Applications of energy harvesting for ultralow power technology

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Abstract. Ultra-low-power (ULP) technology is enabling a wide range of new applications that harvest ambient energy in very small amounts and need little or no maintenance-self-sustaining devices that are capable of perpetual or nearly perpetual operation. These new systems, which are now appearing in industrial and consumer electronics, also promise great changes in medicine and health. Until recently, the idea of micro-scale energy harvesting, and collecting miniscule amounts of ambient energy to power electronic systems, was still limited to research proposals and laboratory experiments. Today an increasing number of systems are appearing that take advantage of light, vibrations and other forms of previously wasted environmental energy for applications where providing line power or maintaining batteries is inconvenient. In the industrial world, where sensors gather information from remote equipment and hazardous processes; in consumer electronics, where mobility and convenience are served; and in medical systems, with unique requirements for prosthetics and non-invasive monitoring, energy harvesting is rapidly expanding into new applications. This paper serves as a survey for applications of energy harvesting for ultra low power technology based on various technical papers available in the public domain.

1. Introduction

We’ve all heard the familiar saying “there’s no free lunch.” It seems to apply to so many situations in life as well as in circuit design. But still, we all like the idea of getting something for nothing. The concept of “Energy Harvesting” has been getting some attention lately because of newly available technologies that allow us to take advantage of free energy sources like sunlight, ambient heat, or the vibration from traffic on a roadway (Figure 1). So do we finally get our free lunch?

You may also be familiar with the adage “If it sounds too good to be true, it probably is.”
2. Harvesting energy system

Radio Frequency (RF) communication has of course been used for over a hundred years, and microprocessor technology has been common for many decades. In the last few years, low power RF technology, combined with ultra-low power microcontrollers, have enabled many new end-applications like wireless sensor and control systems [4], [12]. But the limiting factor has often been the power source. If a remote sensor needs a wired electrical power supply, then it can’t really be very remote, after all. And if we use a battery, that battery will eventually need to be recharged or replaced, a hindrance, at best, for something that’s truly “remote” [19]. How can we build an intelligent remote device that can operate indefinitely once installed in a hard-to-reach location?

Energy harvesting can help provide part of the solution to this problem. But while the long-term source of fuel, sunlight, heat or vibration, may indeed be free, that source is unreliable and highly variable. Unlike the AC mains or a gas powered generator, the availability of the power source is not guaranteed. There are two main steps to determining the rest of the solution [17].

First, we need power conversion circuitry that can convert the low voltage signal from a transducer (such as solar panel or thermoelectric generator) into a stable, regulated output to operate the rest of the system (microcontroller, radio, indicators, etc.) [1].

Second, we need energy storage elements, batteries or large capacitors, that provide a stable source of energy to the system when the ambient environment is not cooperating. These storage elements must be chosen to provide enough capacity to keep the system operating through the time periods when the “free” energy source may not be providing any output. For critical applications, multiple storage elements might be needed for reliability. But we hope that the “dark times” don’t last forever, otherwise we will need a really large storage element.

The low-input-voltage power conversion aspect can be handled by a number of integrated boost converter devices [2]. However since the ultimate source of the energy may have very weak / limited output power capability, the converter also needs to operate with extremely low quiescent current and high conversion efficiency. Even one wasted milliamp can render an energy harvesting source useless. Furthermore, to minimize design complexity from the system designer’s point of view, we would like the boost converter to keep the storage element charged up automatically, as well as
provide a regulated output voltage at the appropriate level to operate the rest of the system. For example the bq25570 device satisfies these requirements; while the bq25505 allows for a second (backup) storage element if needed. The TPS627xx devices are also suitable for external ultra-low power DC-DC regulation if additional output rails are required (Figure 2).

![Figure 2. Components of an intelligent remote sensor system.](image)

Getting back to the free lunch concept, we can see that some initial cost is required for the added circuitry and storage elements needed to take advantage of the free energy that might be available from the environment. But once this initial investment is made, assuming the transducer and storage elements are sized properly, it is actually possible to implement a remote sensor / controller device that can operate for long periods of time (theoretically forever) with no maintenance (removal / replacement of batteries or refueling).

As mobile phones morphed from wireless analog telephones to handheld computers, users kept demanding more and more energy-consuming features, such as web browsing, videos, gaming, and email, while still requiring extended battery life. Since battery makers were not much help, semiconductor manufacturers devised numerous energy-saving techniques to make it all possible. They have been wildly successful [18].

Low power has been the most important electronic design criterion for at least the last ten years. Thanks to Moore’s Law and a lot of smart engineers, semiconductor power levels have dropped dramatically, often consuming milliwatts in run mode and nanowatts in standby mode. As a direct result, ultra-low-power wireless sensorless networks finally became possible and their adoption has been dramatic. Now, sensors stand alone in remote or hard-to-reach areas to warn of building and bridge stresses, air pollution, forest fires, pending landslides, worn bearings, and wing vibration. Low-power wireless sensor networks are at the heart of numerous industrial, medical, and commercial applications [10], [14].

However, off-grid, as well as portable sensor nodes, rely on batteries for power and face the same problem as cell phones. In such cases, it is advisable to prolong battery life by harvesting environmental energy sources – most often available as light, heat, vibration, motion, or ambient RF [6], [9]. If a device’s energy requirement is low enough and battery replacement would be difficult or expensive, it may be possible to dispense with the battery altogether and rely exclusively on harvesting.
ambient energy sources for power [12]. The combination of ultra-low-power MCUs and energy harvesting have given rise to a wealth of applications that previously were not possible [15].

The energy harvesting market is large and growing rapidly. According to analysts at IDTechEx, energy harvesting was a $0.7 billion market in 2012 and is expected to exceed $5 billion by 2022; by then 250 million sensors will be powered by energy harvesting sources. The market for thermoelectric energy harvesting alone will reach $865 million by 2023.

3. Current technologies and applications
There is several energy harvesting technologies in common use, with some innovative techniques just over the horizon. The most common energy sources are light, heat, vibration, and RF. Short of rooftop solar panels none of them generate a great deal of energy (Figure 3), but one or more of them may be more than adequate to power low-power devices in a particular environment [3], [13].

| Source          | Source Power | Harvested Power |
|-----------------|--------------|-----------------|
| Light           |              |                 |
| Indoor          | 0.1 mW/cm²   | 10 µW/cm²       |
| Outdoor         | 100 mW/cm²   | 10 mW/cm²       |
| Vibration/Motion|              |                 |
| Human           | 0.5 m at 1 Hz|                 |
|                 | 1 m/s² at 50 Hz| 4 µW/cm²       |
| Machine         | 1 m at 5 Hz  |                 |
|                 | 10 m/s² at 1 kHz| 100 µW/cm²     |
| Thermal         |              |                 |
| Human           | 20 mW/cm²    | 30 µW/cm²       |
| Machine         | 100 mW/cm²   | 1-10 mW/cm²     |
| RF              |              |                 |
| GSM BSS         | 0.3 µW/cm²   | 0.1 µW/cm²      |

Figure 3. Power available from energy harvesting sources.

3.1. Solar harvesters
There is hardly a home or office that does not have at least one solar-powered calculator – actually, a calculator with a coin-cell battery and a small front panel photovoltaic (PV) cell to top it up. These polycrystalline silicon or thin-film cells convert photons to electrons with a typical efficiency of about 15 to 20% for polycrystalline and 6 to 12% for thin film cells. Since the power available from indoor lighting is typically only about 10 µW/cm², their usefulness depends on the size of the module plus the spectral composition of the light [7].

Small solar cells are frequently used in consumer and industrial applications, including toys, watches, calculators, street lighting controls, portable power supplies, and satellites. Since light sources tend to be intermittent, solar cells are used to charge batteries and/or supercapacitors to provide a stable energy source [16].
3.2. Thermoelectric harvesters
Thermoelectric harvesters exploit the Seebeck effect, where a voltage is created when a temperature differential exists at the junction of two dissimilar metals. Thermoelectric generators (TEGs) consist of an array of these thermocouples connected together in series to a common heat source such as an engine, water heater, or even the back of a solar panel [21]. Output depends on the size of the TEG and the temperature differential that can be maintained. TEGs are typically used to power wireless sensor nodes in high-temperature environments such as industrial heating systems. A TEG mounted between a power transistor and its heatsink can recycle some of the energy that would otherwise be lost as heat.

Micropelt’s TE-CORE7 Thermal Energy Harvesting Modules convert locally available waste heat to provide long-life operation for low-power devices. The TE-CORE TEG converts heat to an electrical charge which is then boosted, stored in a 100µF capacitor, and regulated to supply up to 5.5V. Running at 50°C the TE-CORE7 can deliver 6.424mAh annually, the equivalent of three to four AA batteries – at that rate the batteries would need to be changed every few months [22].

Forcing a current to flow through the junction of dissimilar metals will cause heat to transfer from the hot to the cool junction – the Peltier effect, essentially the opposite of the Seebeck effect. The Peltier effect is the basis for thermoelectric heat pumps [20].

3.3. Piezoelectric harvesters
Piezoelectric transducers generate electricity when stressed, which make them good candidates for vibration sensors when they are used in energy harvesting modules that detect motor bearing noise and the vibration of aircraft wings. The MidéVoltüre™ V-20W Vibration Energy Harvester employs a cantilever that attaches to a piezoelectric crystal. When vibrations set the cantilever in motion it generates an AC output voltage that is rectified, regulated, and stored in a supercapacitor or thin-film battery.

![Figure 4: MidéVoltüre piezoelectric energy harvester (Courtesy of Midé).](image)

3.4. Radio Frequency – RF harvesters
RFID works by rectifying a strong local signal (not ambient RF) aimed directly at the sensor [8]. Similarly Powercast’s P2110 RF Powerharvester receiver converts low-frequency RF signals to 5.25V, providing up to 50mA output current. In conjunction with a low-power MCU, sensors, and a radio module, the P2110 can provide a complete, battery-free wireless sensor node that can operate with as little as -11.5dBm RF input. Applications for the device include battery-free wireless sensors for industrial monitoring, building automation, smart grid, agriculture, and defense applications. Mouser carries Powercast development kits for battery charging and wireless sensors.

Side-by-side figures. Where possible, try to place figures side-by-side to reduce the amount of space used. Use a table to do this. For example, to put two figures side-by-side create a table with three
columns and two rows. Make the middle column narrow to provide some space between the graphics, as shown below. Note that the table borders are shown as broken lines for guidance only; they should not, of course, be shown in your actual paper.

3.5. MEMS pyroelectric generator
Oak Ridge National Laboratories has developed a unique pyroelectric generator that can cool electronic devices, photocells, computers, and even large waste-heat producing systems while generating electricity. The device is based on a MEMS pyroelectric capacitor at the end of a bimetal cantilever that oscillates between hot and cold surfaces. The tip of the hot cantilever comes into contact with a cold surface, the heat sink, where it rapidly loses its heat and causes the cantilever to move back and make contact with the hot surface. The oscillation continues as long as there is a sufficient temperature differential – anywhere from a few degrees to several hundred degrees – between the two surfaces. The cantilever structures are only about 1 mm² and generate 1 to 10mW per device; however 1,000 of them can be attached to a one square inch substrate, creating a relatively high output power source. Due to the fast cycle time of the cantilever, the developer projects 10 to 30% efficiency – far better than current thermoelectric and piezoelectric energy harvesting devices.

3.6. Nantennas
Photovoltaic cells are the most widely used energy harvesting source, but they are not very efficient. The best monocrystalline PV cells – with a theoretical maximum efficiency of 30% – do well to top 20% efficiency. Now scientists at the University of Missouri and the Idaho National Laboratory have developed a flexible solar film that can theoretically achieve 90% efficiency.

In contrast to conventional photovoltaic cells, the film is essentially an array of nanoantennas (or “nantennas”), each tuned to a specific frequency of light. Rather than generating single electron-hole pairs, as in the case of PVs, the incoming electromagnetic field from the sun induces a current in the antenna that is then collected at the feed point, rectified, and stored. Nanoelectronic electromagnetic collectors (NECs) can be configured as frequency selective surfaces to efficiently absorb the entire solar spectrum. Or NECs can be configured as a reflective bandpass filter centered at a wavelength of 6.5µm; this would enable them to absorb infrared rays, thus recycling waste heat from engines, furnaces, and other high-temperature power sources.
NEC devices have been successfully prototyped on both silicon and polyethylene substrates, however developing economical mass production processes will require further funding and time. The researchers foresee a product that complements conventional PV solar panels by capturing currently unused infrared energy. As a film, it could be incorporated into building materials and infrastructure. NECs can be integrated into polymer materials so they might also be incorporated into the skin of consumer electronic devices to continuously charge batteries [16].

3.7. Medical and Fitness Devices
Some novel uses for piezoelectric energy harvesting are starting to emerge. Researchers at the University of Michigan have developed a device that harvests energy from the reverberation of heartbeats through the chest and converts it to electricity to run a pacemaker or an implanted defibrillator, hopefully obviating the need for periodic battery replacement. Research is also under way looking for ways to scavenge body heat, movement, and vibration to power other implantable devices.

RF is already being used experimentally to recharge the batteries in pacemakers and implanted transcutaneous electrical nerve stimulation (TENS) devices. The patient sits in a chair that contains a low-frequency RF source whose output is received, rectified, and stored by the device. Researchers at MIT and Harvard have developed a chip that can be implanted into the inner ear, with power provided by harvesting the energy in sound waves. The chip is designed to monitor biological activity in the ears of people with hearing or balance impairments.

Engineers at MIT are also developing glucose fuel cells to power neural implants. The fuel cell operates by stripping electrons from glucose molecules to create a small electric current. Fuel cells integrated with ultra-low power circuitry, onto a silicon chip, enables entirely self-powered devices
such as brain implants. Such implants are being developed to help people with spinal cord injuries or who have suffered strokes. Advances in neuromodulation have resulted in implants that influence the nervous system to control pain, and help eliminate the tremor in patients suffering from Parkinson’s disease [11].

![Figure 7. Imaging. Ingestible electronic devices.](image)

The ingestible Pillcam (Figure 7) developed by Given Imaging. Ingestible electronic devices, using energy harvesting and/or tiny solid-state batteries, can perform a number of tasks. The ‘Pillcam’, the size of a large vitamin capsule, is used like an endoscope to visualize the digestive system, detecting abnormalities as it passes through, avoiding the alternative lengthy and uncomfortable procedures.

Targeted drug delivery for certain types of cancerous tumors is another important application for ingestible implantable devices. The ability to direct an active device to a precise location, minimizing the drug dosage administered and avoiding damaging adjacent cells, is proving particularly efficacious. Exploiting body heat to power electronic devices is an obvious candidate for energy harvesting. Chip-based thermoelectric generators (TEGs) are now envisioned that can be inserted under the skin, or in the skull, exploiting the small temperature differences between the brain and skin tissue.

Fitness buffs will be happy to learn that they can recapture some of the energy they expend at the gym. Three British universities have teamed up to develop a piezoelectric energy harvesting device that attaches to the knee, generating power as they walk or run on the treadmill [5].

Riga Technical University offers a mechanical energy harvester that requires magnets to be sewn into the sleeves and coils into the pockets of a jacket; swinging the arms past the pockets while walking generates a current that can be stored in a battery. Anything to keep that iPhone charged!

4. Conclusion
The development of ultra-low-power has created a huge and rapidly expanding energy harvesting market on which they are becoming increasingly dependent. The first wave of energy harvesting has given rise to low-power wireless sensors, which are turning up seemingly everywhere. But the ripple effect will continue throughout consumer, industrial, and medical markets, creating new applications that we can only begin to imagine. Whether planning portable battery-powered devices or the desire to improve the energy efficiency of larger ones, all design engineers should consider incorporating energy harvesting techniques into their products.

This study provides an overview of ultra-low power energy harvesting application, especially recent technology developments in medical domain and existing barriers.

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