoelectric buzzers are popular today. These buzzers are used in intruder alarms, alarm clocks, fire alarms etc. Besides sensors, piezoelectric actuators are also available. These are used in micro robotics [37]. Figure (h) shows a 'RoboBee' invented by the Harvard Micro robotics Laboratory [38].

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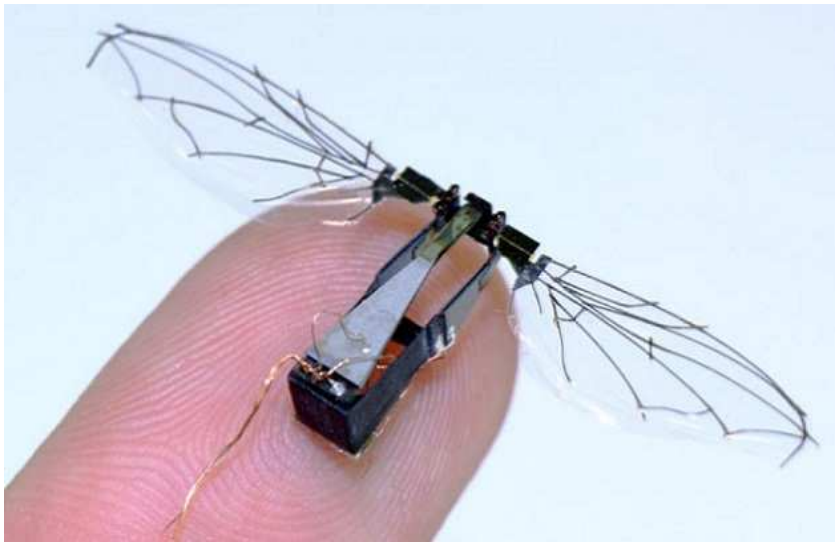

**Figure h. RoboBee: http://bgr.com/2015/10/29/harvard-robobee-fly-swim-insect/ dated: 29/03/2018 [Ref. 38]**

**Figure i.EXACTO Bullet: http://www.darkgovernment.com/news/self-guided-sniper-bullets-wanted-by-us-dod/ dated: 01/04/2018 [Ref. 43]**

Similar types of actuators are also used in route changing bullets nowadays. DARPA (Defense Advanced Research Project Agency) invented a bullet called EXACTO (EXtremeACcuracy Tasked Ordnance) which can change its path while travelling. Figure (i) shows the EXACTO bullet. Apart from these, this technique is used in cigarette lighters or gas lighters.

## FUTURE SCOPES

Besides the above mentioned applications, there are many scopes to develop it further. This piezoelectric energy harvesting process can be exploited to make a power generating pavement. Public dance clubs can be modified into power supply using piezo materials under the dance floor so also in case of gyms, floor mats etc. [39]

## ELECTROMAGNETIC ENERGY HARVESTING

A time altering electric field produces an time varying magnetic field and vice versa [11]. The electromagnetic energy harvesting operates on the basis of Faraday's law of Electromagnetic Induction which states that a time varying magnetic flux will induce a voltage within a closed loop conductor [2, 3]. Precisely, an inductive coil

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is used which forms a transformer to generate alternating electromagnetic field. Likewise, another coil is associated with the device requires to be charged. The device withdraws power from electromagnetic field and converts it into electrical current to charge the battery [3]. There are two methods of harvesting electromagnetic energy- a) relative motion, b) rigid body. Here Figure (j) shows both the mechanisms.

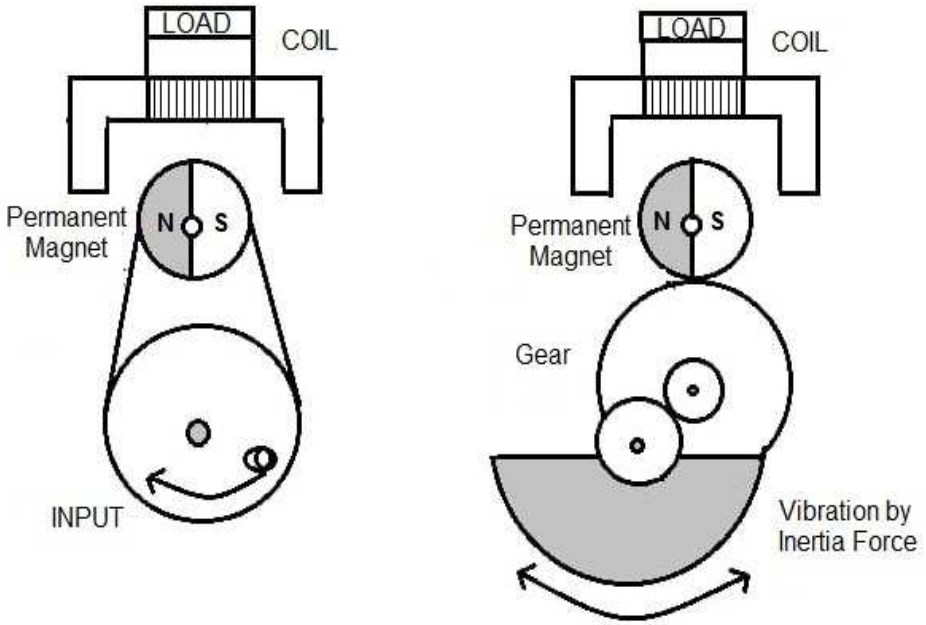


**Figure j.Types of Mechanical Generators- Relative Movement (left), Rigid Body (right): Paulo *et al.* [Ref. 11]**

The relative movement of the armature connected to the permanent magnet generates energy. Conversely, rigid body inertia is directly employed on permanent magnet which generates energy. [11]

## ADVANTAGES

This type of configuration offers high output current [3]. There is no need of external voltage source for operation [9]. It is easy to implement because of its robustness [3]and affordability [40]. Besides these, high efficiency in case of high input frequency of this configuration is also a notable feature [40]. Also it has a long lifetime [3].

## DISADVANTAGES

Electromagnetic energy harvesting mechanism gives low output voltages of the order of 0.1 Volts [3, 9]. In real life, we can obtain at most of few Hertzs of mechanical vibration from both the human and machines. So this low input frequency results relatively low efficiency of the system [3]. Also it is very difficult to implement this method in MEM device because of its bulky structure [3].

## APPLICATIONS

The relative motion systems are deployed on bicycles, radios and mobile phones [11]. RFID or AEI is powered through this process [3]. Also newly invented Perpetuum PMG17 and nPower PEG are using this method of energy harvesting techniques [9]. Now SEIKO kinetic watches also use electromagnetic energy harvesting procedure [4].

## FUTURE SCOPES

In future, there is a scope of developing the inertial generator from two pole magnet to four poles. It will provide flux path in opposite direction also resulting more power. Scientists will develop cantilever beam structure as it generates more power than the other methods [4].

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## ELECTROSTATIC ENERGY HARVESTING

An alternative procedure of mechanical energy harnessing is electrostatic energy harvesting. This technique is based on principle of variable capacitance. The device is designed such that either the space between the two electrically charged plates or the normal area of plates is varied when vibration occurs. Figure (k) illustrates the operation of the electrostatic energy harvesters.

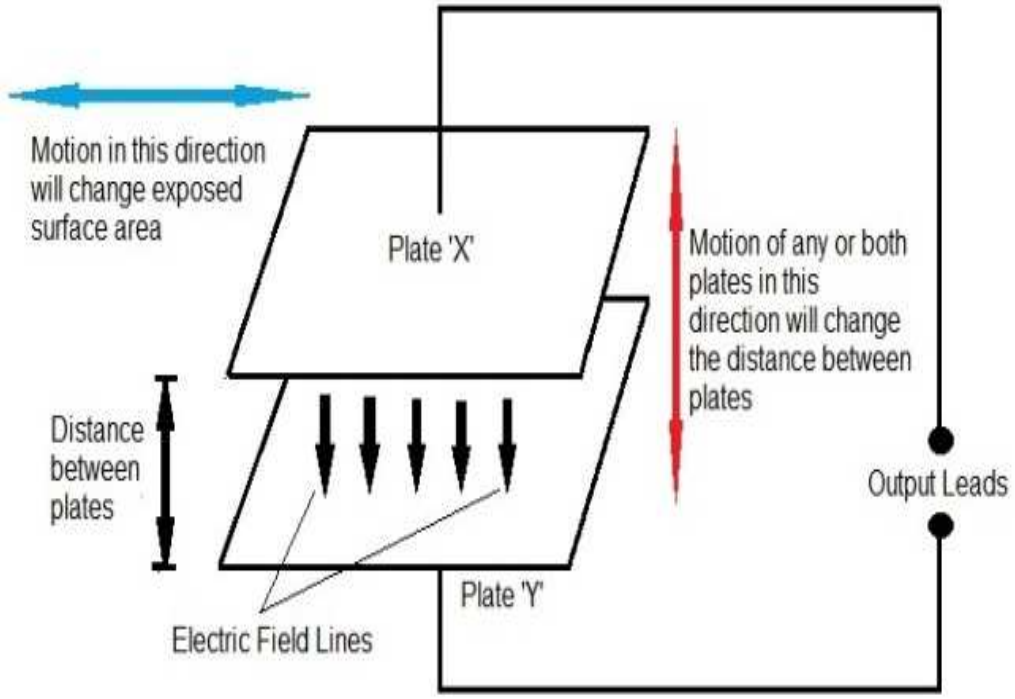


**Figure (k): Basic Electrostatic Energy Harvester using Variable Capacitance: http://www.vlsiegypt.com/home/?p=845 dated: 01/04/2018 [Ref. 44]**

## ADVANTAGES

This process gives high output voltage [3, 5] of the order of 2-10 Volts [9]. Also it can be fitted in IC form [3]. So this configuration is compact. This compactness or reduced size gives rise to the capacitance value which results in high charge storing capacity [3]. The cost of this process is relatively lower than the other ones [3].

## DISADVANTAGES

Electrostatic energy harvesting method needs some mechanical restrictions to perform well [9]. These kinds of devices are needed to be charged before operation [4, 9]. Due to compactness of the device, high impact of stray capacitances occurs. It is the capacitance which acts due to proximity of the different components inside the device. For low value of capacitance, it discharges quickly. [3]

## APPLICATIONS

This method is often used as power supply to the implantable medical devices such as cardiac pacemaker [4]. Electret microphones are available where electret supplies the threshold voltage for capacitors to operate [2].

## FUTURE SCOPES

There are various scopes for developing this process. One of the methods is to improve capacitive design. As low frequency of vibration gives rise to high source impedance, so working bandwidth can be widen for much better performance. [9]

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**Figure l.Thermocouple: https://www.aliexpress.com/item/5PCS-Lot-Stainless-Steel-Temperature-Sensor-K-Type-Thermocouple-Bayonet-Compression-Spring-with-2m-Cable-Wire/1717230149.html dated: 26/03/2018 [Ref. 36]**

## THERMAL ENERGY HARVESTING

Another distinct source of energy scavenging is thermal energy harvesting. Thermal energy is abundant in ambient nature in the form of waste energy from furnaces, heaters [5, 7], domestic radiators, human skin, vehicular exhausts [7] and from friction sources [5] etc. Engaging these sources with thermo-electric and pyro-electric materials, we can generate electricity.

Thermo-electric energy harvesting method utilizes the temperature gradient and this gradient between two materials (metals or semi-conductors) generates a voltage drop at the junctions. This effect is known as Seebeck effect and this can be achieved by thermocouples, which are made by linking two different metals or semi-conductors maintaining their junctions at different temperatures. Figure (l) shows a typical thermocouple used commercially.

Mathematically, the voltage generated due to temperature gradient ($T_1$.$T_2$) is given by,

$$V = \int_{T_1}^{T_2} [S_B(T) - S_A(T)]dT$$

where $S_A$ and $S_B$ are Seebeck co-efficient of two materials A and B respectively [26].

Pyro-electric energy harvesting is also a method of thermal energy harvesting. Some materials (like gallium nitride) generate momentary voltage when they are heated or being cooled, these are called pyro-electric materials [33] and the electricity generated is called pyro-electricity [5]. When pyro-electric crystals are subjected to heat or being cooled, it generates a small electrical charge inside crystal. When the temperature is constant inside the material, the charge generation ceases [34]. The power density and efficiency is given by,

| **Power Density (µW/cm$^3$) [2]** | **Efficiency (%) [7]** | |
|---|---|---|
| Theoretical | 17 | 0.1-3 |
| Practical | 3 | |

### ADVANTAGES

There are plenty of sources of waste heat in ambient nature, so there is no need to use natural resources for thermal energy harvesting. These processes are reliable and maintenance-less. There are no moving parts like rotor etc. [10]so there is no need to generate mechanical energy. In case of the pyro-electric crystals, they can be used in wide temperature range as they are stable up-to 1200$^0$C. Also these crystals have increasing thermodynamic efficiency [5]. In order to design an electronic circuit, it is easy to integrate within Printed Circuit Boards (PCBs) [10]. Generally these methods are suitable for low power applications [5, 14].

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**DISADVANTAGES**

Although thermal energy harvesting is advantageous in many ways, it has efficiency less than 1% for temperature gradient less than $40^0$C [7]. And if we want to achieve such large temperature gradient, ambient sources of nature would not be sufficient [7, 14]. Also it is a costly affair [19].

**APPLICATIONS**

The notion of thermal energy harvesting is being used in a number of fields. SEIKO made a wristwatch based on the concept of thermalenergy harvesting using a TEG (Thermoelectric Generator) [14, 17]. A normal SEIKO thermic wristwatch is shown in Figure (m).

Automotive performance supervising, home-land and military surveillance, biomedicines, wilderness & agricultural management, space and terrestrial applications [5] are being done by this energy harvesting process. Also it is used as power supply for implantable pacemakers [16]. Recently Pyro-sensorslike the one shown in the Figure (n) use thermal energy harvesting [34].


**Figure m.SEIKO Thermic Watch: https://museum.seiko.co.jp/en/collections/ clock_watch/category3/collect041.html dated: 26/03/2018 [Ref. 36]**

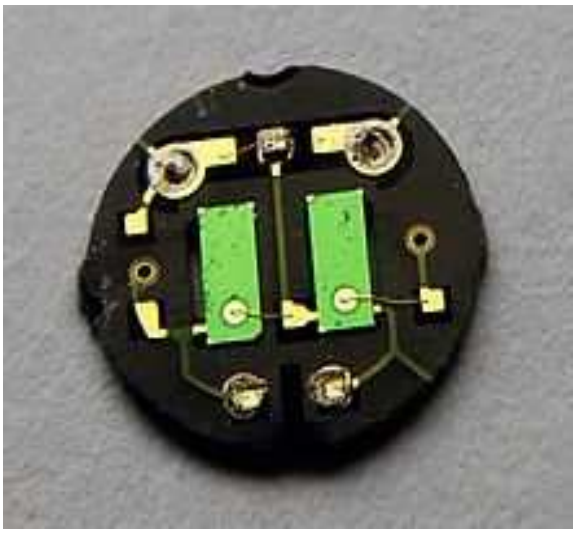

**Figure n.Pyro-sensor: https://en.wikipedia.org/wiki/Pyroelectricity dated: 26/03/2018 [Ref. 33]**

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## FUTURE SCOPES

New thermoelectric materials will be developed to overcome low energyconversion efficiency [19]. Insulin infusion pumps may also be powered by thermal energy harvesting. The temperature difference in body parts of an athlete during exercise can be utilized for thermal energy harvesting [11].

## RADIO-FREQUENCY ENERGY HARVESTING

Now-a-days Radio Frequency (RF range: 3kHz to 300 GHz) Energy can be considered as a significant source of energy harvesting because of the rapid improvement of the wireless communication system that increases the use of wireless communicating devices that uses the RF as the communication medium [27].

Conversion of RF Energy to DC electricity is known as RF Energy Harvesting [23, 17]. The main source of power for RF energy harvesting can be the TV towers, cellular towers etc. or it can be a separately dedicated RF transmitter [17]. A typical structure of RF energy harvesting device is illustrated as below in the figure (o).

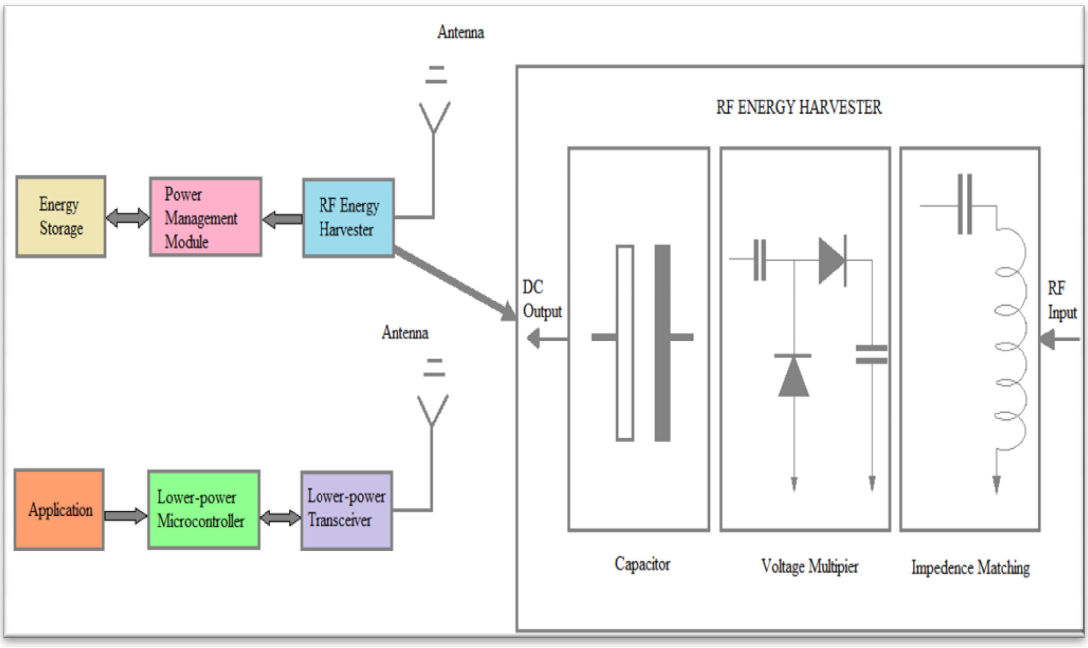


**Figure o.Structure of RF Energy Harvesting Device: Ahmed *et al.* [Ref. 17]**

The RF energy harvesting process primarily depends on the efficacy of an antenna as well as the impedance matching of an antenna with multiplier of voltage. The total process converts RF signal to the DC voltage [17]. This harvested voltage has the low power due to the low efficiency of RF energy to DC voltage conversion. This DC voltage can be used to power up the low power devices. [23, 17, 27]

## ADVANTAGES

The RF energy causes no environmental pollution. RF energy is the renewable source of energy because it is too much available in our environment.

## DISADVANTAGES

For RF energy harvesting, main requirement is magnetic induction, which is produced by the transmitters, is harmful for human health [23]. Model wireless transmitter made by the researchers will not affect the public health, but have the limitations regarding cost, generated power, radiation intensity, distance etc. [23] RF energy harvesting not too much productive due to the production of low power. [27]

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## APPLICATIONS

Harvested voltage can be used to power up low power devices like sensors. According to the latest experiments, mobile phone can be charged. Using Villard cascade and higher frequency value, medium power devices may be charged. [23, 27]

## FUTURE SCOPES

Lots of researches must be done to gather sufficient knowledge regarding the topology of RF harvesting network so that enough power can be generated to power up the daily used electronic devices. Further studies must go on to determine the minimum and the maximum distance between the RF tower and the RF harvesting network so that we can achieve the maximum functioning of the RF harvesting network[27].

## ENERGY HARVESTING BY HUMAN POWER

Electricity generation from human power both actively and passively is in the attention of the researchers for years [5]. Various studies are going on the possibility and usefulness of generation energy from human body [6]. Energy can be extracted passively from human power like- exploiting, shaking, squeezing, pushing, pulling etc. [5]. Also uninterrupted supply can be available from human actions like- typing, walking, exhalation etc. [6, 13]. The estimate of generated power for an average person using some fundamental laws of physics is given below.

| **Body Function** | **Generated Power (Watt) [6,13,28]** |
|---|---|
| Body Heat | 6.4 |
| Breathing | 0.83 |
| Blood Pressure | 0.93 |
| Walking | 67 |
| Arm Motion | 60 |
| Finger Motion | 0.0069-0.019 |
| Exhalation | 1 |

## PASSIVE OR INDIRECT METHOD- ENERGY HARVESTING OUTSIDE HUMAN BODY

Turning the fat within the human body into energy is somewhat difficult. So harvesting energy indirectly from human activities is implemented widely. For this purpose transducers are used such as, piezoelectric substances, thermoelectric generators, variable capacitors, inductive generators etc. Thermoelectric generators work taking intoaccount the difference in temperatures between the device carrying body and air and allows heat to travel to the cooler region, there by inducing electron flow and hence current which can provide a good amount of energy [28]. Piezoelectric materials work on the principle of piezoelectric effect [4, 6, 11, 13, 28] that converts the mechanical stress into equivalent current of voltage. Crystalline materials exhibit piezoelectric effect.

## RESEARCHES

Many researches revealed when blood pressure is exposed to piezogenerator it can generate power. Piezo inserted shoes are able to produce 8.4 mW of power in normal walking conditions. $4\mu W/cm^3$ of power can be created from vibrational micro generators by human motion [14]. Some researches introduced various locations in human body from where power can be generated. After that the survey on wearable devices and sensors goes on increasing [5, 13]. MIT researchers suggested that most useful

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power is available in foot motion of human during walking or running [5].

### APPLICATIONS

SEIKO developed a kinetic watch which works based on human movement. Here battery is replaced by the power generated by the arm motion [11]. In early 90's, FREEPLAY, a commercial company marketed various products like lanterns, torches, radios etc. which incorporate human motion energy harvesting resulting in high availability of power [5, 11]. They have introduced generators that employs crank which helps to power mobiles etc. [11]. Space commander, developed by Robert Adler, is a wireless human powered remote for zenith televisions utilizes this kind of harvesting [5]. Piezoelectric materials are able to create sufficient power. Scientists developed a piezo element consisting of resonantly matched transformer, generates nearly 1 mJ energy when it is hit [5]. Such piezo element can be incorporated inside the soles of shoes to harvest energy from daily motion of human like walking and running [5, 11, 13]. Also in dance floors piezo materials can be implanted and power can be generated from continuous foot motion of humans [11]. In medical field, human energy harvesting has numerous applications. In body monitoring which includes personal health care, telemonitoring and self-treating of chronic diseases etc. application of energy harvesting is seen. This technique can be applied in orthotics as well as in prosthetics [28].

## ACTIVE OR DIRECT METHOD-ENERGY HARVESTING INSIDE HUMAN BODY

Within body, the movement or kinetic energy of human body is one of the vital sources of power. Also blood pressure can be channelized effectively to generate desired electricity [28]. A human body dissipates 10.5 MJ of energy on a daily basis which corresponds to near about 121W of power [5]. So the researchers have conducted several studies to utilize this huge energy coming from human body.

### APPLICATIONS

The power harvested from human body can be used to drive both implantable and swallow-able devices. Swallow-able cameras help in monitoring various body parts by navigating inside the body. So for high staying time of the device inside the body, it is necessary to energize the motor of the battery by human generated power rather than battery which requires replacement [28]. Implantable devices like pacemakers, infusion pumps utilize Nano generator which is able to convert mechanical energy of human body to electric power [11, 28].Micro fuel cells can be driven by human body-fluid [28].

### ADVANTAGES

The increased requirement to continuously monitor health conditions requires the usage of devices that can be transplanted inside human body and can be energized from human power itself. Energy harvesting helps in this regard. The use of wireless, implantable devices reduce the cost effectively hence gathering popularity. This technology gives independence to the user as they do not need to charge the battery. Also technology development occurs in flexible electronics by energy harvesting. One of the natural actions of human, breathing is used in power generating rubber films [28].

### DISADVANTAGES

There are disadvantages of this technique as well. More flexible thermoelectric generators are needed to generate more power from the temperature difference in the range of $1^0$ to $5^0$C. The scheme of mechanical energy harvesters banks on the location of the body. So unobtrusive harvesters are needed ad specially designed for areas like foot, leg, knee etc. Again inertial devices used in implantable sensors have limitations as they have to be properly positioned

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to account for maximum displacement during motion. Without satisfying the national and international regulatory standards, energy harvesting method cannot be put to use in power generating devices [28].

### FUTURE SCOPES

The future applications of using human motion for energy harvesting include the development of human battery which will extract energy from the glucose of the blood. The sudden death syndrome of new born and infants is one of the greatest concerns of health issues. This needs to be monitored correctly. This can be done by connecting a piezoelectric strap around the chest of the baby. The piezo material will undergo mechanical bending when the baby breaths. This will supply the required electricity to run the monitoring device perfectly. Pulse devices like watches are used to measure blood pressure. As it is worn in wrist, it can be energized by constant movement of the arm, thereby reducing the need to replace the battery and enabling people to keep a constant eye on their blood pressure levels [11].

## OTHER SOURCES

Nano-cellulose or cellulose Nano substances are potential energy harvesting sources. Generally plants and trees are abundant of cellulose as their cell walls are made of the same compound. It has been demonstrated that thin CNCs (Cellulose Nano Crystals) shows piezoelectric effect when subjected to strain or shear. Also in case of magnetostrictive energy harvesting method, currently heavy and not easily moldable materials (like Terfenol-D) are being used. But CNCs are effective alternatives for Terfenol-D as it is nano-sized and moldable [24]. Also Biological parasitic is also a clean energy source. It extracts the metabolic energy from living beings like a parasite without killing its host. Such energy harvesters generate power from tree roots [2]. Biochemical reactions can be another source as the heat generated from the metabolic process can power up Implantable Medical Devices [9]. Atomic particle motion can also be utilized to generate clean energy.

## CONCLUSION

A synopsis of origins of renewable, non-conventional and ambient energy was portrayed. Energy harvesting is becoming increasingly practical as a power source for small electronic devices. Also, nowadays, technical-gadget dependency is growing so rapidly that we need to power up those gadgets instantly. Hence, an included small power source can drastically simplify the device installation and reduce its maintenance costs. Description of various energy harvesting mechanisms was proposed with respect to pros and cons of each technique. Solar and vibration energy are best suited as a source of power for electronic devices as both fit the most power density and availability requirements for autonomous systems. More research and testing are required to gain higher power from the scavenged energy. Energy is everywhere; we just need to have the full utilization of the wasted energy.

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