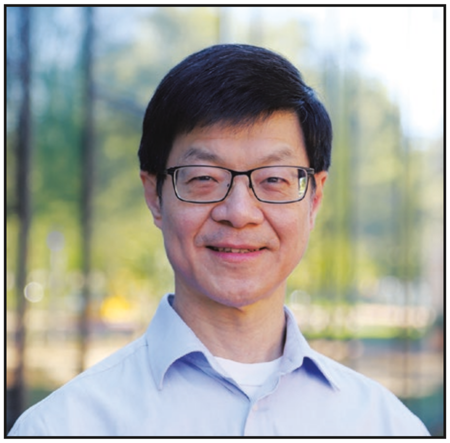
The Grid Gets Smart

Adaptive electric vehicle chargers and advanced battery designs are some of the ways Caltech researchers are building a more sustainable electric grid.

By Andrew Moseman

Picture an office parking lot lined with electric-vehicle (EV) chargers. As a new workday dawns, dozens of drivers plug in and the chargers pump power to all those thirsty vehicle batteries. Although it is convenient for drivers to recharge their cars while they work, this sudden demand for voltage stretches the parking lot's electrical system to its limits.

Electrical engineer Steven Low knew this problem would grow more acute as electric vehicles became more popular and placed more of a strain on the energy grid. But he also realized that all the vehicles in this scenario would not need to draw maximum charge simultaneously. So his group invented the Adaptive Charging Network (ACN), a flexible platform capable of real-time communication, measurement, and actuation. When drivers plug into one of his chargers, they tell a smartphone app how much charge they need and how long they plan to stay. Low's algorithm uses this information to direct energy to vehicles with the most urgent need. For example, one person may leave their EV parked for a full workday but need relatively little energy to top off the battery. That person could wait until late in the day to charge. Another employee, who needs to charge before driving to a lunchtime meeting, could begin to receive electricity immediately. Low's ACN technology, licensed through a startup called PowerFlex, is now in Caltech's parking structures and is being deployed elsewhere in California.

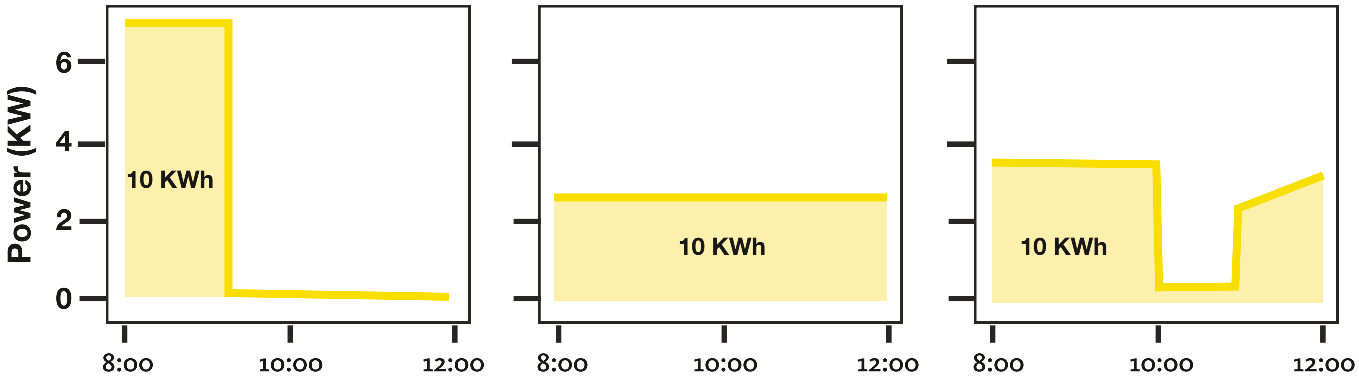


Flexible EV chargers are emblematic of the kinds of solutions required to build the next generation of energy grids: so-called smart grids that integrate information technology to flexibly and responsively manage society's energy needs in the decades to come. Not that the grid of today has not served society well: it represents one of the greatest engineering achievements of the 20th century, Low says. The modern grid is a complicated web of power lines, transmission towers, transformers, and other physical infrastructure. Combined with the economic forces that manage energy markets, today's grid constitutes a gigantic system that transmits and distributes electricity exactly where and when it is needed across regions, or even continents, to facilitate all aspects of modern life.

But Low and others warn that this grid is unprepared for the challenges of the 21st century, particularly a major move toward renewable energy sources such as solar and wind power as a way to slow climate change.

A recent study in *Nature Communications*, co-authored by Nate Lewis (BS '77, MS '77), the George L. Argyros Professor and professor of chemistry, demonstrated solar and wind power could meet most of the world's energy demands. However, according to the U.S. Energy Information Administration, more than 60 percent of electricity generated in the United States in 2020 still came from fossil fuels, mainly natural gas and coal. What is more, today's electricity grid was designed to distribute a steady flow of electricity created by burning fossil fuels. But the sun and wind do not provide a steady flow: the sun does not always shine and the wind does not always blow; thus, these renewable sources of energy are variable in a way that does not mesh well with the grid. Meanwhile, electricity demand is set to soar, especially as the world embraces EVs in an attempt to decarbonize the transportation sector.

"The current grid will very soon hit a wall where, when we add renewable energy, it sits unused because the demand isn't there at a time when the solar is running," says computer scientist Adam Wierman. That is why he, Low, and other Caltech researchers are working on ways to break down that barrier to help empower an energy transformation.



Balancing act

A smarter grid calls for equal parts technology and strategy. On one hand, the world must construct increased renewable energy capacity if countries are to meet most or all of their energy needs using green sources. But it is not enough just to build more wind and solar farms.

"We have to be prepared for the sun to not be shining or the wind to not be blowing," Wierman says. "If you're not smart about running the grid, then for every large solar farm you install, you have to still build a traditional generator. As long as you're doing that, you're not getting the benefit from the renewable generation that you should."

Wierman's research focuses on how to make the grid more compatible with the uncertainty of renewable energy, which starts with a simple concept: if our energy supply is a little less predictable, then our energy demand needs to be a little more flexible.

For instance, suppose the weather forecast calls for a cloudy but hot day tomorrow. Most people will want to run their air conditioners, but less solar energy will be available. One solution would be pre-cooling. It takes more energy to cool a building than to keep it that way, Wierman says. People and businesses alike could run their ACs earlier in the day when demands on the grid are lower, so the temperature in their home or building is comfortable when the hottest part of the day rolls around.

This kind of time flexibility will be crucial to a more sustainable grid, Wierman says. Electric cars could charge when the sun is out and the largest amount of solar energy is available. Dishwashers and laundry machines could ask their owners whether they need those clothes and dishes cleaned right away, or if they could wait a few hours until the grid is less stressed. The enormous data centers run by technology giants such as Google and Amazon could schedule energy-intensive activities, like archiving their data, for times that maximize renewables.

But this smart scheduling alone will not fix the problem; it also requires a major overhaul in how the grid is managed, Wierman explains. Today's system relies on a centralized approach, meaning there must be a human in the loop to make sure enough electricity is directed to where it is needed. The smart grid, on the other hand, uses a decentralized approach, in which everything from dishwashers to data centers can interact with and glean information from the grid to optimize energy use without human intervention.

"You want a building to be responsive to what's going on in the grid more broadly," Wierman says. "You want EV charging to be responsive to what's going on in the grid more broadly as well rather than just have this myopic view of what it needs now. It's about making sure the grid can be both more reliable and more sustainable."

Bettering the battery

When a sweltering heat wave smothered California in August of 2020, it caused rolling blackouts at a level not seen in two decades. Yet all the energy needed to stabilize the grid and avoid those outages was right there, parked in garages across the Golden State. There are roughly 600,000 all-electric vehicles in California, Low says, and if just a third of those cars had fed 10 percent of the energy in their batteries back into the grid, the blackouts could have been avoided entirely.

It may sound far-fetched that the battery in your electric car could mitigate a power outage, Low says, but the idea illustrates the importance of inventing clever energy-storage solutions, another crucial component of a smarter, more sustainable, electrified future. Innovative battery technologies could allow EVs to drive farther between charging stops, which would improve the lives of drivers and potentially lower the stress on the grid. And the ability to store energy at a large scale, whether

Steven Low **(above left)** and a graphic **(left)** that depicts different ways his smart chargers could deliver 10 kilowatts of energy to an electric vehicle during the day. Spreading out the energy demand eases the strain on electric infrastructure. **Right:** Adam Wierman.

in giant batteries or through other means, would help the grid to mitigate the on-and-off nature of renewable energy sources.

Already, Caltech's hometown of Pasadena has experienced stability problems with the grid because of the growing use of solar panels and electric vehicles, both of which are trends the city promotes. In an effort to help the city stabilize energy supply and distribution, Low and Wierman are working with the city's utility provider, Pasadena Water and Power, on a project to install batteries that could store solar and wind energy to use at times when energy supply is low.

"We help them ask, 'Where should we install those batteries? How much battery storage do you need? And how do we schedule the charging and discharging process of those batteries onto the grid in the most efficient way?'" Low says.

Other Caltech researchers, like materials scientist Julia R. Greer, are pushing the limits of the batteries themselves. The Greer lab focuses on engineering at the nano- and microscale, creating materials that can be extremely strong, lightweight, and failure-resistant all at the same time. Her research uses nanostructures as building blocks to construct "architected materials" that bring elusive and exotic abilities to the scale of everyday human experience, and it did not take long for her to realize that batteries could be one of the most immediate applications for this work.

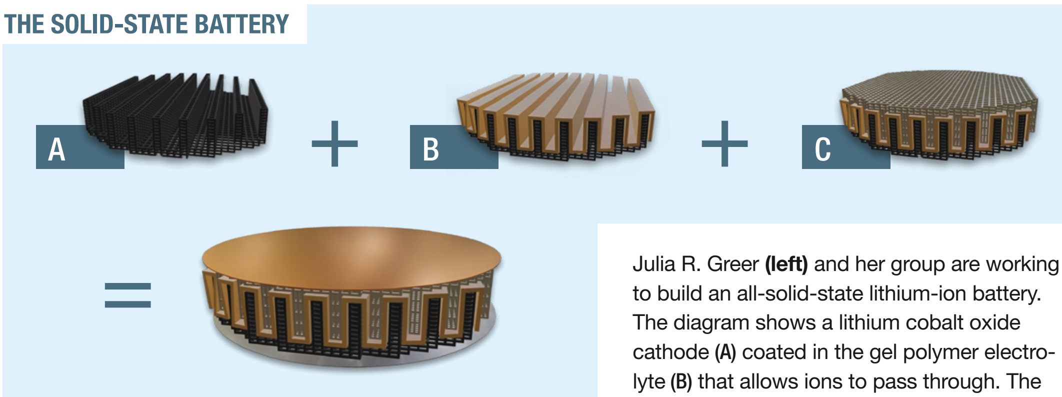
"Our micro-architected materials are lightweight and mechanically resilient; they have unique functionalities, unusual properties, and combinations of properties that haven't really been possible before," Greer says.

Armed with new materials, researchers like Greer are trying to reinvent how batteries are designed and built. Most commercial batteries, whether they power a TV remote control or a car, contain two electrodes: the positively charged cathode and negatively charged anode. Between the two is a liquid or gel called the electrolyte. Charged ions pass through the electrolyte on their way from one electrode to the other. Those are the essential components, Greer says, but building a stable, safe, and reliable battery invariably means adding in a variety of other elements. The problem is, these additions make the battery heavier, more wasteful, and less powerful.

Greer envisions a battery in which all the components add to its power and efficiency. One example: her lab is developing a design in which a battery's anode and cathode are not fixed points at the far end of a battery. Instead, the anode and cathode materials are in the form of 3-D lattices that comprise the volume of the battery. The two different material lattices are interlocked without contacting one another, with a polymer electrolyte between them providing both a cushion and ion transport medium. In such a setup, the ions carrying the electrical charge need only travel a small distance to the corresponding electrode that is directly across from them as opposed to traveling across the length of the whole battery.

This short distance between the cathode and anode would allow Greer to experiment with the use of a solid electrolyte between them rather than a liquid. The so-called solid-state electrolyte is a hot topic in current battery research, Greer says. A big reason for the interest in solid-state electrolytes is that tiny spikes called dendrites grow on the metal electrodes, especially in high-performance metals like lithium. These spikes degrade the battery's lifespan and, in some cases, can cause a short or fire. The idea is that solid-state electrolytes could physically push against the electrode and slow the dendrites' growth.

But solid-state electrolyte batteries have their own challenges, including that ions typically cannot move as



Julia R. Greer **(left)** and her group are working to build an all-solid-state lithium-ion battery. The diagram shows a lithium cobalt oxide cathode (A) coated in the gel polymer electrolyte (B) that allows ions to pass through. The carbon anode is then added (C), followed by the final step of adding the current collectors to make a full battery. **Right:** Kimberly See, whose lab aims to improve battery technologies through alternative chemistries.

freely through a solid as through a liquid or gel, making the short traveling distance in Greer's design essential.

In addition to rethinking battery design, Caltech researchers are scouring the periodic table for better materials. As chemist Kimberly See notes, many of the materials used in today's common lithium-ion batteries, including lithium, cobalt, and nickel, are environmentally damaging to mine or rare and thus difficult to attain. See investigates elements such as calcium, magnesium, and

zinc, which can do the job lithium ions perform inside batteries but are much more abundant in Earth's crust.

The challenge for See is that all these battery chemistries are nascent compared to the more mature lithium-ion battery, and therefore much of her work requires a search for stable ways to build batteries from these materials.

"There are materials that theoretically would be better than lithium-ion, or at least on par with it, for all of those elements," See says. "But we're not there yet."

It is worth the effort, however, See notes, since getting there will open the possibility of making more sustainable batteries to not only power smartphones and EVs but also to balance the smart grid.

The price of power

Flip the switch, the light comes on. Pump a few gallons of gas and your car's ready to go. The seamless reliability of America's energy system has sheltered all of us from having to think about how it actually works. People tend to think about energy only when the power goes out or the cost of gas climbs too high.

If society transitions to a smart grid, Wierman says, a grid powered by renewables could be just as invisibly reliable as the fossil-fuel-powered system we have enjoyed to date. Still, citizens will inevitably become more attuned to the "whens" and "hows" of their energy use. This will happen most visibly through what Wierman calls "price signals." The cost of energy will move up or down over time depending on energy supply and demand; this will provide individuals with financial incentives to change their energy use.

"I do think that with a smart grid, price signals are going to be increasingly visible to consumers, especially for those with EVs," Wierman says. "The time of day you charge will be a significant factor in how much you pay for that charge, whether you're at home or in a parking garage. It's going to be something that may be frustrating for some but maybe exciting for others in terms of chasing the deal."

Indeed, Wierman says, some of the biggest hurdles to achieving a smart grid are not technological but sociological. The public needs both to overhaul the way it thinks about energy and to summon the political and economic capital to commit to infrastructure improvements to make the grid smarter and safer.

"I think that's a challenge that you often face in investing in sustainability as a society," he says. "The biggest investments, like installing and managing large-scale storage in the grid and doing that effectively, are not going to be things people see in their daily lives, except that there will be fewer power outages because of it. It will make the grid more sustainable."

And, with the help of Caltech scientists and engineers, smarter as well.

Julia R. Greer is the Ruben F. and Donna Mettler Professor of Materials Science, Mechanics and Medical Engineering. She also serves as Fletcher Jones Foundation Director of the Kavli Nanoscience Institute. Her work on architected nanomaterials is funded by the Department of Defense and the Department of Energy.

Steven Low is the Frank J. Gilloon Professor of Computing and Mathematical Sciences and Electrical Engineering. His work on electric-vehicle charging and smart-grid infrastructure is funded by the National Science Foundation, Advanced Research Projects Agency–Energy, Department of Energy, Resnick Sustainability Institute, Defense Threat Reduction Agency, Southern California Edison, and PowerFlex Systems Inc.

Kimberly See is an assistant professor of chemistry. Her work on battery technology is funded by the Arnold and Mabel Beckman Foundation, David and Lucile Packard Foundation, National Science Foundation, Department of Energy Office of Science, Resnick Sustainability Institute, JPL, and Office of Naval Research.

Adam Wierman is a professor of computing and mathematical sciences and director of the Caltech Information Science and Technology (IST) initiative. His smart-grid research is funded by the Resnick Sustainability Institute, Center for Autonomous Systems and Technologies, Ronald and Maxine Linde Institute of Economic and Management Sciences, IST, National Science Foundation, VMWare Inc., and Beyond Limits Inc.