NANOGENERATORS FOR ENERGY HARVESTING BASED ON PIEZOELECTRIC METHOD

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Abstract— **As technology becomes more advanced, it is critical that energy resources are up-to-date and focusing on developing and applying undiscovered energy in the world. Piezoelectric energy is a newly discovered technology that involves harvesting mechanical energy for use in powering electronics. Piezoelectric nanogenerators are micro-scaled energy harvesters that are small enough for use inside fabrics and even inside the body. With advances in this technology, one can foresee a future world where flexible piezoelectric nanogenerators are built into everyday items. These items would have the ability to harvest the mechanical energy produced from movement to power electrically dependent appliances. Piezoelectric nanogenerators are deeply embedded in the future of technology. Piezoelectricity as a alternate energy source. The motive is to obtain a pollution-free energy source and to utilize and optimize the energy being wasted. In this paper important techniques are stressed upon to harness the energy generated from piezo crystals. This paper reviews the principles and state-of-art in motion-driven miniature energy harvesters and discusses trends, suitable applications, and possible future developments.**

Keywords: **piezo-elecric effect, energy harvesting, nanogenerators, motion-driven energy**

I. INTRODUCTION

With the threatening of global warming and energy crises, searching for renewable and green energy resources is one of the most urgent challenge to sustainable development of human civilization [1, 2]. At the large-scale, besides the well known energy resources that power the world today, such as petroleum, coal, hydraulic, natural gas and nuclear, active research and development are being taken in exploring alternative energy resources such as solar, geothermal, biomass, nuclear, wind, and hydrogen. At a much smaller scale, energy and technologies are desperately needed for independent, sustainable, maintain-free and continuous operations of implantable biosensors, ultrasensitive chemical and biomolecular sensors, nanorobotics, micro-electromechanical systems, remote and mobile environmental sensors, homeland security and even portable/wearable personal electronics. A nanorobot, for example, is proposed to be a smart machine that may be able to sense and adapt to the environment, manipulate objects, taking actions and perform complex functions, but a key challenge is to find a power source that can drive the nanorobot without adding much weight. An implanted wireless biosensor, for example, requires a power source, which may be provided directly or indirectly by charging of a battery. In general, the size of the battery is much larger than the size of the nanodevices, which largely dictates the size of the entire system.

The near future research is the integration of multi-functional nanodevices into a nanosystem so that it can function as a living species with capabilities of sensing, controlling, communicating and actuating/responding. A nanosystem is composed of not only nanodevices but also nano-power-source (or nanobattery). But the small size of the nano-battery largely limits the lifetime of the battery. It is highly desired for wireless devices and even required for implanted biomedical systems to be self-powered without using battery, which not only can largely enhance the *adaptability* of the devices but also greatly reduce the size and weight of the system. Therefore, it is desperate to develop nanotechnology that harvests energy from the environment for selfpowering these nanodevices.[3] The goal for nanotechnology is to build self-powered nanosystems that exhibit ultrasmall size, supersensitivity, extraordinary multifunctionality and extremely low power consumption. As a result, the energy harvested from the environment may be sufficient to power the system.

Energy harvesting is the process of extracting, converting and storing energy from the environment that can also be described as a response of smart materials when they are subjected to an external stimulus such as pressure, vibrations, motion and temperature emanating from wind, rain, waves, tides, light and so on. The efficiency of devices in capturing trace amounts of energy from the environment and transforming it into electrical energy has increased with the development of new materials and techniques. This has sparked interest in the engineering community to establish more and more applications that utilize energy harvesting technologies for power generation. Some of the energy harvesting systems which use different sources to generate electrical energy and their efficiencies are given below; [4]

- mechanical energy into electricity-generators (20-70% efficiency), piezoelectric systems (0,5-15% efficiency)
- chemical into electricity; fuel cells (25-35% efficiency), primary batteries, rechargeablebatteries
- heat/cold into electricity; seebeck-elements (2-5% efficiency)
- electromagnetic radiation into electricity; photovoltaic systems.

Piezoelectric effect is a unique property that allows materials to convert mechanical energy to electrical energy and conversely, electrical energy to mechanical energy. The stimuli for piezoelectric materials can be human walking, wind, rain, tide and wave etc. This effect can be an inherent property of the material or it can be imparted to an existing non-piezoelectric material. However, not every material can be made piezoelectric, only certain ceramics and polymers have the ability to become piezoelectric. Therefore, this paper will explains fundamentals of piezoelectric effect, a historical review on piezoelectric energy harvesting and recent developments such as flexible piezoelectric fibres which can be integrated or embedded into flexible structures.

II. SELF-POWERED SENSOR NETWORK AND SYSTEMS

A nanosystem is an integration of multi-functional nanodevices with the capability to sense, control, communicate and actuate/respond. Their low power consumption means it is possible to use the energy harvested from the environment to power such a system. Power on the scale of microwatts is usually needed for independent, sustainable, maintain-free operations of implantable biosensors, remote and mobile environmental sensors, nanorobotics, micro electromechanical systems, and even portable/wearable personal electronics. A nanorobot, for example, could sense and adapt to the environment, manipulate objects, taking actions and perform complex functions, but a key challenge is to find a power source that can drive a nanorobot without adding too much weight. Self-powered sensors, meanwhile, are needed for monitoring oil/gas transportations line over long distances. Self-powered sensors are a key component of the *defect tolerantsensor networks*, which use information sensing equipment such as radio frequency identification (RFID), sensors, global positioning systems (GPS) and laser scanners to connect objects with the internet to carry out communication, identification, positioning, tracking, monitoring and management. By replacing the traditional finite number of discrete sensors with a large number of independent and mobile sensors distributed in the field, a statistical analysis of the signals collected through the internet over the distributed sensors can give precise and reliable information. An internet of things that can correlate everyday objects and devices to large databases and networks (the internet) are the future of health care, medical monitoring, infrastructure/environment monitoring, product tracking, and smart home.

However, such a sensor network will be almost impractical if each sensor has to be powered by a battery because of the huge number and also environmental and health concerns. Therefore, new technologies that can harvest energy from the environment as *sustainable self-sufficient micro/nanopower* sources offer a possible of solution. But the mechanical energy available in our environment has a wide spectrum of frequencies and time-dependent amplitudes. This type of energy is called *random energy* and can come from irregular vibrations, light airflow, noise and human activity.

The working mode of a wireless sensor can have an active mode but most importantly, a standby mode, during which the device is at “sleeping” with minimum energy consumption. The power generated by an energy harvester may not be sufficient to continuously drive the operation of a device, but an accumulation of charges generated over a period of time is sufficient to drive the device for a few seconds. This could be of practical use for devices that have standby and active modes, such as glucose and blood pressure sensors, or even personal electronics such as blue tooth transmitters (driving power ~5 mW; data transmission rate ~ 500 kbits/s; power consumption 10 nW/bit), which are only required to be in active mode periodically. The energy generated when the device is in standby mode is likely to be sufficient to drive the device when it is in active mode.

III. HARVESTING MECHANICAL ENERGY

Photovoltaic, thermal electricity and electromagnetic induction are the well established technologies for energy harvesting, why do we need to harvest mechanical energy? We now consider the following occasions. In a case of individual sensors are difficult to get to (e.g. in hostile territory), or if the sensor network consists of a large number of nodes distributed over a large geographic area, then it may not be possible to replace batteries when required. A self sufficient power source deriving its power from the environment and thus not requiring any maintenance would be very desirable. In order for any system to be self sufficient, it must harness its energy from its surrounding environment and store this harnessed energy for later use. A nanorobot, for example, is proposed to be a smart machine that may be able to sense and adapt to the environment, manipulate objects, taking actions and perform complex functions, but a key challenge is to find a power source that can drive the nanorobot without adding much weight. If a nanorobot is placed in the body for performing sensing, diagnostic and therapeutic action, one can easily introduces it in the body, but it will be rather difficult/impossible to fish it out to replace the battery. In the context of military sensing/surveillance node placement may be in difficult to reach locations, may need to be hidden, and may be in the environment of dusty, rainy, dark and/or deep forest. This precludes the use of solar cell technologies because light is typically not available. Methods of energy harvesting that might be applicable to the problem at hand may include systems utilizing random vibration (e.g. vibrations near a roadway), temperature gradients (e.g. ground temperature is fairly constant sufficiently below the surface), or any other phenomenon that could be exploited to provide energy. Therefore, it is highly desired to develop technology for harvesting mechanical energy. What types of mechanical energies are we aiming at to harvest? There are abundant amount and types of mechanical energy exist in our living environment, such as light wind, body movement, muscle stretching, acoustic/ultrasonic waves, noises, mechanical vibrations, and blood flow. The sources of mechanical energy we are looking at have the following characteristics. First, the magnitude of such energy could be small and tiny, which may exclude the application of some conventional energy harvesting technologies because the available mechanical force may not be strong enough to drive the generator. Second, the frequency range of the available signal can be quite wide, and most of the energy is in low-frequency range. This requires a technique that operates from low (~Hz) to relatively high (~kHz) frequency range. Finally, the situation of the environment can vary. This requires a technique that has a high adoptability. The nanogenerator we developed in the last 7 years is a potential technology for solving these problems.

Table 1.1. Sources of mechanical energy around us each and every day that can be harvested for electricity

Human body/motion	Transportation	Infrastructures	Industry	Environment
Breathing, blood flow/pressure, exhalation, walking, arm motion, finger motion, jogging, talking …	Aircraft, automobile, train, tires, tracks, peddles, brakes, tubine enginin, vibration, noises …	Bridges, roads, tunnels, farm, house structure, control-switch, water/gas pipes, AC system …	Motors, compressors, chillers, pumps, fans, vibrations, cutting and dicing, noise…	Wing, ocean current/wave, acoustic wave…

Table 1.2. Mechanical energy from typical body motions and the theoretically electricity that can be generated.

Activity	Mechanical energy	Electrical energy	Electricity generated per movement
Blood flow	0.93 W	0.16 W	0.16 J
Exhalation	1.00 W	0.17 W	1.02 J
Breath	0.83 W	0.14 W	0.84 J
Upper limbs	3.00 W	0.51 W	2.25 J
Finger type	6.9-19 mW	1.2-3.2 mW	226-406 uJ
Walk	67 W	11-39 W	18.8 J

IV .PIEZOELECTRIC ENERGY HARVESTING

One of the most widely used smart materials is piezoelectric materials because of their wide band width, fast electro mechanical response, relatively low power requirements and high generative forces. Figure 1 presents a market review on piezoelectric materials corresponding to their applications and market share (%) in 2007. As it can be seen in Figure 1, information technology/robots is the leader of the market with 31.7% global market share while acoustic devices and resonators have the lowest share in the market with 3.1%. The others in the global market between these two applications can be given from high market share to low; semiconductor manufacturing and precision machines (18.6%), sonar (12.5%), bio/medical (11.1%), ecology and energy harvesting (7%), accelerators and sensors (5.8%), non-destructive testing (5.7%) and miscellaneous which includes gas igniters, piezo printing heads and telecommunication devices (4.5%). It has been reported by Innovative Research and Products (iRAP) Inc. that the global market for piezoelectric devices equals to US$10.6 billion and a high growth is expected over a 5-year period and to reach a value of US$19.5 billion by 2012. Energy harvesting applications for piezoelectric devices is less than 10% however it can change dramatically if the importance of piezoelectric materials is recognized for alternative energy from nature with zero carbon foot print.

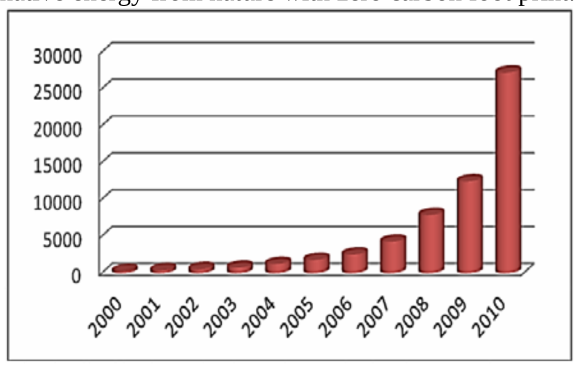

Figure 1. Piezoelectric devices market share overview on applications [5]

V .FUNDAMENTALS OF PIEZOELECTRIC MATERIAL

Piezoelectricity is the ability of some materials (notably crystals and certain ceramics) to generate an electrical potential in response to applied mechanical stress. This may take the form of a separation of electric charge across the crystal lattice. If the material is not short circuited, the applied charge induces a voltage across the material. The word is derived from the Greek word piezien, which means to squeeze or press. The conversion of mechanical energy into electrical one is generally achieved by converters alternate or type or commonly known dynamo. But there are other physical phenomena including piezoelectricity that can also convert mechanical movements into electricity. The phenomenon that produces an electric charge when a force is applied to piezoelectric material is known as the piezoelectric effect. The piezoelectric effect exists in two domains, the first is the direct piezoelectric effect that describes the material’s ability to transform mechanical strain into electrical charge[6] , the second form is the converse effect, which is the ability to convert an applied electrical potential into mechanical strain energy figure 2.

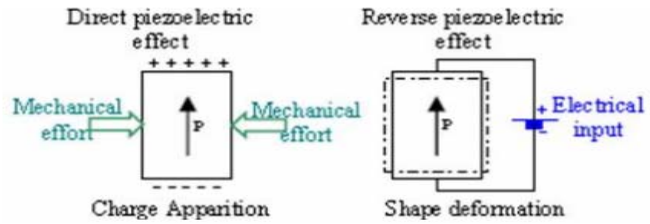

Fig.2: Electromechanical conversion via piezoelectricity phenomenon.

The direct piezoelectric effect is responsible for the materials ability to function as a sensor and the converse piezoelectric effect is accountable for its ability to function as an actuator. A material is deemed piezoelectric when it has this ability to transform electrical energy into mechanical strain energy, and likewise transform mechanical strain energy into electrical charge. The piezoelectric materials that exist naturally as quartz were not interesting properties for the production of electricity, however artificial piezoelectric materials such as PZT (Lead Zirconate Titanate) present advantageous characteristics. Piezoelectric materials belong to a larger class of materials called ferroelectrics. One of the defining traits of a ferroelectric material is that the molecular structure is oriented such that the material exhibits a local charge separation, known as an electric dipole. Throughout the artificial piezoelectric material composition the electric dipoles are orientated randomly, but when a very strong electric field is applied, the electric dipoles reorient themselves relative to the electric field; this process is termed poling. Once the electric field is extinguished, the dipoles maintain their orientation and the material is then said to be poled. After the poling process is completed, the material will exhibit the piezoelectric effect. When the material is deformed or stressed an electric voltage can be recovered along any surface of the material (via electrodes). Therefore, the piezoelectric properties must contain a sign convention to facilitate this ability to recover electric potential[7-8].

The piezoelectric coefficient displayed by the nanowires having a diameter of 2.4 nanometers is 20 times higher for ZnO nanowires and 100 times higher for GaN nanowires when compared to the coefficient displayed by the same materials at macro scale. piezoelectric zinc oxide (ZnO) nanowires that can be grown on any substrate (e.g., metals, ceramics, polymers, and textile fibers) of any shape.

The advantages of using Piezoelectric materials (1)Small size, (2)Broad frequency range, (3)Light weight, (4) 2-wire operation, (5)Ultra low noise, (6) Wide dynamic range, (7)Wide temperature range, (8)Simple signal conditioning and (9)Cost effective implementation

VI. DIFFERENT STRUCTURE USED FOR PIEZO-ELECTRIC METHOD

A. *Cantilever type*

A cantilever type vibration energy harvesting has very simple structure and can produce a large deformation under vibration. Flynn and Sander[9] imposed fundamental limitations on PZT (leadzirconate titanate) material and indicated that mechanical stress limit is the effective constraint in typical PZT materials. They reported that a mechanical stress-limited work cycle was 330W/cm3 at 100 kHz for PZT-5H. Elvin et al.[10] proposed a theoretical model by using a beam element and performed experiment to harvest power from PZT material. They showed that a simple beam bending can provide the self-power source of the strain energy sensor. Wright et al. presented series of vibrational energy harvesting devices[11-14]. First, they indicated low-level vibrations occurring in common household and office environments as a potential power source and investigated both capacitive MEMS and piezoelectric converters[11]. The simulated results showed that power harvesting using piezoelectric conversion is significantly higher. They optimized a two-layer cantilever piezoelectric generator and validated by theoretical analysis (Fig. 3)[12]. They also modeled a small cantilever based devices using piezoelectric materials that can scavenge power from low-level ambient vibration sources and presented new design configuration to enhance the power harvesting capacity[13]. It used axially compressed piezoelectric bimorph in order to decrease resonance frequency up to 24%. They found that power output to be 65–90% of the nominal value at frequencies 19–24% below the unloaded resonance frequency[14].

Sodano et al.[15] investigated monolithic piezoelectric (PZT) and MFC and estimated the efficiency of both the materials. They also investigated three types of piezoelectric devices experimentally, a monolithic PZT, bimorph QP and MFC energy harvesting devices to determine their capacity to recharge a discharged battery[16]. Shen et al.[17] proposed a PZT piezoelectric cantilever with a micro machined Si proof mass for a low frequency vibration energy harvesting application. The average power and power density were 0.32 W and 416 W/cm3. Liu et al.[18] developed an array of power generator based on thick-film piezoelectric cantilevers in order to improve frequency flexibility and power output. They reported an improved performance of 3.98 mW effective electrical power and 3.93 DC output voltage to resistance load. Choi et al.[19] developed an energy harvesting MEMS device using thin film PZT to enable self-supportive sensors. Resonating at specific frequencies of an external vibrational energy source can create electrical energy via the piezoelectric effect. The effect of proof mass, beam shape and damping on the power generating performance were modeled to provide guideline for maximum power harvesting from environmentally available low frequency vibrations.

B. *Cymbal type*

Cymbal structure can produce a large in-plane strain under a transverse external force, which is beneficial for the micro energy harvesting. Kim et al.[20] reported that piezoelectric energy harvesting showed a promising results under pre-stress cyclic conditions and validated the experimental results with finite element analysis. Li et al.[21] presented a two ring-type piezoelectric stacks, one pair of bow-shaped elastic plates, and one shaft that precompresses them (Fig. 4). The reported that flex-compressive mode piezoelectric transducer has the ability to generate more electric voltage output and power output as compared to conventional flextensional mode.

C. *Stack type*

Stack type piezoelectric transducer can produce a large electrical energy since it uses d33 mode of piezoelectric materials and has a large capacitance because of multi-stacking of piezoelectric material layers. Adhikari et al.[22] proposed a stochastic approach using stack configuration rather than cantilever beam harmonic excitation at resonance and analyzed two cases, with inductor in the electrical circuit and without inductor. Lefeuvre et al.26 proposed a synchronized switch damping (SSD) in vibrational piezoelectric energy harvesting (Fig. 5). They claimed that SSD increases the electrically converted energy resulting from the piezoelectric mechanical loading cycle.

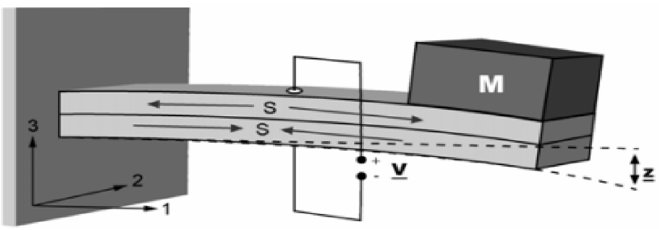

Fig. 3 A two-layer bender mounted as a cantilever (a) Cantilever type (b) Cymbal type[24]

D. *Shell type*

Since shell structure can generate larger strain than flat plate, it can improve the efficiency of piezoelectric energy harvesting. Yoon et al.[24] employed a curved piezoceramic to increase the charge because of mechanical strain (Fig. 6). They optimized the analytical model using shell theory and linear piezoelectric constitutive equations to develop a charge generation expression. Yoon et al.[24] investigated a ring-shaped PZT-5A element exposed to gunfire shock experimentally using pneumatic shock machine. They found dependence of piezoelectric constant on load-rate, the shock-aging of piezoelectric effect, and the dependence of energy-transfer efficiency on the change in normalized impulse. The proposed structure harvested electrical energy from torsional vibration.

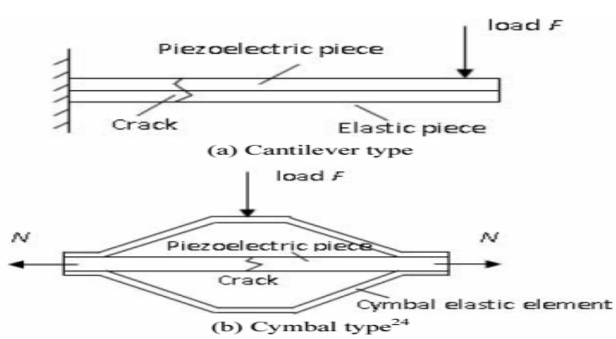

Fig. 4 Conventional piezoelectric energy harvesters

This stack type can be weak under mechanical shocks.

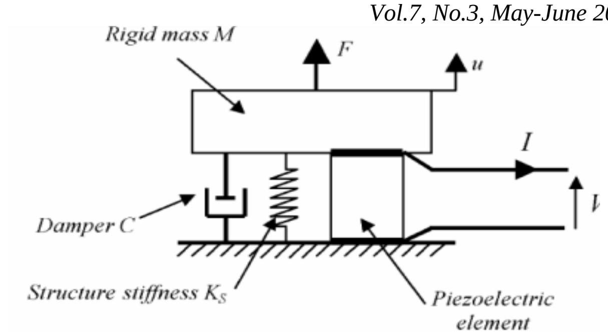

Fig. 5 Model of a vibrating structure including a piezoelectric element [23]

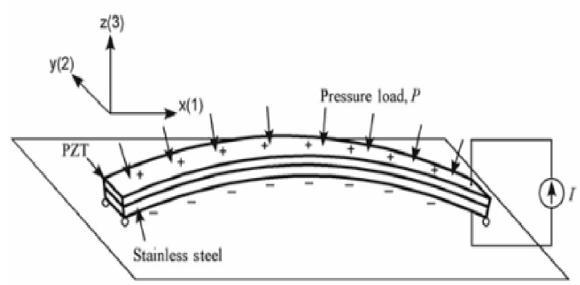

Fig. 6 Curved PZT unimorph excited in d31-mode by a normal distributed force [24]

VII. THE NANOGENERATOR

We first proposed the self-powered nanotechnology in 2006, and we had developed the nanogenerator the self-powered system. The nanogenerator converts random mechanical energy into electric energy using piezoelectric zinc oxide nanowire arrays. The mechanism of the nanogenerator relies on the piezoelectric potential created in the nanowires by an external strain: a dynamic straining of the nanowire results in a transient flow of the electrons in the external load because of the driving force of the piezopotential. The advantage of using nanowires is that they can be triggered by tiny physical motions and the excitation frequency can be one Hz to thousands of Hz, which is ideal for harvesting random energy in the environment. By integrating the contribution from thousands of nanowires, a gentle straining can output 1.2 V, which can drive an LED and a small liquid crystal display. The discovery of nanogenerators is the top 10 world discoveries in science according to academicians of Chinese Academy of Science. The fiber based nanogenerator was elected as one of the top progresses in physics in 2008 by *Physics World*.[25, 26] The nanogenerator has been selected as the top 10 sci-fi discoveries that can have the equal importance as the invention of cell phones in 10-30 years, according to *New Scientist*. The nanopiezotronics is the top 10 emerging technologies in 2009 according to *MITTechnology Review*. The nanogenerator was among the top 20 discoveries in nanotechnologies that you may not known by *Discovery* Magazine (2010), and it is now in the top six future and emerging technologies selected by European Commission for support in the next 10 years [27]. The development process of the nanogenerator is a scientific story. The objective of this book is to introduce the fundamentals of the nanogenerator. We start from the very basic materials growth, followed by the description of the physical mechanism and basic theory. Then we will demonstrate the engineering approaches for achieving high output power. Lastly, we will present the hybridization of the nanogenerators with other energy harvesting techniques. Finally, we will show the prototype self-powered systems.

VIII. PRACTICAL APPLICATIONS OF ENERGY HARVESTING

As typical human applies over 100 % of his own weight across the shoes at every heel strike therefore, cushioned shoe soles can be significantly compressed even during normal walk. Assuming an average person weighting 75 kg, 5 mm sole compression, regular walking speed of 2 steps/s this indicates that roughly about 7 W of power could be available just from heel strikes. Company SRI Intl. has designed and tested a multilayer EAP(electroactive polymers) shoe generator, schematically illustrated in fig. 7. When the device is compressed, the coupling liquid or gel medium contained in the bellows forces out and stretches a thin, elastic layer of electroded EAP through circular openings in the upper perforated plate sealing the bellows. In normal walking conditions such boot energy scavenger was delivering energy output of 0.8 J per every step with just 3 mm heel compression and provided 0.8 W of power [28].

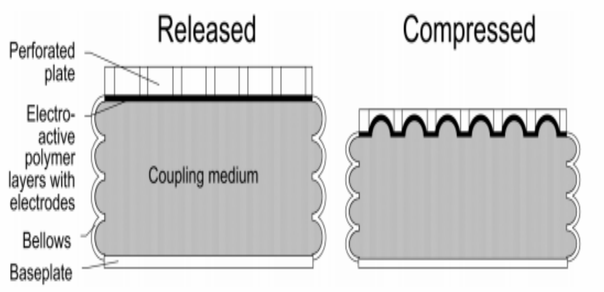

Figure 7. Schematic view of electroactive polymer heel energy harvester module developed by SRI Intl. (sketch based on [29]).

Effective piezoelectric energy harvesting requires piezoelectric materials with elevated electromechanical coupling coefficients, thus ceramic (PZT) materials dominate those designs. The company Adaptiv Energy is promoting its kinetic energy harvesting solutions based on Ruggedized Laminate Piezo (RLP) composite combined with efficient, very-low-loss MOSFET power extraction electronics. The RLP technology allows to compress piezoceramic material in order to increase the voltage per strained unit area. The RLP is a stainless steel flat spring double-side laminated with a piezoelectric ceramics and copper electroding layers. Appropriate thermal cycling during bonding process introduces initial compressive prestressing into the piezoelectric material, giving greater density and flexibility and thus provides added output voltage. RLP transducer uses calibrated mass to match the exploitable vibration spectrum [30]. Ocean Power Technologies company exploits strips of piezoelectric foil to harness the power of flowing water, in the form of 18-inch-long “eels” that flap in turbulent water flow like a weeds in the wind [31]. Energy scavenging by piezoelectric generators has also been recently perceived by automotive industry, especially car automation designers and manufacturers. Kim *et al.* discuss the use of a piezoelectric cymbal transducers to generate electricity to supply car remote onboard sensors from the vibration of a car engine [32]. Dynamic strain coupled from the rolling tire of a car has also been recently patented as a power source for a wireless tire condition monitoring system [33].

Energy scavengers operating in continuous mode may also be used to extract energy from human motion. A heel strike may be used to flatten a piezoelectric (PZT) unimorph bender and toe-off action may bend a multilayer polymeric piezoelectric bimorph stave made of PVDF (polyvinylidene fluoride) foil. Such combined system was shown to produce 1.3 to 8.3 mW during a standard walk depending on the location of transducer (toe/heel) and available displacement range [34]. The East Japan Railway Company has been testing an experimental system that produces electricity as people pass through subway ticket gates. The gates are fitted with floor embedded energy-scavenging mats with series of piezo element diaphragms that generate electricity as commuters walk over and compress the mat. 90 m2 energy-scavenging floor was producing on average 0.14 kWh of energy a day with peak performance of 0.21 kWh on busy weekends [35].

An array of aligned ZnO nanowires is covered by a zigzag silicon electrode coated with platinum(fig.8). The platinum coating not only enhances the conductivity of the electrode but also creates a Schottky contact at the interface with the ZnO that functions like a p-n junction or diode[36].

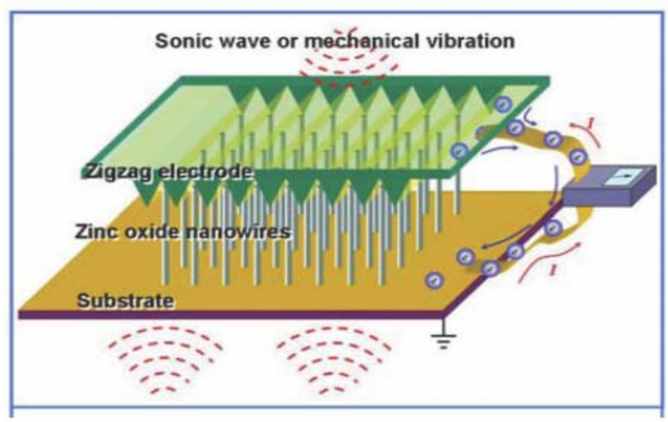

Figure 8 Schematic diagram showing the DC nanogenerator built using aligned ZnO nanowire arrays with a zigzag top electrode.[37]

The nanowires were grown on gallium nitride substrates, which served as a common electrode for directly connecting with an external circuit. The asymmetric piezoelectric potential across the width of a ZnO nanowire and the Schottky contact between the metal electrode and the nanowire are the two key processes for creating, separating, preserving, and outputting the charges. A top electrode is designed to achieve the coupling process and to replace the role played by the AFM tip, and its zigzag trenches act as an array of aligned AFM tips. The DC nanogenerator is driven by ultrasonic waves. Once the wave is on, a nanogenerator measuring 2mm2 delivers a current output of 30nA. The design is new, cost-effective, and meets the stipulated requirements. The approach provides a basis for optimizing and improving the performance of the nanogenerator for its applications in nanotechnology. The principle and technology demonstrated here have the potential to convert energy from mechanical movement (such as body motion, muscle stretching, and blood pressure), vibrations (such as acoustic and ultrasonic waves), and hydraulic movement (such as flow of body fluid and blood, or contraction of blood vessels) into electrical energy to power nanodevices and nanosystems. Relevant applications include implantable biosensing, wireless and remote sensing, nanorobotics, microelectromechanical systems, and sonic wave detection[36-37].

A. *POWER GENERATING SIDEWALK*

The piezoelectric crystal arrays are laid underneath pavements, side walks(Fig.9), speed breakers for maximum voltage generation. The voltage thus generated from the array can be used to charge the chargeable Lithium batteries, capacitors etc. These batteries can be used as per the requirement[38].

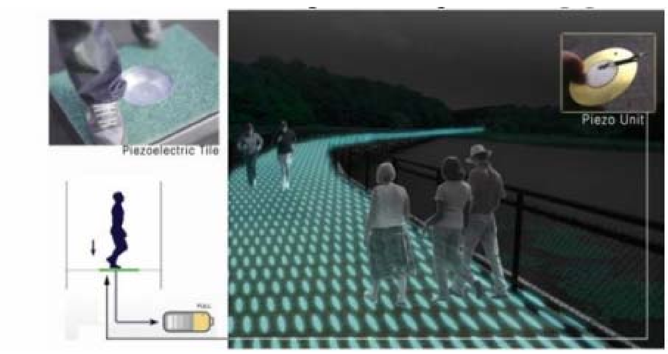

Fig.9: Pathways with Piezo material generating electricity.

The energy generated from the moving vehicles is stored in huge batteries and from the batteries the energy is used for the city's energy consumption. This can be used for example to light the street lights at night from the entire energy stored in the batteries. It can also be used for powering the household gadgets and in short the city as a whole saving lots of fuel used in electricity generation in an eco-friendly way.

B. *POWER GENERATING BOOTS OR SHOES*

In United States Defense Advance Research Project Agency (DARPA) initiated a innovative project on Energy harvesting which attempts to power battlefield equipment by piezoelectric generators(fig.10) embedded in soldiers' boots [38]. However, these energy harvesting sources put an impact on the body. DARPA's effort to harness 1-2 watts from continuous shoe impact while walking were abandoned due to the discomfort from the additional energy expended by a person wearing the shoes[38].

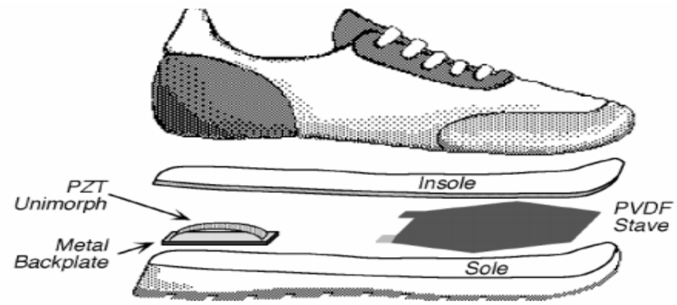

Fig.10: Shoes with Piezoelectric material.

C.*GYMS AND WORKPLACES*

Researchers are also working on the idea of utilizing the vibrations caused from the machines in the gym(fig.11) At workplaces, while sitting on the chair, energy can be stored in the batteries by laying piezoelectric crystals in the chair. Also, the studies are being carried out to utilize the vibrations in a vehicle, like at clutches, gears, seats, shock-ups, foot rests[39].\

Fig.11: Piezoelectric material in machines in gyms.

D. *PEOPLE POWERED DANCE CLUBS*

In Europe, certain nightclubs have already begun to power their night clubs, strobes and stereos by use of piezoelectric crystals. The crystals are laid underneath the dance floor(Fig.12). When a bulk of people use this dance floor, enormous amount of voltage is generated which can be used to power the equipments of the night club[39].

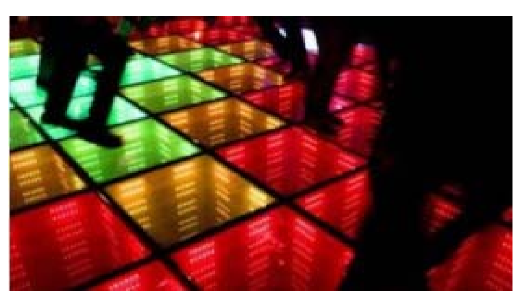

Fig.12: Dance floors with Piezoelectric material.

Imagine a dance floor packed with moving bodies where the energy from the dance which previously seemed to be impractical now produces electricity enough to run the entire club[40].

E *SITTING CHAIRS*

In the capital city of Athens , Chairs(Fig.13) are arranged and each is made with aPZT stack generators (part number T18-H5-104, Piezo Systems, Inc. Cambridge, MA), with a volume of 0.5 cm3 (5 mm x 5 mm x18mm). The piezoelectric material of the stack has a piezoelectric constant of 0.013 VmN-1 and a relative dielectric constant of 5400. The thickness of each layer is 0.11 mm and the stack contains approximately 164 layers. These values were specified by the manufacturer. Ten layers of these generators cover the space of 45 cm x 40 cm x 18 cm in the metro seat[41].

Figure 13: Athens metro seat[41]

This leads to approximately PPMS=1.22 Watt. Depending on the passenger strength the annual power generation will be in thousands of kilowatts.

F.*CAR PARKING*

According to *The Daily Mail*, a Sainsbury's supermarket in Gloucester, UK (you've never been there), has installed kinetic plates in the parking lot that use the weight of shopper's cars to pump a series of hydraulic pipes, which in turn drive a generator. The system is said to generate up to 30kw of energy an hour -- or enough to power the store's checkouts[42].

The technology "*is based on piezoelectric generators; the piezoelectric effect converts mechanical strain into electrical current or voltage*." In other words, when a piezoelectric material is deformed, the energy from the deformation of the material gets converted into electricity. Innowattech has created three different versions of what it calls the Innowattech Piezo Electric Generator (IPEG): a Roadway Generator, a Railroad Generator, and a Runway Generator. Innowattech claims that its IPEGs can "*harvest energy from weight, motion, vibration and temperature changes*."[42].

While it might not be noticeable to the casual observer, whenever a vehicle passes over a roadway, the roadway actually deforms somewhat beneath the vehicle. If you have ever had your foot run over by a car, you have experienced a version of this--albeit, likely a painful one. The same thing happens to rail beds and runways when trains and planes pass over them--these surfaces deform slightly as well. Innowattech wants to implant networks of its IPEGs into these surfaces so that vehicles will also deform the piezoelectric generators as well, which in turn would generate electricity. In fact, the heavier a vehicle is and the faster it is moving, the more energy gets transferred to the IPEGs. Innowattech claims that 1km of a railroad can produce up to 150kW of electricity per hour; and 1km of roadway or runway can produce up to 0.5mW (500kW) of electricity per hour. The electricity harvested by the IPEG network could be added to local electrical grids[42].

The roadway and airport IPEGs can also "*record the weight, frequency and speed of passing vehicles as well as the spacing between vehicles in real time*." This can create "*smart roads*" and airports where the data can be used to help manage traffic and alert drivers and emergency responders

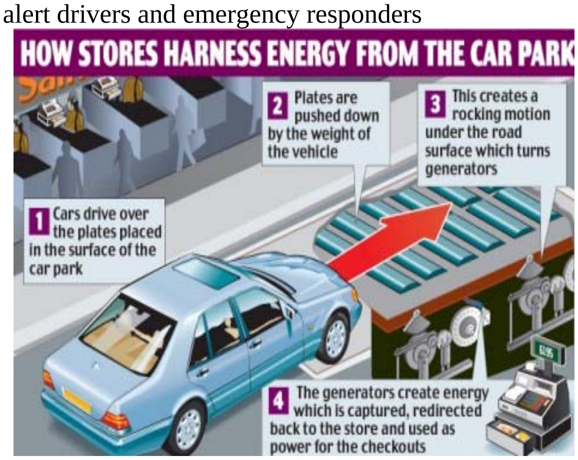

Figure 14 Harness of Energy from the car park
http://heightech.blogspot.in/2013/05/piezoelectric-road-harvests-traffic.html
.

What makes this such an innovative approach is that it doesn't force drivers or car manufacturers to have to make any significant changes, such as switching over to electric cars or other fossil fuel alternatives. By the same token, it makes no difference to the IPEGs what is powering the vehicles passing overhead, so as automobile engines continue to evolve over time away from fossil fuels, the IPEGs will continue harvesting their energy. It remains to be seen, however, if this "*green*" technology will ever see real-world applications[43].

G *NANOLEAF TREE*

To complete the tree for multi energy exploitation, the petiole twigs and branches are incorporated with Nano piezo-electric elements[44]. A Nanoleaf is thin like a natural leaf, when outside forces, like the wind pushes the Nanoleaf back and forth, mechanical stresses appear in the petiole, twig and branches. When thousands of Nanoleaves flap back and forth due to wind, millions and millions of Pico watts are generated, the stronger the wind, the more energy is generated. Our Nanoleaves only reflect a small part of the sunlight that strikes them, mostly the green light, and the rest of the spectrum is efficiently converted into electricity. Besides converting the visible spectrum of light, Nanoleaves also convert the invisible light, known as infrared light or radiation, we can't see it, but we can feel it - it's warm - that's why we call it radiation. Due to the unique combination of photovoltaic and thermo voltaic in our Nanoleaves it converts this thermal radiation into electricity, even hours after the sun has set. The more wind there is, the more Nanoleaves are moved. Wind that is moving thousands of Nanoleaves in a tree canopy are causing mechanical strain in the petiole, twigs and branches. Nano piezo-electric elements incorporated in the petiole twigs and branches are the tiny Nano piezo- electric elements that will generate millions and millions of Pico watts as these thousands of Nanoleaves flap back and forth due to wind. The stronger the wind, the higher the "flap" frequency, and therefore the larger the watts generated in the petiole, twigs and branches. With the progress in nano technology, the photovoltaic, thermo voltaic and piezo electric materials are becoming more efficient and combined in one system[44].

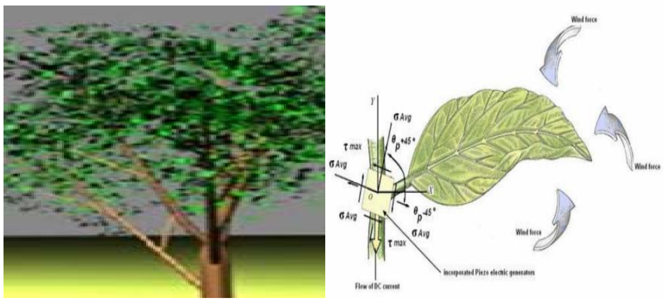

Figure 15 Nanoleaf tree harnessing energy.

This technology is an inventive method of green energy collection, combining the conversion of light, heat and wind power. Integrated nano technologies enable the nanoleaves to convert solar radiation (light and heat) into electricity. Furthermore, the leaf petiole or the stem and twigs comprise nanopiezoelectric material- these tiny generators produce electricity from movement or kinetic energy caused by wind or falling raindrops. A Fundamental flaw in conventional solar cells is that electrons give too much energy by sunlight and lose that energy in heat form, as the electrons move thermally to the bottom of the conduction band.

The Energy harvesting trees generate electricity in three ways:

- Nano-photovoltaic generators in the leaf directly convert solar energy into electricity.
- Nano-thermoelectric cells convert solar heat to electricity.
- Nano-piezoelectric generators can also convert wind energy into electricity

The Nanoleaves transform the whole solar scale converting detectable light, infrared and Ultraviolet in a unification with piezo-electric generators that alter wind energy into electricity

The Energy Harvesting Trees are multifunctional, efficient, renewable energy system. These super ecofriendly synthetic trees will make use of renewable energy from the sun along with wind power, which are an effective clean and environmentally sound medium of gathering solar radiation and wind energy. With the progress in nanotechnology, the photovoltaic, thermo voltaic and piezoelectric materials are becoming more efficient and combined in one system which will lead to implementation of Energy Harvesting Trees sooner

Oh et.al[45] demonstrated an experimental investigation of a tree shaped wind power system using piezoelectric material (Fig. 16). PVDF was used to make the leaf element, whereas PZT was applied to the trunk portion of the tree requiring rather strong winds to generate any power. The soft flexible one is used to make the leaf element, whereas the hard one is applied to the trunk portion of the tree requiring rather strong winds to generate any power. Although small, each leaf deems to play the role of a power producer as currents are continuously trickling down to a storage battery installed at the bottom of the system[45].

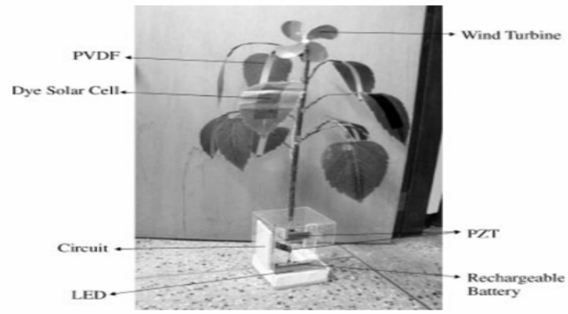

Fig. 16 A prototype tree-shaped wind power system[45].

IX.CONCLUSIONS

The term "global warming" has been highlighted more and more every day since it is considered as one of the biggest dangers to life on earth. It is a fact that one of the factors which cause global warming is high carbon emission. Growing population and the increasing technology consumerism contribute to the enhanced usage of energy from coal, oil, electricity etc. However, sooner or later the mankind is anticipated to run out of the coal and oil reserves since they are finite and are not renewable. Energy harvesting properties of both piezoelectric and photovoltaic materials have been known for a long period of time however recently more attention has been paid to produce usable materials for energy generation in the form of electricity to decrease carbon foot print. Piezoelectric materials can convert almost any kind of mechanical energy to electrical energy. The most suitable piezoelectric material is chosen for a particular application depending on the properties needed. Thus, the maximum energy output, with minimum carbon emission, can be provided to power an electronic device on-line or to be stored.

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