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A Comprehensive Review of Energy Harvesting Techniques and its Potential Applications

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ABSTRACT
In the recent years, obtaining a sustainable form of energy to power various autonomous wireless and portable devices is increasingly becoming a matter of concern and various alternate sources of energy have been explored. This paper discusses energy harvesting or energy scavenging as an efficient approach to cater to the energy needs of portable electronics. A comparison of various ambient sources for harvesting energy is done and an insight into some applications based on this concept is made. Also discussed are some modifications to the existing harvesting architecture in which the selection of the source is considered as important criteria in designing the energy harvester. This concept can be used to produce variable outputs to power energy requirements of the various systems.

General Terms
Energy harvesting

Keywords
Energy scavenging, ambient sources, TEG, RF, piezoelectric (PZT), biomedical, power ball, feedback energy harvester, PFCB, wind energy harvesting, smart wallpaper.

1. INTRODUCTION
Owing to the recent advances made in wireless technology and low power electronics, wireless sensors to be used in diverse scenario are being developed. The wireless nature of these systems makes it necessary to have a provision for self – powered devices. The devices are generally powered by a battery offering finite power supply. But batteries increase the size, and sometimes the cost of the devices in question and pose an additional burden of replacement or recharging. Thus there is an increasing effort to develop new sources of long-lasting and regenerative power to meet the energy needs of these wireless systems. Alternative approaches to this challenge are (i) making use of a locally-available higher-capacity power supply,(ii) use an active source to deliver power wirelessly, or (iii) to extract power from ambient sources in an efficient way. The concept of energy harvesting (EH) or energy scavenging or power harvesting is thus a mechanism of deriving energy from the sources present in the environment. It is usually associated with capturing some left over energy which could be a by-product of a natural phenomenon or an automated process and is therefore considered free-energy. Using this energy will enable wireless and portable electronic devices to be completely self-sustaining, so that battery maintenance can be eventually removed.

Examples of potential energy harvesting sources include electromagnetic energy in the form of solar, infrared or RF, mechanical energy in the form vibration, stress and strain, thermal energy from furnaces, combustion engines and other heat sources, human energy from various metabolisms and activities inside or outside the human body, sound energy, etc. Energy from these sources can be captured using different sensors and converted to usable energy i.e. electrical voltages and currents. This can further be harvested, stored and processed as per the requirements of the low power wearable electronics and WSN (wireless sensor network) applications.

The basic components of a conventional energy harvesting system can be seen in Fig.1. The input to this system is the residual energy from ambient environmental source captured by appropriate sensors. It is converted to electrical form and stored from where it can be supplied to different loads (devices).Optionally some conditioning circuits can be used to get better energy outputs. The storage module ensures that energy can be available continuously even when the ambient source is not available.

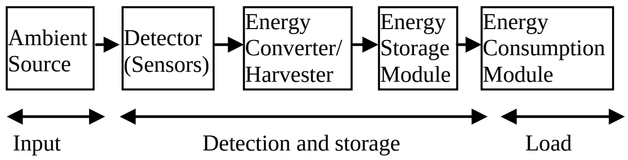

Fig 1.Conventional EH system

2. LITERATURE REVIEW
Energy harvesting is not entirely a new concept; one of the earliest methods being the conversion of solar energy to electrical energy. Off late, this concept has been extended to many other sources like RF energy, piezoelectric energy, thermal energy etc. A wide range of research is being done in many of these domains. In this section, a brief discussion about some of the works involving energy harvesting is done.

The non-traditional power sources such as solar cells (photovoltaic cells), thermoelectric generators (TEGs) have been discussed by R. Trykozko [1], [2] and also an energy harvester IC, LTC 3105 has been developed by Jeff Grutter [3]. Although thermal variations in the environment can be directly converted to electrical energy through the Seeback (thermoelectric) effect, a large thermal variation is needed to produce practical voltage and power levels [4]. Pyroelectric effect which converts temperature changes into electrical voltage or current has been used in Pyroelectric nanogenerators for harvesting thermoelectric energy by Yang etal [5]. It is also possible to use ambient RF energy sources from multiple wireless sources of different frequencies like TV, radio broadcasts, mobile phone base stations, mobile phones, wireless LAN and radar [6],[7].A specialized antenna called as rectenna is designed in [8] to capture ambient RF energy. Another promising source for harvesting energy is vibration from vehicles, civil structures, railway tracks, human motions and ocean waves [9]. The vibration produced from piezoelectric materials is discussed by Sodano [10], Tabesh [11],[12] etc. Also, Sodano has performed a comparative study of piezoelectric materials PZT, MFC and Quick pack actuator [10] and concluded that PZT is the best among the three based on efficiency at different frequencies and time required to charge. Energy harvesting for wireless sensor devices has been considered in [13]. Acoustic noise is yet another energy source which has been studied extensively [14]. Researchers have proposed and conducted several studies to capture power from the human body. For example P.D. Mitcheson has researched and investigated some energy harvesting techniques to power wearable electronics [15],[16]. MIT researchers have suggested that the most reliable and exploitable human energy source occurs at the foot during heel strikes when running or walking [17].

There are many applications based on EH in various domains like WSN (wireless sensor network), industrial applications and biomedical applications,etc. The concept of vibration energy been used to develop a piezoelectric shoe by Faruk Yildiz [16]. A 1 KW Thermoelectric Generator for low-temperature geothermal resources was developed by Changwei Liu [18], [19]. A detailed analysis of these sources and applications is done in the following sections. The remainder of this paper is organized as follows: In section III, various potential sources for EH are discussed followed by the applications developed around these sources in section IV. Section V discusses some possible advancements in the harvesting procedure that can be suitable to power future energy requirements of various systems.

3. SOURCES FOR AMBIENT EH

Though there are many sources that can be used for harvesting energy, it is important to consider the output power levels from these sources and also the mechanism involved in energy conversion in addition to the power saving and the cost incurred. The sources of energy available for harvesting can be basically put into the following types: RF electromagnetic radiation (light, RF, thermal gradients), sound energy, human energy and mechanical energy (vibration) and wind energy.

3.1 Electromagnetic Radiation

The electromagnetic spectrum contains regions with variable energy levels. For an efficient conversion into electrical energy, it would be advisable to select the part of the spectrum which offers maximum energy.

3.1.1 Light Energy

Energy from the sun is an abundantly available and a free source of energy. Photovoltaic cells or panels can be mounted on surfaces where strength of the incident solar energy is good enough to be captured .The average solar energy received at the top of the earth's atmosphere is near about 10^{18} kWh/year with a surface power density of about 1,353kW/m^2 [2].The harvested energy ranges from 100 mW/cm^2 (direct sun) to 100W/cm^2 (illuminated office) [1].Techniques for maximizing the output of photovoltaic cell is discussed by Pai H. Chou et.al in [20] where MPPT (maximum power point tracking) is adopted. Here the supply conditions are tracked continuously and the corresponding load that maximizes the transferred power is determined form the I-V curve of a solar cell. Although EH from solar energy is a scalable method, it is limited by the availability and intensity of light due to which additional storage units may be needed to enable continuous supply of the harvested energy.

3.1.2 Thermal(IR) Energy

Thermal energy can be obtained from heat present in the ambience or from heat generated during some process. Either thermoelectric or pyroelectric effects can be used to harvest energy. Thermoelectric effects like Peltier effect, Seeback effect and Thomson effects [4] can generate power as long as a heat source is present. Extraction of energy from a thermal source requires a thermal gradient and conversion efficiency mainly depends on the temperature difference between the heat source and the environment (i.e. the cold and the hot side). A greater temperature difference leads to a better output. Pyroelectric effect [5] based on the spontaneous polarization in certain anisotropic solids due to a time-dependent temperature variation can be used when there is a uniform temperature gradient in the ambience i.e. there is not much variation in temperature. The energy output from thermal variation is about 10μW/cm^2 and can go up to 60 W/cm^2 in case of a thermoelectric source [1]. Though this technology is scalable and durable, since the temperature gradients are usually low, the conversion efficiency and the output voltage are low. Other methods like piezo-thermomechanic and piezo-thermofluidic conversion have been investigated in [21] opening doors for a wide area of applications.

3.1.3 RF Energy

RF energy is omnipresent owing to cell phone towers, TV broadcast stations, satellite and radar stations, WiFi routers and other communication networks and is essentially a free-energy. But the energy levels vary due to factors like terrain, number of users, network congestion, etc. In order to harvest useful levels of electrical energy in these ambient conditions, large broadband antennas with high gain, scalability and easy fabrication are required [7]. Also it is difficult to differentiate the useful RF signal and the waste RF signal. Considering these factors, there have been only a few attempts at true ambient RF energy harvesting. For example, a *rectenna* made up of an omnidirectional patch antenna, having an efficiency of 18%, and power of 20 dBm was designed by G.P. Ramesh [8]. Also some powercast RF harvesters [22],[23] have been reported. The output power from RF is however very low of the order of 1 μW/cm^2 [1]. By using methods to include wideband frequency ranges, and automatic frequency tuning, the power output can be increased thus making RF as a potential source of EH.

3.2 Mechanical Energy

Mechanical sources provide a promising alternative to harvest energy with their outputs in the range of 4W to 800W [1]. There are various forms in which mechanical energy sources can appear such as steady-state source, intermittent source and vibration source of which vibration source is the best. Steady state sources are based around fluid flow for example wind, air currents, water flow through natural channels or pipes, etc. Cyclic energy may be available from motion like from vehicles passing over an energy harvesting module or intermittent human activity such as walking or running. A particularly attractive source of energy in this context is footfall or heel strike [16]. Normal walking involves dissipation of significant energy in the sole of the shoe and the walking surface, and the user might be unaware if some of this energy were converted to electrical energy. Harvesting energy from vibration is thus a promising technology. However, majority of current researches have obtained 10 mW to 100 mW powers, which has only limited applications in self-powered wireless sensors and low-power electronics. Vibrations in some situations can be very large, like in case of the vibrations of civil structures like tall buildings, railroads, ocean waves, and even human motions and can give a better output power. Sources for conversion of vibration energy into electrical energy include electric field (electrostatic), magnetic field (electromagnetic), or strain on a piezoelectric material [24],[25]. Table 3.1 shows a comparison of these sources.

Table 3.1. Comparison of Vibration EH Techniques [1]

	Electrostatic	Electromagnetic	Piezoelectric
Complexity of process flow	Low	Very High	High
Energy density	4 mJ cm-3	24.8 mJ cm^{-3}	35.4 mJ cm^{-3}
Size	Integrated	Macro	Macro
Problems	Very high voltage and need of adding charge source	Very low voltage at the output	Low output voltages

As can be seen from the above table, piezoelectric method yields a better output and can be explored further for developing applications. The prototype in [26] is of a micro-generator based on electrets with a harvested power of $50\mu W$ for a 0.1cm^2 of surface.

3.3 Human Energy

Humans are a rich source of energy as there is a lot of chemical energy stored in the human body that is converted into positive mechanical work. Energy can be harvested outside the body indirectly from everyday human actions or might be intentionally generated by a human. The related systems need to be wearable and typically consist of sensors, signal conditioning electronics and wireless transmission technology. Energy can also be harvested inside the body from movement (kinetic) using implantable sensing devices. It would be a good idea to combine human energy and piezoelectric effect to produce maximum output[15-17].The amount of energy produced from passive activities like body heat is around 2.1-4.8W, while exhalation and breathing produce less than 1W. Active human energy can be in the form of arm motion (<60W), finger motion(6.9-19mW) or footfalls (heel strike)which produces around 67W of energy [27].

3.4 Sound Energy

Most energy harvesting methods have focused on vibrations, ambient light and temperature gradients as environmental sources of energy. Sound energy yet another form of unused energy which if harvested can prove to be a very good candidate source for EH. Acoustic noise which is result of the pressure waves produced by a vibration source is detected and translated to equivalent electrical signals by human ear in the frequency range of 20 Hz to 20 000 Hz [1]. Sound energy is almost present continuously and at a considerable level in the environment for e.g. on the railway track, runway, ship yard, or on the road (engine noise of vehicles and horns), loud music played in clubs or parties, at construction sites and other such sources. Sources like telephone dial tone (80 dB), train whistle (90 dB), hand drill (98 dB), jet engine (140 dB), aircraft (194 dB), etc give sufficient sound pressure levels (SPL) that can be used for EH [28]. It would be novel idea to power the lights on the runways from the energy harvested from aerodynamic noise. Analysis of acoustic energy harvesting with application in railway noise reduction has been discussed by Kralov et al [13].

3.5 Wind Energy

Wind energy is a conventional method of harvesting energy. The direction and speed of wind changes due to earth's terrain, water-bodies, and vegetative cover. This wind flow, or motion energy, when harvested using huge wind turbines, can be used to generate electricity on a large scale. An interesting idea however is to use small windmills on highways and other bridges nearby seas where the wind pressure is very large which in combination with speed induced by vehicular motion can be use to generate energy. This generated energy can be used to power lights and traffic signals on highways. Works in [29], [32] have covered some approaches of wind energy harvesting for low-power devices. A combination of wind energy and piezoelectric energy has been done in [30], [31]. The wind energy harvester module in [32] was tested for various wind speeds and the harvested energy was in the range of 4.372 mW to 4.635 mW. Wind energy in combination with other sources can give a usable output power for low-power applications.

The relative advantages and disadvantages of the different sources for energy harvesting have been briefly discussed in this section. It can be observed that by considering one source at a time, there are just one or two sources which yield good power levels that can be used for applications. It is therefore required to develop methods to increase the generated power and also possibility of taking multiple sensors to capture the energy from all directions to get the best results.

4. APPLICATIONS OF ENERGY HARVESTING

4.1 Applications of WSN

Energy harvesting concept has found a variety of applications in wireless communication & networks. Some adhoc sensor networks follow minimum energy path to optimize energy usage at a node such that the limited resources at sensor nodes can be used more effectively. At the same time, if a low energy path is used frequently, it may lead to reduction in the node energy along that path and may even cause network partition. Hence occasionally sub-optimal paths based on energy aware routing protocols may be used to improve the performance with the help of EH. Use of energy harvesting helps to eliminate the need of battery replacement and maintenance and to prolong the lifetime of sensor nodes. It is possible to use energy sensing and allocation algorithms for some sensor nodes such that they consume only as much energy as can be obtained from the ambience or occasionally they can be put into sleep mode when the energy levels are below the required threshold. Jason Hsu [33] has presented a duty cycling algorithm which is adaptive in nature i.e. the sensor nodes can autonomously adjust their duty cycle as per the energy availability in the environment. In this work energy neutrality, efficiency of system performance and ability of the energy source to dynamically adapt to run-time is considered. Energy neutrality in this context means the energy consumed should be less than or equal to the energy available in the environment. In the paper by Jingxian wu [34], a best-effort random sensing scheme is proposed where a set of random sensor nodes perform sensing at a particular instant if and only if there is sufficient energy available. Otherwise an energy outage is declared and the sensor remains silent. Here the ratio of energy harvesting rate and consumption rate gives the probability of energy outage during sensing. The concept of transmitting energy and information simultaneously [35] has been gaining attention recently where the receiver should be able to receive signals and harvest the energy from the same signal. This model is currently not realizable due to design limitations of the circuit components. The concept of communicating with EH transmitter and receiver has been Stimulated using a 2-node network where optimization is obtained by scheduling the sensing activity of the nodes [36].

4.2 Biomedical Applications

The extension of the energy harvesting concept for portable medical devices has been extensively studied by J.Paulo [26]. The portable medical devices are expected to be smaller in size, light weight and most of the times either wearable (for e.g. the sphygmomanometer) or implanted inside the body (for e.g. the pacemaker). As these devices are smaller in size, their energy consumption is also less. The energy consumption of some portable devices is shown in Table 4.1. Batteries of smaller size are enough to meet these requirements. However the batteries have not undergone the same size-evolution trend as that of the devices due to some technical and technological issues. This puts a restriction on the operational time and performance of the portable devices as these batteries need to be replaced or recharged periodically. A person with lithium battery pacemaker will require battery replacement surgery every 8 years. Likewise, implantable neurostimulator and infusion pumps have a reduced lifespan of 3 to 5 years. Thus dependence on batteries need to be reduced in this field giving rise to energy harvesting as an alternative solution. Piezoelectricity, thermal energy and electromagnetic energy w.r.t to human body are mainly considered for biomedical EH. A zinc oxide nanogenerator based on piezoelectric effect in [5] can be easily used inside the human body as it is not toxic in nature. Thermoelectric devices are also an attractive source of energy as it directly converts temperature gradients in to power. Though thermoelectric generators (TEG) were available for quite some time, it is only recently that low power medical implants have been researched and developed. Some of the factors to be considered for biomedical applications are (i) biocompatibility and toxicity of materials used, (ii) implantability of the device, (iii) charging cycle and recharge interval of the device. It is possible to charge the battery with the help of a low frequency rotating magnetic field. And also magnet can be implanted inside the human body to trigger a micro-generator. The high rotation speed of the micro-generator gives a high voltage which can be used to charge a battery [6].

Table 4.1. Medical devices and their power requirements [37]

Medical Equipment	Power requirement (W)
Insulin infusion pumps	12
Arterial pressure monitor	3
Blood coagulation monitor	0.5
Glucose level monitor	0.5
Pacemaker	5.6

4.3 Other Industrial Applications

Energy harvesting has also found its scope in some industrial applications, for e.g. a TEG developed through an AC Condenser using measurements from several thermometers placed inside its condenser unit is a recent application based on thermal energy [4].It was observed that the TEG had a power generating capacity of 20W. Another similar application was a 1KW TEG developed for geothermal applications [17]. Piezoelectric shoe [16], [15] is another application where a piezoelectric material (PFCB) is inserted inside the sole of the shoe. A sensor senses the walking, running or other vibrations occurring on the PFCB and converts it to energy which can be used to power small electronics. An average of 330 $\mu W/cm^2$ was produced during walking. The first application of shoe inserts was to power a low power wireless transceiver mounted to the shoe soles. This could be commercially developed as a product that can be used by anybody without putting an extra effort i.e. energy can be generated form daily activities like walking, running, exercising, etc. Another example is prototype of an inflatable ball called 'Power ball' or 'Soccket' [38] built by a few Harvard under graduates in 2009. It had an induction coil mechanism inside to generate energy to detect the rolling motion or the bouncing motion of the ball when kicked. Improved prototypes were developed in the following years. Currently they are working on a version that has a USB connection, which would allow a wider array of electronics to be connected to the ball. This initiative was called 'kick a ball, turn on a light'. Another example is energy harvesting in a club environment by placing an energy conversion mechanism on the dance floor which will convert the vibrations due to dancing motion into electrical energy. This idea has been explored in [39] and the generated energy was used to power LED lighting systems in the club thus saving electricity. References [40 – 44] cover some of the recent applications which are in the process of being developed as commercial applications. 'Energy harvesting trees' [40] is a new generation of highly efficient trees based on nano-technology capable of converting energy from sun, wind and rains to usable energy. Oyster [41] is 2.4 Mega Watts hydroelectric wave generator installed in Scotland which is estimated to power roughly 2500 homes. Solar windows [42], smart wall papers [43] and light weight solar cells [44] are some applications based to solar energy conversion.

A lot more research is going on and more applications are being developed. These applications are now concentrating on combination of various sources rather than using a single source as can be seen in case of piezoelectric shoe, powerball, human powered dance floor, etc where mechanical energy in the form of vibrations is combined with passive or active human energy.

5. MODIFICATIONS FOR THE FUTURE EH ARCHITECTURE

Recent works in energy harvesting are concentrating on increasing the efficiency of the harvesting module and also the possibility of using multiple ambient sources. Several multi-source applications are discussed in [15], [16],[17],[38],[40],[39]. Work in [45] considers a multi-source EH based on solar and wind which incorporates a power management unit to connect various loads. It also uses a feedback mechanism i.e. recharge control circuit to decide the charging and discharging of battery based on a threshold value.

The multi-source architectures discussed till now have considered a maximum of 2 sources at a time. In the future, an effort to use more than two sources with an emphasis on source selection will help to yield a higher and instantaneous output. It is not an easy task to combine multiple sources. The work in [46] discusses the design issues to be considered for a multi-source smart harvesting architecture.

Some modifications to the existing architecture can be (i)source scheduling and/ or selection based on instantaneous energy requirements of the load in question;(ii)feedback mechanism with a threshold level to sense the ambient energy levels of the sources to enable selection of the most apt source for smart energy harvesting; (iii) including device priority at the load side to sense and service the most power-needy device.(iv) adding the energy outputs of the various sources to meet the load requirement rather the taking a single independent source with the maximum output power; (v) Intelligently selecting the best source or the best combination of sources to get maximum captured energy. These modifications will make it possible to intelligently and dynamically harvest energy based on the source energy levels and the load energy requirements.

6. CONCLUSION

Energy harvesting can be viewed as a maintenance-free alternative to battery technology. It may involve some initial installation cost but in the long run it is cost effective and beneficial as the sources for EH are available naturally. Since the source availability is not continuous, the problem of getting a consistent output remains a challenge. Further improvements in the storage efficiency will make it possible to increase the reliability of the EH over the battery and plug-based connections. This paper has mainly concentrated on reviewing the various sources that can be used to harvest energy and some potential applications to WSN, biomedical and other areas were discussed. It was observed that out of the many sources available, only a few sources have contributed to the development of good harvesting architectures. Some applications have also combined two sources of energy like human and vibration energy [15], [16], [17], [38]. In future it would be an interesting idea to combine multiple sources using a feedback mechanism from the load to meet its power requirements. The selection of the sources may be based on various criteria like (i) the required output power, (ii) the potential output from each source at that instant, (iii) the efficiency and speed of the conversion module, to name a few. This system could be called *'Feedback Energy Harvester'*.

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