

# Energy harvesting

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**Energy harvesting** (also known as **power harvesting** or **energy scavenging** or **ambient power**) is the process by which energy is derived from external sources (e.g., solar power, thermal energy, wind energy, salinity gradients, and kinetic energy, also known as **ambient energy**), captured, and stored for small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks.

Energy harvesters provide a very small amount of power for low-energy electronics. While the input fuel to some large-scale generation costs resources (oil, coal, etc.), the energy source for energy harvesters is present as ambient background and is free. For example, temperature gradients exist from the operation of a combustion engine and in urban areas, there is a large amount of electromagnetic energy in the environment because of radio and television broadcasting.

One of the earliest applications of ambient power collected from ambient electromagnetic radiation (EMR) is the crystal radio.

The principles of energy harvesting from ambient EMR can be demonstrated with basic components.<sup>[1]</sup>

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## Operation

Energy harvesting devices converting ambient energy into electrical energy have attracted much interest in both the military and commercial sectors. Some systems convert motion, such as that of ocean waves, into electricity to be used by oceanographic monitoring sensors for autonomous operation. Future applications may include high power output devices (or arrays of such devices) deployed at remote locations to serve as reliable power stations for large systems. Another application is in wearable electronics, where energy harvesting devices can power or recharge cellphones, mobile computers, radio communication equipment, etc. All of these devices must be sufficiently robust to endure long-term exposure to hostile environments and have a broad range of dynamic sensitivity to exploit the entire spectrum of wave motions.

## Accumulating energy

Energy can also be harvested to power small autonomous sensors such as those developed using MEMS technology. These systems are often very small and require little power, but their applications are limited by the reliance on battery power. Scavenging energy from ambient vibrations, wind, heat or light could enable smart sensors to be functional indefinitely. Several academic and commercial groups have been involved in the analysis and development of vibration-powered energy harvesting technology, including the Control and Power Group and Optical and Semiconductor Devices Group at Imperial College London, IMEC and the partnering Holst Centr,<sup>[2]</sup> AdaptivEnergy, LLC, ARVENI, MIT Boston, Victoria University of Wellington,<sup>[3]</sup> Georgia Tech, UC Berkeley, Southampton University, University of Bristol,<sup>[4]</sup> Micro Energy System Lab at The University of Tokyo (<http://www.mesl.t.u-tokyo.ac.jp/>), Nanyang Technological University,<sup>[5]</sup> PMG Perpetuum, ReVibe Energy (<http://www.revibeenergy.com>), Vestfold University College, National University of Singapore,<sup>[6]</sup> NiPS Laboratory at the University of Perugia,<sup>[7]</sup> Columbia University,<sup>[8]</sup> Universidad Autónoma de Barcelona and USN & Renewable Energy Lab at the University of Ulsan (Ulsan, South Korea). The National Science Foundation also supports an Industry/University Cooperative Research Center led by Virginia Tech and The University of Texas at Dallas called the Center for Energy Harvesting Materials and Systems.

Typical power densities available from energy harvesting devices are highly dependent upon the specific application (affecting the generator's size) and the design itself of the harvesting generator. In general, for motion powered devices, typical values are a few  $\mu\text{W}/\text{cm}^3$  for human body powered applications and hundreds of  $\mu\text{W}/\text{cm}^3$  for generators powered from machinery.<sup>[9]</sup> Most energy scavenging devices for wearable electronics generate very little power.<sup>[10]</sup>

## Storage of power

In general, energy can be stored in a capacitor, super capacitor, or battery. Capacitors are used when the application needs to provide huge energy spikes. Batteries leak less energy and are therefore used when the device needs to provide a steady flow of energy.

## Use of the power

Current interest in low power energy harvesting is for independent sensor networks. In these applications an energy harvesting scheme puts power stored into a capacitor then boosted/regulated to a second storage capacitor or battery for the use in the microprocessor.<sup>[11]</sup> The power is usually used in a sensor application and the data stored or is transmitted possibly through a wireless method.<sup>[12]</sup>

## Motivation

The history of energy harvesting dates back to the windmill and the waterwheel. People have searched for ways to store the energy from heat and vibrations for many decades. One driving force behind the search for new energy harvesting devices is the desire to power sensor networks and mobile devices without batteries. Energy harvesting is also motivated by a desire to address the issue of climate change and global warming.

## Devices

There are many small-scale energy sources that generally cannot be scaled up to industrial size:

- Some wristwatches are powered by kinetic energy (called automatic watches), in this case movement of the arm is used. The arm movement causes winding of its mainspring. A newer design introduced by Seiko ("Kinetic") uses movement of a magnet in the electromagnetic generator instead to power the quartz movement. The motion provides a rate of change of flux, which results in some induced emf on the coils. The concept is simply related to Faraday's Law.
- Photovoltaics is a method of generating electrical power by converting solar radiation (both indoors and outdoors) into direct current electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels composed of a number of cells containing a photovoltaic material. Note that photovoltaics have been scaled up to industrial size and that large solar farms exist.
- Thermoelectric generators (TEGs) consist of the junction of two dissimilar materials and the presence of a thermal gradient. Large voltage outputs are possible by connecting many junctions electrically in series and thermally in parallel. Typical performance is 100-300  $\mu\text{V}/\text{K}$  per junction. These can be utilized to capture mW.s of energy from industrial equipment, structures, and even the human body. They are typically coupled with heat sinks to improve temperature gradient.
- Micro wind turbine are used to harvest wind energy readily available in the environment in the form of kinetic energy to power the low power electronic devices such as wireless sensor nodes. When air flows across the blades of the turbine, a net pressure difference is developed between the wind speeds above and below the blades. This will result in a lift force generated which in turn rotate the blades. Similar to photovoltaics, wind farms have been constructed on an industrial scale and are being used to generate substantial amounts of electrical energy.
- Piezoelectric crystals or fibers generate a small voltage whenever they are mechanically deformed. Vibration from engines can stimulate piezoelectric materials, as can the heel of a shoe, or the pushing of a button.
- Special antennas can collect energy from stray radio waves,<sup>[13]</sup> this can also be done with a Rectenna and theoretically at even higher frequency EM radiation with a Nantenna.
- Power from keys pressed during use of a portable electronic device or remote controller, using magnet and coil or piezoelectric energy converters, may be used to help power the device.<sup>[14]</sup>

## Ambient-radiation sources

A possible source of energy comes from ubiquitous radio transmitters. Historically, either a large collection area or close proximity to the radiating wireless energy source is needed to get useful power levels from this source. The nantenna is one proposed development which would overcome this limitation by making use of the abundant natural radiation (such as solar radiation).

One idea is to deliberately broadcast RF energy to power remote devices: This is now commonplace in passive radio-frequency identification (RFID) systems, but the Safety and US Federal Communications Commission (and equivalent bodies worldwide) limit the maximum power that can be transmitted this way to civilian use. This method has been used to power individual nodes in a wireless sensor network<sup>[15]</sup>

## Fluid flow

Airflow can be harvested by various turbine and non-turbine generator technologies. For example, Zephyr Energy Corporation's patented Windbeam micro generator captures energy from airflow to recharge batteries and power electronic devices. The Windbeam's novel design allows it to operate silently in wind speeds as low as 2 mph. The generator consists of a lightweight beam suspended by durable long-lasting springs within an outer frame. The beam oscillates rapidly when exposed to airflow due to the effects of multiple fluid flow phenomena. A linear alternator assembly converts the oscillating beam motion into usable electrical energy. A lack of bearings and gears eliminates frictional inefficiencies and noise. The generator can operate in low-light environments unsuitable for solar panels (e.g. HVAC ducts) and is inexpensive due to low cost components and simple construction. The scalable technology can be optimized to satisfy the energy requirements and design constraints of a given application.<sup>[16]</sup>

## Photovoltaic

Photovoltaic (PV) energy harvesting wireless technology offers significant advantages over wired or solely battery-powered sensor solutions: virtually inexhaustible sources of power with little or no adverse environmental effects. Indoor PV harvesting solutions have to date been powered by specially tuned amorphous silicon (aSi) a technology most used in Solar Calculators. In recent years new PV technologies have come to the forefront in Energy Harvesting such as Dye Sensitized Solar Cells (DSSC). The dyes absorbs light much like chlorophyll does in plants. Electrons released on impact escape to the layer of TiO<sub>2</sub> and from there diffuse, through the electrolyte, as the dye can be tuned to the visible spectrum much higher power can be produced. At 200 lux a DSSC can provide over 10 μW per cm<sup>2</sup>.

## Piezoelectric

The piezoelectric effect converts mechanical strain into electric current or voltage. This strain can come from many different sources. Human motion, low-frequency seismic vibrations, and acoustic noise are everyday examples. Except in rare instances the piezoelectric effect operates in AC requiring time-varying inputs at mechanical resonance to be efficient.

Most piezoelectric electricity sources produce power on the order of milliwatts, too small for system application, but enough for hand-held devices such as some commercially available self-winding wristwatches. One proposal is that they are used for micro-scale



picture of a batteryless and wireless wallswitch

devices, such as in a device harvesting micro-hydraulic energy. In this device, the flow of pressurized hydraulic fluid drives a reciprocating piston supported by three piezoelectric elements which convert the pressure fluctuations into an alternating current.

As piezo energy harvesting has been investigated only since the late 1990s,<sup>[17][18]</sup> it remains an emerging technology. Nevertheless, some interesting improvements were made with the self-powered electronic switch at INSA school of engineering, implemented by the spin-off Arveni. In 2006, the proof of concept of a battery-less wireless doorbell push button was created, and recently, a product showed that classical wireless wallswitch can be powered by a piezo harvester. Other industrial applications appeared between 2000 and 2005,<sup>[19]</sup> to harvest energy from vibration and supply sensors for example, or to harvest energy from shock.

Piezoelectric systems can convert motion from the human body into electrical power. DARPA has funded efforts to harness energy from leg and arm motion, shoe impacts, and blood pressure for low level power to implantable or wearable sensors. The nanobrushes are another example of a piezoelectric energy harvester.<sup>[20]</sup> They can be integrated into clothing. Multiple other nanostructures have been exploited to build an energy-harvesting device, for example, a single crystal PMN-PT nanobelt was fabricated and assembled into a piezoelectric energy harvester in 2016.<sup>[21]</sup> Careful design is needed to minimise user discomfort. These energy harvesting sources by association affect the body. The Vibration Energy Scavenging Project<sup>[22]</sup> is another project that is set up to try to scavenge electrical energy from environmental vibrations and movements. Microbelt can be used to gather electricity from respiration.<sup>[23]</sup> Finally, a millimeter-scale piezoelectric energy harvester has also already been created.<sup>[24]</sup>

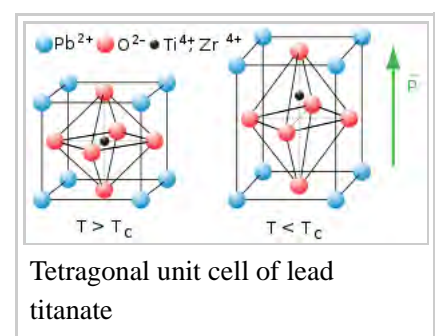
The use of piezoelectric materials to harvest power has already become popular. Piezoelectric materials have the ability to transform mechanical strain energy into electrical charge. Piezo elements are being embedded in walkways<sup>[25][26][27]</sup> to recover the "people energy" of footsteps. They can also be embedded in shoes<sup>[28]</sup> to recover "walking energy". Researchers at MIT developed the first micro-scale piezoelectric energy harvester using thin film PZT in 2005.<sup>[29]</sup> Arman Hajati and Sang-Gook Kim invented the Ultra Wide-Bandwidth micro-scale piezoelectric energy harvesting device by exploiting the nonlinear stiffness of a doubly clamped microelectromechanical systems (MEMSs) resonator. The stretching strain in a doubly clamped beam shows a nonlinear stiffness, which provides a passive feedback and results in amplitude-stiffened Duffing mode resonance.<sup>[30]</sup>

## Energy from smart roads and piezoelectricity

Brothers Pierre Curie and Jacques Curie gave the concept of piezoelectric effect in 1880.<sup>[31]</sup> Piezoelectric effect converts mechanical strain into voltage or electric current and generates electric energy from motion, weight, vibration and temperature changes as shown in the figure.

Considering piezoelectric effect in thin film lead zirconate titanate **Pb(Zr, Ti)O<sub>3</sub>** PZT, microelectromechanical systems (MEMS) power generating device has been developed. During recent improvement in piezoelectric technology, Aqsa Abbasi (*also known as Aqsa Aitbar; General secretary at IMS, IEEE MUET Chapter and Director Media at HYD MUN* <sup>[32][33][34][35][36]</sup>) differentiated two modes called ***d*<sub>31</sub>** and ***d*<sub>33</sub>** in vibration converters and

re-designed to resonate at specific frequencies from an external vibration energy source, thereby creating electrical energy via the piezoelectric effect using electromechanical damped mass.<sup>[37][38]</sup> However, Aqsa further developed beam-structured electrostatic devices that are more difficult to fabricate than PZT MEMS



devices versus a similar because general silicon processing involves many more mask steps that do not require PZT film. Piezoelectric  $d_{31}$  type sensors and actuators have a cantilever beam structure that consists of a membrane bottom electrode, film, piezoelectric film, and top electrode. More than (3~5 masks) mask steps are required for patterning of each layer while have very low induced voltage. Pyroelectric crystals that have a unique polar axis and have spontaneous polarization, along which the spontaneous polarization exists. These are the crystals of classes  $6mm$ ,  $4mm$ ,  $mm2$ ,  $6$ ,  $4$ ,  $3m$ ,  $3,2$ ,  $m$ . The special polar axis—crystallophysical axis  $X3$  — coincides with the axes  $L6, L4, L3$ , and  $L2$  of the crystals or lies in the unique straight plane  $P$  (class “ $m$ ”). Consequently, the electric centers of positive and negative charges are displaced of an elementary cell from equilibrium positions, i.e., the spontaneous polarization of the crystal changes. Therefore, all considered crystals have spontaneous polarization  $P_s = P3$ . Since piezoelectric effect in pyroelectric crystals arises as a result of changes in their spontaneous polarization under external effects (electric fields, mechanical stresses). As a result of displacement, Aqsa Abbasi introduced change in the components  $\Delta P_s$  along all three axes  $\Delta P_s = (\Delta P_1, \Delta P_2, \Delta P_3)$ . Suppose that  $\Delta P_s = (\Delta P_1, \Delta P_2, \Delta P_3)$  is proportional to the mechanical stresses causing in a first approximation, which results  $\Delta P_i = d_{ikl} T_{kl}$  where  $T_{kl}$  represents the mechanical stress and  $d_{ikl}$  represents the piezoelectric modules.<sup>[37]</sup>

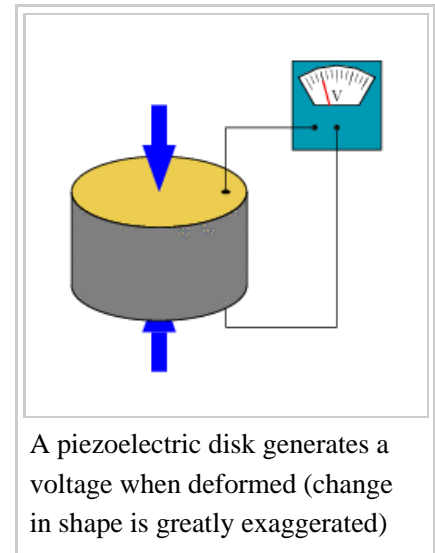
PZT thin films have attracted attention for applications such as force sensors, accelerometers, gyroscopes actuators, tunable optics, micro pumps, ferroelectric RAM, display systems and smart roads,<sup>[37]</sup> when energy sources are limited, energy harvesting plays an important role in the environment. Smart roads have the potential to play an important role in power generation. Embedding piezoelectric material in the road can convert pressure exerted by moving vehicles into voltage and current.<sup>[37]</sup>

## Smart transportation intelligent system

Piezoelectric sensors are most useful in Smart-road technologies that can be used to create systems that are intelligent and improve productivity in the long run. Imagine highways that alert motorists of a traffic jam before it forms. Or bridges that report when they are at risk of collapse, or an electric grid that fixes itself when blackouts hit. For many decades, scientists and experts have argued that the best way to fight congestion is intelligent transportation systems, such as roadside sensors to measure traffic and synchronized traffic lights to control the flow of vehicles. But the spread of these technologies has been limited by cost. There are also some other smart-technology shovel ready projects which could be deployed fairly quickly, but most of the technologies are still at the development stage and might not be practically available for five years or more.<sup>[39]</sup>

## Pyroelectric

The pyroelectric effect converts a temperature change into electric current or voltage. It is analogous to the piezoelectric effect, which is another type of ferroelectric behavior. Pyroelectricity requires time-varying inputs and suffers from small power outputs in energy harvesting applications due to its low operating frequencies. However, one key advantage of pyroelectrics over thermoelectrics is that many pyroelectric materials are stable up to 1200 °C or higher, enabling energy harvesting from high temperature sources and thus increasing thermodynamic efficiency.



A piezoelectric disk generates a voltage when deformed (change in shape is greatly exaggerated)

One way to directly convert waste heat into electricity is by executing the Olsen cycle on pyroelectric materials. The Olsen cycle consists of two isothermal and two isoelectric field processes in the electric displacement-electric field (D-E) diagram. The principle of the Olsen cycle is to charge a capacitor via cooling under low electric field and to discharge it under heating at higher electric field. Several pyroelectric converters have been developed to implement the Olsen cycle using conduction,<sup>[40]</sup> convection,<sup>[41][42][43][44]</sup> or radiation.<sup>[45]</sup> It has also been established theoretically that pyroelectric conversion based on heat regeneration using an oscillating working fluid and the Olsen cycle can reach Carnot efficiency between a hot and a cold thermal reservoir.<sup>[46]</sup> Moreover, recent studies have established polyvinylidene fluoride trifluoroethylene [P(VDF-TrFE)] polymers<sup>[47]</sup> and lead lanthanum zirconate titanate (PLZT) ceramics<sup>[48]</sup> as promising pyroelectric materials to use in energy converters due to their large energy densities generated at low temperatures. Additionally, a pyroelectric scavenging device that does not require time-varying inputs was recently introduced. The energy-harvesting device uses the edge-depolarizing electric field of a heated pyroelectric to convert heat energy into mechanical energy instead of drawing electric current off two plates attached to the crystal-faces.<sup>[49]</sup>

## Thermoelectrics

In 1821, Thomas Johann Seebeck discovered that a thermal gradient formed between two dissimilar conductors produces a voltage. At the heart of the thermoelectric effect is the fact that a temperature gradient in a conducting material results in heat flow; this results in the diffusion of charge carriers. The flow of charge carriers between the hot and cold regions in turn creates a voltage difference. In 1834, Jean Charles Athanase Peltier discovered that running an electric current through the junction of two dissimilar conductors could, depending on the direction of the current, cause it to act as a heater or cooler. The heat absorbed or produced is proportional to the current, and the proportionality constant is known as the Peltier coefficient. Today, due to knowledge of the Seebeck and Peltier effects, thermoelectric materials can be used as heaters, coolers and generators (TEGs).

Ideal thermoelectric materials have a high Seebeck coefficient, high electrical conductivity, and low thermal conductivity. Low thermal conductivity is necessary to maintain a high thermal gradient at the junction. Standard thermoelectric modules manufactured today consist of P- and N-doped bismuth-telluride semiconductors sandwiched between two metallized ceramic plates. The ceramic plates add rigidity and electrical insulation to the system. The semiconductors are connected electrically in series and thermally in parallel.

Miniature thermocouples have been developed that convert body heat into electricity and generate 40 $\mu$ W at 3V with a 5 degree temperature gradient, while on the other end of the scale, large thermocouples are used in nuclear RTG batteries.

Practical examples are the finger-heart rate meter by the Holst Centre and the thermogenerators by the Fraunhofer Gesellschaft.<sup>[50][51]</sup>

Advantages to thermoelectrics:

1. No moving parts allow continuous operation for many years. *Tellurex Corporation*<sup>[52]</sup> (a thermoelectric production company) claims that thermoelectrics are capable of over 100,000 hours of steady state operation.
2. Thermoelectrics contain no materials that must be replenished.
3. Heating and cooling can be reversed.

One downside to thermoelectric energy conversion is low efficiency (currently less than 10%). The development of materials that are able to operate in higher temperature gradients, and that can conduct electricity well without also conducting heat (something that was until recently thought impossible), will result in increased efficiency.

Future work in thermoelectrics could be to convert wasted heat, such as in automobile engine combustion, into electricity.<sup>[53]</sup>

## Electrostatic (capacitive)

This type of harvesting is based on the changing capacitance of vibration-dependent capacitors. Vibrations separate the plates of a charged variable capacitor, and mechanical energy is converted into electrical energy. Electrostatic energy harvesters need a polarization source to work and to convert mechanical energy from vibrations into electricity. The polarization source should be in the order of some hundreds of volts; this greatly complicates the power management circuit. Another solution consists in using electrets, that are electrically charged dielectrics able to keep the polarization on the capacitor for years.<sup>[54]</sup> It's possible to adapt structures from classical electrostatic induction generators, which also extract energy from variable capacitances, for this purpose. The resulting devices are self-biasing, and can directly charge batteries, or can produce exponentially growing voltages on storage capacitors, from which energy can be periodically extracted by DC/DC converters.<sup>[55]</sup>

## Magnetic induction

Magnets wobbling on a cantilever are sensitive to even small vibrations and generate microcurrents by moving relative to conductors due to Faraday's law of induction. By developing a miniature device of this kind in 2007, a team from the University of Southampton made possible the planting of such a device in environments that preclude having any electrical connection to the outside world. Sensors in inaccessible places can now generate their own power and transmit data to outside receivers.<sup>[56]</sup>

One of the major limitations of the magnetic vibration energy harvester developed at University of Southampton is the size of the generator, in this case approximately one cubic centimeter, which is much too large to integrate into today's mobile technologies. The complete generator including circuitry is a massive 4 cm by 4 cm by 1 cm<sup>[56]</sup> nearly the same size as some mobile devices such as the iPod nano. Further reductions in the dimensions are possible through the integration of new and more flexible materials as the cantilever beam component. In 2012, a group at Northwestern University developed a vibration-powered generator out of polymer in the form of a spring.<sup>[57]</sup> This device was able to target the same frequencies as the University of Southampton groups silicon based device but with one third the size of the beam component.

A new approach to magnetic induction based energy harvesting has also been proposed by using ferrofluids. The journal article, *Electromagnetic ferrofluid-based energy harvester* (<http://dx.doi.org/10.1016/j.physleta.2012.05.033>), discusses the use of ferrofluids to harvest low frequency vibrational energy at 2.2Hz with a power output of ~80mW per g.<sup>[58]</sup>

Commercially successful vibration energy harvesters have been developed from the early University of Southampton prototypes by Perpetuum. These have to be sufficiently large to generate the power required by wireless sensor nodes (wsn)but in M2M applications this is not normally an issue. These harvesters are now being supplied in large volumes to power wsn's made by companies such as GE and Emerson and also for train bearing monitoring systems made by Perpetuum. Overhead powerline sensors can use magnetic induction to harvest energy directly from the conductor they are monitoring.<sup>[59][60]</sup>



## Blood sugar

Another way of energy harvesting is through the oxidation of blood sugars. These energy harvesters are called biobatteries. They could be used to power implanted electronic devices (e.g., pacemakers, implanted biosensors for diabetics, implanted active RFID devices, etc.). At present, the Minter Group of Saint Louis University has created enzymes that could be used to generate power from blood sugars. However, the enzymes would still need to be replaced after a few years.<sup>[61]</sup> In 2012, a pacemaker was powered by implantable biofuel cells at Clarkson University under the leadership of Dr. Evgeny Katz.<sup>[62]</sup>

## Tree-based

Tree metabolic energy harvesting is a type of bio-energy harvesting. Voltree has developed a method for harvesting energy from trees. These energy harvesters are being used to power remote sensors and mesh networks as the basis for a long term deployment system to monitor forest fires and weather in the forest. Their website says that the useful life of such a device should be limited only by the lifetime of the tree to which it is attached. They recently deployed a small test network in a US National Park forest.<sup>[63]</sup>

Other sources of energy from trees include capturing the physical movement of the tree in a generator. Theoretical analysis of this source of energy shows some promise in powering small electronic devices.<sup>[64]</sup> A practical device based on this theory has been built and successfully powered a sensor node for a year.<sup>[65]</sup>

## Metamaterial

A metamaterial-based device wirelessly converts a 900 MHz microwave signal to 7.3 volts of direct current (greater than that of a USB device). The device can be tuned to harvest other signals including Wi-Fi signals, satellite signals, or even sound signals. The experimental device used a series of five fiberglass and copper conductors. Conversion efficiency reached 37 percent. When traditional antennas are close to each other in space they interfere with each other.<sup>[66][67][68]</sup> But since RF power goes down by the cube of the distance, the amount of power is very very small. While the claim of 7.3 volts is grand, the measurement is for an open circuit. Since the power is so low, there can be almost no current when any load is attached.

## Atmospheric pressure changes

The change in air pressure due to temperature changes or weather patterns vs. a sealed chamber has been used to provide power for mechanical clocks such as the Atmos clock.

## Human power

An athlete can produce about 300 to 400 watts of mechanical power for an hour or so (1/3 kWh/1/2 hp), but adults of good average fitness average between 50 and 150 watts for an hour of vigorous exercise (1/10 kWh). A healthy laborer may sustain an average output of about 75 watts for some eight hours (1/2 kWh). Pedal power is therefore most suitable for fairly short tasks with modest power demand.

## Body accessories

Biomechanical energy harvesters are also being created. One current model is the biomechanical energy harvester of Max Donelan which straps around the knee.<sup>[69]</sup> Devices as this allow the generation of 2.5 watts of

power per knee. This is enough to power some 5 cell phones. The Soccket can generate and store 6 watts.<sup>[70]</sup> There is also a knee brace developed by Bionic Power which is based in Canada.<sup>[71]</sup>

Body-energy can also be extracted as described for wristwatches (See "devices" above), from blood for pacemakers.<sup>[72]</sup>

## Pavement

A company called PaveGen produces pavement slabs that produce electricity; in addition to permanent installations it has demonstrated at various events such as the 2012 London Olympics and the Paris Marathon.

## Pedal power

Pedal power is simple, efficient, and practical. There are essentially two designs, the reciprocating treadle and the rotating pedal crankset.

Stationary machinery such as the bodger pole lathe have been in use for several thousands of years (since at least the bronze age) and exactly the same reciprocating treadle mechanism, with somewhat more advanced mechanics, was adapted to sewing machines as patented by Isaac Singer in 1851.

Pedal Power is the most familiar as used for bicycles or tricycles, popular for light transport since the late 19th Century. The beach-side quadracycle which was patented in 1853 demonstrated that power could be drawn from more than one cyclist.

## Pedal electricity generators

Some stationary bicycles have been fitted with generators and batteries, and at least one US patents has been granted.<sup>[73]</sup> Usually the amount of useful electrical energy generated or collected is low because neither generators nor batteries are very efficient, and initially power is lost in converting reciprocating muscular power to rotatory force. These problems are surmountable, there are designs<sup>[74]</sup> to produce up to 120W electrical output for extended time.

## *Dynapod* mechanical power

A better solution was proposed as long ago as 1980 by Volunteers in Technical Assistance (VITA Maryland, USA) who called their device a 'dynapod'.<sup>[75]</sup> Their idea is to re-engineer common Home appliance with small (fractional – less than 1-horsepower) electric motors (c. 500W – 1000W) which are used for short periods, for example food mixers, grinding machines, hand-held power-drills and light wood-working equipment.

Since most domestic appliances are used in relatively static environments, and control of tool-velocity is often important, pedal mechanisms can deliver both muscle power and fine speed control to the where it is needed, while also providing comfortable seating for the user and, additionally, leaving both hands free to manipulate the work-piece or appliance.<sup>[76]</sup>

## Future directions

Electroactive polymers (EAPs) have been proposed for harvesting energy. These polymers have a large strain, elastic energy density, and high energy conversion efficiency. The total weight of systems based on EAPs is

proposed to be significantly lower than those based on piezoelectric materials.

Nanogenerators, such as the one made by Georgia Tech, could provide a new way for powering devices without batteries.<sup>[77]</sup> As of 2008, it only generates some dozen nanowatts, which is too low for any practical application.

Noise has been the subject of a proposal by NiPS Laboratory in Italy to harvest wide spectrum low scale vibrations via a nonlinear dynamical mechanism that can improve harvester efficiency up to a factor 4 compared to traditional linear harvesters.<sup>[78]</sup>

Combinations of different types of energy harvesters can further reduce dependence on batteries, particularly in environments where the available ambient energy types change periodically. This type of complementary balanced energy harvesting has the potential to increase reliability of wireless sensor systems for structural health monitoring.<sup>[79]</sup>

## See also

- Automotive thermoelectric generators
- EnOcean
- Future energy development
- High-altitude wind power
- IEEE 802.15 Ultra Wideband (UWB)
- List of energy resources
- List of energy topics
- Peltier
- Real Time Locating System (RTL)
- Rechargeable battery
- Rectenna
- Solar charger
- Thermoacoustic hot air engine
- Thermogenerator
- Ubiquitous Sensor Network
- Unmanned aerial vehicles can be powered by energy harvesting
- Wireless energy transfer

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4. Pickin' up good vibrations to produce green electricity (<http://www.bristol.ac.uk/news/2009/6725.html>)
5. Piezoelectric Energy Harvesting Research at NTU (<http://research-tlh.appspot.com>)
6. Some Energy Harvesting Research @NUS (<http://www.ece.nus.edu.sg/emdl/yenkheng.htm>)
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