*W H I T E   P A P E R*

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# *Energy Harvesting*

ULP meets energy harvesting:
A game-changing combination for design engineers

### Executive summary

*Macro-scale energy harvesting technologies in the form of windmills, watermills and passive solar power systems have been around for centuries. Now, as designers seek to cut the cords, they turn to micro-energy harvesting systems that can scavenge milliwatts from solar, vibrational, thermal and biological sources. However, understanding ultra-low power from the sourcing side brings challenges as harvested power derived from ambient sources tends to be unregulated, intermittent and small.*
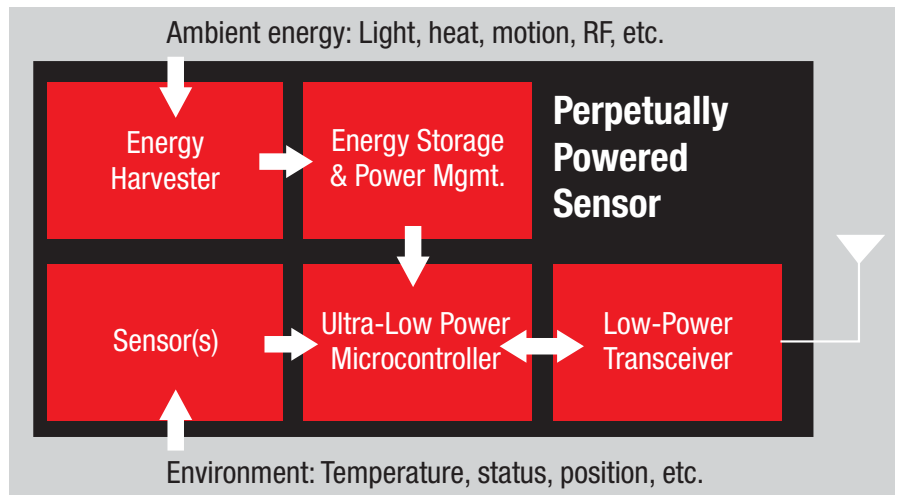
Energy harvesting has been around for centuries in the form of windmills, watermills and passive solar power systems. In recent decades, technologies such as wind turbines, hydro-electric generators and solar panels have turned harvesting into a small but growing contributor to the world's energy needs. This technology offers two significant advantages over battery-powered solutions: virtually inexhaustible sources and little or no adverse environmental effects.

Macro-scale harvesting technologies differ in many ways but have one thing in common: they "feed the grid," typically adding kilowatts or megawatts to the power distribution system. As such, they are not game changers for electronic designers whose mission in life is to snip the wires – including power cords and even battery-powered systems where the perpetual device is the ultimate design goal.

For this second goal, micro-energy harvesting systems are the answer. Energy harvesting's new frontier is an array of micro-scale technologies that scavenge milliwatts from solar, vibrational, thermal and biological sources. A few years ago, micro-harvesting could have been called a scientific curiosity. But the design community's long march to ultra-low-power (ULP) technology has had the unexpected result of pushing micro-scale energy harvesting out of the lab and onto the designer's bench.

Now, designers are sizing up ULP not just from the consumption side but from the production perspective as well. Understanding ULP from the sourcing side will be every bit as

challenging as it was from the consumption side not that many years ago. Primary reason: harvested power is derived from ambient sources so it tends to be unregulated, intermittent and small.

**Figure 1: Macro v. micro energy harvesting comparison**

| Macro vs. Micro | Energy Source | Solutions | Ultimate Goal |
|---|---|---|---|
| Macro | Renewable energy (e.g., solar, wind) | Energy management solutions | Reduce oil dependency |
| Micro | Energy from the environment (e.g., vibration, body heat) | Ultra-low-power solutions | Perpetual devices |

**ULP sets targets**

While there is no widely accepted definition of ULP, it's helpful to consider it in the context of batteries because they are easily the most common energy source for ULP designs today.

Medical applications in which electronic devices are implanted in or attached to the body are good examples of ULP designs that run on batteries. Here are three examples.

- **Implanted medical device.** Size and battery life are primary considerations. Power dissipation of 10 µW and battery life of 15,000 hours would be typical.
- **In-ear device.** Size becomes more important that life, which indicates button cell. Typical power dissipation of 1 mW and 1,500-hour life.
- **Surface-of-skin device.** Limiting factor is the ability of skin surface to dissipate heat. Typical power dissipation of 10 mW and 150-hour life.

Medical applications that consume milliwatts set the energy-production bar for harvesting devices. The good news is that milliwatts are the same order of magnitude that micro-harvesters can generate.

Some non-medical products already use micro-harvesting sources. These include calculators, watches, radios and *Bluetooth*® headsets. There are also applications that consume on the order of milliwatts as well, but have not yet been adapted to micro-harvesting. The most promising application is being remote sensors.

**Harvester technologies**

The most promising micro-harvesting technologies extract energy from vibration, temperature differentials and light. A fourth possibility – scavenging energy from RF emissions – is interesting, but the energy availability is at least an order of magnitude less than that of the first three. Estimates vary, but Figure 2 shows the approximate amount of energy per unit available from four micro-harvesting sources.

**Figure 2. Energy harvesting estimates**

| Energy Source | Harvested Power |
|---|---|
| **Vibration/Motion** | |
| Human | 4 µW/cm$^2$ |
| Industry | 100 µW/cm$^2$ |
| **Temperature Difference** | |
| Human | 25 µW/cm$^2$ |
| Industry | 1–10 mW/cm$^2$ |
| **Light** | |
| Indoor | 10 µW/cm$^2$ |
| Outdoor | 10 mW/cm$^2$ |
| **RF** | |
| GSM | 0.1 µW/cm$^2$ |
| WiFi | 0.001 µW/cm$^2$ |

Micro-harvesting provides power at the same order of magnitude that carefully designed ULP circuits typically consume. The three most promising technologies – based on light, motion and thermal scavenging – have different characteristics.

- Large solar panels have made photovoltaic harvesting a well characterized technology. Approximately 1 mW of average power can be harvesting from each 100-mm$^2$ photovoltaic cell. Typical efficiency is roughly 10 percent and the capacity factor of photovoltaic sources (the ratio of average power produced to power that would be produced if the sun was always shining) is about 15 to 20 percent.

- Commercially available kinetic energy systems also produce power in the milliwatt range. Energy is most likely to be generated by an oscillating mass (vibration). But electrostatic energy harvested by piezoelectric cells or flexible elastomers is also classified as kinetic energy. Vibrational energy is available from structures such as bridges and in many industrial and automotive scenarios. Basic kinetic harvester technologies include: (1) a mass on a spring; (2) devices that convert linear to rotary motion; and (3) piezoelectric cells. An advantage of (1) and (2) is that voltage is not determined by the source itself but by the conversion design. Electrostatic conversion produces voltages as high as 1,000 V or more.

- Thermoelectric harvesters exploit the Seebeck effect, which states that voltage is created in the presence of a temperature difference between two different metals or semiconductors. A thermoelectric generator (TEG) consists of thermopiles connected thermally in parallel and electrically in series. The latest TEGs are characterized by an output voltage of 0.7 V at matched load, which is a familiar voltage for engineers designing ultra-low-power applications. Generated power depends on the size of the TEG, the ambient temperature, and (in the case of harvesting heat energy from humans), the level of metabolic activity.

  According to the Belgian-based research corporation IMEC, at 22°C a wrist-watch type TEG delivers useful power of 0.2 to 0.3 mW on average for normal activity. Typically, a TEG continuously charges a battery or super-capacitor and requires advanced power management to optimize efficiency.

Despite their differences, photovoltaic, motion and thermal harvesting also have a few things in common: They generate erratic voltages instead of the steady 3.3 V or 1.8 V design engineers sometimes take for granted; they also provide intermittent power and sometimes no power at all.

Conversion technology is only part of the solution. Since micro-harvesters tend to generate intermittent power, the most common system architectures are called hybrids because they include energy storage in thin-film batteries.

A typical energy-harvesting system includes conversion, temporary storage and a heavy dose of sophisticated power management circuits, analog converters and ULP MCUs. To take ULP to the next level, it is highly desirable to integrate as many of these circuits as possible on a single chip.

## Best practices

Energy harvesting doesn't exactly rewrite the rules of realizing the best power efficiency in circuit design, but some of its best practices may be counter-intuitive to many engineers.

The key design goal is to match the power circuits to the application circuits for the best overall performance. Applications can then be developed knowing that technology will support that product.

Several techniques that solve the unfamiliar power management problems that micro-harvesters present include:

- Optimizing switched power supplies because they can boost very small source voltages. By chopping the input signal, switchers allow designers to control its magnitude and frequency. Switching topologies also dissipate very little power but introduce unwanted frequencies that must be normalized.
- Since tasks such as charging the gate capacitance of a MOSFET could consume a large percentage of the harvested energy, a current-source gate charge rather and a voltage-source gate charge will often make sense.
- Another technique is to use more than one power converter circuit. The first circuit could be unregulated but capable of charging a capacitor. Once sufficient energy is stored in the capacitor, it can be discharged and the signal conditioned by a more sophisticated power converter circuit.

### Silicon implications

What are the implications of micro-harvesting for ICs? The most common system component would be an MCU. Because MCUs have more to do than just be stingy with energy, other criteria have to weigh in, including: wake up time (which also has an impact on energy consumption), operating voltage, frequency and code density. Texas Instruments platform of MSP430 microcontrollers offer an excellent example of a controller well-suited to energy harvesting applications. The MCU portfolio's typical specifications outlined below make it well suited for ULP applications.

- Low standby current
- Low active current
- Efficient 16-bit architecture with industry's highest code density
- Integrated low power ADC for precision measurements
- Low operating voltage
- Low pin leakage

The most recent generation of MSP430 MCUs, the MSP430F5xx generation, allows designers to tap into peak execution performance of up to 25 MHz while consuming as low as 160 µA/MHz (microamp per Megahertz).

A system powered by a small battery – or micro-energy harvesting device – will need to communicate information to another system or to a central collection point. Supplying power to a network of sensor-transmitters has traditionally required expensive wiring installation or routine battery changes. Gathering data from difficult or dangerous-to-reach locations using wired sensors may be impossible and or even compromise the safety of personnel installing wiring and replacing batteries.

Low power, wireless communication for energy-harvesting applications is the clear alternative. When discussing low-power radios, we will focus on radios that have the following capabilities or features: they can go to sleep mode and be off 95 percent of the time; they can go from deep sleep to ready to transmit in 300 ms or less; they consume less than 500 µA of current in the transition phase and typically consume less than 16 mA when transmitting and 20 mA when receiving data.

The following best practices will accelerate the development process of products featuring energy harvesting and RF technology

1. Use the lowest possible duty cycle. Send your data only when needed and do not send more data than necessary. A large amount of sensor activity is exception-based messages. Only send the message when the sensor value has gone out of limits set up for the application.
2. Minimize the receive window length of your radio in application testing. This window length can be adjusted adaptively. The default is to use a narrow window and increase the window when packets are missed as a result of receive timeout.
3. Use the built-in receive signal strength indicator (RSSI) feature of the radio to reduce the transmit power or receive sensitivity in your point-to-point product so that the radio can dynamically adjust based on the other devices operating in the vicinity of your radio. There is no need to increase your transmit power and shout across the room when you can talk or whisper and get your message through the first time. The difference in transmit mode current can be as much as 10 mA between using output levels of –12 dBm and 0 dbm.
4. Use the lowest possible voltage setting. RF devices have reduced current draw at low voltages and use the on-chip regulator with low quiescent current to maximize battery lifetime.
5. When you have data to send, use the FIFO buffer function of the RF-IC to store it. Use the buffer read/write mode to minimize SPI operations. SPI communications consume power.
6. When you receive incoming messages, discard false packets that are not intended for your product possibly coming from another unwanted radio system. Minimize the time in RX processing false packets by checking the carrier sense, valid preamble, valid sync word, valid byte length and valid address feature options built into today's radio technology. Once you have done that, wake up the MCU and use the automatic CRC check and discard the packet if the CRC fails. Interrupt the MCU if the CRC is okay.
7. Spend time selecting a crystal that takes into consideration clock drift between the two devices. Increased drift means increased time in the receiver to ensure packet reception. The receiver must be turned early, especially in polling mode architectures. The problem with turning on early means an increased probability of receiving false packets that require additional receiver time where we are driving to maximum sleep time for battery life.
8. Spend time squeezing every possible electron from transition states of the radio. For example, spend time drilling into the state diagrams of the data sheet. Develop a power budget spreadsheet which includes the typical values for power-down, crystal oscillator start-up, PLL start-up, full TX_RX time and power-down for your application. For two-way protocols, go as quickly as possible from transmit to receive mode or vice-versa.

With TI's CC430 platform, the combination of the power-efficient, highly functional MSP430F5xx MCU and a TI low-power RF transceiver on a single chip offers a unique low-power/performance mix and high

integration to help break down barriers to RF implementation such as stringent power, performance, size and cost requirements helping bring wireless connectivity to new applications.

**Integration adds value**

From an IC architecture perspective, integration is almost always a good thing. With ULP designs, the benefits are particularly helpful. Of the five important components of a harvesting system – conversion, temporary storage, power management circuits, analog converters and ULP MCUs – the last four are the most likely first step toward high integration.

In fact, TI's MSP430 MCU family already integrates many high-performance analog and controller functions needed for energy-harvesting applications. The addition of power management and the radio circuits are all that is required – and that formula is exactly what TI's new CC430 platform will deliver.

The full MSP430 MCU peripheral set will be available on the CC430 devices including intelligent, high-performance digital and analog peripherals like a 12-bit ADC, and comparators that provide high performance even during RF transmissions and consume no power when not in operation. These peripherals also speed design by integrating functions such as an integrated Advanced Encryption Standard (AES) accelerator that encrypts and decrypts data sent wirelessly for more secure alarm and industrial monitoring systems.

With a 50 percent reduction in printed circuit board (PCB) space, CC430-based devices help enable smaller devices in a wide variety of wireless applications. Examples may include smart hospital tracking that can communicate patient or medical equipment information to a central location or personal area networking between sports watches, pedometers, chest-strap heart-rate monitors and PC-based health and fitness analysis programs. Smaller board space and reduced complexity also help shrink the size of heat-cost allocators and AMI smart metering systems, which are expected to make up 28 percent of all electric meters by 2013.

In addition to delivering low-power advantages, integration also reduces package size and cost which is a high priority for small sensor applications that might be deployed, for example, in a mesh network or some other "network of things" – for example, innovative RF sensor networks that report data to a central collection to analyze and regulate information such as smoke in the atmosphere to detect forest fires, moisture or pesticide information in crop fields or even humidity levels in a winery.

According to the ARC Advisory Group, the worldwide market for industrial applications of wireless technology will grow at a 32 percent compound annual growth rate (CAGR) over the next five years, and is projected to exceed U.S. $1 billion in 2010.

A major stumbling block to date in deploying wireless technology in industrial settings has always been powering the radio and the application circuits. Both installation and periodic maintenance have been identified as being problematic. If line power has to be extended to the application, the value of wireless communication is reduced. If batteries are used, they have to be replaced from time to time.

The combination of ULP and micro-harvesting is likely to be the most cost-sensitive, sensible approach to addressing these challenges; the CC430 technology platform is an ideal solution to provide the micro-harvesting and ULP needed for these applications. Sensing applications are limitless, power supplies are not; solutions like the CC430 platform that combine low power and high functionality with the know-how to take the mystery out of RF design help bridge this gap to help usher in a new age of energy solutions.

**For further information on energy harvesting technology, please see www.ti.com/energyharvesting.**

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