MICROINVERTERS
Make a Simple DIY Installation

by Guy Marsden

My wife Rebekah and I have always wanted to live a PV-powered life, but the high price of the technology—an estimated $30,000 to cover all our electricity needs—had always been outside of our budget. Then came microinverter technology, which would allow us to start small and easily expand our system in the future. That, low mortgage rates, a drop in PV module prices, and the 30% federal solar tax credit sealed the deal.

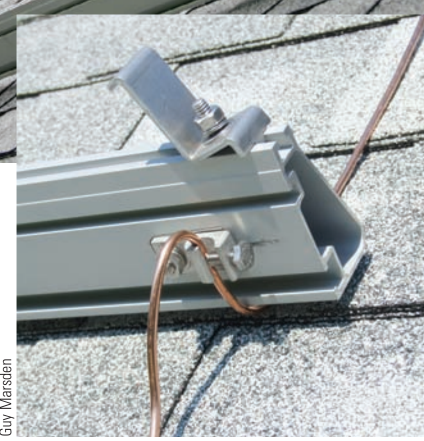
Guy Marsden

I'm an active member of the Midcoast Green Collaborative, a local volunteer organization committed to creating a sustainable economy in coastal Maine. In 2009, one of our goals was to get feed-in tariff legislation passed. The proposed law was modeled on the successful German feed-in tariff law, which levies a small fee—usually $1 or so—on every electric ratepayer's bill. The utility uses these funds to pay a premium per kWh to small-scale renewable energy generators. This helps make it cost-effective for homeowners to finance installing a PV or wind-electric system, since the income typically covers the loan payments. Once the loan is paid off—typically in 20 years—you're set up to become a profitable electric micro-utility!

I testified at a hearing before the Maine Utilities and Energy Committee, where I presented a spreadsheet showing how the financing would work with a 20-year, low interest loan and a 20-year generation contract with Central Maine Power (CMP)—our local utility. I showed that a payment from CMP of 50 cents per kWh would significantly incentivize small-scale residential solar generators.

Testifying led me to do more research on the cost and feasibility of installing my own grid-tied PV system. My first call was to my friend Naoto Inoue, the owner of Solar Market, a solar dealer and installer in Maine. He helped me design the solar heating system for my workshop back in 2001 (see "Solar Heat for My Maine Workshop" in *HP89* and "Solar Heat Upgrade: Expanding & Improving an Owner-Installed System" in *HP119*) and sold me much of the equipment. He mentioned an emerging technology—microinverters—that was changing the paradigm of PV installations. Instead of the modules being wired together to create high-voltage DC that is sent to a large, single inverter, each module is equipped with its own small inverter. The power is converted to 240 VAC right at the module, which can make the system more efficient and the design more flexible. It eliminates the shading issues


Courtesy Terrill Waldman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Above: The rails, installed and ready to receive the microinverters.

Inset: A detail of a rail, showing the module clip and grounding system.

Wiring a PV module to one of the 21 Enphase microinverters.


Courtesy Rebekah Younger

One of two strings of AC connections, connected in a junction box to wiring that goes to a subpanel with the two arrays' breakers.


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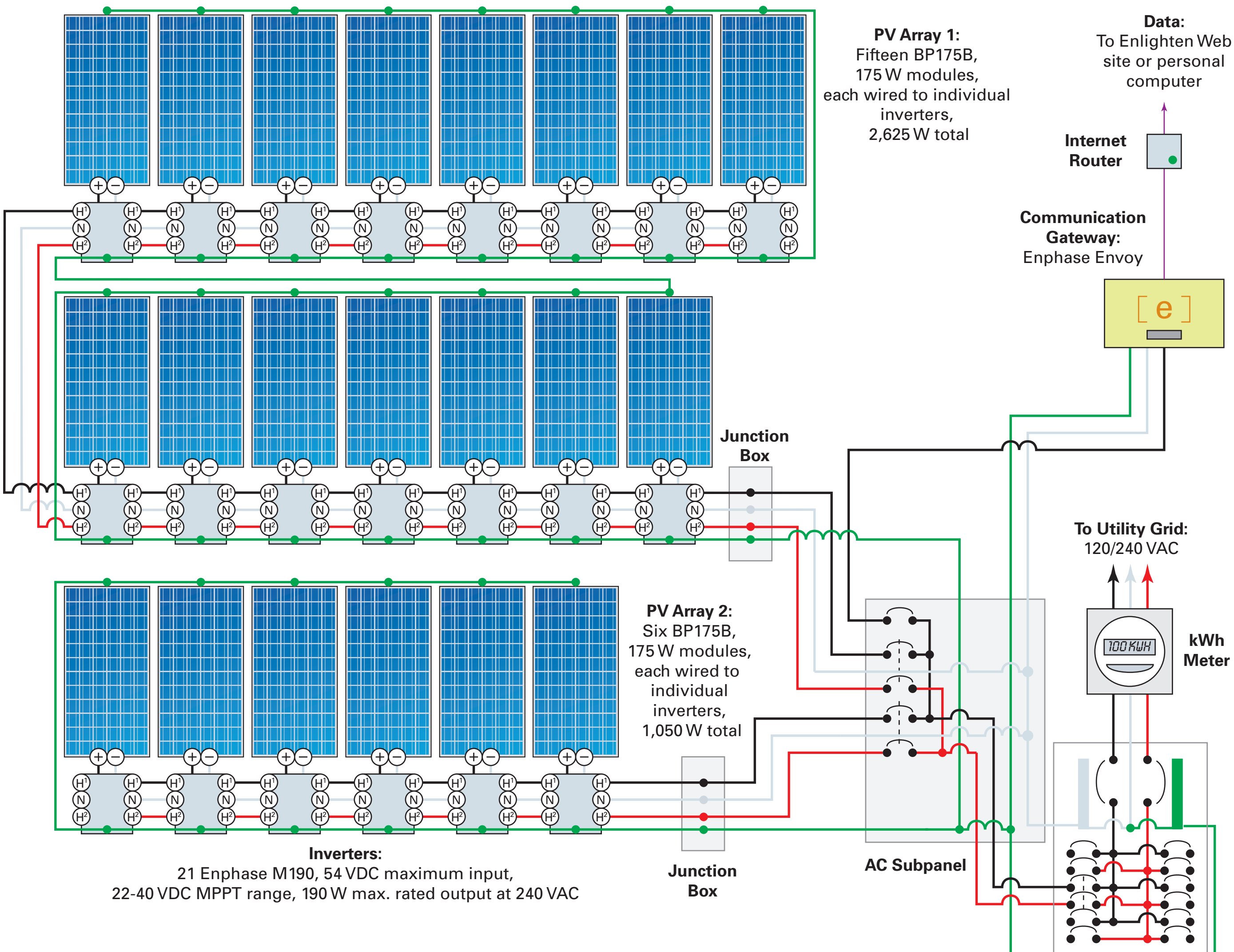
MARSDEN BATTERYLESS GRID-TIED PV SYSTEM



Note: All numbers are rated, manufacturers' specifications, or nominal unless otherwise specified. WEEB grounding clips were used between modules and rails; the only ground wire is between the rails and from the rails to ground rod.

that can compromise the performance of DC systems when modules are wired in series, since shading part of one module in the series can compromise the whole string. Also, modules of different capacities can be mixed, allowing system growth over time without worrying about module mismatch.

Designing the System

Typically, the first step in designing a PV system is to know how much power you use—or will use. But before that, to reduce your system costs, most people need to work at reducing their usage. Rebekah and I had reduced our energy footprint, both with conservation practices and efficient lighting and appliances. Our past 12 months of electric bills showed an average use of 550 kWh per month. To compare, in 2006, the average U.S. household used 880 kWh per month. Take a look at your recent electric bills and see how your home stacks up—there may be room for improvement! We use propane for cooking; propane, solar, and woodstoves for space heating; and propane and solar for water heating, so our electricity use was mostly for appliances and electronics.

Producing 550 kWh as a design ideal was the starting point. PV systems are usually rated by the total kW capacity of the modules—not the AC power produced. Energy losses come from inverting the DC to AC, wire heating, module soiling and mismatch, and other losses like module production tolerances; so a derate factor—typically 0.77—is applied by sizing tools like PVWatts (see Access). This derate and module temperature losses are used to estimate the AC kWh of a given solar array. However, the Enphase microinverters I planned to use have an efficiency of 0.95 (vs. 0.92 assumed by PVWatts) and will circumvent module mismatch issues. When incorporated into the calculation, the derate factor was 0.81—a significant improvement over 0.77!

Installing Microinverters

The M190 Enphase microinverters were in high demand and short supply, and my vision of a "barn-raising" installation—with half a dozen friends, taking a day or so to finish—turned into a piecemeal approach while I waited for the inverters to arrive.

I began at the bottom right of the lowest rack, wired the female cable end into the roof-mounted junction box, and then mounted the first inverter. I had planned to daisy-chain the AC cables up three rows, left one module, and then down three rows until I had placed all 15 microinverters. But when I installed the second inverter in the row above the first, I found that the AC cable built into the inverter was not long enough. Oops.

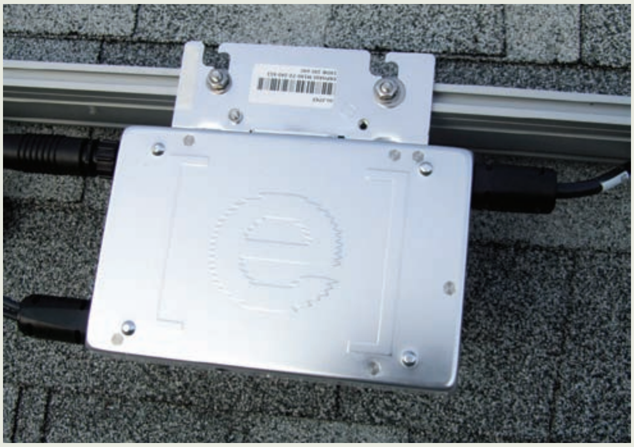
I called Enphase tech support and asked the technician to look at my blog posting photos so he could see the racking layout and understand my problem. He immediately offered to send me some 6-foot-long extension cables—free. I asked for four cables, anticipating changing the wiring sequence to start at bottom right, go left for five modules, then up one module, right five modules, then up one, then left five. Using this approach, I would only need to go up twice per block of inverters. Enphase later lengthened the cables an additional 8 inches to address this issue.

Enphase's earlier model M175 had AC cables with male and female ends; my M190 microinverters have a male cable and a female connector built into the unit. I think the two-cable design was better as it allowed more flexibility in installation.

I mounted the inverters with an extra-large washer, regular washer, lock washer, and nut over the right mounting slot. The large washer covers the WEEB grounding washer between the inverter flange and the mounting rail to ensure it gets even pressure. I used a torque wrench to tighten the nuts to 10 foot-pounds, per the Wiley Electronics' documentation for Iron Ridge mounting rails.

Enphase provides a chart that you use to indicate which inverter goes where so that their Enlighten Web interface can locate them. I removed one of the two bar-coded serial numbers that are stuck to each unit and stuck it onto the chart in the correct placement. This chart gets faxed to Enphase so that they can build the Web data page and validate the installation.

Enphase microinverters bolt easily to the PV mounting rails. They must be mounted under the modules to prevent interference with the module frame and mounting clips.



Guy Marsden (2)

PVWatts further calculates the array performance based on system location, power rating, tilt, and orientation. I decided to use 21, 175 W BP 175B modules for a 3,675 W array. Our derate factor and our array's westerly orientation showed an annual production of about 3,600 kWh. PVWatts also showed the array's estimated average monthly production at 300 kWh, 250 kWh less than our average consumption, and 150 kWh less than our consumption that is billed at a higher rate. The way we are billed, the first 100 kWh is provided at a lower rate (about 12 vs. 18 cents), so there is less incentive to offset that first 100 kWh.

PV system AC subpanel, housing two double-pole 15 A breakers, which act as the PV system's disconnects. A single 15 A breaker is wired to the required AC outlet to power the Envoy communications gateway.

Guy uses a torque wrench to tighten the bolts on the module hold-down clips. Also note the spacing block that ensures a quarter-inch gap.

Part of the original impetus to install our own PV system came from my experience of watching proposed feed-in-tariff legislation get strangled to death by well-intentioned members of the Maine Utilities and Energy committee. I testified and then spent many long afternoons in the committee room observing the deliberations. The bill passed, but it had no teeth—the payout was based on historic high wholesale prices and no tariff, thus zero incentives.

In the process of preparing my testimony for the committee, I began to realize that Maine's net metering law could provide at least some benefits to make the PV system more affordable. I estimated that if we were to install a system that generated all the electricity that we typically use, our annual bill would be reduced to the minimum connection fee—about $8.00 per month. It was actually financially prudent to slightly undersize the system, so that we would not be giving away any surplus. Annual system energy production values are often conservatively estimated and the system may exceed initial estimates. Under Maine's annualized net-metering agreement, the utility does not pay for a surplus at the end of the year, but only credits the excess power generated in any given month.

Budgeting for the System

The federal tax credit allowed us to deduct 30% of the cost of the system from our federal taxes. We would have normally set funds aside on a weekly basis to pay quarterly estimates, and by avoiding having to pay them in 2009, we saw an immediate reduction in expenses. This year, we will avoid paying nearly $6,000 in taxes. We also took advantage of the Maine Public Utilities Commission's Efficiency Maine program, which offers a solar rebate that pays $2 per watt for the first 1,000 W (capped at $2,000).

To pay for the system, we refinanced our house. We had an adjustable rate mortgage that could adjust up this year, and we figured that it was a good time to lock in a 20-year fixed mortgage. To keep the money in the local economy, we found a mortgage with a local bank. I watched the economic indicators and changing mortgage rates carefully and then locked in a low loan rate in late April 2009.

We originally budgeted $26,000 for a slightly larger system that would fill the workshop roof, but decided to scale back to 21 modules, saving about $5,000. We tacked on the system cost (about $21,000) to the new mortgage for an attractive rate that was better than an equity loan or line of credit. We also explored the option of MaineHousing's Home Energy Loan Program. They limit their loans to 15 years and $30,000, but despite a better interest rate, the monthly payment would have been about the same as the new mortgage. Also, our loan officer advised us that the paperwork for these loans is significant and there are a lot of restrictions that could have precluded installing the array myself.

Over the 20-year loan term, the added expense of the PV system would translate to about $180 per month. When we account for the fact that our electric bill will drop about $60—from an average of $100 per month to about $40 per month—I estimated that our monthly mortgage would only increase by an average of $120. This was not an undue burden.

I am still hopeful that Maine will adopt a substantial feed-in tariff law, which would help pay for our PV system. In fact, if the law did offer a substantial incentive, we would probably fill both the workshop roof and the house's east-facing roof with PV modules since we would likely make a small profit from selling the energy. This is the central premise of the feed-in tariff plan—to encourage renewable energy generators by making systems affordable and even profitable.

Solving Site Issues

While we have lots of roof space on the house and workshop, no roof faces south. To mount the solar thermal collectors used to heat my workshop, I constructed a small addition. For our PV system, I originally envisioned mounting the modules on a two-axis tracking array. But its size—about 10 by 20 feet—would have made it a giant eyesore in our garden.

A tracking array keeps the modules faced directly at the sun, increasing performance by 25% to 40%. But Naoto advised me against that decision, because he was worried that a large array's motors might not hold up well under heavy wind and snow loads.

After weighing all our options, we decided to cover the entire west-facing roof with modules. This setup would avoid shading from trees and other obstructions. According to PVWatts, the system would produce about 1,300 fewer kWh per year than a true south orientation, but would be more straightforward to install and be less obtrusive visually.

But then there was the condition of the roof—shingles were curling up at the corners, indicating that they were due for replacement. To ensure a long-lasting roof, I opted for thicker, more durable architectural shingles, which could be installed over the existing shingles, and selected a light gray color to decrease inside heat buildup in the summer.

Getting Wired

As a DIY kind of guy, I chose to install the system myself, but relied on Naoto's considerable professional experience to specify the system components.

Modules. My PV module preference was based in part on their embodied energy, which includes the fuel consumed in shipping. My first choice was Evergreen, because they are made in Massachusetts—about a three-hour drive for me—but their modules weren't on the Enphase compatibility list. The BP Solar modules I purchased are made in Frederick, Maryland. So I voted with my dollars to support "locally" made modules. I did end up driving 60 miles to Solar Market to pick up the modules in my Ford Escape Hybrid, and it took two trips (at 30+ mpg) to get them all.

Microinverters. Until very recently, solar-electric modules in batteryless grid-tied systems were required to be wired in series strings to produce 150 to 600 VDC, then these strings were combined and fed into a central inverter. In 2008, Enphase microinverters hit the residential PV market. Each module/inverter pairing operates independently, eliminating most shading performance issues.

So instead of a single central inverter, I used 21 small ones. Each inverter reports its performance to an Envoy communications gateway via the AC wiring, then the gateway sends data to a Web site to track performance for each module/inverter pair.

The AC wiring from the particular model of microinverter I selected can parallel up to 15 units. They plug into each other like extension cords. Since we have 21 units installed, we ended up with two AC circuits that are fed into a subpanel (through two 15 A breakers) and then to the building's main load center, where it backfeeds a 30 A breaker.

Real-World Performance

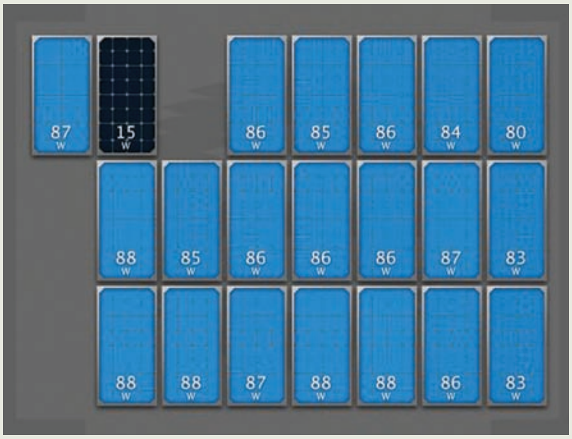
A Central Maine Power (CMP) utility crew came out to replace our single kWh meter with a double unit that allows for two readings: energy delivered by them and energy exported by our PV array. Only one meter spins at a time, indicating which way the current is flowing. As we watched, one meter would stop and the other would start as loads changed in the house. This was in the morning before the modules reached full power on a sunny August day; later, the export meter spun rapidly.

The double meter serves two main functions. First, it tells CMP how much energy I am putting into the grid, which they report to state agencies as part of the state's mandated 30% renewable energy portfolio. Second, it ensures I'm credited for every kWh that my system exports—at the full retail premium rate of 18 cents per kWh that I pay for green-sourced energy. CMP's computers do not have the capacity for crediting back to small residential producers like me, so the billing has to be hand-processed each month and both meters read by a CMP employee.

Automated Troubleshooting

Thanks to the Enlighten feature that allows the user to review the PV module energy statistics graphically, I was alerted that my solar attic fan was causing a shading issue on one of the modules for more than an hour in the late morning.

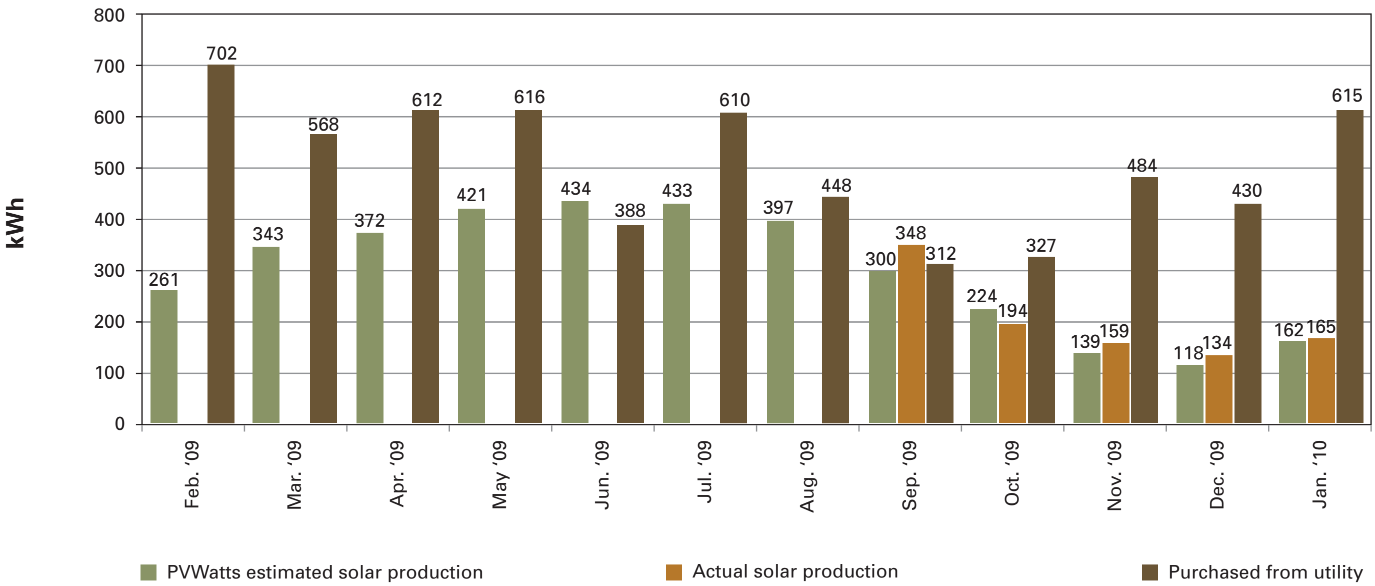
The solution was obvious: I just had to climb up and lower the module on the attic fan to reduce the shading. Now the vent module is oriented toward the sun in the late afternoon rather than midday, but that is when the heat is highest in the attic, anyway.



The Enlighten software shows the shaded module producing only 15 watts.

Adjusting the small PV module on the attic fan helped reduce shading on an adjacent module.

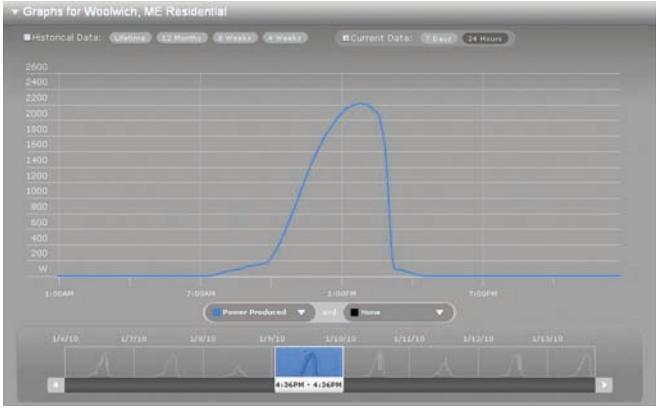
Estimated PV, Actual PV & Utility-Supplied Energy



The graph above compares the energy that our PV system should generate based on PVWatts calculations with the actual energy produced, obtained from monthly reports provided by the Enphase Enlighten Web interface. The system design goal was to generate a slight surplus in June and July and generate about 25% of our needs in the middle of winter. With the various inefficiencies accounted for, our 3,675 W rated system actually has a peak power closer to 3,130 W.

Due to our business use of energy-intensive power tools and lighting, our usage varies, but on average, we use between 15 and 21 kWh a day. If we were to eliminate our business loads, our daily average would likely drop to below 13 kWh per day. Note that, in June, when Rebekah was out of town for three weeks, our consumption dropped significantly, since her business use of a 1,500 W clothing steamer, sump pump, and well pump draws were reduced. Since the system's commission in September 2009, it has usually outproduced the original PVWatts estimates and met about 55% of our annual average electricity needs.

An Enphase Enlighten graph showing the system's total power output on January 9, 2010.



Overall, the Enphase inverter-based system is quite simple to install—it's pretty much "plug and play." The Enphase staff is very helpful, friendly, and supportive. And I am delighted with the Enlighten Web reporting system, which costs me $2 per inverter per year. I check the performance daily and have posted the near real-time data to my Web site. While my array site did not have shading issues that would have made the Enphase inverters particularly valuable, the Enlighten stats do help identify snow-clearing issues.

Access

Guy Marsden (guy@arttec.net) is a self-employed engineer who designs electronic products for a living. He owns ART•TEC LLC, manufacturing solar-powered differential temperature controllers for solar thermal applications in his solar-powered and solar-heated workshop. He also gives public talks on sustainability, and makes wood furniture and electronic art.

Resources:

Enphase Energy • www.enphaseenergy.com

PVWatts • www.nrel.gov/rredc/pvwatts

Solar Market • www.solarmarket.com

Wiley Electronics • www.we-llc.com/WEEB.html

Guy's installation blog (with real-time stats) • www.arttec.net/SolarPower