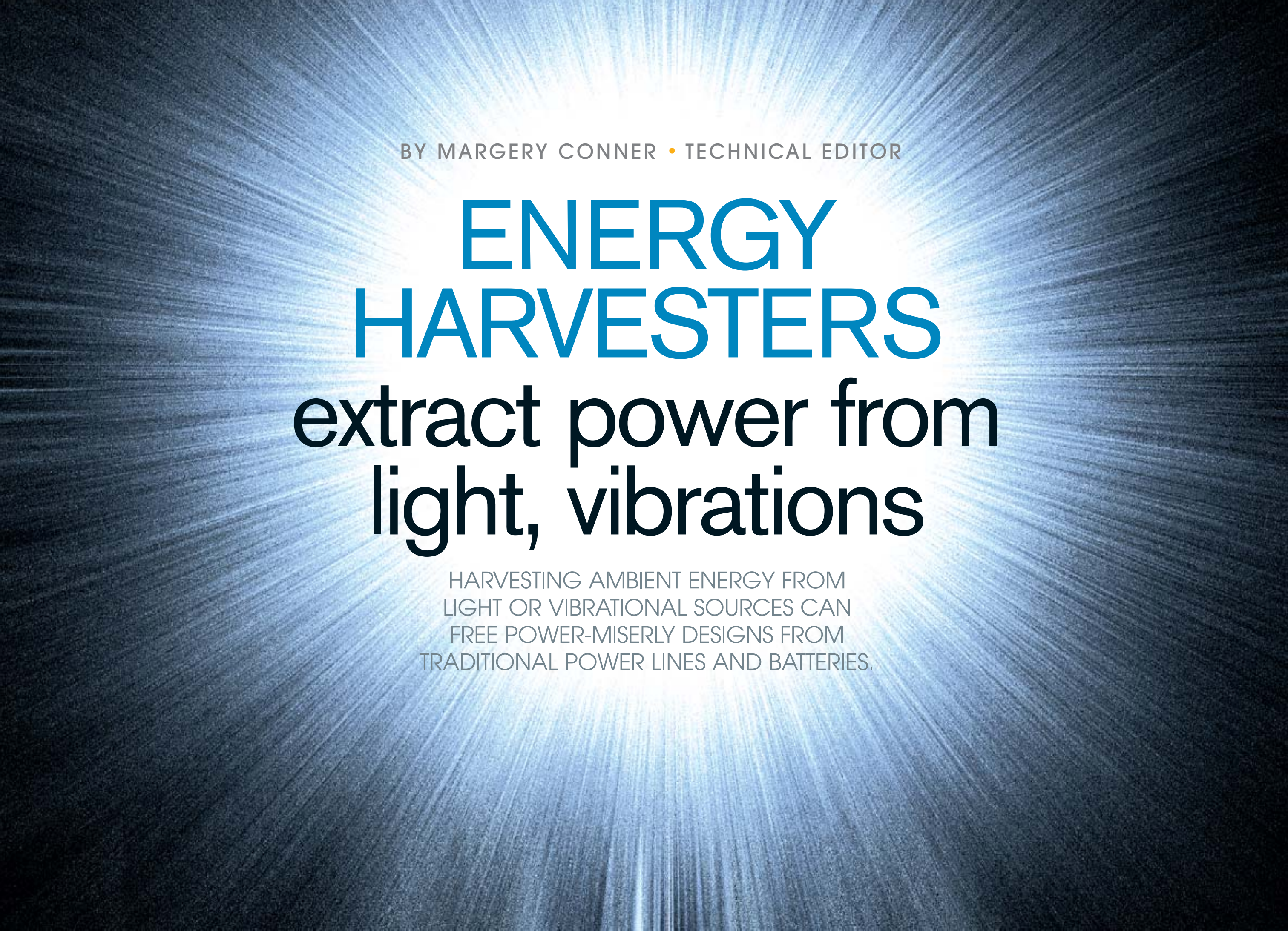

BY MARGERY CONNER • TECHNICAL EDITOR

ENERGY HARVESTERS extract power from light, vibrations

HARVESTING AMBIENT ENERGY FROM LIGHT OR VIBRATIONAL SOURCES CAN FREE POWER-MISERLY DESIGNS FROM TRADITIONAL POWER LINES AND BATTERIES.

Many systems, such as tiny wireless-networked sensor nodes and low-cost calculators for the consumer market, have severely constrained power sources resulting from remote location, cost considerations, portability requirements, or other factors. In addition, the move toward wireless communications, which obsoletes many system cables, makes designers want to further untether systems from power cords and recharge units using energy harvesters. These small devices convert the freely available energy inherent in most operating environments into conditioned electrical power. The most common energy harvesters are based on small solar cells or electromagnetic devices that convert mechanical vibrations.

Energy harvesters also find use in environments that have ready access to power lines, such as factory floors. Roy Freeland, chief executive officer of energy-harvester vendor Perpetuum, points out that initial installation can be a significant portion of system costs for networked machinery monitors. "The cost of taking that factory power and wiring it up to the sensor and transmitter accounts for about 80% of the cost of installing condition-monitoring equipment." In contrast, the installation of self-contained power units with magnetic holders involves only walking up to a machine and snapping the unit in place.

Batteries also can free a system from a power cord but at the cost of limiting the system's service-free life. After two years of usage, a vibrational energy harvester is a superior source to a lithium battery (**Figure 1**, **Reference 1**). If your application's lifetime is 10 years or longer, a vibrational or a solar source is superior to any battery technology. Labor costs can add a prohibitive premium to the system's lifetime-ownership cost, so just changing the battery is not an option.

On the downside, systems relying on harvested energy must operate on a bare minimum of power. Wolfgang Heller, PhD, product-line manager for wireless-sensor manufacturer EnOcean, cautions against trying to design a wireless-sensor network separately from the power source. "We've had discussions with customers who have their own radio and want to buy just the energy harvester. It always turns out that the radio they have consumes 100 or 1000 times more energy per bit transmitted than our design. It's

AT A GLANCE

- Tiny solar panels are the most common energy harvesters.
- Piezoelectric and thermal-gradient technologies will become more common in the next year.
- Only systems with ultralow-power appetites can survive on harvested energy.

not feasible to use these tiny energy harvesters with any other radio."

EnOcean offers network nodes that can receive power from several types of energy harvesters, including light-switch actuators, linear-motion converters, mechanical vibration, thermal gradients, and the sun. EnOcean's PTM 200 light-switch actuator integrates a relay with a magnet and a coil, so that moving the switch to turn the light on or off changes the flux through the coil, generating a voltage (**Figure 2**). The switch module wirelessly transmits the on/off command to the room light. This information is useful in a smart building (**Reference 2**). It also can drastically reduce the wiring labor costs for a building. When the room lights are all under a local wireless network, installing them does not require an electrician. Thermal-gradient-powered devices are candidates for industrial applications in which the production processes produce heat. Thermal-powered harvesters should become commercially available within six months.

OFF THE GRID

EnOcean also makes solar-powered STM100 network nodes (**Figure 3**). The modules have a two-section solar cell; one section is larger than the other. The smaller section charges a small capacitor that powers the sensor and RF circuitry during quick-start/wake-up mode. The larger section charges an ultracapacitor that powers the system during periods of darkness. Says Heller, "If we had only one solar-cell section, it would take hours to start up because the ultracapacitor needs more time to achieve the necessary voltage level. So, we power the quick-start mode with the smaller part of the solar cell, and then we achieve several days of operation in darkness."

EnOcean's solar-powered modules use a polycrystalline solar cell. Polycrystalline cells convert solar energy to electric power at an efficiency of 11 to 16% and are familiar sights on residential and industrial off-the-grid solar-panel systems. Another popular type of solar cell is amorphous silicon, but its efficiency is only 8%, or about half that of polycrystalline. Besides being less efficient, amorphous-

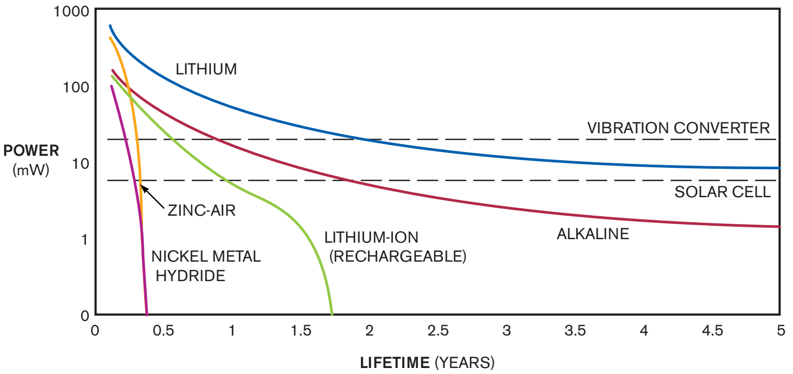

Figure 1 Although lithium batteries can supply small amounts of current for years, a solar-cell or mechanical-vibration energy harvester has a virtually unlimited lifetime.

SOLAR-POWERED CALCULATORS OFFER GUIDELINES FOR LOW-POWER DESIGN

Solar-powered calculators have been available for more than 30 years, and they serve as excellent design examples for ultralow-power portable devices operating on harvested energy. Russ Rosenquist, senior designer for calculator products at Texas Instruments, offers these design tips for power-constrained, processor-based systems:

- **Use a processor with very long instruction words. "The name of the game is to do as much work as possible in every clock cycle. Using very long instructions with parallel paths gets more work done in a clock cycle."**
- **Use process technology with very low leakage, so that each clock cycle draws the minimum energy.**
- **"Extend the clock gating within the processor: When an instruction is not using part of the chip, turn off local clocking signals, so that nodes in that part of the chip don't toggle unnecessarily."**
- **Choose the right architecture for math-intensive systems. Calculations can be in pure binary form with a hexadecimal basis or in BCD (binary-coded decimal). BCD is more efficient in computing cycles and, thus, power.**
- **Use both the rising and the falling edges of the clock cycle. "Today's design tools stress that you use synchronous-design techniques, which implies that you use only one edge of the clock: the rising edge. But, with calculator design, if you can do any work on the falling edge, you do it." Focus on minimizing the number of cycles it takes to complete the calculation. "When you do that, you operate the processor at a lower frequency and still get the answer in a reasonable amount of time."**

silicon cells' conversion efficiency degrades 15 to 35% per year in direct sunlight. Despite these significant drawbacks, amorphous cells are popular because they cost about an order of magnitude less than polycrystalline cells—a significant advantage in high-volume consumer electronics. For example, a typical 55×11-mm polycrystalline cell costs about $3 compared with less than 25 cents for an amorphous-silicon cell. One solar-powered electronic device that uses amorphous-silicon cells is the ubiquitous solar-powered calculator, such as that from Texas Instruments.

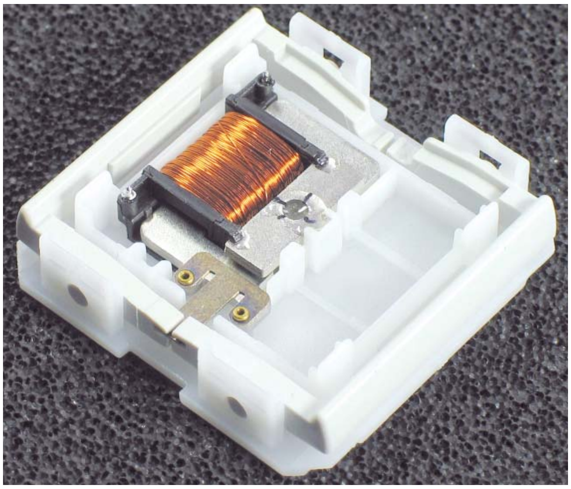

Figure 2 EnOcean's batteryless, 40×40×11.2-mm PTM 200 switch module harvests enough energy to power remote control of light switches within buildings. The actuating force is 5N over 1.5 mm.

Russ Rosenquist, senior designer for calculator products at Texas Instruments, breaks solar-cell selection into how much power a system requires based on its computational power and display needs and what size solar cell will generate that power in the expected operating environment. Two typical environments for calculator use are classrooms, which usually have fluorescent lighting, and hotel rooms, which usually have dimmable, incandescent lighting. "We try to design to operate at the lowest light levels you can possibly find in the workplace or school," says Rosenquist. "There is a limit: There are places where people can see the display of the calculator, but there's not enough energy with that light level to actually run the product. We normally design down to light levels of 50 to 75 lux. At that level, you can see pretty well; it's not so dark that you can't see things across the room. That's the lowest level we've been able to achieve with the amorphous panel at a size that's appropriate for our calculator footprint." Another benchmark for what to expect in a well-lit environment is that most school classrooms in the United States have lighting levels of 200 to 500 lux. "Classrooms are well-lit environments," he says.

In addition to the lower cost, one of the advantages of an amorphous-silicon cell is that it's more efficient than a polycrystalline cell under fluorescent and incandescent lighting. Amorphous-silicon cells respond differently to different wavelengths, says Rosenquist. "You get more power out of 50 lux of incandescent than 50 lux of fluorescent—roughly 25% more," he says.

Rosenquist also notes that users can sometimes employ a calculator in bright sunshine. In typical room lighting, the solar cell generates less than 1.5V, and in bright sunshine, it may generate much more than 2V. "We put an LED in parallel with the cell, so that, when you're in very bright light, the LED starts to sink a lot of the extra current and hold that voltage at 1.5V," he says. The LED becomes a simple, inexpensive voltage clamp.

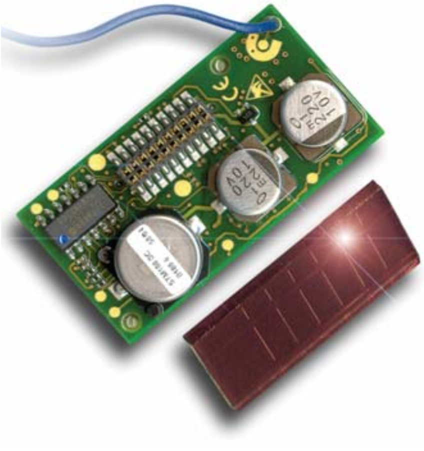

Figure 3 The solar cell that powers EnOcean's STM100 network-transmitter node has two sections: The square area on the left charges a conventional capacitor, and the larger area on the right charges an ultracapacitor.

As with most of the design engineers working with harvested-energy sources, designing your overall system to be miserly with power is just as important as selecting an energy source (see **sidebar** "Solar-powered calculators offer guidelines for low-power design"). (For more on ultralow-power-system design, see **Reference 3**.)

GOOD VIBRATIONS

Not all operating environments have reliable, constant light. For example, machinery-monitoring sensors may not have reliable light but have plentiful vibrational energy. Vibrational-energy harvesters can be either electromechanical or piezoelectric; electromechanical harvesters are more common. Perpetuum's Freeland says the company originally pursued piezoelectric technology but eventually concluded that it simply did not generate enough power at the amplitude and frequency of vibrations in machines and buildings. Instead, Perpetuum turned to electromagnetics, including coils, magnets, and a resonant beam, and designed a generator that could produce significant amounts of electricity from readily available vibrations. "These are vibrations from typical machinery, or even a domestic refrigerator: around 50 Hz in Europe, 60 Hz in the United States, or 100 to 120 Hz. At these frequencies, if you've got 0.5 to 0.1g, then you are generating enough to power electronic circuits." The module includes a power-conditioning circuit that produces 3 or 3.3V dc from the generator's initial ac power. Current depends on the strength of the vibrations but, for typical machinery, can be approximately 1- to 3-mW power generation.

Freeland describes a wireless-sensor sys-

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tem that one of Perpetuum's customers designed. "The device included a temperature and a humidity sensor and transmitted twice a second. Typically, a transmitter needs about 30 mW, but the device transmits for only tens of milliseconds, and there is normally a capacitor in the circuit that is charged up and that then discharges to drive the transmission, which is the heaviest power requirement." Perpetuum's generator costs $30 (volume quantities).

Ferro Solutions also makes vibrational generators. The company based its initial product on electromagnetic technology but has recently patented and produced a piezoelectric version that amplifies the piezoelectric-bender (a strip of flexible, piezoelectric material) magnetostrictive component, which changes shape based on a magnetic field. The price is approximately $30.**EDN**

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