MICROGRID IN A BOX

A plug-and-play microgrid will make rooftop solar grid-friendly

BY SCOTT HINSON

A **A few years ago, I found** myself in the laundry room of a house in Austin, Texas, looking at some disturbing electrical signals on an oscilloscope. In my capacity as chief technology officer for the nonprofit clean-energy-research firm Pecan Street, examining the effect on the grid of homes with rooftop photovoltaics is my job. But what I was seeing that day in the house's connection to the grid sparked an idea. "If I added energy storage to this house, I could fix this," I remember saying.

If only it were that simple. Rooftop solar seems like it should be straightforward. When the sun shines, you should be able to reduce or eliminate your home's input from the grid and maybe even sell some of your power back to your utility company. With a home battery-storage unit, you should be able to do that even after dark.

But the picture is more complicated from the utilities' perspective. Quite apart from their worries that solar will reduce their ability to pay for grid upkeep, residential rooftop solar has the potential to amplify a problem that already exists in most U.S. homes.

At the heart of the problem are switch-mode power supplies—the kind that drive most small appliances, entertainment systems, lighting, computers, mobiles, and other devices. If these power supplies are not painstakingly designed—and some of them are not—they can have a corrupting effect on the quality of the power on the grid. On their own, the effect of a house, or even a whole neighborhood, is minimal. But add in grid-connected rooftop solar and the quality problem has the potential to strain the resources of the local distribution network, as was shown in a 2015 U.S. Department of Energy (DOE) study on integration of renewables in Texas.

In investigating the specific problems in that customer's house, we decided that the best way to solve them was with something more far-reaching than just energy storage: a residential microgrid in a box. It's a system that turns the user's photovoltaics into a reliable source of high-quality power, not just for the home's own use but for the neighborhood and even the wider grid. We weren't the first to try this solution, and we certainly hope we won't be the last. Because we've come to believe that without something like it, or a change to consumer power-supply

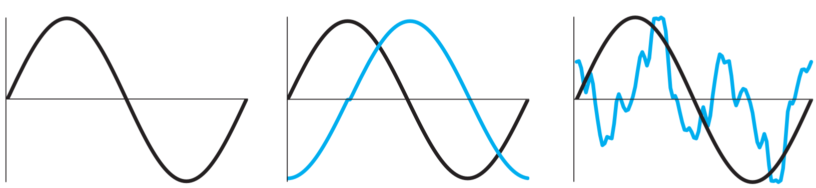
PHOTO-ILLUSTRATION BY Lincoln Agnew

requirements, residential rooftop solar will simply never reach anything like its full potential.

To understand why residential rooftop solar demands a microgrid, you need a bit of background on the electricity distribution grid, how the flow of power on it is managed, the importance of the quality of that power, and how today's residential solar works.

Let's start with the grid. From the beginning of the electricity industry more than a century ago, all power consumed on the grid was generated by a limited number of plants. The output of these facilities was, and still is, controlled by a hodgepodge of regulatory and market regimes. The system planning, modeling, and control of the grid was relatively uncomplicated up until about two decades ago because the flow of power was always in one direction—from a utility-controlled generator to the residential load. There was little that happened in your house that could alter that.

With distributed generation, power sometimes flows in the opposite direction. But the utility on the receiving end doesn't have high confidence in how much solar generation will be delivered at any particular time. Variable cloud cover and changing seasons mean that from the utility's perspective, residential solar compares poorly with organized central generation, where production is controlled, reliable, and predictable. Nevertheless, grid operators have learned to handle such weather-related vagaries.



POWER FACTOR: The relationship between the voltage and current waveforms influences power factor, a measure of how much current on a line is doing work versus the capacity of the line. In the ideal situation, the two waveforms are perfectly in phase with each other [left]. Inductive or capacitive loads can cause the current to lead or lag the voltage, reducing the power factor [center]. Harmonic distortion [right], which occurs when current flows at different frequencies than the voltage, reduces the power factor even further.

Availability isn't the only concern regarding today's residential solar power systems. Another is their impact on power quality. Power quality is a catch-all term for the effect on the grid of the devices plugged into it. It's measured in terms of frequency stability, voltage stability, and harmonic distortion of voltage and current.

To understand power quality, start with the fact that, ideally, voltage and current oscillate in phase with each other (at 60 hertz in North America and the Caribbean, and at 50 Hz in much of the rest of the world). Simple resistive loads, like old-school incandescent lightbulbs, don't affect that perfect synchrony. But more complex ones with capacitance or inductance, such as an air conditioner's compressor, can cause current to lead or lag voltage. The farther the voltage and current slip out of phase, the less usable power is delivered.

Think of the situation this way: Power is the product of voltage and current. When they are perfectly in phase, the products of both humps of the AC wave are positive, meaning that power flows in only one direction, from the generator to the load. All the power is the useful type, called active power. As current slips farther and farther out of phase with voltage, the active power decreases until it reaches zero, where the current waveform is 90 degrees out of phase with voltage. Power is then 100 percent reactive, flowing in equal amounts in both directions and doing no useful work.

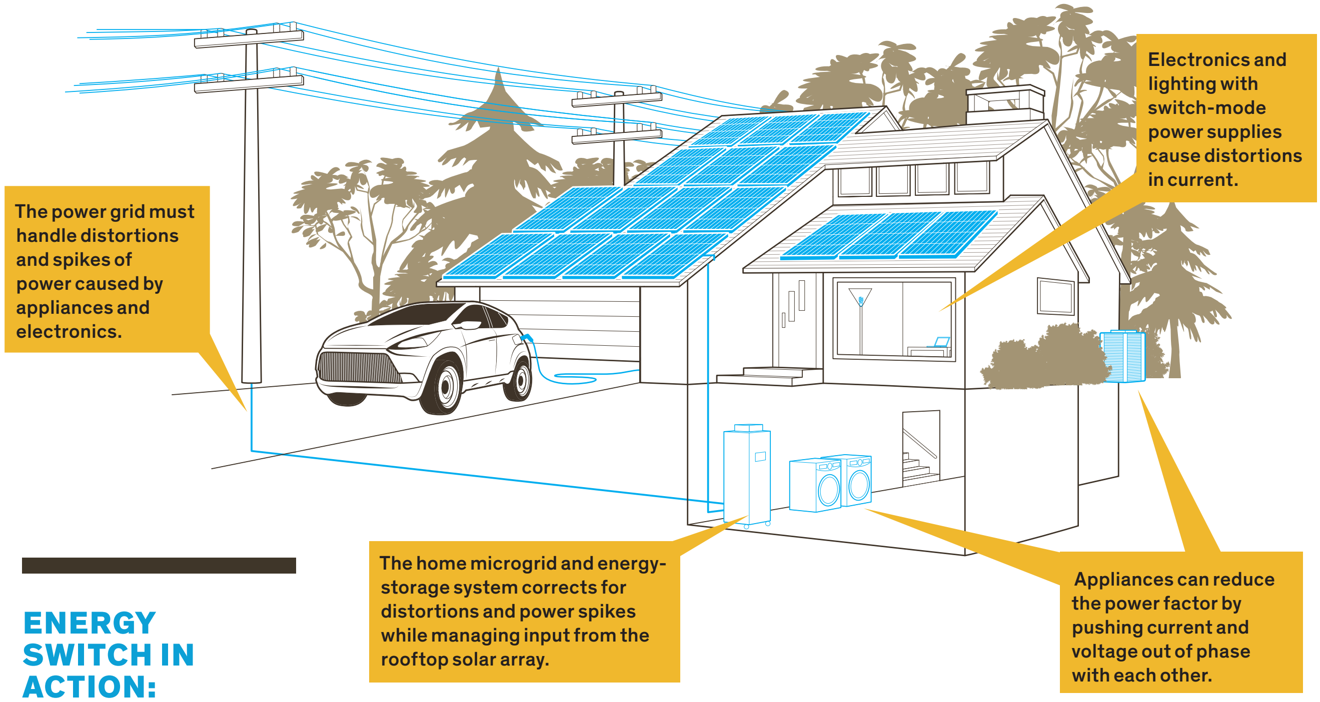
Certain loads, such as those using the switch-mode power supplies I mentioned earlier, add another wrinkle—harmonic distortion. Here, voltage and current aren't just out of phase with each other; they don't even share the same frequency.

All of these effects can be summed up in one term—power factor. It's basically a measure of how much current on a line is doing work versus the capacity of the line. The best way to explain it is with a couple of examples. When the current in the load is perfectly in phase with the voltage and there is no distortion in the current, the power factor (PF) is 1.0. As harmonic distortion increases or the phase angle of the current starts to lead or lag the voltage, the power factor starts to drop. A PF of 0.7, for example, might have a current that leads the voltage by about 45 degrees but without any distortion. A PF of 0.5 could have a leading current as well as significant total harmonic distortion.

As the power factor drops and reactive power increases, the utility has to make up for the change by generating compensatory reactive power to shift current and voltage back into phase with each other. Without such support, voltage on the grid can sag and lead to blackouts. Historically, this compensatory reactive power is almost always capacitive, because some of the biggest loads in homes and particularly in industrial facilities are inductive. For example, the compressors in refrigerators and air conditioners are driven by motors that have coils.

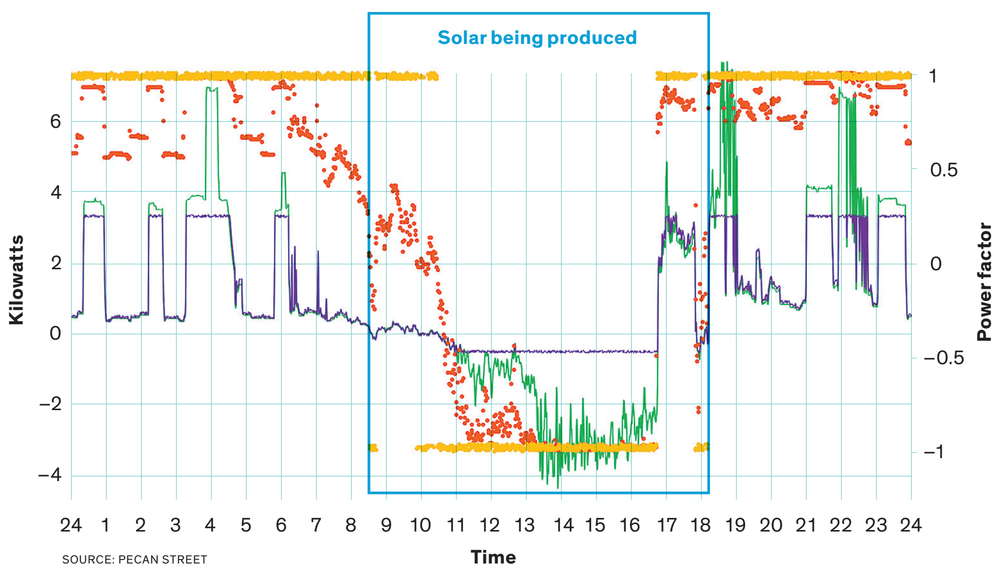
Traditionally, utilities have been able to assume that a residential structure is a reasonably high-quality load. Historical measurements on individual appliances and homes have borne this out, with power factors of 0.9 or better and relatively low harmonic distortion.

However, as more and more lighting and electronics have moved to switch-mode power supplies, the power factor of the typical home has dropped and the reactive power support requirements have increased. Switch-mode supplies work by first rectifying the voltage from the AC mains and then chopping it up into a high-frequency signal that allows for the use of relatively small transformers and other components. This signal's voltage is then stepped down, rectified, and filtered to produce the desired direct-current out-



ENERGY SWITCH IN ACTION:

During the day, as different appliances are turned on and off, the house draws varying amounts of power [green]. These appliances reduce the home's power factor [orange] by shifting current and voltage out of phase or by distorting the current waveform. The power factor decreases even more as the home's solar array begins to produce power [center]. The grid must be able to compensate for both phase and distortion. The Energy Switch—the home's energy-storage and microgrid system—limits the biggest power draws [purple]. The system also takes some of the burden from the grid by increasing the power factor. As a result, the home acts as either a simple load [yellow] or a power generator.



SOURCE: PECAN STREET

put at lower voltage. Unfortunately, those high frequencies in the power supply can show up as spikes of current in the mains, contributing to harmonic distortion.

Traditional residential-grid-tied solar installations in many regions are pretty simple systems that don't provide any reactive power compensation. This means that the solar array will allow any phase displacement or distortion from the home's load right through to the utility without any reduction–essentially amplifying the problem. IEEE Standard 1547-2018 and regional mandates such as California's Rule 21 Interconnection Tariff require solar installations that can help support the grid by producing reactive power; however, they do not solve any of the harmonic distortion issues.

Consider a modern house in North America with rooftop solar panels, a large central air conditioner, and several other common appliances and electronics. When the rooftop panels are producing electricity, the system provides current at the correct 60-Hz fundamental frequency, but it doesn't do anything to cancel out the harmonic distortion from the power supplies running some of the appliances. So the house at times produces more than 100 percent total harmonic distortion at the grid connection. In that situation, the home is supplying more current at harmonic frequencies than it does at the 60-Hz frequency that the distribution grid was designed to accommodate.

ILLUSTRATION BY MCKIBILLO

SOLAR TOWN: Utilities want to know what effect rooftop solar will have on the grid so that they can compensate for it. Some neighborhoods in Austin, Texas, already have high solar penetration.

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When only a few houses on the grid present this type of load, it's not that big of an issue. But more solar arrays mean more challenges for the utility. This was shown in the previously mentioned DOE study, which examined the power on feeders to two neighborhoods in Texas. One had rooftop solar and the other didn't; otherwise they were pretty similar. The feeder to the solar neighborhood saw harmonic distortions that regularly drove the power factor below 0.65, while the nonsolar neighborhood's power factor never fell below 0.94. For solar to safely spread, we need a better way.

At Pecan Street, we specialize in data collection and field trials for renewables to reduce carbon, so we felt we were in a good position to come up with a solution. Working with the technology development firm Concurrent Design, also in Austin, in cooperation with the DOE's SunShot program, we designed and built a residential energy-storage system that turns a home into its own microgrid. It's a solution that addresses all of solar's integration issues at once. The goals were to improve power quality so that utilities can be more comfortable accepting energy from residential solar installations; to manage residential batteries so that consumers can use energy or deliver it to the grid even when the sun isn't shining; and to allow homes to break off from the grid and power themselves during outages without so much as a flicker during the transition. This combination, we believe, will enable higher penetration of solar and other distributed resources on existing grids designed for traditional, centralized generation; it will also make these distributed sources an asset for utilities instead of the potential operational liabilities they are now.

We call this system the Energy Switch. We built a total of four of these systems, two for lab testing and two for field trials. The two field units were installed in the homes of some very gracious volunteers, who gave up a sizable chunk of their garages for the project. Even with the advances in energy storage, the Energy Switch isn't small—it's roughly the size of a tall, skinny home refrigerator at 61 centimeters wide, 61 cm deep, and 180 cm tall. And it's rather heavy, at almost 900 kilograms (close to 2,000 pounds). Still, it's a giant improvement over our first energy-storage system, developed six years ago, which weighed in at 1,360 kg and was three times the size.

The homes for field trials were about 220 square meters (close to 2,400 square feet) and were built in an area of Austin where the developer had specified aggressive energy-efficiency measures. Both homes had solar arrays connected directly to the grid and rated at about 5,500 watts, as well as heating, ventilation, and air-conditioning (HVAC) units. One of the homes had a plug-in electric vehicle, and the other had an electric oven. The Energy Switch was used to power the homes in September and October of 2016. With daytime temperatures often over 38 °C (100 °F), air-conditioning usage is still quite high in Austin during those months.

Initially we gave the Energy Switch five operating modes: 1) maximize self-consumption of solar production; 2) maximize solar energy delivery to the utility grid; 3) operate off-grid without secondary generator support; 4) operate off-grid with secondary generator support; and 5) system bypass: connect directly to the grid for system maintenance or battery-lifetime preservation.

Clearly, we were thinking as engineers, not consumers. We thought these options would give homeowners the flexibility they wanted. But in hindsight, we probably should have simplified it to two visible operating modes, or maybe even just one. And we should have left the other choices, such as self-consumption or grid production, for the system to decide based on grid needs and conditions. When we explained these operating modes, one of the participants' children caught on faster than his parents:

> Him: "You mean...if the power goes out I can still play video games and have solar?"
> Us: "Yes, and you'll still have air-conditioning..."
> Him: "Sweet!!"

Getting to "Sweet!" was an enormous amount of work that had to be done very quickly. The total DOE grant period was 12 months, and we needed to reserve three months at the end for demonstration, testing, and reporting. That left just nine months to design and build these systems.

We did have access to some legacy hardware that we'd previously developed. However, to perform all of the power-factor correction, load control, generation control, and grid-support services we envisioned would require a substantial revamping of the entire system design.

We wanted the Energy Switch to go beyond what other systems—even new commercial systems like Tesla's Powerwall 2 AC—could do. We wanted the Energy Switch to enable a home to push solar energy onto the grid with or without a full battery and have full-time power-factor correction. We also wanted the system to be fully integrated with the home's other energy systems so that it would be able, for example, to accept energy from a backup generator in addition to solar, to keep the house going in an extended blackout.

To meet these challenges, we designed a system that could monitor and control 24 different load-bearing circuits in the home. The system makes about 300 decisions per minute, configuring its circuitry based on tens of thousands of measurements of the batteries, the grid, the quality of its electrical output, solar production, and the loads in the home. These decisions make sure that all systems are operating at their highest possible efficiency and the homeowner and the utility are getting the most they can out of the rooftop solar and the power-quality support system.

Of course, any energy-storage system must include comprehensive safety measures. We designed the system so that any of a wide variety of battery or electronics mishaps would result in a system shutdown long before the fault reached a critical level. That was tested on the first day of field trials, when a bad capacitor—easily fixed—in one home's HVAC triggered a surge of current that shut the entire system down with a loud and dismaying relay *clunk*.

MICROGRID IN A BOX: The Energy Switch combines 5,500 watts of energy storage with circuits that limit the power draw from the grid and also correct for distortion produced by appliances and electronics in the home. The system also manages power from rooftop solar and backup generators when needed.

In its two months of service, the Energy Switch proved its effectiveness in correcting the power-quality issues. It kept harmonic distortion close to a harmless and constant 20 percent, preventing the wild swings in distortion that a home can cause. And it reduced reactive power so that the homes' power factor stayed quite close to 1.0 when powered by the utility.

When the two homes generated enough power to put it back on the grid, the Energy Switch ensured that the power going to the grid had only a minor distortion-related reactive component. So from the utility's perspective, the homes were now either generators or resistive loads, making the job of voltage control a lot easier for the utility.

Lastly, the system also provided programmable power regulation, limiting the amount of power put back onto the grid and the power drawn from the grid. This is helpful for areas where growing populations are straining utility distribution capacity. In this case the Energy Switch was set to limit the draw from the grid to 3.5 kilowatts and generation to 0.5 kW. Without the Energy Switch the homes would have occasionally drawn and generated more than 4 to 5 kW.

The Energy Switch successfully demonstrated many advanced functions—functions beyond the scope of typical energy-storage systems. These functions and operating capabilities will need to become more commonplace if residential solar is to become a significant part of the grid, both because they improve utility operations and because consumers want them.

With the Energy Switch, consumers get a reliable power source, savings on their utility bill, and a degree of immunity to blackouts. While all those features have benefits you can count in dollars and cents, the last also gives a palpable sense of security. After the trial was over, both families in our Austin experiment said they missed the feeling of security that the Energy Switch gave them, even though the utility didn't have a single outage in the neighborhood during the trial.

That said, we designed a system that the volunteer participants wanted, not necessarily what they could afford. When we interviewed potential volunteers for field trials, we discussed battery sizing options. In the interviews we conducted, people almost universally rejected any storage solution that would run only a small subset of their appliances. Once the idea of battery backup for the whole home became a possibility, participants quite definitely wanted that functionality—though, predictably, they were wary of the cost. At the time the project ended we estimated that whole-home battery systems like the Energy Switch could be sold for about US $10,000 to $20,000, depending on features, battery size, and advancements in electronics integration. Admittedly, with costs like that, systems such as the Energy Switch aren't for everyone. But we hope that at least it will point to a more affordable solution.

From a utility's perspective, combining photovoltaics, storage, and a home microgrid turns residential solar into something that takes less active management. And that means utilities have fewer reasons to want to restrict the spread of rooftop solar. Fearing instability, utilities have sometimes capped the portion of residential solar systems they'll allow to be tied to a neighborhood feeder line at 30 percent or even lower. Why can't it be 100 percent? We think residential microgrids can help us get there. ■

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