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The Field Of Energy Harvesting Begins To Ripen

Case histories show how the pieces of the energy-harvesting puzzle fit together.

One cannot talk about energy harvesters without discussing wireless mesh networks, sensor batteries (particularly thin-film batteries), and supercapacitors—along with concepts of power management—nearly in the same breath. Harvesting is a complex and evolving discipline that promises rewards and challenges for engineers who want to take existing skills in new directions.

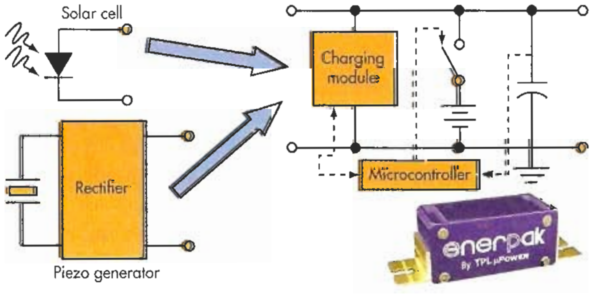
Most of the technical background information in this report was derived from interviews with companies that presented papers at the NanoPower Forum put on by the Darnell Group, a market analysis organization, in June in Costa Mesa, Calif. For a top-down look at applications, see "Energy-Harvesting Critical Success Factors," p. 40.

QUESTIONS OF SCALE

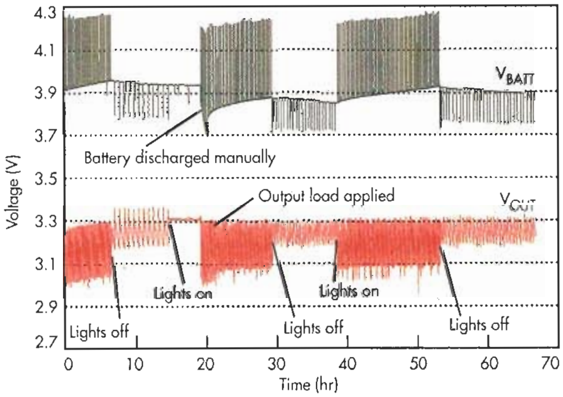
Before anything else, the terms "nanopower" and "harvesting" need to be sorted out. "Harvesting" gets applied indiscriminately to things as diverse as grid-tied solar systems and patient-powered heart monitors.

In one way, "harvesting" sounds like big combines and threshers working through vast fields, collecting tons of produce. Photovoltaic (PV) and geothermal energy harvesting fit that description. In another way, it's more like gleaning—following after the threshers and collecting what's been passed over.

Either way, collecting the energy is only a small part of the picture. You then have to store it, which involves power density versus energy density considerations in the storage medium, along with equivalent series resistance (ESR) and charge/discharge characteristics. That, in turn, leads to considerations of power management—not just in terms of how you run the application, but in terms of how you husband those electrons you've harvested or gleaned.



1. TPL's EnerPak incorporates a supercapacitor, internal battery, and microcontroller for power management. It works with any kind of energy harvester. Presented at the NanoPower Forum last June, it offers a number of insights into how to design a system that collects small amounts of energy and uses that energy to collect data, store it, and periodically broadcast it in bursts over a wireless mesh network.



2. This annotated display shows the EnerPak output voltage (top) and battery voltage (bottom) over a 68-hour period. During daylight hours, the backup battery is charged, and during darkness, the battery is used to maintain V_{OUT}.

On the large scale, harvesting that power management would be something like maximum power-point tracking, But for this article, we're focusing on the small-scale gleaning companies spotlighted at the NanoPower Forum.

A CASE HISTORY

I don't know of any explicit design examples of small-scale energy-harvesting systems that are as thorough as what Charles Lakeman of TPL's Micropower Division presented at the forum, so I've adapted that here for its instructional value. Lakeman described a product called EnerPak that combines smart, ultra-low-power charge management circuitry and electrochemical energy storage *(Fig. 1)*.

As Lakeman described the design problem that's facing the engineer, any wireless sensing application, a class that embraces most of the things people are trying to do with small-scale energy-harvesting today, has three basic modes: data collection, data communication, and idle (sleep) modes. The power demands for each of these modes are significantly different. The default sleep mode draws perhaps a few microwatts. Sense and compute functions draw a few tens of milliwatts or less, while wireless data transmission can require several hundreds of milliwatts, but only in bursts.

To accommodate these disparate power needs, designers usually simply design for a battery that is capable of handling the system's highest power demands—those for data transmission. That's not such a good idea, Lakeman said, as it leads to selecting a battery that's oversized for most of the operational lifetime and capabilities of the system. It's better to combine a smaller battery with a supercapacitor.

In that synergistic pairing, the supercapacitor delivers energy efficiently. It exhibits high specific power, which allows it to supply the radio (or wireless mesh network node) when it needs to transmit, while the battery stores energy efficiently and provides backup when the harvester isn't providing enough power. Using a low-impedance supercapacitor as the primary energy-delivery device is much more efficient than oversizing the battery.

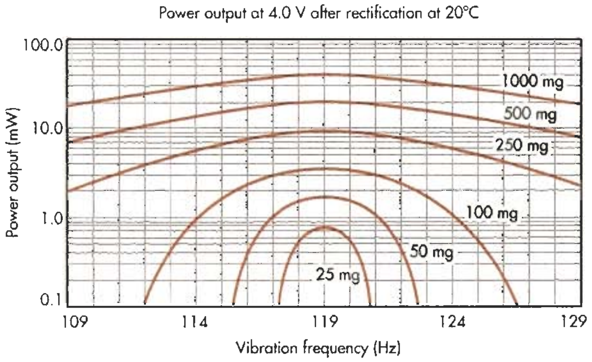
Then there's power management. In the EnerPak, an ultra-low-power TI MSP43 microcontroller (MCU) monitors the state of charge of both the battery and supercapacitor. Simultaneously, it dynamically adjusts the operation of the charging module to accommodate any fluctuations in the level of energy delivered by the harvester. Should the incoming energy not be sufficient to recharge the supercapacitors (e.g., in a solar-powered system at night), the MCU switches in the battery. There's also some IP in the MCU.

"Because energy harvesters only produce very small amounts of power, this circuitry has been designed to operate extremely efficiently to transfer as much of the available power as possible to the energy storage devices without wasting it in the charger," Lakeman said.

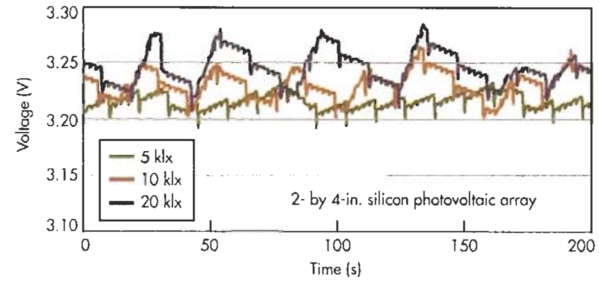
CHARACTERIZATION DATA

Part of the engineering involved in a field this new is determining the operating characteristics of the product. This is more of what Lakeman presented at the forum. In a test of the system's operation over a period of roughly 68 hours, it charged the battery when there was sufficient incoming energy, e.g., the positive voltage spikes and an overall increase in battery voltage *(Fig. 2)*.

When the PV energy harvester couldn't collect enough ambient energy, the MCU detected that there was insufficient incoming energy to refresh the supercapacitors and instead used the battery to maintain the output voltage. With the power-management software, even under conditions of diurnal ambient light flux on the PV array, it was still possible to maintain the output voltage, supply current to an external load, and charge the backup battery.



4. Datasheet curves from a Perpetuum vibration harvester emphasize the necessity of designing harvesters with a high Q in order to extract the most energy at low vibration levels. Naturally, it implies that you don't get much energy-transfer off-resonance.



3. As described in the text, the three curves show the output voltage from the EnerPak under three ambient lighting conditions while the Pak is connected to an actual ZigBee mote operating under the conditions described.

In other tests, TPL characterized EnerPak performance to assess how rapidly it could recover from simulated pulse loads of different levels under various conditions of solar flux. Measurements were carried out using a 1- by 2-in. silicon PV array illuminated with an array of incandescent bulbs. Illumination levels of 1 to 30 klx (corresponding to dull overcast to bright sunny conditions) were used. At 3.3 klx, the PV array delivers approximately 2.5 mA at 1.8 V, or 4.5 mW.

The table shows the time required for the EnerPak to recover its programmed voltage after being subjected to a series of short loads that simulated the transmission demands of a wireless mesh network mote sending bursts of data. Recovery times could be as short as eight seconds on a bright day with a light (50 mW-s) pulse load to as long as 46 minutes on dull overcast days with the heaviest (500 mW-s) pulse loads. Depending on the pulse level, the system's efficiency in replacing the delivered energy varied from 56% to better than 95%.

To gather further empirical data, TPL bench-tested the EnerPak with an actual ZigBee mote, a Crossbow Technology Mica2 wireless sensor radio platform. At 3.2 V, the Mica2 mote consumes 13 mA in transmit mode, 3.8 mA in sense mode, and 267 µA in sleep mode.

The mote was programmed to query the sensor and measure the battery voltage every two seconds and transmit the accumulated data every five sense cycles (10 seconds). At the end of transmission, the processor switched off the radio, and the mote re-entered deep sleep mode.

In the tests with the Mica2, the system used two 1- by 2-in. PV arrays to accommodate the mote's relatively high average power draw made necessary by the high sampling and data-transmission rates. Figure 3 shows the output voltage from EnerPak under this regime and under different input light levels.

The periodic load profile is evident—four small voltage drops are followed by a larger one corresponding to the transmit pulse. The profile of the system maintaining the output voltage is superimposed on top of these features (bearing in mind the constant current drain in sleep mode).

Recovery Time Following A Transmit Pulse

Pulse load (mW-s)	Bright day (30 klx)	Shadow (3.3 klx)	Dull overcast (1 klx)
500	1:20	9:02	46:00
400	1:15	5:07	31:00
300	0:45	4:11	22:45
200	0:36	3:01	15:00
100	0:17	1:50	8:00
50	0:08	0:40	4:30

At low illumination levels, it takes between 50 and 70 seconds to refresh the voltage from a low of roughly 3.2 V to 3.23 V. At higher illumination, this refresh time is on the order of eight seconds.

While the EnerPak examples harvest solar energy, other applications look to recovering vibrational energy. In October, a presentation offered by EoPlex Technologies *(www.eoplex.com)* at the Electronic Design Group's One Powerful Day, a virtual power-technology series of seminars that was held online *(http://planetee.com/events)*, discussed a manufacturing method for piezo-beam vibration harvesters for next-generation, automotive tire-pressure monitoring systems.

By way of design examples, I've previously reported on vibrating magnet/spring transducers already being used in water-treatment plants *(see "Energy Harvesting Gets Big—And Small" at* www.electronicdesign.com, *ED Online 15844)*. They monitor and report on the condition of pump bearings and on proof-of-concept testing related to highway structures and railway rolling stock. The critical factor about vibration harvesting in these apps should be fairly obvious—you don't get much energy transfer unless the system is at resonance.

To illustrate, consider the resonance characteristic from the datasheet for Perpetuum's PMG17-120 *(Fig. 4)*, which is tuned for applications associated with pumps driven by electric motors in North America that run on 60-Hz power. Typical vibration is about twice the line frequency, and that tunes the magnetic slug and spring system inside the harvester. At the forum, Perpetuum and supercapacitor maker CAP-XX updated the audience about ongoing projects in the U.K. at water-treatment plants *(see "Energy Harvester Perpetually Powers Wireless Sensors," ED Online 20033, and "Ultracapacitors Branch Out Into Wider Markets," ED Online 20034)*.

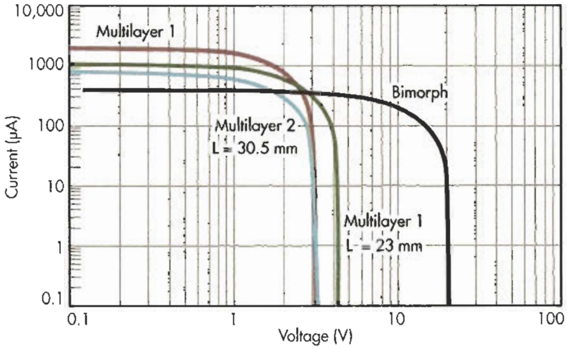
Perpetuum also makes a PMG27 for helicopters. Based on analyses of the complex vibration patterns of vibrations during typical helicopter missions, it's tuned to a 17.2-Hz resonant frequency. At the forum, a group from the University of Bristol presented a dedicated self-powered helicopter system.

Some of the most interesting talks at the NanoPower conference dealt with thermal energy harvesting. As with vibrational harvesting, I was struck by another reminder from those basic mechanical engineering classes—in this case a bit of simple thermodynamics.

A Peltier or other thermoelectric device is a heat engine. The heat difference across the junction depends on the head flux through it, which implies the necessity of getting rid of heat on the hot side. Moreover, maximum efficiency for any ΔT is never going to be better than the efficiency of a Carnot cycle. Within those parameters, there still appears to be a lot of promise for patient-powered biomedical devices.

GETTING COMPLICATED

So far, all of this may seem a little too basic. But much greater sophistication is certainly out there as well. According to Ferro Solutions' chief scientist, MIT's Bob O'Handley (who is one of *the* go-to guys for magnetostriction), when you sandwich piezos between magnetostrictive layers and pre-stress them with a field, interesting things start to happen.



5. Once you have the right tools, the door is open to asking questions. Here, for example, it's about the suitability of different configurations of piezo cantelever vibration harvesters. The particular issue in this case was output versus ruggedness.

Other examples of blue-sky research were in evidence at the Darnell conference. IMEC Nederland reviewed research on body-powered and PV-powered patient-monitoring medical applications. A team from the National University of Singapore presented a paper on powerline harvesting, while another team from the University of Colorado at Boulder discussed rectennas and far-field harvesting.

Reporting from New Mexico, TPL evaluated a number of configurations of piezoelectric cantilevers for use with the EnerPak. Figure 5 illustrates the I-V performance TPL observed from a conventional bimorph (bends in two directions) with a metal shim and two multilayer unimorphs with different layer thicknesses.

While the multilayer devices were susceptible to fracture under high loads (low frequency, high acceleration), their performance was noticeably superior to that of the bimorphs at low acceleration values. On the other hand, at high amplitudes, bimorphs delivered voltages that significantly exceed the input voltage level of the control electronics, although at low current values.

Energy-Harvesting Synergies

When talking about energy harvesting, the discussion tends to focus on photovoltaics or piezo beams, electrothermal devices, and other ways of turning stray energy into electrons. However, other technologies also can make energy harvesting useful. Let's look at a few:

- Wireless mesh networks: These have made it possible to place low-cost radios (the jargon is "motes") and receptive gateways into tough-to-monitor environments. Despite their low power, these networks are robust. Each mote not only transmits but also receives and retransmits signals from its neighboring radios. Each radio then supports the network dynamically—if one radio drops out, others pick up and support the signals it was conveying in a self-healing fashion. The mesh network is also relatively cheap. The motes themselves are low-cost, easy to install, and wiring-free, and with energy harvesting, there's no periodic maintenance cost for battery replacement.
- MEMS sensors: We've reached a point in micromachining where the latest-generation sensors are smaller, more sensitive, more rugged, and more accurate than ever before. Paralleling that, available amplifiers and analog-to-digital converters (ADCs) can achieve acceptable accuracy and dynamic range with lower input and operating voltages than previous generations.
- Small, efficient microcontrollers: Similar to the above developments, microcontrollers (MCUs) have followed their own path to low power and decent performance. Indeed, for data conversion, the standard peripherals on many basic MCUs are plenty "good enough."
- Thin-film batteries: Their slimness is crucial for energy-harvesting applications, because they can be implanted in circuit boards. Perhaps even more significant is that they have virtually no equivalent series resistance (ESR), so they're almost as easy to get power into as supercaps are to get energy into. On top of that, they don't self-discharge, so they remain ready for use virtually forever. Coupled with supercapacitors, as in the EnerPak applications described in the main article, they round out the energy-storage picture for most mesh-network applications. It is also possible, as Front Edge Technology discussed at the NanoPower Forum, to integrate a photovoltaic cell with a thin-film battery to make a self-charging battery.

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Energy-Harvesting Critical Success Factors

Numerous opportunities exist for ultra-low-power (ULP) energy-harvesting technologies and related power-management ICs and energy storage. The challenge in analyzing this market boils down to the sheer number of potential applications and the requirements of each market, many of which overlap with portable applications. Any "roadmap to commercialization" has to consider not only pricing, but also the technology performance metrics that must be matched to appropriate application segments.

Energy harvesting has an "edge" over batteries, which are often needed in large quantities and then have to be replaced. But before energy-harvesting devices can be widely deployed, a case must be made for them as a power source alternative to energy-storage-based solutions. Darnell Group's report on "Energy Harvesting, Micro Batteries & Power Management ICs: Market Forces and Demand Characteristics" *(www.darnell.com/eh)* identifies six "critical success factors" that could open opportunities for energy harvesting:

- Applications: The "early adopters" of energy harvesting are building automation systems, particularly lighting control. Emerging opportunities include automated meter reading, medical applications, military/aerospace applications, tire-pressure sensing, and RFID.
- Standards/architectures: Nearly half of the wireless sensing network nodes deployed in 2007 were based on IEEE 802.15.4, which includes WirelessHART, ISA100, and ZigBee. Although several proprietary technologies have been deployed, the race is boiling down to industrial versus consumer/commercial standards. Energy efficiency regulations will also drive adoption, particularly where there are tax incentives involved. The U.S. Energy Policy Act of 2005, for example, contains an "Energy-efficient Commercial Building Deduction." Most wireless sensor network energy-harvesting architectures have been "custom" solutions to meet very specific applications. In the next few years, expect the arrival of standard architectures based on the increasingly focused standards mentioned above. These will have power implications, particularly the utilization of power in the system.
- Power costs: Wireless sensor nodes (WSNs) have different "power costs" based on function. Energy harvesting is touted as a solution only for applications that use very, very small amounts of power intermittently. If looking at a single function, this is true. But energy harvesting is a "system solution," so the entire WSN system needs to be considered when computing the overall power cost. Sleep mode accounts for over 98% of system time, so the actual average "worst-case" power cost is about 400 µW. It could be as low as 10 µW. This system power cost range is closer to what energy harvesting can deliver.
- Installation costs: Most wireless networks being deployed augment an existing wired network. The commercial readiness of thin-film battery technologies now makes it possible for battery backup along with energy-harvesting solutions, without the size, maintenance, and replacement issues of traditional batteries. Neither battery-based solutions nor energy-harvesting solutions are significant contributors to the cost of an overall wireless-sensor-network system. The value has to be based on the relative cost of using traditional battery solutions versus an energy-harvesting solution, at installation. A comparison of three companies' solutions showed a cost reduction of anywhere from 10% to 90%.
- Process technologies and price decline: As they are replaced by newer process technologies, older CMOS processes can enable emerging technologies when they "come down the food chain." With die sizes shrinking each generation, the cost is cut in half every four to eight years. Thus, energy harvesting could become more cost-effective than existing solutions.
- Materials: Optimizing energy-harvesting performance via advanced materials is a major focus of both researchers and companies developing energy-harvesting technologies. Such materials will drive down costs either due to improved performance at acceptable cost increases; suitability to microfabrication; easy integration into standard complementary CMOS technologies; or increasing service life.

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