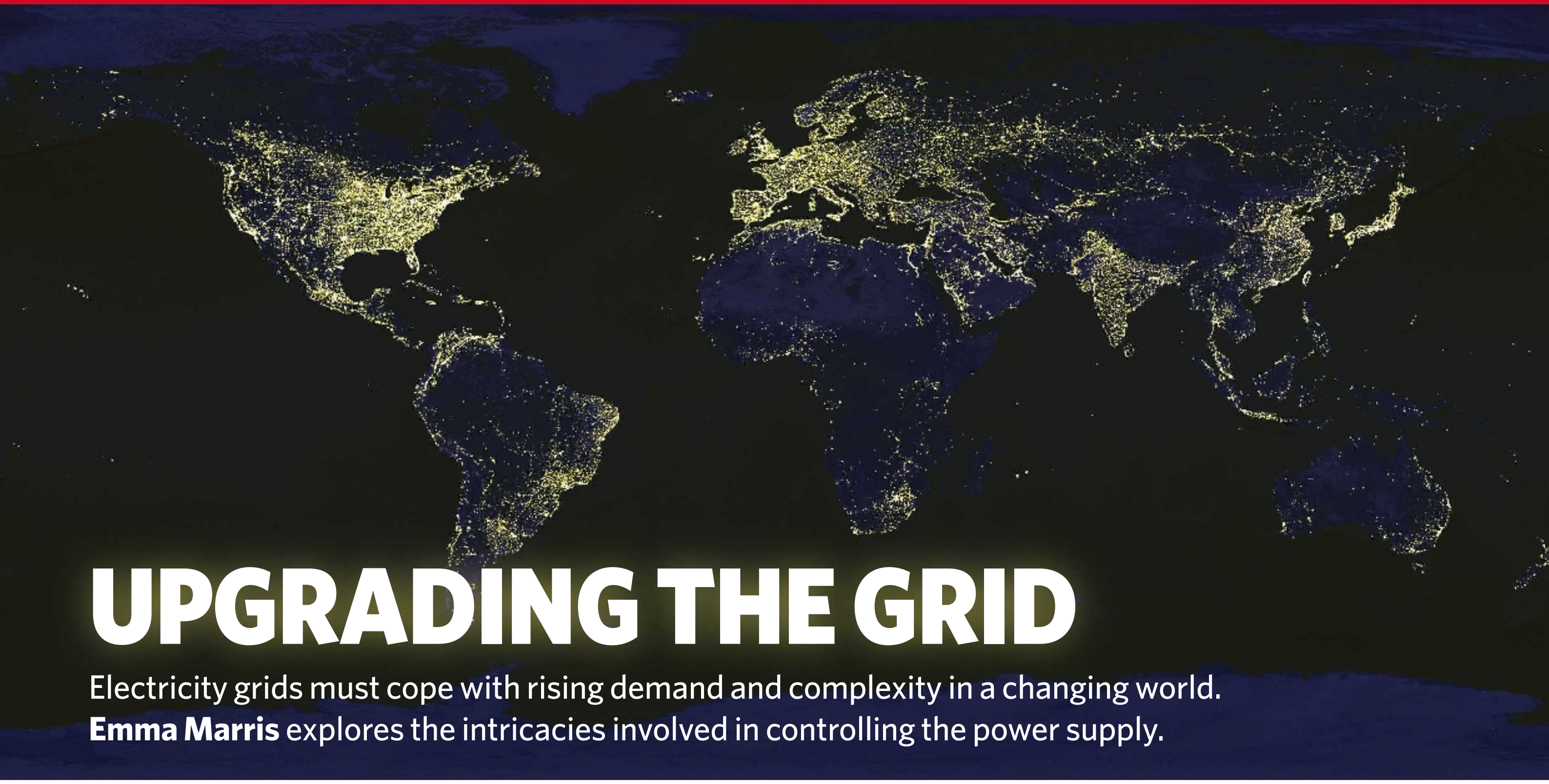

UPGRADING THE GRID

Electricity grids must cope with rising demand and complexity in a changing world. **Emma Marris** explores the intricacies involved in controlling the power supply.

C. MAYHEW/R. SIMMON/NASA/GSFC, NOAA/ NGDC, DMSP DIGITAL ARCHIVE

On a hilltop in the small city of Vancouver, Washington, just across the Columbia river from Portland, Oregon, sits a concrete building owned by the the Bonneville Power Administration (BPA), the federal agency that runs the electricity grid in the Pacific Northwest. In that building's basement one can find Albert Orona enthroned behind a bank of monitors, facing a wall-sized map of the region's power grid.

Orona is a dispatcher, one of the unseen men and women who keep power moving smoothly through the grid. It is not a job that would even occur to most users. Electricity is taken for granted: just flip a switch and the light goes on. But to Orona, contending with a network of almost unfathomable complexity, electricity is anything but a given.

From his basement command post he oversees more than 24,000 kilometres of high-voltage wires channelling power from one nuclear power plant, several coal plants, 31 dams scattered throughout Washington, Oregon, Idaho and Montana, and an ever-increasing number of wind farms. And that is just the 'bulk transmission grid'; the local distribution from substation to customer is handled separately by the utility companies, the people you send your money to each month.

In Orona's domain, something always needs adjusting. When a generator goes down for scheduled maintenance, or fails, he and his team will call for other generators to increase their output. If a disturbance in the grid is imminent, Orona will 'island' parts of the system to isolate them from power fluctuations that could otherwise cause a blackout. And if a blackout threatens to spread — well, it is hard to imagine the calmly competent Orona discombobulated. "If I was a kid," he says, "I would love to do this for free. It is a fun job." But in a crisis, he admits, "there is a certain adrenaline flow".

That adrenaline is flowing through the whole electric-power industry these days. Demand for electricity is soaring worldwide. And yet, at least in developed countries such as the United States, a combination of high costs, environmental concerns, and uncertainty over post-Kyoto carbon regulation is making it harder and harder to build new power plants or run new transmission lines. So the grid is increasingly run on the ragged edge of failure, flirting dangerously with 'unstudied states' — situations in which, as Orona puts it, "if I lose another element, that might lead to cascades that would take out that part of the world".

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> — Albert Orona

The challenges that Orona faces at Bonneville are all too typical of these global issues. Fortunately for him and for others in his position, research is now being conducted on ways to hold those unstudied states at bay. New tools include sensors and other 'smart-grid' technologies that will make the grid better able to manage itself. They include energy-smart appliances, local wind- and solar-power generators, as well as 'demand-side' technologies that will help consumers control how much power they draw from the grid.

And, of course, they include measures to get both approaches — smart grids and demand management — working together. After all, the more that sources of power generation diversify, and the more information that clever appliances send back up the wires, the smarter the grid will have to be to cope with the complexity.

The result could be something completely new. If today's grid is Hollywood in the 1930s — with a few big studios piping content for viewers to watch passively in a theatre — tomorrow's grid will be YouTube, with thousands of smaller players and the line between consumer and supplier considerably blurred.

Mapping the system

One of Orona's colleagues is on a ladder updating the aqua-tiled wall display with paper status tags. The board shows the grid like a subway map. A lit bulb indicates that a plant or substation is offline. And black dots indicate power plants that can 'black start', or begin generating power from scratch without any power flowing in. Meanwhile, Orona is sipping his soft drink and flipping through different screens on his seven monitors. Alarms are going off at the rate of about two a minute. One sounds like a van backing up, another like the wrong answer on a game show. Some Orona seems to ignore, others cause his head to flick momentarily to one monitor or another.

There are three fundamental facts that ensure Orona's job is never dull. First, electricity moves at nearly light speed, so that transmission is essentially instantaneous; the electric field illuminating your light bulb this second was born in a dam or some other generator this same second. Second, electricity cannot be stored, except on a very limited scale. Taken together, these two facts mean that Orona and his counterparts elsewhere have to keep generation almost exactly balanced with demand on a second-to-second basis. When a baseball stadium flips on the lights in Seattle, the Grand Coulee Dam in eastern Washington has to route a bit more water to its turbines.

Except that it isn't that simple — which is the third fundamental fact: the grid is extraordinarily complex. The power flowing through the stadium lights cannot actually be traced back to a single generator; it comes from the common flow of energy fed by all the generators. (Think of dipping a bucket into a reservoir fed by many rivers: it pulls up water from all of them.) So the grid has to be managed as an integrated whole. Yet the grid is also a hotchpotch: in much of the world it has been 'integrated' over the decades by patching together small, local grids as the opportunities arose. And the energy pulsing through that hotchpotch can be downright wilful. If a transmission line goes dead, the electricity will spontaneously reroute itself along any other path it can find. So if there aren't a lot of redundancies in the system — as often happens these days — and if the extra power moves to other lines that are already near capacity, those lines might also overload and shut down. This can lead to still more shutdowns, in an ever-increasing chain reaction that becomes a region-wide blackout.

Or maybe not. Anticipating every conceivable sequence of failures is all but impossible in a system this complex. That's why Orona talks about unstudied states. Even the grid's normal operation is difficult to predict. All the current computer simulations are lousy, says Bonneville modeller Scott Simons, despite ongoing efforts to improve them. "We are getting pretty good for one hour from now, not so good for two hours," he says. "Three hours is pretty bad."

In short, humanity has come close to building a machine that is so intricate that it can't be comprehended. But Orona and his fellow power dispatchers have to manage that machine anyway; modern society depends on it.

Given the increasing complexity of the grid, the most immediate priority is to give the dispatchers an upgrade in the 'situational awareness' department. Situational awareness, a favourite phrase of grid managers, means 'knowing what is happening'. Bonneville is already working to modernize all those displays and alarms. For example, since May, when the visit described in this article took place, the aqua-tiled wall display has been replaced with an electronically updatable digital version. Efforts are also under way to improve the user interface so that Orona can get the same data about the grid on fewer monitors.

Web of information

Out in the field, next-generation sensors will soon be feeding Orona better data. New 'synchrophasor' units, for example, use the precision of the clocks on Global Positioning System satellites to compare two frequency measurements taken in different parts of the grid at the exact same time. This allows them to hunt for sudden changes that hint that the grid is under a lot of stress, or that something major has gone out and the rest of the grid is shifting accordingly. Compared with the grid's older mix of analogue and digital sensors, says Carl Imhoff, an engineer at the Pacific Northwest National Laboratory in Richland, Washington, "phasor networks sample the grid 30 times a second instead of once every 6 seconds".

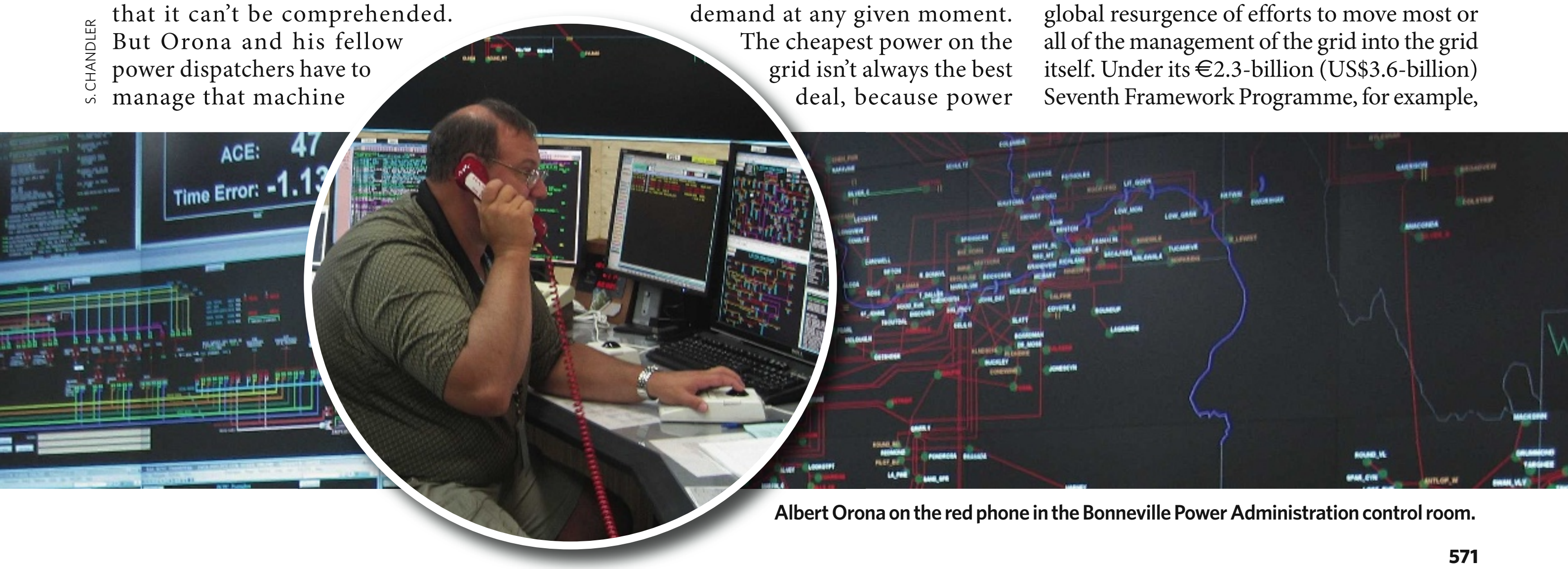
> **"The grid is always changing, and it is almost self-correcting."**
> — Jon Ludwigson

Meanwhile, improvements in real-time simulations of the grid are helping dispatchers to make better use of that information. Simons is working on one such computer model that will provide operators with the most economical mix of generation to meet demand at any given moment. The cheapest power on the grid isn't always the best deal, because power leaks out of the lines at a rate that depends on distance and wire type. According to Simons, the model even takes into account whether certain efficiency gains are too puny to be worth a dispatcher's time to make the requisite phone call. "If we called Grand Coulee Dam and said 'tell you what, move your generation up two megawatts' [about 0.03% of the dam's total capacity of 6.8 gigawatts] the laughter would deafen you," says Simons.

Still, despite the computer programs, and the efforts to reduce the cognitive load, Orona's chief tool in managing the grid continues to be a red telephone of the direct-line-to-the-Kremlin variety. When there is a problem, or even the hint of a potential problem, Orona gets on the red phone and, for example, asks another utility to make an adjustment. In the not-too-distant future, however, his part of the grid may very well be able to talk to that part of the grid without human aid. Indeed, there has been a global resurgence of efforts to move most or all of the management of the grid into the grid itself. Under its €2.3-billion (US$3.6-billion) Seventh Framework Programme, for example,

KAJ R. SVENSSON / SPL

Wind power is now an important electricity source.



S. CHANDLER

Albert Orona on the red phone in the Bonneville Power Administration control room.

the European Commission is planning to fund a number of projects in smart energy networks.

And the recent US Energy bill, signed into law on 19 December 2007, calls for a 'Smart Grid Task Force' to run up to five demonstration projects focused on smart grids and energy reliability, and calls on the National Institute of Standards and Technology to develop a set of standards that will allow all such smart grids to be interoperable.

The self-managing grid

In some ways the grid is already intelligent. No human needs to trigger a circuit breaker on an overheated transmission line; that happens automatically. "The grid is always changing, and the way it is designed it is almost self-correcting," says Jon Ludwigson, a grid expert at the federal government's General Accountability Office in Washington DC. "If a power line goes out, the grid still flows."

To add to this, the controllers are aided by programmed remedial action schemes, also called special protection schemes. These are rules that will automatically trigger an action when a particular threshold is reached. Imagine, for example, that a significant transmission line is lost on a congested route over a mountain pass. To avoid a cascading outage, the reprogrammed routine might automatically cut back on power generation and, to keep things in balance, reduce the load on the grid by shutting off a few power lines downstream of a substation. A few blocks of one town might go black, but the rest of the towns won't even know what a close call they had. "We stretch the power lines to the limits, and the remedial action scheme allows us to run it at the limits," says Orona.

But in a truly smart grid, the analogous programs would run in processors attached to the various key components of the grid, and would be fed by a rich stream of real-time data flowing in from sensors all over the grid. In principle, says Massoud Amin, an electrical engineer at the University of Minnesota in Minneapolis, such a smart grid could be not only self-managing, but "self-healing" (see graphic). In his vision, he says, the processors in the future grid will be able to "localize and anticipate the consequences of disturbances, whether they are natural disturbances, such as lightning or hurricanes, or intentional disturbances". By the time the wind-snapped or sabotaged line hits the ground, the whole grid will have shimmered into a new configuration to stymie disastrous cascades. "Electricity travels almost at the speed of light," says Amin, "so we have a few milliseconds to take this action before it becomes widespread." He estimates that such a grid in the United States would take ten years to roll out and cost between $10 billion and $30 billion a year to install, shouldered by a public–private partnership. That's no budget operation but, according to Amin, it would cost just a seventh or an eighth of the current annual cost to society of power interruptions.

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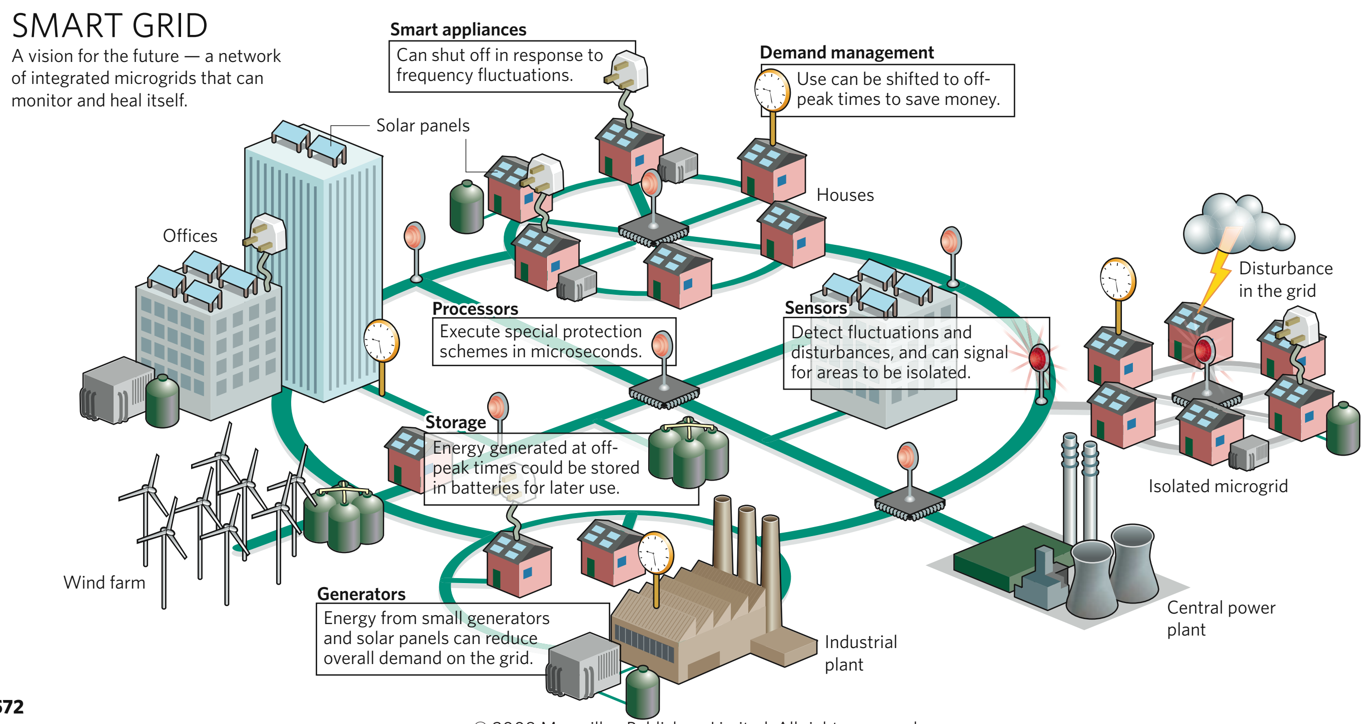
— Massoud Amin

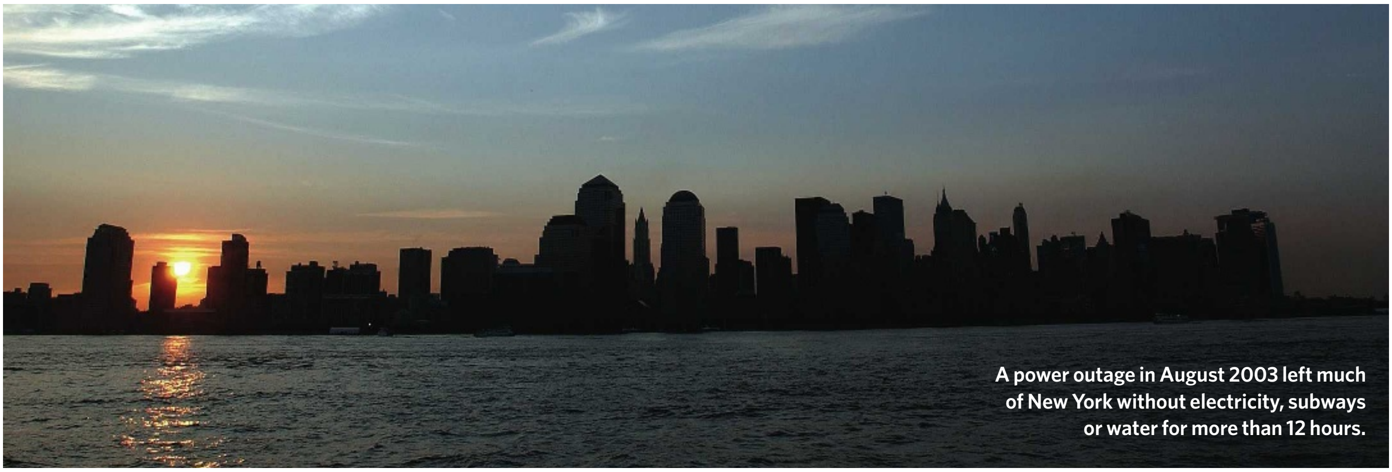
Many grids outside the United States are further ahead in the intelligence-raising process, with particularly advanced projects in Italy, Sweden, and in the state of Victoria in Australia. Enel, Italy's largest utility company, replaced 30 million old power meters with smart, microprocessor-equipped meters that have made possible new pricing structures that encourage customers to shift their power usage to off-peak hours.

However, no matter how smart the grid becomes, it will eventually be overwhelmed if demand keeps rising. So industry planners are also moving to embrace micro-generation and to reduce demand. "In the old days we kept the whole thing balanced with one wrench: the supply side," says Imhoff. Being able to tweak the system from the demand side will be a huge improvement; it will also make the grid that much more complex.

Currently, most consumers suck up electricity in a predictable and mostly unconscious pattern. In the morning, people turn on lights and radios, use kettles and toasters, adjust thermostats and check e-mails. Spike number one. Then people head to work or school, and the electricity dispatchers can have a cup of coffee. After the midday lull, the pattern reverses. People drive home, turn on the heat or air conditioning, cook dinner, do the laundry, surf the Internet and watch television. Spike number two.

But if electricity were to cost a lot more during peak hours, and if people's appliances could tell them so, perhaps that unconscious pattern would change. Then again, maybe it wouldn't be enough. Until it is tried, all anyone can say





REUTERS/CORBIS

A power outage in August 2003 left much of New York without electricity, subways or water for more than 12 hours.

for sure is that the usage peaks would be less predictable. Price fluctuations would ripple because of people's behaviour and then price signals would race backwards towards buyers and sellers in a highly nonlinear set of feedback loops. Small home generators might simply cut off the top of peaks of demand — or they might turn the peaks into troughs, by sending extra electricity into the grid. Suddenly, the game would have a lot more players.

Supply and demand

The first steps towards this future may look familiar and reassuring to consumers. At the Pacific Northwest National Laboratory (PNNL) in Richland, Washington, a decidely normal-looking demonstration kitchen sits in the corner of a lab. But if the stolid white refrigerator detects a disturbance in the grid — as evidenced by frequency fluctuation — it will shut off for a few seconds to shed load. Crucially, however, it will not shut off power to the circuit for the little light bulb inside the fridge; the customer will never notice that the appliance is off. Likewise, the clothes in the dryer will keep tumbling even though the heat has been momentarily shut off. Recently, the PNNL tested 150 such dryers in homes in the area. Consumers didn't notice a thing and said they'd be happy to buy them. The researchers think that if the whole country has such appliances, 20% of national demand could be put on hold at any moment.

But that is just the beginning. The PNNL is also working on dynamic pricing and distributed generation. Many commercial customers in California already have the option of saving money by running their machinery at night, but PNNL is examining how real-time price fluctuations could be extended to every end user. In a pilot project on the Olympic Peninsula of Washington state that ran from March 2006 to March 2007, residential, commercial and municipal customers in this mountainous region could track prices on their computers, with updates every five minutes. Residential users could set their thermostats, dryers and heaters to respond to certain price points. Small generators — for example, backup diesel generators for a municipal water-pumping plant — were programmed to kick in when grid power got too expensive.

In the end, the experiment smoothed out grid congestion and customers saved, on average, 10% on their electricity bills. One enthusiastic participant, Jerry Brous, wrote a memo for the project's final report about paying attention for the first time to how he and his wife Pat use electricity, and discovering just how cold or hot they could tolerate their house and water. "It is also great fun," Brous wrote, "to sit at a picnic table at an RV park and jump online through a Wi-Fi connection and tell the water heater and heat pump in our house to wake up and get to work, we are coming home early."

Similar projects around the world have generally been received favourably by participants. If such technology is deployed widely, then in 20 years the average residential consumer might well be much more strategic and conscious about their use of energy. That prospect becomes even more likely if small household generation with solar panels or other renewables becomes commonplace; coupled with smart-grid technology in the distribution network as a whole, this would enable neighbourhoods inside a city to 'island' themselves from the wider grid when there is a disturbance.

> "The entire grid and how we interact with it will change." — Gil Bindewald

Another piece of the puzzle is provided by energy storage. In Japan, to take just one example, the Tokyo Electrical Power Company has co-sponsored the development of large commercial sodium–sulphur batteries that can hold electricity made in off-peak hours for deployment during peak demand times. Denmark, which produces more wind power per inhabitant than any other county, is likewise looking into storing off-peak energy in vanadium-based fuel cells.

Of course, none of these developments is going to put Orona and his team out of work anytime soon; some cognitive leaps are still beyond computers. "Sometimes you can have a problem that occurs because you have bad data," says Orona. "Only the human can say, 'Hey — those are bad data.'"

When Bonneville engineer Lawrence Carter was asked how long it would take for a major blackout to develop if all the dispatchers at Ditmer and other operations centres suddenly disappeared, he took a while to answer. "Eventually, the system would fault," he said at last. "It can't run itself." A high-speed computer, Carter says, would take three years to compute every single fault path in the system. But a human is smarter. "People learn about their paths," he says. "You may not have to do those 30 million simulations; you might be able to just say, 'This is going to go next'."

Still, there is no doubt that the future of the grid will involve an ever-expanding cornucopia of new technologies: smart appliances, dynamic pricing, micro-generation, energy storage, built-in protective responses — on and on. "No one by themselves is going to help us address all the challenges that we have," says Gil Bindewald, acting deputy assistant secretary for research and development at the Department of Energy's Office of Electricity Delivery and Energy Reliability. "You might have underground cables in one place, overheads in another, a plug in hybrid there, a microgrid there. I think the entire grid and how we interact with it will change. It is just not the socket in the wall." ■

Emma Marris writes for *Nature* from Columbia, Missouri.

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