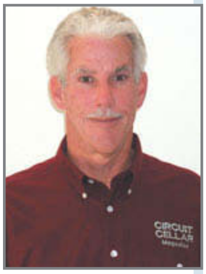
by Tom Cantrell



# LiOn King

## A Look at "Battery-in-a-Chip" Technology

Got Energy? Energy harvesting is all the rage, but like a real harvest you need a place to store the crop. This month, Tom introduces the next advance in thin-film rechargeable lithium battery technology: a battery-in-a-chip.

With the price of oil all over the map, a trip to the local gas station feels like a trip to Vegas. The gas pump is a slot machine: you put your money in, watch the dials spin, and hope today's your lucky day.

It's safe to say that "Green" is the new black and embedded designers must do their part in this new era of energy consciousness. Beyond the headline grabbers, innovations like hybrid vehicles and efficient light bulbs are a myriad of mainstream apps that should go on a digital diet.

Hats off to the silicon wizards for delivering chips that not only do more for less, but also consume less energy doing it. However, these silicon advances put the ball back in the designer's court. It's up to you to figure out innovative applications and clever design techniques that make the most of the energy-saving opportunities.

### ENERGY IN A CHIP

Battery technology will play a pivotal role in the Green revolution. For instance, if the question is about the widespread move to

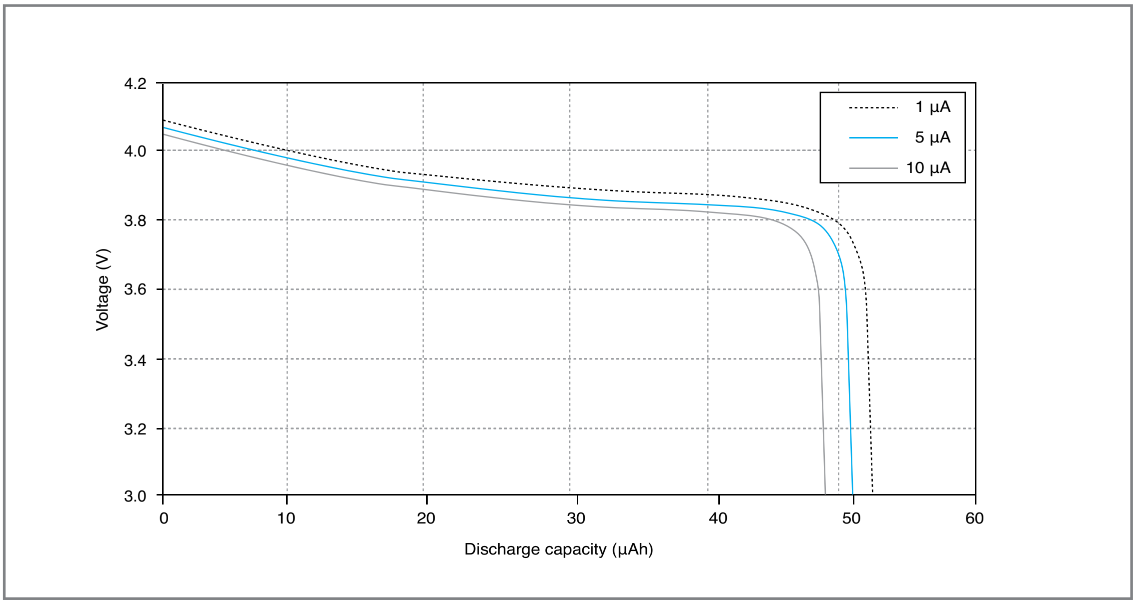


**Figure 1**—One advantage for lithium batteries, including EnerChips, is a flat discharge curve. Just watch out as you approach the "cliff" since deep discharge isn't good for the battery.

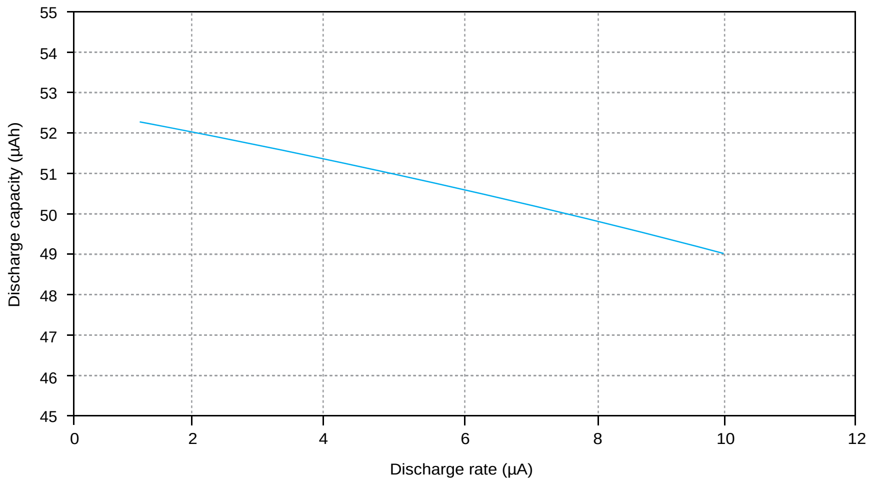


**Figure 2**—Although capable of relatively high discharge (e.g., 300 µA for 20 ms), note that effective capacity decreases with increasing loads.

electric vehicles, the answer is battery technology that can deliver the range and performance fossil-fuelers are used to.

At the other extreme, Cymbet is taking a "small is beautiful" tack with their "EnerChip" thin-film rechargeable lithium battery technology. In short, as the name implies, it's a battery-in-a-chip. Combined with the latest in nanopower silicon, the EnerChip offers an intriguing option for designers to consider.

Just keep in mind we're not talking about a lot of energy here. So far, the Cymbet batteries top out at 50-µAh capacity (CBC050) with a lesser 12-µAh model (CBC012) also offered, although this is on the order of a thousand times less than the familiar lithium "coin cell." At least the output is a healthy 3.8 V. That's suitable for use in typical (e.g., 3.3-V) designs. Of course, as with any battery technology, you can always lash them together to increase voltage, current, and capacity.

It's a fact of life for all batteries that specs like "50 µAH" and "3.8 V" are overly simplistic and tend to obscure the fact that a myriad of other application factors come into play. The Cymbet batteries are no exception. Let's take a closer look to get a better understanding of how they can serve existing designs or, better yet, enable exciting new ones.

Although on a tinier scale, the Cymbet batteries exhibit the same desirable performance characteristics that have made their larger lithium coin cell cousins so popular. For instance, the voltage discharge curve is as flat as a board, which guarantees virtually full output until the bitter end (see Figure 1). If there's a downside, this means you can't really expect to use the voltage output level as a foolproof indicator of remaining battery life. Power management will have to be smarter than that, which is all the more reason to better understand the specs.

With a throwaway coin cell, using it until it's dead (and then replaced) is standard procedure. By contrast, with the Cymbet rechargeable, you need to be careful not to run it off the cliff shown in Figure 1. There's no simpler way to say it than the CBC050 datasheet does: "Failure to cutoff the discharge voltage at 3.0 V will result in battery performance degradation."

Another benefit of lithium cells is the ability to deliver surprisingly high surge currents—in the case of the CBC050, up to 300 µA. But

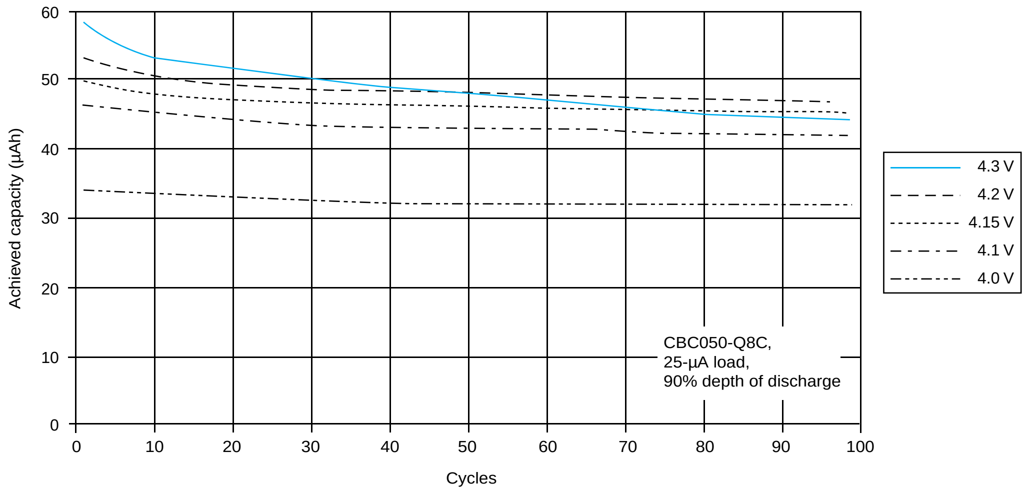


**Figure 3**—To recharge an EnerChip, you'll need a power supply that delivers exactly 4.1 V—no more, no less. The proper charge voltage both maximizes charge capacity while minimizing "cycle fade."

watch out, because the capacity declines almost linearly with the load as shown in Figure 2. If you think a "50-µAh" lithium cell should be able to run a 300-µA load for 10 minutes (i.e., 50/300, or 1/6 of an hour), you've got quite a surprise coming. Extrapolate the line in Figure 1 to the right and you'll see what I mean. Using a car analogy, drive with a heavy foot on the throttle and your mileage will suffer, so a full tank of gas won't take you as far as if you drive more sedately.

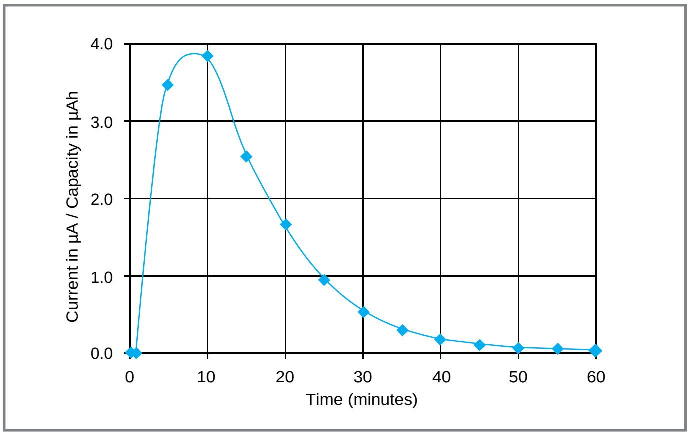


**Figure 4**—While the charge voltage should be precise (e.g., 4.1 V), not much current is required, just 200-µA peak for the 50-µAh CBC050.

In the old days, NiCad batteries were the all the rage for rechargeable applications. Do you remember the infamous "memory effect"? That referred to the propensity for NiCad batteries to "remember" repeated partial discharge levels and get stuck at a less-than-rated capacity. To counter, users in the know would be careful to "deep discharge" their NiCads to wipe the "memory" clean.

The Cymbet rechargeable lithium technology is somewhat the opposite. It's more like a car (i.e., lead acid) battery in that deep discharge is something you want to avoid because it reduces the number of potential recharge cycles. Ponder the specs and you'll see the effect is by no means trivial. For instance, keep the CBC050 "topped off" by limiting discharge to 10% and you can expect to get a full 5,000 discharge/recharge cycles out of it. But if you routinely run it down to half full (i.e., 50% discharge), that spec drops by a factor of five to 1,000 cycles.

Temperature also plays a role. The aforementioned specs are for 25°C operation. Boost the temperature to 40° and cycle counts are cut in half (i.e., 2,500 and 500 cycles at 10% and 50% discharge, respectively). Also take note of the operating temperature range of –20° to 70°C, a possibly limiting spec in "harsh-environment" applications.

Self-discharge can be a problem for lesser battery technologies. For instance, I have an older digital camera with rechargeable NiMH batteries that I might use once a month to take a picture for this column. Despite being nearly fully charged when I last used it, it is invariably drained when I fire it up a month later.

By contrast, the CBC050 is quite happy to sit idly by for many months or even years. The self-discharge spec comprises two parts. The first is "recoverable" self-discharge. Yes, the capacity will decline over time, but the next recharge will make everything right again with no permanent damage. There's also a "non-recoverable" self-discharge, or "aging," that's more serious in that it represents a permanent loss of capacity.

That all sounds scary until you look at the CBC050's specs. The "recoverable" self-discharge rate is 8% and the "non-recoverable" rate is 2.5%. But that's per year! At a total of 10.5% per year, that means the CBC050 could come to life after almost 10 years in storage, and it would still be quite serviceable (i.e., able to charge back up to 75% of the original rated capacity).

Put all the specs together and you start to get a realistic picture of what a CBC050 can deliver in a particular application. Consider these different application scenarios.

The first has the CBC050 fulfilling the typical role of "battery-backup" for a low-power CMOS chip (i.e., MCU, SRAM, RTC). It's quite well-suited to the task, but faces notable competition from an unlikely source: not another battery, but the so-called "SuperCap" high-value capacitors. But put on your "Green" eyeshade to look closely at a SuperCap datasheet and notice the very high self-discharge spec. In essence, SuperCaps need to be kept on the charger at all times in order to be ready for a call to action. It also means there's energy wasted keeping them topped-up. The difference may not seem like a big deal, but from a holistic "energy consciousness" point of view, the potential self-discharge energy advantage is significant. According to Cymbet, up to one-third the energy spent charging a SuperCap (e.g., 0.2 F) is lost to self-discharge versus a tiny fraction of a percent for an EnerChip.[1]

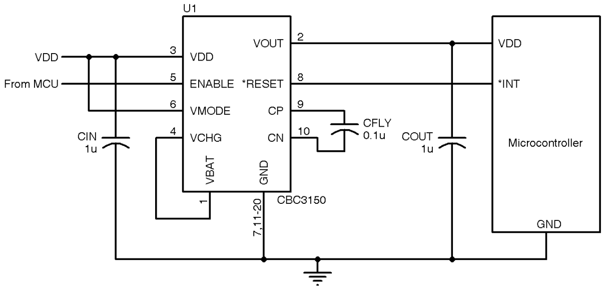


**Figure 5**—The EnerChip "Charge Controller" parts combine an EnerChip battery and charge control electronics in a single chip.

Safety is something easy to overlook, at least until it jumps up and bites you. Everyone has seen the headlines about exploding laptops and such. Fortunately, Cymbet says that even a dead-short won't lead to unwanted pyrotechnics.[2]

> Cymbet takes their EnerChip technology a major step further with the so-called 'CC' upgrade that combines the battery with power-management logic and packs a complete mini-me Uninterruptible Power Source (UPS) in a chip ...

## CHARGE IT

Recharging an EnerChip battery is simple enough. The easiest approach is simply to connect it to a 4.1-V supply and the battery will fully recharge in less than an hour. Alternatively, a two-phase scheme can be used that starts with a constant current (e.g., 50 µA) phase and finishes with a constant voltage (4.1 V) phase. The documentation notes the two-phase approach may be required for future EnerChips; but for these initial batteries, the single-phase constant voltage approach is fast and easy.[3]

The main consideration is that the 4.1-V supply needs to be rather precise—within a few percentage points (see Figure 3). If the voltage is too high (e.g., 4.3 V), the battery will exhibit "cycle fade," in which the capacity declines with each recharge cycle. Too low (e.g., 4.0 V) and the battery won't recharge to full capacity.

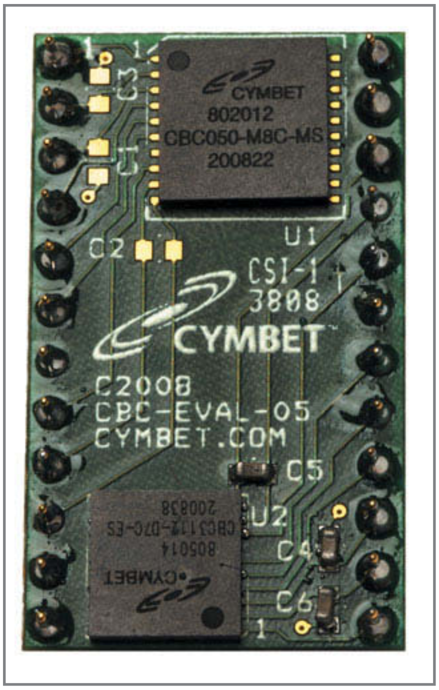


Photo 1—The CBC-EVAL-05 includes both 50-µAh (CBC3150) and 12-µAh (CBC3112) EnerChips. It's easy to switch between one or the other just by rotating the module.

The EnerChip internal impedance is high enough that there's no need for extra components to limit the charge current, at least as long as the charging voltage isn't too high (i.e., it should not be greater than 4.3 V). As shown in the typical battery-charging profile (see Figure 4), the charge current peaks at about four times the battery capacity (i.e., 48 µA for the CBC012 and 200 µA for the CBC050).

## UPS-LITE

Cymbet takes their EnerChip technology a major step further with the so-called "CC" upgrade that combines the battery with power-management logic and packs a complete mini-me Uninterruptable Power Source (UPS) in a chip that's just slightly larger than the battery alone.

EnerChip CCs are available using either the 50-µAh (CBC3150) or 12-µAh (CBC3112) batteries. They're packaged in a 9 mm × 9 mm 20-pin package, but as shown in Figure 5, there are really only a few pins to deal with.

With a wide 2.5- to 5-V input range, VDD is the primary power source for the EnerChip CC, just as wall power is the primary source for a 120-VAC UPS. VBAT is directly connected to the battery. VOUT is the uninterruptable 3.3-V (typical) output to the load.

An internal charge pump (with an external capacitor connected to the CP and CN pins) generates a precise 4.1 V on the VCHG pin to charge the battery. It's simply a matter of connecting the VCHG and VBAT pins to close the loop. If you're wondering why Cymbet didn't just connect them for you internally, the answer is that a single EnerChip CC can work with up to 10 external EnerChip batteries for applications that need higher current and capacity than the on-chip battery provides. While it doesn't hurt the battery to charge it all the time, needless charging consumes power to keep the charge pump running, so the ENABLE (EN) pin provides an external On/Off switch.

The EnerChip CC automatically handles the switchover between primary (VDD pin) and back-up (VBAT) power delivery, the threshold being set with the VMODE pin. If VMODE is connected to VDD, the threshold is 4.5 V (i.e., suitable for 5-V designs). If VMODE is grounded, the threshold is 3.0 V (i.e., for 3.3-V designs). A third option requires a pair of external resistors, the ratio between them setting the threshold voltage anywhere between 2.5 and 5 V. The RESET* pin is driven low when the EnerChip CC is providing power

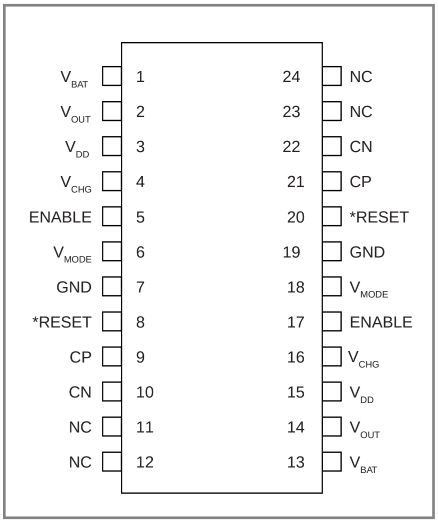


Figure 6—The CBC-EVAL-05 module makes it easy to experiment with Cymbet EnerChip technology.

Photo 2—This design shows how EnerChips and coin cell batteries can work together.[4] The EnerChip keeps the system alive when the coin cell needs to be replaced.

to VOUT from the internal battery.

Battery-protection is also built-in, with the output (VOUT) automatically disconnected from the battery when VBAT falls too low. The combination of precise charge voltage and battery protection maximizes the capacity and number of recharge cycles the battery delivers.

Cymbet offers some handy evaluation modules that make it easy to experiment and prototype with EnerChip batteries and CC controllers. Consider the CBC-EVAL-05 (see Photo 1), which includes both a CBC3112 and a CBC3150 packaged in a 24-pin DIP format. Notice on the pinout (see Figure 6) how the left and right sides of the DIP are mirror images. One side connects to the CBC3112 and the other the CBC3150 so you can test either by simply rotating the module.

The module has the flexibility to support a variety of experiments. For instance, if you're mainly interested in playing with the batteries, but not Cymbet's charge controller, just leave the VCHG pin disconnected from the VBAT pin and have at it.

There's also a hybrid option that has one CC, pardon the pun, in charge of the other's battery (i.e., CBC3150 charge controlling the CBC3112 battery and vice versa). A variation runs both CBCs simultaneously by connecting their VBAT pins with either VCHG pin (not both).

## DUST STORM

When comparing Cymbet's EnerChips to existing solutions such as coin cells and SuperCaps, it's all too easy to fall into the "us vs. them" trap. There are no doubt applications where an EnerChip is the clear-cut winner and should replace the earlier devices. But "us vs. them" overlooks the fact that there are a lot of situations where "us and them" can work well together. Let's take a look at some EnerChip-based gadgets and you'll see what I mean.

Photo 2 shows what might seem an unlikely pairing of a coin cell battery and an EnerChip, but it's actually a combination that makes a lot of sense. The application would generally draw from the coin cell, calling on the EnerChip to "bridge" the power-gap when it's time to replace the coin-cell. The EnerChip would allow "in-flight refueling" (i.e., application continues to run) and preserve critical data across battery swaps. For instance, keeping a real-time clock alive with an EnerChip would put an end to the embedded equivalent of the flashing "12:12:12" problem (i.e., devices that lose their minds and need to be re-initialized when you change the battery).

Look no further than Cymbet's "Solar Energy Harvesting" demo kit (CBC-EVAL-08) to see how EnerChips and capacitors can be best buddies too. The kit utilizes a three-tier hierarchy of power generation starting with a solar panel that picks up what energy it can, when it can, from ambient light. The solar panel output feeds a boost converter that steps up the voltage to a useful level (3.5 V). When solar energy is sufficient, it drives the load and charges a pair of CBC050 batteries. If the light fades, the EnerChips take over supplying the load.

So far, so good. The only gotcha being said load had better be pretty small. `Whether powered by the solar panel in bright sun, or running off the EnerChips, we're talking about only tens to hundreds of

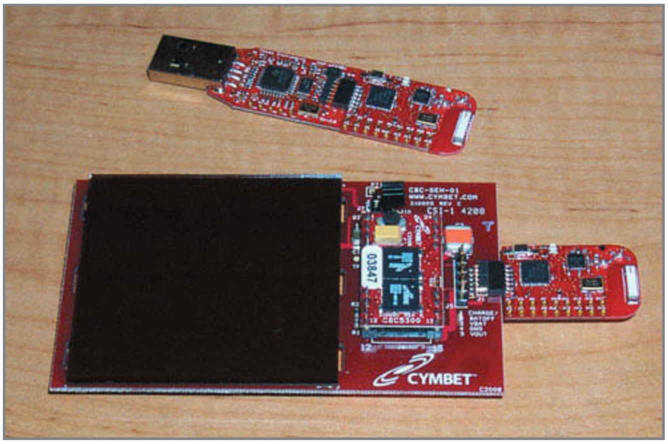


Photo 3—The Texas Instruments eZ430-RF2500 Solar Energy Harvesting kit puts Cymbet EnerChips to work with TI silicon in a "zero-power" wireless sensor application.

microamps on tap.

Here's where our little friend the capacitor comes in. Capacitors may be leaky, but they're also more than willing to give it all they've got in a big bang (i.e., high discharge current). That brings us to the third tier in the power-generation pyramid: a 1,000-µF capacitor. Although hardly a "SuperCap" (real ones are measured in Farads), it can nevertheless deliver a whopping 30-mA discharge for 20 ms, fully 50 times the 600-µA surge the pair of EnerChip batteries can provide. Of course, there's no free lunch. The battery resistance and the capacitor form an RC network that takes a few seconds to recharge.

Is that enough energy to do anything useful? Texas Instruments says so, and to prove it, they've come up with the eZ430-RF2500 Solar Energy Harvesting kit (see Photo 3) that uses the Cymbet Solar Energy Harvester to power a wireless sensor solution based on their MSP430 flash memory MCU and CC2500 802.15.4 radio chips.

The kit comes with the Solar Energy Harvester, a USB adapter that connects to your PC, and a plug-in MCU-plus-radio module for each. The software comprises a simple temperature-sensing application with TI's home-grown SimpliciTI network stack running on the nodes, and a PC-monitoring program that displays the network in action (see Photo 4).

Yes, the application is trivial, but the design implications aren't. This stuff really works! The solar panel was able to power the load and keep the EnerChip charged in moderate lighting conditions, even indoors. But when there wasn't enough light, the EnerChip seamlessly kicked in, able to keep the node on the air for up to 400 additional packets on battery power alone.

## TIPS & TRICKS

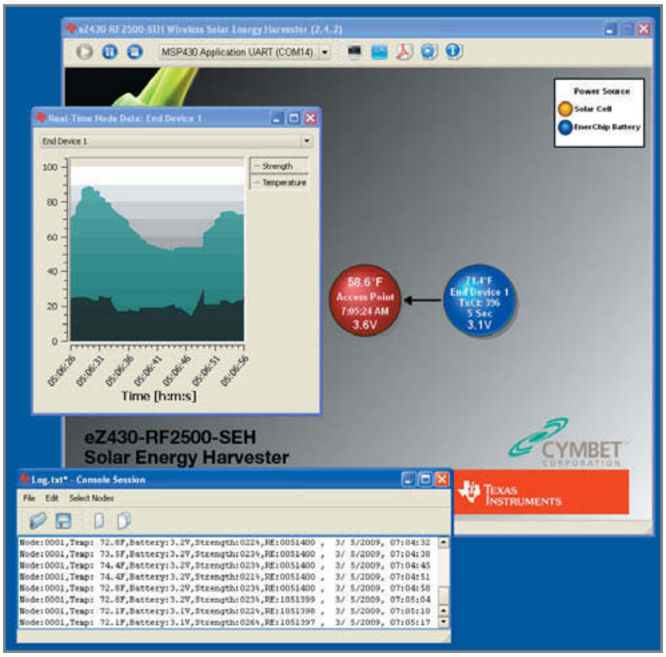
By now most designers are familiar with the typical low-power design techniques (i.e., sleep mode, powering down unused logic, up/down-shifting the clock rate, and so on). But getting on the energy-harvesting bandwagon requires taking low-power design techniques even further. When you're talking millionths of an amp for a power budget, every little bit adds up.

For example, when was the last time anyone really thought much about all those lowly pull-up resistors littering most designs? Well, think again. Consider the typical 100-kΩ pull-ups inside most MCUs, not just on the I/O lines, but also on the control inputs such as interrupts and reset. The bad news is that a 100-kΩ pull-up at 3.3 V burns 33 µA just sitting there. We always new that, but just didn't care. Now we do.

So, for example, you don't want to leave the pull-ups on your software-scanned matrix keypad enabled all the time. Instead they should only be powered during the active scan. Indeed, where possible (i.e., external pull-ups), use a higher value resistor (e.g., 1 MΩ). But pay close attention to your rise and fall times since chips burn more power during the time an input transitions through the "floating" region between rails.

Similarly, be on the lookout for subtle leakage paths between chips. For instance, an RTC powered by a battery can leak power through its pins to an attached MCU, even if the MCU is powered off. Use diodes and transistors as hose clamps and valves to seal even the tiniest leaks.

The cyclic nature of the capacitor discharge power supply poses all manner of creative challenges for designers. You no longer have the luxury of consuming all the clock cycles you want whenever you want them. Instead your hardware and software design has to deal with the reality that the power supply drives the schedule. Imagine how this complicates an already tricky and timing-sensitive task like wireless networking. The



```
Node:0001,Temp:  72.8F,Battery:3.2V,Strength:022%,RE:0051400 ,   3/ 5/2009, 07:04:32
Node:0001,Temp:  73.5F,Battery:3.2V,Strength:023%,RE:0051400 ,   3/ 5/2009, 07:04:38
Node:0001,Temp:  74.4F,Battery:3.2V,Strength:023%,RE:0051400 ,   3/ 5/2009, 07:04:45
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Node:0001,Temp:  72.8F,Battery:3.2V,Strength:023%,RE:0051400 ,   3/ 5/2009, 07:04:58
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Node:0001,Temp:  72.1F,Battery:3.1V,Strength:026%,RE:1051397 ,   3/ 5/2009, 07:05:17
```

Photo 4—The PC software that comes with the TI kit shows the network in action. Note how the node counts down the number of packets it will be able to send on EnerChip power alone (i.e., in the dark).

| 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$^2$ |
| Wi-Fi | 0.001 μW/cm$^2$ |

**Table 1**—The environment is filled with ambient energy free for the taking.[5] All you have to do is figure out ways to harvest it.

MCU may have to "stairstep" its way through complex procedures one short burst of energy at a time.

With all the starting and stopping, you even need to pay attention to the energy overhead of waking up and shutting down. After all, if your workday was only 10 minutes long, how fast you tie your shoes would suddenly matter a lot.

## HARVEST TIME

When you think about it, the environment is filled with huge amounts of energy we can tap (see Table 1). Our old pal Sol(ar) gets most of the headlines, but there are plenty more sources free for the taking. Piezo transducers can capture energy from the vibration of a motor or the shock of a shoe hitting the pavement. Tomorrow's smart wardrobe might literally include "smart clothes" that run off power harvested from the heat of your skin. Or imagine, as Tesla did a century ago, being able to skim power from the RF chatter that bombards us.

We're only at the beginning of the green revolution, and already it's clear that energy harvesting is well beyond the (sunny) "blue sky" hype phase. The technology from Cymbet and TI is clearly viable for some real-world applications today and, with inexorable advances in technology, many more tomorrow. If you want to reap the benefits of energy harvesting, it's time to sow some new and clever designs. ◾

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