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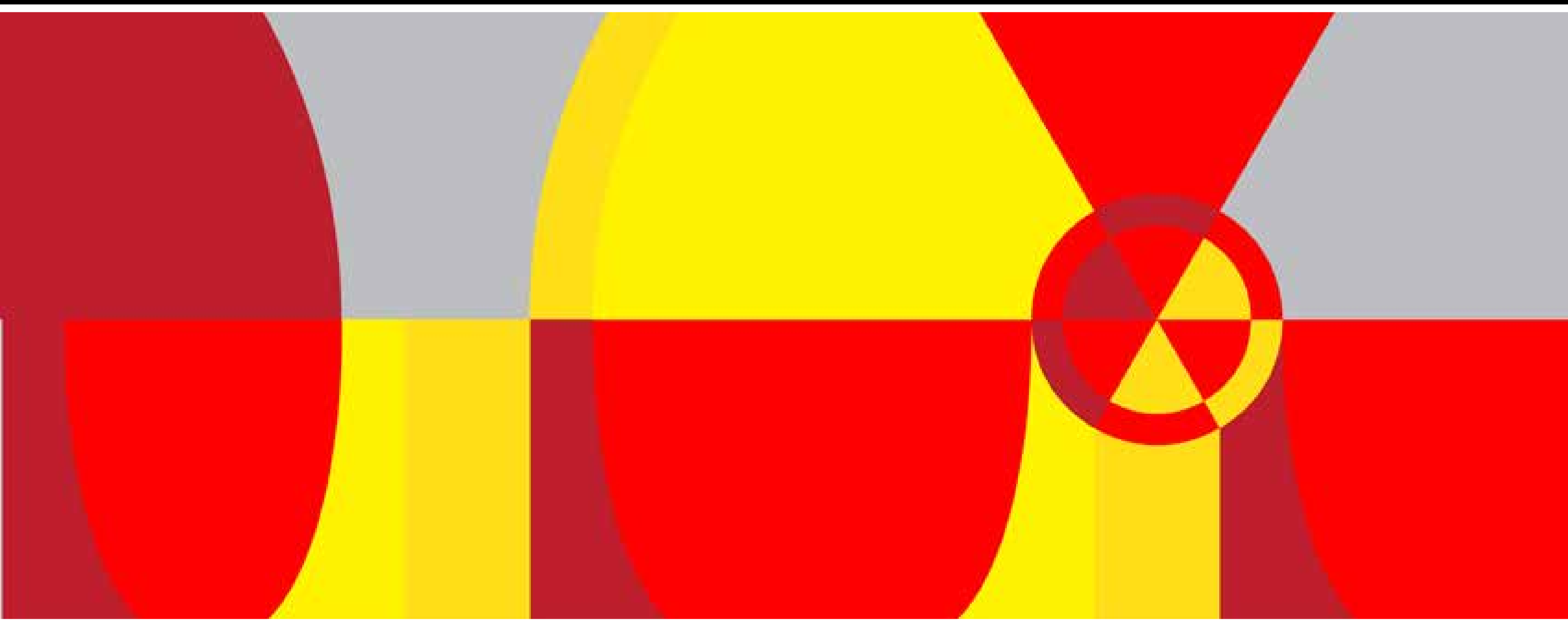
AFTER FUKUSHIMA, EPRI DEEPENS ENGAGEMENT IN JAPAN



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Viewpoint—"The Big Bang" and The Grid—Can It Happen Again?

Mike Howard, President and Chief Executive Officer, EPRI

During the late 19th Century, the electric power system emerged from a "Big Bang" of technological innovation. In those early years, rapid progress in alternating current transformers, generators, and other electrical equipment resulted from the many scientists, inventors, and researchers exploring the new science of electricity and magnetism.

Today's society has witnessed a similar Big Bang in computer and communication technology. This combines with intensive research in climate and other sciences to create expectations for big breakthroughs in electricity production, delivery, and use.

EPRI Journal interviewed Lynn Orr, Under Secretary for Science and Energy at the U.S. Department of Energy, to discuss a potential reinvention of the power system. In that interview, Orr said this: "There is a huge opportunity to invent the energy technologies and systems of the future, and our job now is to build and execute a portfolio of research that makes that possible. We need both the applied side and fundamental research. This is a time where we can put science and energy research to work in the interests of the nation."

Note his emphasis on both applied and fundamental research, spanning energy and other sciences. These are important to consider as we ponder a potential Big Bang in the electricity sector. I encourage you to read the articles and Secretary Orr's interview in this edition of *EPRI Journal* and to notice the breadth and diversity of research that's reported. We and many others are, in fact, reinventing the power system. Are we moving toward another Big Bang or toward decades of steady, incremental progress? Consider that question as you read these and other articles:

Global demand for high-voltage direct current (HVDC) transmission is growing, and power companies are seeking EPRI guidance as they consider building new transmission lines or attempt to derive more value from existing lines. Utilities that need to integrate significant renewable resources can use this guidance to identify scenarios in which HVDC can be a cost-effective solution. EPRI research shows that converting AC lines to DC operation can increase capacity as much as constructing one or more AC lines, and we are discussing with several utilities field demonstrations of AC-to-DC line conversion.

The question of coal is often framed in terms of phasing it out: how long this will take and what will replace it in the generation portfolio. As researchers, we take a more open-ended approach. An EPRI white paper discusses whether technology is available or under development that would enable coal plants to meet emissions standards without carbon capture and storage, and the answer is a qualified "yes." By combining both fundamental and applied research, in both energy and other sciences, we may yet see a sequence of breakthroughs that keep coal in the mix for decades to come.

EPRI is working to advance distributed energy resources management systems (DERMS), which are new types of software and communication systems to manage millions of distributed energy resources. DERMS must be able to aggregate distributed resources in a manageable number, handle their settings and identify grid-related services, drive toward minimal cost and maximum power quality, and use diverse technological languages cohesively.

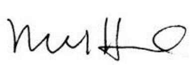
For the energy sector and its stakeholders, energy efficiency has a solid role in the future power system. What becomes important, therefore, is a good understanding of how we get there. EPRI's Technology Readiness Guide for energy efficiency categorizes and scores various existing and emerging technologies by comparing their performance. Utilities can use this to assess their potential for broad deployment. We scout early-stage technologies, assess laboratory testing, conduct and evaluate field tests, validate tests through early deployment, and support full rollouts.

If you're thinking this doesn't sound "Big Bangish," you're right. This is not unusual in technological progress. What arrives in the marketplace with a big splash may seem to consumers like a Big Bang, but to researchers the view spans years or decades of incremental research and development.

One area where society expects steady progress is environmental protection. Today some of our most forward-looking research is in battery technology—an interesting trend considering that batteries were used by the earliest electricity researchers. If batteries have a large-scale role in energy storage, we want to get ahead of recycling challenges. We're looking at the progress made in automotive lead-acid batteries—96% of which are recycled. There's a broader challenge as the power system deploys and retires diverse batteries with a spectrum of potential environmental issues. Our goal is to address these before they become a problem.

So does the picture emerging from all this work point to a Big Bang, a singular transformative technology or application? I expect to see more changes in the electric power system during the next eight years than we have seen in the past 25. What we should look for—and continue to deliver through the future power system—is a big "bang for the buck" for consumers and society to ensure continued availability of safe, affordable, reliable, environmentally responsible electricity.

Mike Howard



President and Chief Executive Officer, EPRI

Feature—After Fukushima, EPRI Deepens Engagement in Japan

All Nuclear Utilities Participate in R&D to Advance Plant Safety

By Brent Barker

On March 11, 2011, EPRI Fellow Rosa Yang awoke to the news that a major earthquake had struck Japan, sending a 60-foot tsunami flooding across the northeastern shore of Honshu Island. Tens of thousands were feared dead or missing, entire towns washed away, and Tokyo Electric Power Company's (TEPCO) nuclear reactors at Fukushima were believed to be in trouble. It was an uneasy coincidence for Yang, scheduled that day to fly to Japan to meet with some of the country's top nuclear officials. "This was to be my first major trip to Japan in my new role as EPRI's nuclear technical lead in Asia," she recalled. "Our new country manager, Michio Matsuda, advised me to come, explaining that there were no pressing hazards in Tokyo, and it was important for me to be here to offer any help."

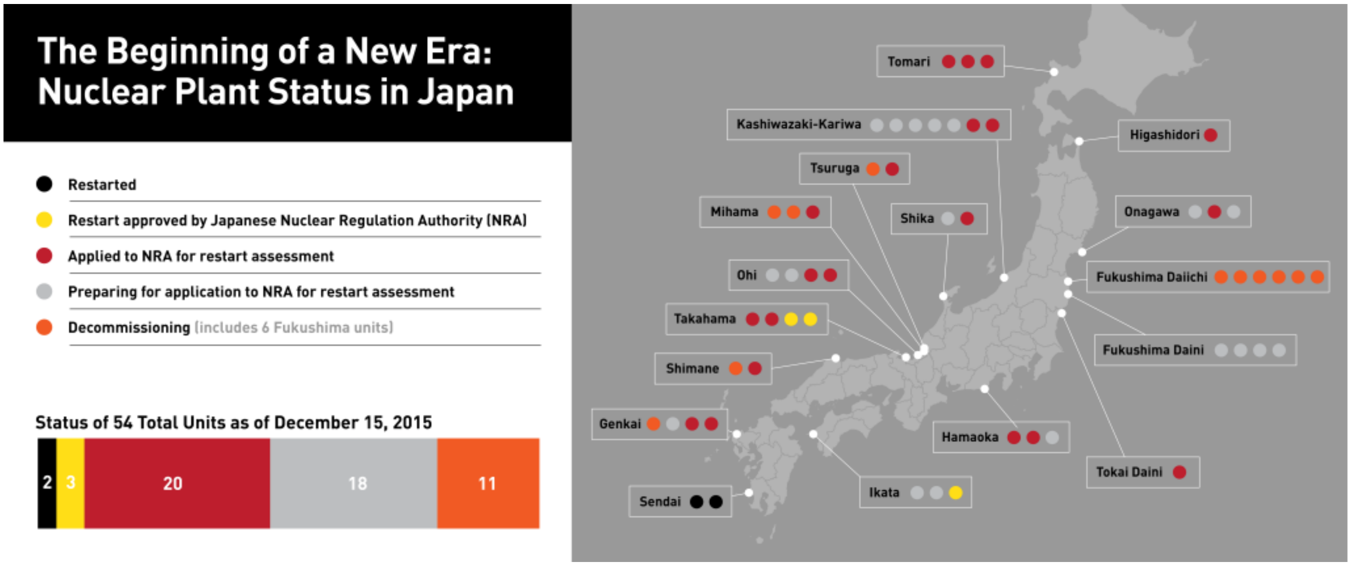
Yang arrived the next day. "The airport was chaotic, Tokyo frantic," she said. "My appointment with TEPCO's chief nuclear officer, a former classmate of mine, was cancelled, but I spent the next two days with another old friend, Shunichi Suzuki, TEPCO's R&D manager, which turned out to be fortunate."

Some might say fateful. A few days after Yang returned home, Suzuki called her about a crisis unfolding in Fukushima's damaged reactors. Cooling water contaminated with radioactive fission products, mostly cesium, was collecting faster than TEPCO could store it. Plant personnel had to find a way to remove the cesium before the rainy season started in two months. Otherwise, the rains would flood the reactor basements and carry the contaminated water into the ocean. TEPCO was seeking EPRI's help.

"I remembered an EPRI technical report published on the subject three months earlier," said Yang. "With Matsuda's help, we made calls and contacts, and EPRI's liquid waste processing and low level waste management expert, Lisa Edwards, was put on the first plane to Japan." TEPCO selected a technology identified in the EPRI report, then gave the specifications to the developer, Kurion, with a nearly impossible deadline. Kurion came through—designing, building, and shipping a first-of-a-kind system in time. "The outcome was extraordinary," said Matsuda. "TEPCO was able to remove more than 99.9% of the cesium before the rainy season started."

"This is testament to the value of R&D," said Yang. "If we hadn't done the R&D, we wouldn't have been able to help them solve an extremely urgent problem. The benefit was not just to TEPCO but to Japan and the world, preventing significant contamination of the ocean."

"Relationships are crucial in Japan," said EPRI Nuclear Vice President Neil Wilmshurst. "The Japanese remember people who help them when they are in trouble. This certainly played a role in sustaining and growing Japan's engagement with EPRI in a time of great financial hardship."



This graphic depicts the status of nuclear plants in Japan.

Surge in Japanese Participation with EPRI

Recognizing the importance of risk—especially the risk of very low-probability, high-consequence events such as the Fukushima accident—the Japanese nuclear utilities have expanded their participation in EPRI R&D.

Full participation in EPRI nuclear research programs began with TEPCO in 2002, followed by Chubu (Japan's third largest utility) in 2006. Participation by other utilities grew after Fukushima. For example, Chugoku and Shikoku came on board with full participation in 2013, and Kansai (second largest utility) joined in 2014. Currently, all 11 Japanese nuclear utilities participate in EPRI research. Five have elected full membership, participating in all 17 EPRI nuclear programs—which range from maintenance and inspection techniques to materials integrity, risk management, and fuel reliability. The entire suite is focused on enhancing nuclear plant reliability, performance, and safety and on reducing the risk of a severe accident in the future.

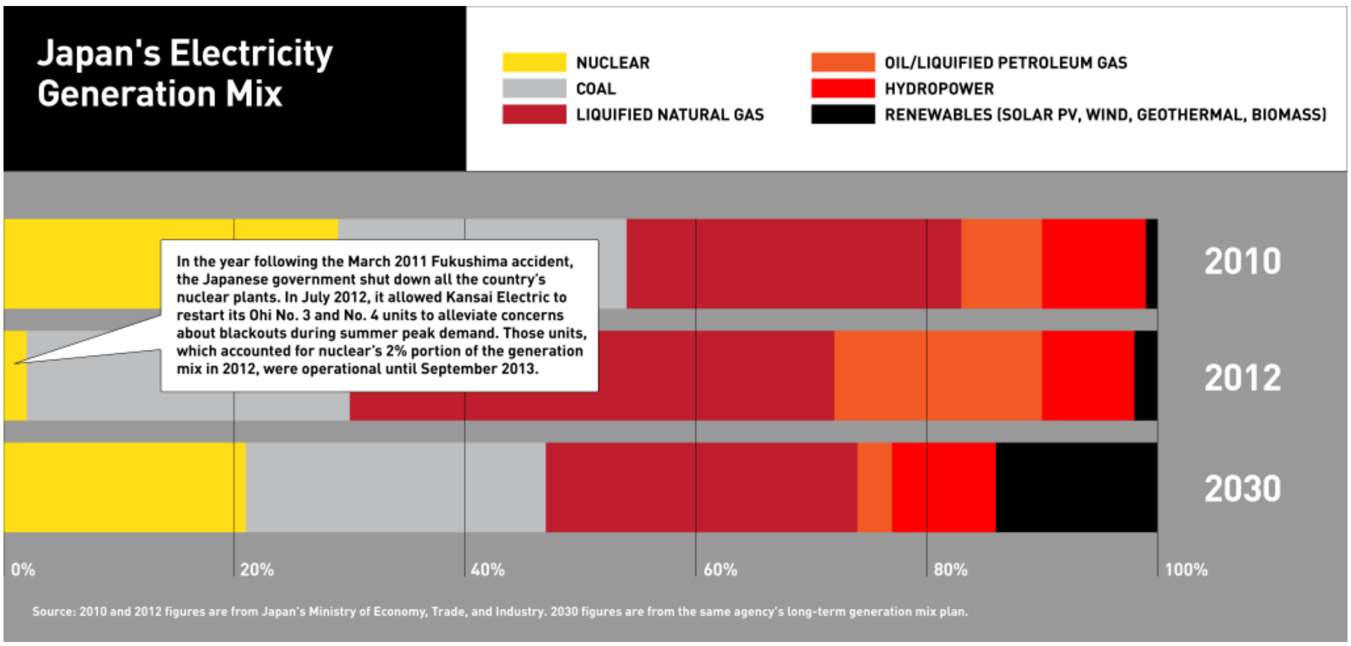
The scope of EPRI research related to the Fukushima accident now includes evaluation of root causes, improvements in severe accident management, and risks from seismic events and flooding. In joining EPRI's Risk and Safety Management Program, Japan's nuclear utilities are helping to establish a more risk-informed framework for nuclear safety. The program is providing them with rigorous training in probabilistic risk assessment. "First, we had educational presentations for chief nuclear officers and a one-day course for middle management," said Matsuda. "Then we had six one-week training sessions for engineers working at the various headquarters and power plant sites."

Changing Nuclear Landscape

Before Fukushima, nuclear represented 30% of the country's power generation and was on course to become 50% by 2030, according to the government's Basic Energy Plan 2010. Following the accident, the government shut down the nation's reactors and refocused power generation on fossil and renewables. Imports of coal, natural gas, and oil soared by more than $35 billion per year. To help offset these costs, utilities increased electricity prices by 20% for residential customers and by 30% for industrial facilities.

At least 11 nuclear units, including the six at Fukushima Daiichi, will be shut down permanently and fully decommissioned. For the remaining units, utilities are evaluating the costs and benefits of restarting after making significant safety modifications, which include increased tsunami and seismic protection. Many plants have submitted applications for restart licenses, while operators of some older units will seek license extensions beyond 40 years. Safety enhancement for restarts has already reached $30 billion.

The pace and scale of Japan's nuclear resurgence is uncertain due in part to a skeptical public and local lawsuits, but the national government remains committed to nuclear power to help meet its target to reduce CO_2 emissions 26% by 2030 relative to 2013 levels. Government guidelines for the 2030 generation mix call for 20–22% nuclear, 20–24% renewables, 26% coal, and 27% natural gas (see chart).



Advancing EPRI's Severe Accident Software

Shortly after the accident, the Japanese government began funding enhancements of EPRI's Modular Accident Analysis Program (MAAP) to assist in Fukushima decommissioning. Based on its long experience with MAAP, Toshiba's nuclear division recommended to the Ministry of Economics, Trade and Industry (METI) that it support the program's further development.

The uses of MAAP are diverse and growing. "MAAP was used since the early hours of the Fukushima accident to help understand what happened," said Yang. "Initially, we had to use generic numbers because we didn't have exact plant data. As data became available—how much water was put in the reactor and when, and equipment conditions during the accident—our understanding has grown. In time, the enhancements funded by the Japanese will help us unravel the full sequence of events." The improvements are also expected to provide insights on the location of highly radioactive core debris in the three damaged units.

Today the software is used by more than 70 organizations in 17 countries. MAAP can be used to help evaluate potential safety benefits of plant design, equipment, operations, and maintenance changes. It can also be used to evaluate potential plant uprating (higher power levels), life extensions, and restarts in Japan and elsewhere.

During a severe accident, MAAP can be used to help predict the timing of key events, to guide evaluations of the effectiveness of operator actions, and to support efforts to predict the release of fission products. With high-powered computing, it can assist operators as they evaluate many possible scenarios and uncertainties during a crisis.

Decommissioning Teams

The cleanup at Fukushima Daiichi will likely take 40 years or more and be extremely costly because of the extensive damage and high radiation fields in the plant. At the government's request, two advisory committees have been formed—both with EPRI participation—to help guide the process. The International Expert Group offers technical advice to TEPCO's decommissioning team, and EPRI's Yang is one of six members.

Yang also sits on the government's Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF). This four-person advisory committee will tap into international expertise and provide mid-to-long-term strategy, identifying alternative decommissioning approaches and critical, unaddressed R&D needs. Priorities include retrieving fuel debris and managing highly radioactive materials.

CRIEPI's Role in Collaborative R&D

Japan's Central Research Institute of the Electric Power Industry (CRIEPI) is a collaborative R&D organization funded by a kilowatt-hour charge on electricity generation. Similar to the U.S. national energy laboratories, it focuses on basic scientific research and is recognized for its expertise in materials science. In 2011, EPRI and CRIEPI signed a joint R&D agreement focusing on fundamental mechanisms for materials aging.

"Asking Rosa to sit on both advisory committees reflects the government's recognition of EPRI's value and Rosa's expertise, as well as the esteem in which they hold her in Japan," said Wilmshurst.

Nuclear Power's Future in Japan

Nuclear power appears to be starting a new chapter in Japan. Eighteen units are seeking government approval to restart (see map). Kyushu's Sendai Unit 1 restarted in August, and Unit 2 restarted operations in October. The Japanese Nuclear Regulation Authority (NRA) has approved restarting Kansai's Takahama Units 3 and 4, pending related court rulings. The NRA has granted safety approval to Shikoku's Ikata Unit 3, and local communities and municipalities generally favor restarting the plant. "The Japanese government's support of nuclear plant restarts comes from its commitment to addressing climate change," said Matsuda.

The ability for nuclear plants to withstand major earthquakes and tsunamis remains a central concern. Geologists consider the area about 125 miles south of Tokyo as the region most vulnerable to tsunamis. Along that shoreline, a one-mile concrete wall has been built to shield the three Hamoaka nuclear units. At 70 feet, it rises 13 feet higher than the Fukushima tsunami. A wave similar in magnitude to Fukushima's may be likely in this region in the next 30 years, according to geologists.

EPRI's Commitment to Nuclear Safety

EPRI's credibility and technical leadership in Japan have been bolstered through its work on Fukushima decontamination and decommissioning, severe accident software applications, risk assessment, and more. Its leadership has deepened with the full participation of five utilities in EPRI's nuclear programs.

"We're fully committed to enhancing the future of nuclear safety in Japan and around the world," said Wilmshurst at the Asian Nuclear Power Council meeting in Kyoto in June. It was a signature meeting, co-hosted by the council's Japanese members and attended by 110 nuclear industry representatives. The many chief nuclear officers in attendance, as well as the CEO of the World Association of Nuclear Operators, recognized EPRI's critical role in Fukushima. EPRI's R&D network represents more than 75% of the world's commercial reactors, and its collaboration with Japanese nuclear utilities opens the door for them to engage with the world's best nuclear safety R&D.

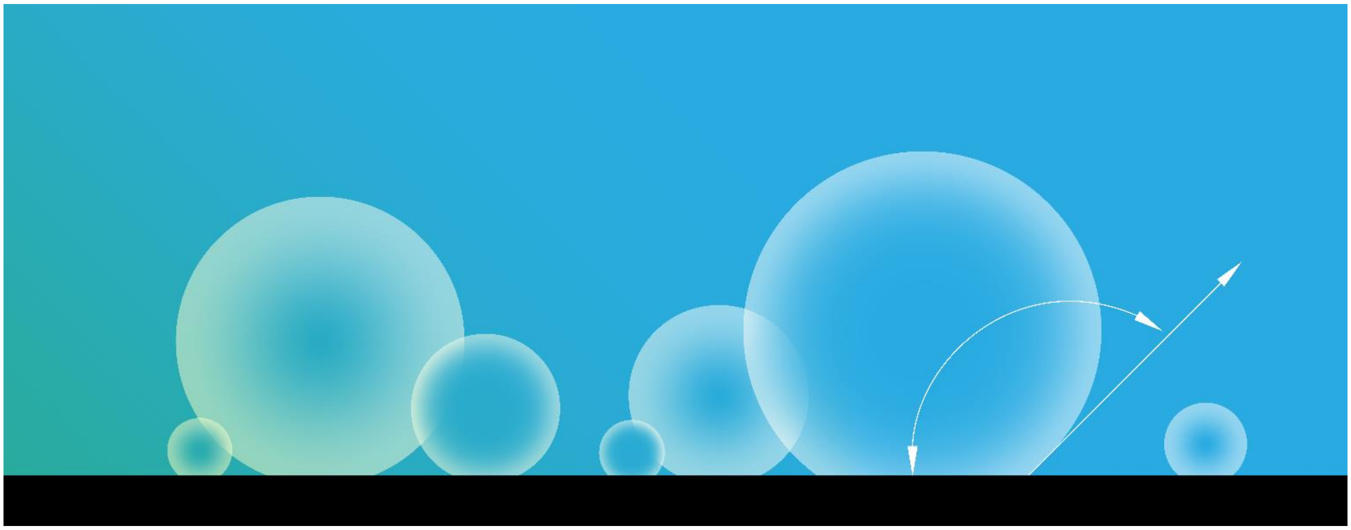
Deregulation of Japanese Utilities

In 2013, the Japanese government unveiled a plan through 2020 to deregulate the electricity industry, unbundling the vertically integrated utilities established for each of the country's 10 traditional regions. In 2015, Japan established an interregional power grid control system similar to the independent system operators in the United States. In 2016, efforts to deregulate the retail markets will begin. Meanwhile, the power industry is closely watching TEPCO's proposed unbundling model with separate thermal/fuel, transmission/distribution, and retail companies under a holding company. The nuclear units will remain an integral part of the holding company.

Key EPRI Technical Experts

Rosa Yang, Michio Matsuda

Feature—Repelling Water and Ice



Researchers Look at 'Super' Coatings for Transmission Systems, Power Plants

By Robert Ito

In December 2013, a massive ice storm slammed into Canada and the northeastern United States. Trees and branches fell on power lines and utility poles, and lines toppled under the weight of accumulated ice and snow. Damage exceeded $200 million, and outages climbed to the hundreds of thousands. To help reduce the occurrence and size of future outages, EPRI researchers are focusing on the latest icephobic and super-hydrophobic coatings.

The power system for decades has used traditional hydrophobic coatings, such as the silicone rubber used to cover high-voltage insulators on transmission lines. But silicone rubber is stickier than the porcelain or glass to which it is applied, so it often collects more contaminants that can damage the material it's supposed to protect. Super-hydrophobic coatings, on the other hand, repel water so completely that droplets roll off the surface, taking salt, silt, and other contaminants along with them.

EPRI evaluated 12 advanced coatings from different manufacturers, focusing on their ability to repel ice, water, and contamination on insulators and conductors in transmission systems. Some of these coatings are commercially available for other applications, such as drilling rigs and cruise ships. EPRI found that several coatings improved performance and had no major flaws that could result in component degradation. Field tests later in 2015 will focus on the successful coatings at three separate sites. In 2016, researchers will explore the use of super-hydrophobic materials on power plant components, including steam turbines, steam condensers, and cooling towers. These coatings have commercial potential to reduce power plant damage due to corrosion and erosion, protect transmission lines from salt and icing, and improve grid reliability.

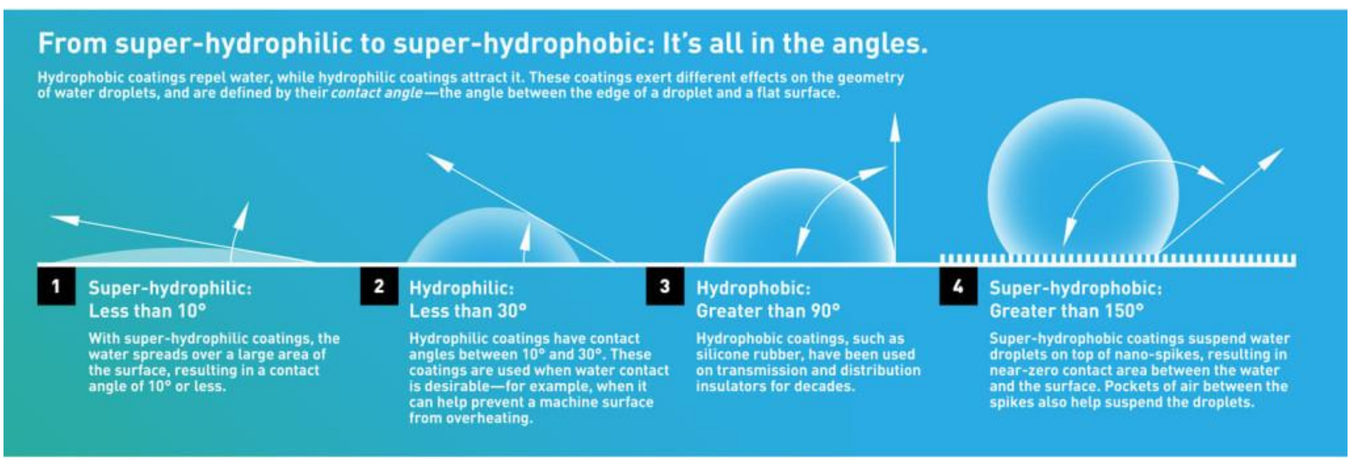
Encouraging Laboratory Tests on Conductors and Insulators

Ice accumulation on conductors, particularly during severe weather, poses enormous dangers to transmission lines. These dangers include conductor galloping, flashovers caused by melting ice, and high dynamic loads when large chunks of ice fall from the conductors. Super-hydrophobic coatings can potentially reduce this accumulation, preventing damage to power lines and improving grid reliability. In coastal regions with salt-laden air or in areas near salted roadways, these coatings have the potential to be used on the insulators that connect transmission line wires to towers as well as to insulators in substations. This can prevent flashovers across insulators due to salt exposure, protecting lines and substation equipment from potential damage.

Since 2012, EPRI Transmission Director Andrew Phillips has led evaluations of these and other applications of icephobic and super-hydrophobic coatings and surfaces. In EPRI laboratories, Phillips' team first tested the extent to which 12 coatings from various manufacturers repel water and ice, reduce contamination buildup, and withstand various environmental conditions and mechanical wear. Next, researchers compared the coatings' performance when applied to insulators and conductors. To test for icephobicity, the team adhered small ice cylinders to coated surfaces and measured the amount of force needed to break them off. To evaluate contamination buildup, they placed coated ceramic insulator bells inside a cage with barn owls at the Carolina Raptor Center and observed their ability to repel owl excrement. To test self-cleaning, they applied a mixture of kaolin and salt to coated surfaces, froze the contaminated samples, and then observed the contaminant layer as the samples thawed.

Findings were particularly encouraging in two key areas—ice adhesion and self-cleaning. In the ice adhesion experiments, coatings reduced the force needed to remove the ice from 900 kilopascals to less than 200 kilopascals, indicating that ice is more likely to fall off with a power line's normal motion in the wind. In the self-cleaning tests, the contaminant layer clumped up away from the surface of all 12 coatings. Future tests will determine how easily and under what conditions these solid clumps will roll off the insulators.

Lab tests on insulators and conductors demonstrated that six different coatings improved performance without damaging components. Following successful field tests on those coatings, commercial applications could come as early as three years, according to Phillips. He expects that initial commercial applications will address problems specific to cold, wet regions, coastal zones, and along freeways.



Identifying Power Plant Applications

In a typical steam turbine at a gas, coal, or nuclear plant, large rotor blades up to 4 feet long spin at 3,600 revolutions per minute. From the steam flow, a film of condensed water builds up on the blades. Droplets form and fly off, striking blades downstream and causing corrosion and other damage to these costly components over time. Super-hydrophobic coatings can potentially reduce this damage by preventing or minimizing droplet formation.

"On a large turbine, a row of blades can cost up to a million dollars, and they need to be replaced about every 10 years," said EPRI Principal Project Manager Sam Korellis. "If we can minimize replacement of these blades, we increase operational time and power production. This application can also increase plant efficiency by improving the condition of the turbine. It's a double win."

Turbine blades are one of several power plant components that Korellis has targeted for potential application of super-hydrophobic coatings and surfaces. Another example: By applying these materials to steam condensers, water beads and drops off immediately, instead of coating condenser tubes with a water film that impedes heat transfer. “This can significantly improve heat transfer in the condenser, resulting in greater efficiency in the steam turbine cycle,” said Korellis, adding that super-hydrophobic coatings also may improve heat transfer in feedwater heaters and cooling towers.

Korellis is looking at material compatibility, durability, and other factors to determine the suitability of different coatings for various power plant applications. For example, some coatings might work well on copper-based tubes but not on steel or titanium. Others might be long-lasting but could scrape off when a component is installed or moved.

Looking to the Future

Phillips begins the final phase of the transmission line research this fall at field sites in New York City (Con Edison), the Catskill Mountains (New York Power Authority), and Georgia (Southern Company). His team will apply six different coatings to insulators and conductors and compare their performance to uncoated insulators and conductors for 18 months. “This research can provide real-world data to help utilities select the most appropriate coating for the specific application under consideration,” said Phillips.

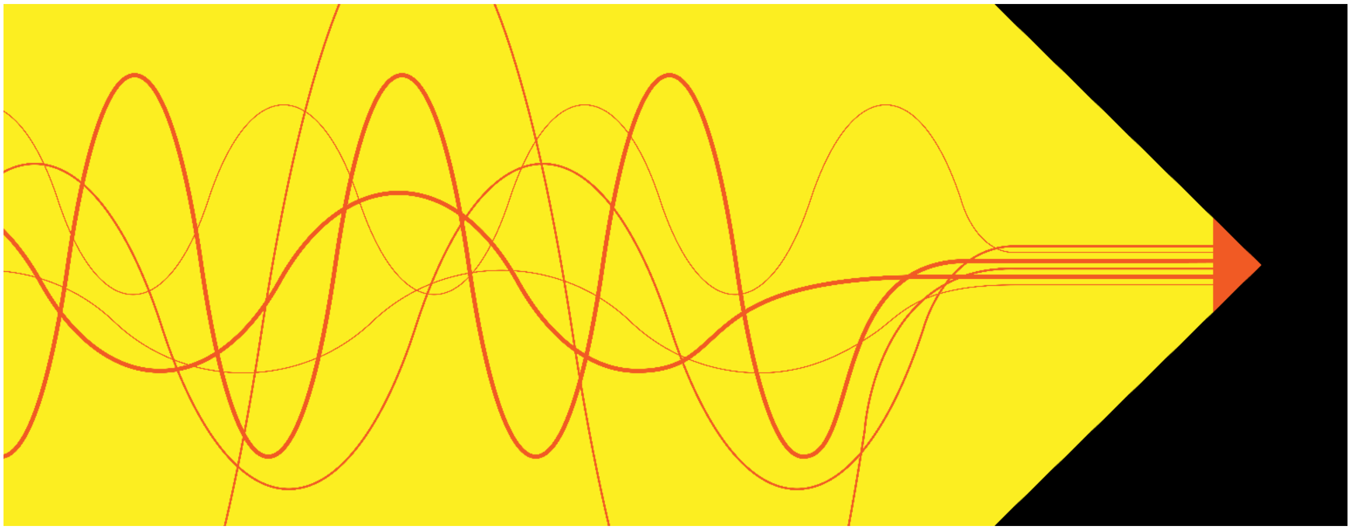
In 2016, EPRI will begin research of super-hydrophobic coatings applied to steam condenser tubes, testing their durability and performance over 12–18 months in the laboratory and, if successful, over a longer period in operating plants. “We’re starting with condenser applications because they offer the biggest and most immediate cost-savings potential,” said Korellis. Also in the near future, he plans to start lab tests on coated and uncoated turbine blades, placing them inside lab-based steam tunnels and observing their performance as high-velocity moisture-laden airstreams hit the blades.

Although various coatings’ longevity and durability remain big unknowns and could pose major obstacles to commercial use, researchers see enormous potential for applications in the power generation. “With further research and testing, these materials can potentially make the power plants more efficient, reliable, and cost-effective,” said Korellis. “They may reduce how much fuel we burn to make a megawatt of electricity, and if we burn less fuel, we pollute less.”

Key EPRI Technical Experts

Andrew Phillips, Samuel Korellis

Feature—HVDC on the Rise



EPRI Helps Industry Navigate New Opportunities with High-Voltage Direct Current Transmission

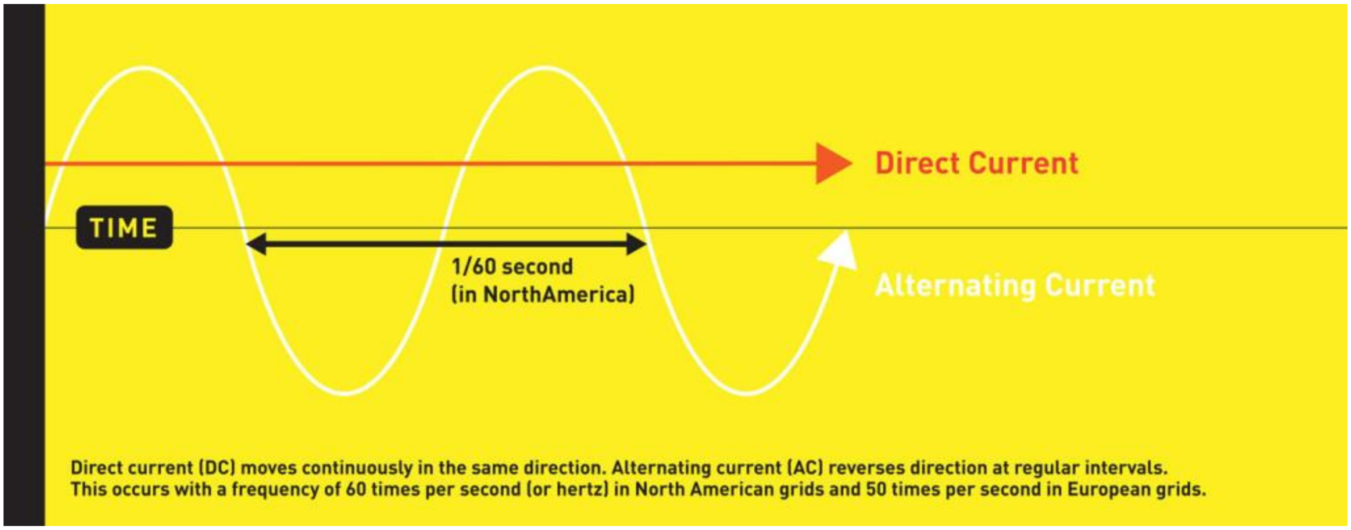
By Matthew Hirsch

Since the construction of the Bipole I high-voltage, direct current (HVDC) transmission line in the 1970s, Winnipeg, Canada, has relied more than most cities on HVDC technology. This reliance grew in the 1980s with the construction of Bipole II and is poised to increase again with the construction of Bipole III for Winnipeg's power supplier, Manitoba Hydro.

The two HVDC lines share a transmission corridor connecting the city with the Nelson River hydropower projects in the far north. When built, they offered a more economical option than the more familiar high-voltage alternating current (HVAC) lines because of the long distance to the hydro generation, decreased power losses, and a smaller right of way.

Unlike HVAC transmission technology, HVDC travels through the entire cross section of a conductor and needs fewer wires, enabling it to move energy over greater distances with less power loss. HVDC also provides controlled power flows, contributing to grid stability. As costs come down for DC transmission, the business case improves for even shorter distances. HVDC links can connect two power networks operating at different frequencies.

HVDC also has many challenges. For example, managing the loss of an HVDC link, which may constitute an extremely large power import into an area, can be difficult. The converters are costly and can generate harmonics, and multi-terminal HVDC systems require expensive communication systems. Many utilities have a lack of familiarity with HVDC maintenance practices. Historically, HVDC power electronics and controllers have had shorter lifetimes than HVAC assets. Each situation requires thorough technical and economic analyses to determine whether HVDC or HVAC makes the most sense.



Globally, demand for HVDC transmission is growing, and power companies are seeking EPRI's guidance as they consider new lines or attempt to derive more value from existing assets. EPRI's High-Voltage Laboratory in Lenox, Massachusetts, provides one of a few labs in North America equipped to test HVDC power, and its global partnerships enable EPRI and its member utilities to conduct research at facilities such as one under development in the United Kingdom, where HVDC vendors can plug in their products and test interoperability with other solutions (see box at end of article).

Driving HVDC: Renewables

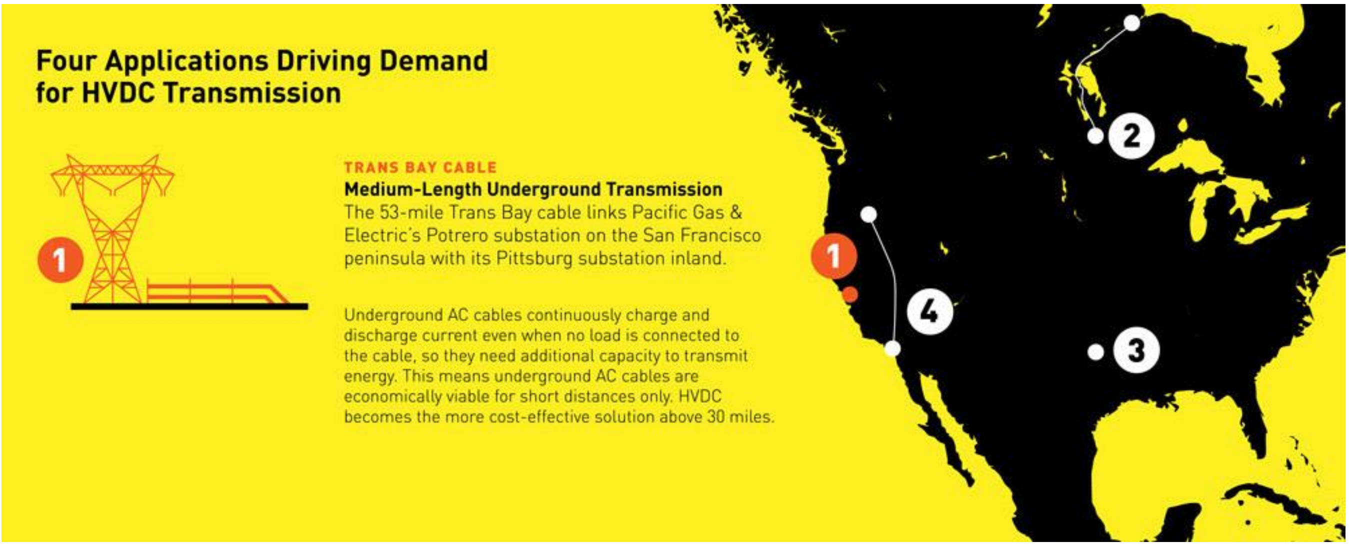
What will drive growth in HVDC technology? For one, the integration of large-scale solar and wind generation is well suited for HVDC. Such generation is typically far from load centers, and increasingly many proposed wind plants are at remote offshore sites. An example is the Atlantic Wind Connection, a proposed undersea transmission cable running from New Jersey to Virginia that would deliver up to 6,000 megawatts of offshore wind energy. Its first phase is estimated to come into service in 2020–21, but the project is already exchanging technical information with the HVDC Cable Interest Group convened by EPRI.

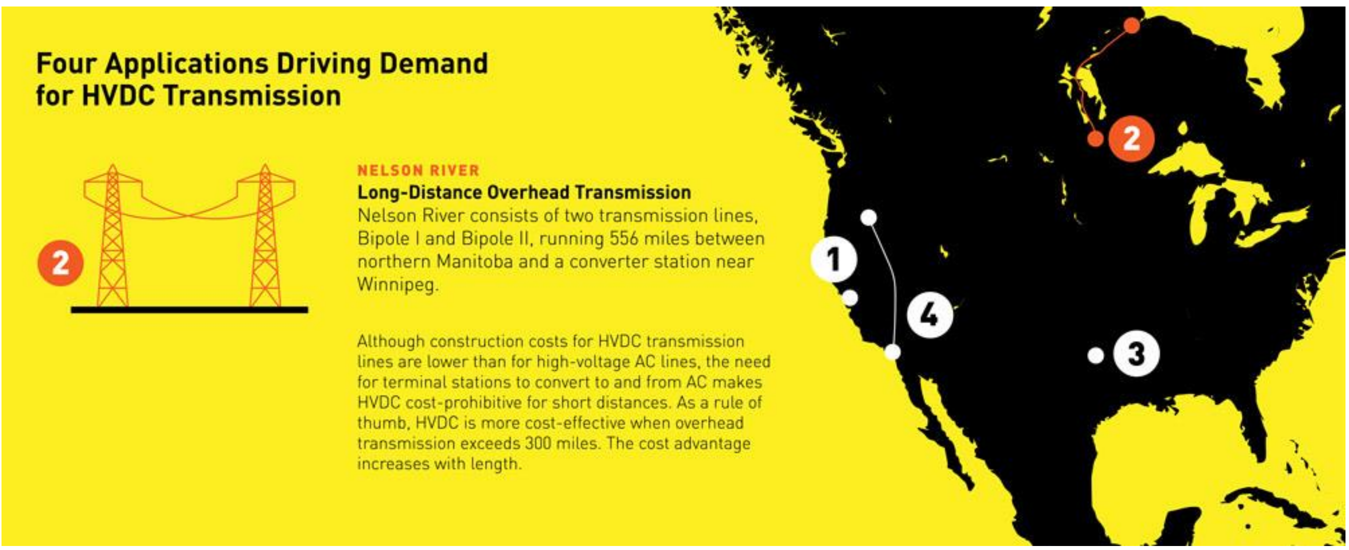
"As utilities face the challenges of integrating renewable resources into the existing power grid, our research has been instrumental in identifying the scenarios where HVDC is a cost-effective solution," said Ram Adapa, an EPRI technical executive in HVDC and power electronics.

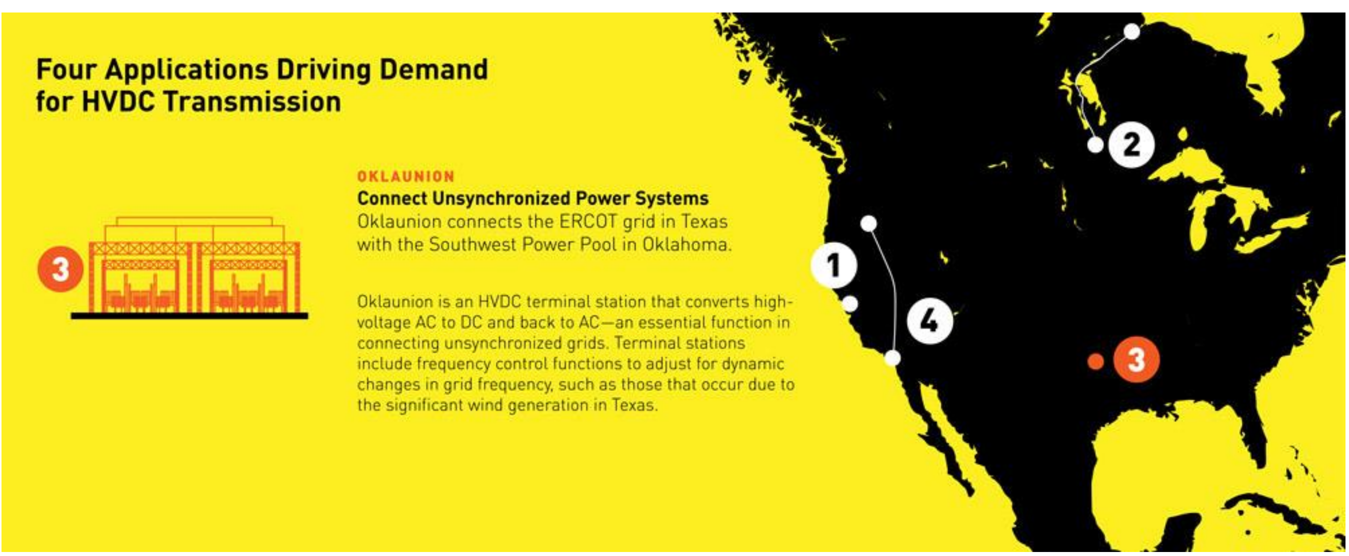
Driving HVDC: Reliability

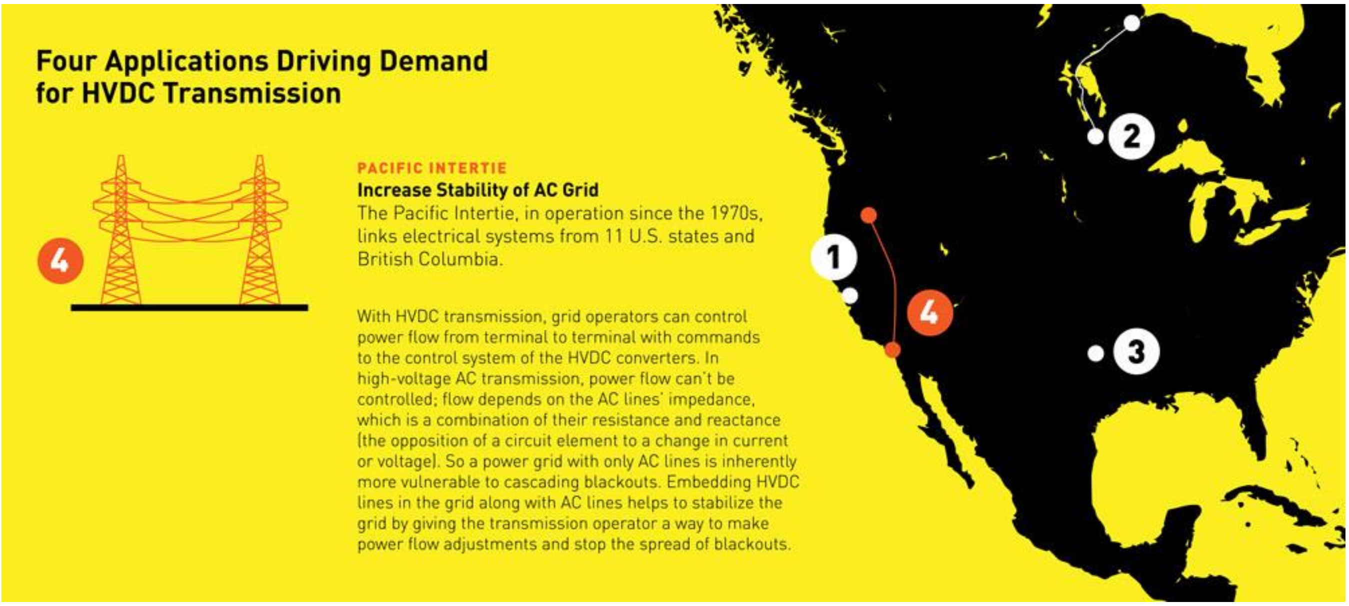
Electricity customers around the world—including those in North America, Europe, and Asia—are experiencing more blackouts and brownouts. The most recent major U.S. blackout in 2003 affected 50 million people in eight states and Canada. HVDC can help reduce the spread of such large-scale disturbances by providing a buffer between regions. EPRI research is helping to improve inspections and maintenance on energized HVDC lines, providing a scientific basis for using proper tools and setting minimum approach distances.

These graphics depict four HVDC transmission applications in North America.









Driving HVDC: Crowded Landscapes, Capacity Constraints

Building new transmission lines becomes more difficult and expensive with rising land costs, lawsuits, and other barriers in permitting. The need to build can be offset by using HVDC to increase capacity on existing transmission lines. EPRI research shows that converting AC lines to DC operation can increase capacity as much as constructing one or more AC lines. EPRI is discussing with several utilities field demonstrations of AC-to-DC line conversion.

EPRI Guidance on Changing Technology

In the mid-1980s, when Manitoba Hydro completed Bipole II, only one converter technology was commercially available: line-commutated converters (LCC). The core of LCC technology is a semiconductor with a controllable switching-on action. The device switches off automatically in response to changing AC voltage characteristics. In 1997, the industry deployed a new technology: a voltage-sourced converter (VSC), which uses power electronics to control both switching-on and switching-off actions. This gives the system flexibility to switch on and off at any time, instead of relying on an outside AC voltage source to turn off the device.

For Bipole III, Manitoba Hydro, which participates in EPRI's HVDC R&D, evaluated the two technologies. Both options had advantages. LCC is an established technology for transporting bulk power through overhead lines. Some LCC projects carry as much as 8,000 megawatts. While it's technically feasible for VSC to carry 2,000 megawatts through overhead lines—the capacity specified for Bipole III—this hasn't been accomplished yet. VSC generally requires less infrastructure and offers greater potential to connect with multiple HVDC transmission lines, such as in a DC grid. In the end, all three bidders proposed LCC projects.

Even though Manitoba Hydro selected the tried-and-true technology, technical information from EPRI task force meetings and on-site workshops has provided the utility with important insights for planning future transmission projects—an important advantage, given the pace of change in HVDC. Already, Manitoba Hydro is preparing to replace converter equipment on Bipole II, and Bipole I will need equipment upgrades about 10 years from now. "To be diligent, we need to assess and consider the possible savings VSC technology may offer on future projects," said Scott Powell, manager of public affairs for Manitoba Hydro.

Improving Transmission Line Reliability

In South Africa, HVDC transmission provides residences and businesses with essential energy needs, and vultures present unique challenges to reliability. These large birds are drawn to areas along the Cahora Bassa HVDC line known as "vulture restaurants" where farmers dump animal carcasses. After eating their fill in the daytime, vultures roost for the night on the HVDC tower. It is believed that during roosting or as the vultures are about to take off into flight, they release a stream of excrement that may lead to an electrical arc on the line known as a *flashover*.

Since 2012, Eskom and EPRI have simulated the Cahora Bassa line configuration at EPRI's Lenox lab to determine if bird streamers are the cause of flashovers and under what conditions they occur. After three rounds of testing, simulations demonstrated the possibility of flashovers occurring when bird streamers bridged the air gap between the power line and the tower. The findings will inform Eskom's consideration of the application of bird guards to keep vultures away from electrical insulators on the lines.

As HVDC technology matures and costs come down, EPRI R&D will continue to help power companies operate existing lines while evaluating and implementing new HVDC transmission. "EPRI's collaborative and unbiased HVDC research provides utilities globally with unique and valuable scientific information," Adapa said.

Building an HVDC Supergrid

Since the first HVDC project launched in Sweden in 1954, most HVDC transmission has been built as a single line connecting one terminal with another. Linking projects with multiple terminals could increase the supply of energy across networks and the ability to control voltage and frequency fluctuations. Two main technical challenges remain: enabling HVDC technology to handle multiple terminals and making devices from different vendors interoperable.

Voltage-sourced converters—a technology developed in the 1990s that uses power electronics to control the converter's switching-on and switching-off actions—have created a simple process to reverse any terminal's power flow. Using this technology, researchers around the world are testing how multiple HVDC systems interact in real time.

With guidance from EPRI, United Kingdom utility SSE is setting up a facility in Cumbernauld, Scotland, to help HVDC system planners, asset owners, and operators learn how an HVDC network could connect with networks from neighboring countries and offshore renewable generation. The project is procuring simulation equipment, and commissioning and testing are expected in 2017.

About a dozen initiatives around the world are attempting to link HVDC transmission across large territories. Examples include the Atlantic Wind Connection in the eastern United States, the Desertec project in North Africa and the Mediterranean, and a supergrid in China.

In a recent article in *IEEE Spectrum*, EPRI Fellow Clark Gellings discusses the construction of a worldwide HVDC supergrid to improve grid stability; tap the world's best solar, wind, and eventually ocean energy resources; and deliver the energy to population centers.

Key EPRI Technical Experts

Ram Adapa, John Chan

Feature—The Power Industry's New Birds

EPRI Explores the Use of Drones for Power Plant Inspections

By Garrett Hering

When a magnitude-9.0 earthquake rocked Japan on March 11, 2011, a tsunami overwhelmed the seawall at Tokyo Electric Power Company's Fukushima Daiichi nuclear power plant, resulting in equipment failures, multiple reactor meltdowns, and the release of radioactive material. Because of the power outage in the early hours of the disaster, utility and government officials could not assess the damage and how best to respond.

EPRI's Modular Accident Analysis Program software has filled in many blanks about how the accident unfolded, yielding essential lessons for the global nuclear power industry's disaster response guidelines. One key lesson: The industry needs a tool for assessing difficult-to-reach sites and providing real-time data to inform responses without endangering workers.

Such a tool may soon become available to nuclear plant operators. The University of North Carolina at Charlotte (UNCC), with technical assistance from EPRI, is developing a radiation-resistant, remote-controlled drone called the Severe Mobile Accident Investigator, or SAMI.

"With SAMI, we are looking at how to use drones to make the best out of a worst-case scenario," said Stephen Lopez, EPRI project manager.

SAMI is one of several drone applications EPRI is investigating. Others include inspecting power lines, transmission towers, fossil plant boilers, wind turbines, solar photovoltaic panels, hydroelectric dams, and cooling towers. These tasks are time-intensive and potentially dangerous, sometimes requiring human inspectors to climb structures as high as several hundred feet or perform work on suspended scaffolding or in areas with hazardous materials. As a result of safety or cost concerns, some power plant inspections may be deferred, leaving stakeholders without up-to-date information about their assets.

"Deploying drones for certain jobs can promote worker and plant safety, reduce inspection costs, assess and extend the life of components and power plants, and enable nondestructive examination for difficult-to-access areas," said EPRI Program Manager John Lindberg. "Utilities want to take this technology in the field and are seeking federal licenses to do so."

Soaring Industry Interest

All commercial drone operators require permission from the U.S. Federal Aviation Administration (FAA) to fly in American airspace, even if solely for demonstration purposes. Over the past year, the FAA has loosened restrictions on commercial operation of unmanned aircraft systems (its formal term for drones), enabling new opportunities for partnerships between utilities and drone vendors.

Since 2014, vendors and power companies have obtained FAA authorization for low-risk, controlled missions in U.S. airspace through an exemption under Section 333 of the FAA Modernization and Reform Act. With streamlined FAA approval, authorizations have soared in recent months.

As of September 2015, the agency had approved approximately 1,550 applications for Section 333 exemptions. Almost all of these authorizations were issued in 2015, including more than 80 for utilities and drone vendors to inspect power lines, transmission towers, or power plants. Hundreds of additional utility and vendor requests are under review.

Although the number of authorized drone operators is growing, Lindberg cautioned that a steep learning curve remains. “Before drones can become part of a commercial utility fleet, we need more research collaborations and demonstrations to see what they can really do for utilities and what limitations need to be addressed,” he said.

Drones to Inform Nuclear Accident Response

A month after the Fukushima accident, Tokyo Electric Power Company deployed drones to take aerial photographs of the damage. EPRI is now investigating ways to deploy drones much earlier in an accident’s progression to reduce its severity.

A key objective of a nuclear accident response is to gather data on plant conditions while minimizing worker exposure to radiation and other hazards. SAMI serves this purpose, as it is intended for deployment shortly after a beyond-design-basis accident.

“Fukushima spurred our interest in developing a drone to fly inside a nuclear facility following a severe accident, survey the site, and inform a quick response,” said Lopez. “Our goal is a small, lightweight, stable, maneuverable, and resilient drone able to withstand high temperatures and radiation inside a nuclear plant.” Radiation resistance is critical for preventing damage to the device’s electronics.

In the SAMI project, UNCC engineering students conducted most of the prototype design, development, fabrication, and testing, with EPRI providing technical assistance.

The team specified several performance requirements for SAMI: maneuverability inside a nuclear plant’s containment structure; payload for recording data on temperature, radiation, humidity, and air pressure; and real-time data transmission off-site for analysis.

Researchers then designed a prototype of a four-propeller helicopter, or quadcopter, approximately 3 feet in diameter with an 8-pound carrying capacity. In a feasibility study, researchers outlined concepts for flight-control and data-collection systems. These include fiber-optic communications between an off-site operation command center and the quadcopter’s base station in the nuclear plant, as well as wireless communications between the base station and the drone.

**GoPro is a registered trademark of GoPro, Inc.*

As built, the prototype was equipped with waterproof motors, a high-resolution GoPro® camera,* infrared temperature sensor, and communications. Researchers operated it to validate power, navigation, and communication systems.

EPRI is planning next stages to include designing a blast-proof base station to house multiple drones for longer missions; improving the heat and radiation resistance of the drone's frame, electronics, camera, and sensors; adding a more powerful motor to boost the carrying capacity; constructing a more radiation-resistant prototype; and durability testing.

Inspect Concrete Structures Safely

Also with EPRI's assistance, UNCC engineering students have developed a quadcopter to detect damage in large concrete structures such as cooling towers, containment structures, and hydroelectric dams.

Hydropower dams are among the electric power sector's oldest concrete structures. "The current generation of dams is on average about 50 years old, but many are 60 to 80 years old, and they must be inspected regularly," said Lindberg. In fact, more than 5,000 dams around the country are at least 100 years old, according to the U.S. Army Corps of Engineers. Routine structural evaluations of dams typically require inspectors to rappel from the top or work on scaffolding that must be erected.

Equipped with a high-resolution GoPro® camera, global positioning system, telemetry radio, and lithium ion phosphate battery, this quadcopter is designed to locate, record, and transmit images of concrete damage to a ground station, where an inspector analyzes the results.

Inspectors then upload information collected by the drone to a robotic concrete crawler for a more detailed examination. The robotic crawler, which EPRI has been developing and testing since 2011, carries equipment to measure and map specified areas of the structure, as well as nondestructive evaluation devices that inspect deeper concrete layers.

A second generation of the concrete-inspecting drone added new features such as an improved camera, GPS system, and propeller guards to protect rotors from damage as the drone hovers close to a structure.

"We're planning a third generation with improved features and flight control capabilities, more payload capacity, and a bigger battery," said Lindberg.

Researchers have tested critical equipment in the laboratory. In one test, the camera detected simulated flaws in concrete structures from different distances. The team has also validated the drone's in-flight stability.

"The prototypes have proven quite effective for our research, but full-scale demonstration in the field requires a jump to commercial products," said Lindberg. "Depending on utilities' needs, we may seek an FAA exemption for a demonstration of commercial drones in 2016 or 2017."

Drones for Boiler Inspection

Inspecting power plant boilers is time-intensive and physically demanding. To prepare for the inspection, plant operators must first shut down the boiler to construct scaffolding inside. Inspectors then climb on the scaffolding and crawl around small, dark, and dirty spaces.

With United Dynamics Advanced Technologies, EPRI has investigated the use of drones to make this task easier and more cost-effective. EPRI previously worked with United Dynamics on diagnosing boiler tube failures and heat recovery steam generator (HRSG) inspection manuals. The company's Magnabot—a rectangular-framed quadcopter measuring 18 inches across—recently attracted EPRI's interest because of its ability to fly inside boilers and conduct inspections.

Through site visits to EPRI's utility members, EPRI has evaluated Magnabot's potential value, identifying additional work needed to ensure effective inspections. "During weekend and forced shutdowns, members have successfully flown Magnabot to inspect their boilers without exposing workers to hazardous conditions," said Bill Carson, manager of EPRI's HRSG Dependability program. "The drone has demonstrated the benefit of inspecting difficult- or impossible-to-reach areas." Carson added that discussions with members in EPRI's Boiler Reliability Interest Group revealed how these inspections provided the utilities with valuable information for planning, as well as for compliance reporting for federal Mercury and Air Toxics Standards.

The drone's payload includes high-intensity floodlights, a high-resolution camera for still shots and video, and communications. The accompanying control station enables focus on areas of interest through live camera feeds. Other features requested by EPRI members include landing on and attaching to boiler tube walls—which could conserve power during inspection—and rollers for climbing boiler tube walls for close-up views.

EPRI plans to work with United Dynamics to deploy nondestructive evaluation devices as potential Magnabot payloads in field trials. For instance, ultrasonic testing can help determine thickness of boiler tubes—a key indicator of their remaining life. EPRI will also continue to evaluate drones from other manufacturers to gauge their potential for boiler inspections.

Drones' Future Flight Path

Whether they're used for severe nuclear accident response or to inspect concrete structures and boilers, drones provide wings for existing inspection devices. Because this means adding payload, drones may need more powerful motors and bigger batteries. EPRI is working with vendors to address these and other limitations for specific applications.

In approving dozens of drones for use in the electric power industry this year, the FAA has validated the enhanced safety enabled by these unmanned aircraft systems. Now it is up to researchers, utilities, and vendors to work together on a flight path for the power sector's new birds.

Key EPRI Technical Experts

Stephen Lopez, Bill Carson, John Lindberg

Feature—Ensuring a Clean Grid—Batteries Not Excluded

EPRI Examines Environmental Aspects of Grid-Scale Battery Deployment

By Chris Warren

One of the great modern-day environmental success stories is found under the hood of most cars: lead-acid batteries. While it may seem unlikely that anything containing flammable acids and lead could reflect environmental stewardship, consider that 96% of lead-acid batteries are recycled—surpassing paper and aluminum.

"It is recycling done well and a model for other industries," said Brittany Westlake, an EPRI engineer scientist who leads cost and technology assessments of energy storage. "Lead is toxic, and the acid in batteries is hazardous. But the lead-acid battery industry has well-established recycling processes and protocols for neutralizing the hazards and reusing valuable materials."

Replicating such success in the electric power industry is a pressing matter. As the power system incorporates growing capacity of variable solar and wind generation, battery storage becomes essential. Understanding the spectrum of potential environmental issues well before they become a problem is key to addressing them.

"Battery recycling and disposal are important but not the only considerations," said Westlake. "Equally critical is understanding the impact of mining the minerals that go into batteries as well as the energy and resources used to make them."

It will take time to develop the infrastructure and processes to recycle and dispose of large numbers of grid-scale batteries and their diverse materials. Fortunately, recycling companies can draw on decades of experience in the lead-acid battery industry to build an effective recycling model.

Many industry observers believe that lithium ion batteries will become widely used by utilities. Already, two companies—Retriev Technologies and Umicore—have taken substantial steps towards creating a recycling infrastructure for this technology. Given a surge in the demand and production of lithium ion batteries, Westlake expects that recycling companies, engineering firms, and others will rise to the challenge.

One helpful aspect: grid-scale batteries have a long life. "The good news is that most batteries are expected to last 10 to 15 years, giving us time to get ahead of environmental concerns," said Westlake. "But preparing the infrastructure could take that long, so utilities have to start planning now."

Many Battery Flavors, Many Challenges

If lead-acid batteries were the only choice for future energy storage, there wouldn't be such an urgent need to figure out disposal and recycling. The reality is that battery technologies are as varied as ice cream flavors. Also, it's possible that multiple technologies will be needed to meet varying grid applications, which could require many processing methods for recycling.

There are numerous environmental issues to consider with lithium ion batteries. Lithium can pose significant disposal hazards. While many lithium compounds used in industrial processes are harmless, even a small amount of elemental lithium reacts violently, sparking flames in contact with water. This makes it critical to prevent leaching from landfills into groundwater. Flammable organic solvents in lithium batteries can be ignited by a spark, also making them potentially dangerous in landfills.

"The good news is that these issues can be readily addressed," said EPRI Project Manager Rachna Handa, who conducts energy storage research. "Lithium can be processed so that it doesn't react with water, and the solvents can be neutralized. Properly handled, they're relatively safe."

Of course, recycling the batteries is preferable to disposal. "Nobody wants millions of batteries in landfills," said EPRI Program Manager Haresh Kamath, who leads efforts to develop and assess energy storage technologies. "We believe cost-effective reuse and recycling strategies are possible for all battery technologies, including lithium ion."

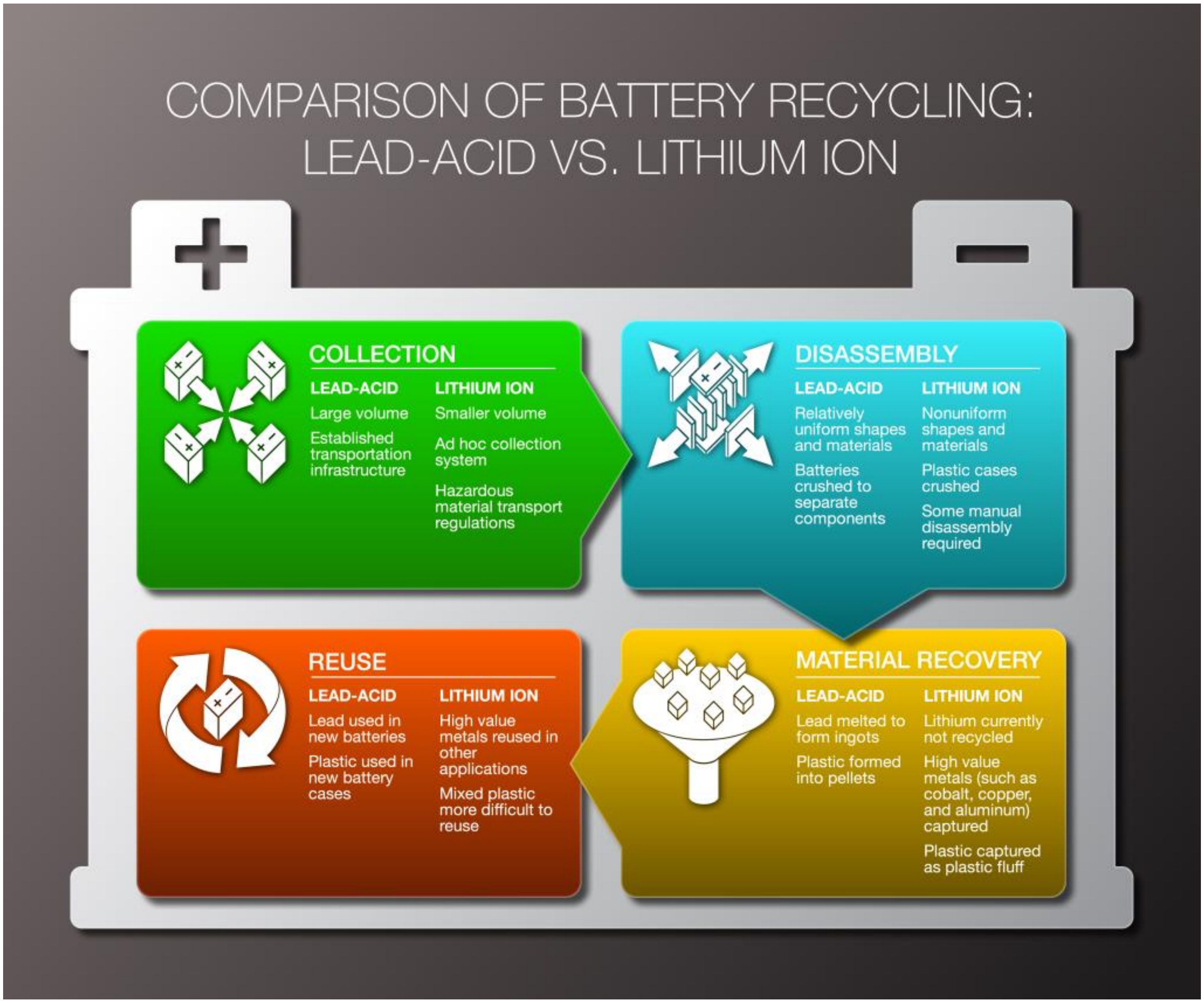
Responding to increasing production of lithium ion batteries, EPRI completed a comprehensive survey of the current methods, costs, and hurdles to recycling and disposal. An important finding: replicating the lead-acid battery industry's infrastructure of independent recycling companies for lithium ion batteries will be no easy task. Lead-acid batteries are easier for recyclers to process because they are more uniform in chemistry and configuration. While prohibitions on the disposal of lead-acid acid batteries in the United States create a powerful incentive to recycle them, lithium ion battery disposal is permitted.

The variety of lithium ion batteries presents a major challenge. They don't come in standard shapes or sizes. The different chemistries include lithium manganese oxide—found in first-generation electric vehicles such as the Chevrolet Volt and Nissan Leaf—and lithium nickel cobalt aluminum oxide in Tesla vehicles. "Different chemistries will have slightly different processes for dismantling and preparing the battery systems for recycling, and that's a challenge for the recyclers," said Handa.

Another challenge is the lack of resale value for the battery components. The commodity price for lithium has hovered consistently at about $3 per pound over the past few years, making it cheaper to mine than to recycle. Several factors could improve the economics of recycling: regulations requiring lithium ion battery recycling, a massive spike in demand, or geopolitical unrest disrupting lithium mining in South America. Today there's little economic incentive for recycling companies to set up infrastructure, with the exception of cobalt in Tesla's lithium cobalt batteries: It costs about $20 per pound and can be resold for use in electronics.

These factors could result in niche lithium ion battery recycling markets rather than one large one. "The biggest problem short-term is that there are no economies of scale for recycling," said Westlake. "It's easier to make a business case if you know you are going to get a steady stream of batteries with the same chemistry and configuration."

There is also uncertainty about which technology will become dominant. “We’re working to set up a recycling infrastructure while the production infrastructure is still being established,” said Kamath. “We are still looking at various scenarios of battery deployment and recycling needs.”



This graphic compares various aspects of lead-acid and lithium ion battery recycling.

Evaluating these issues is integral to EPRI’s work to help utilities determine the role of energy storage in long-term planning. “Instead of picking the winning technology, we are investigating which technologies work best in specific applications,” said Westlake. “For example, which batteries could help a utility defer an investment in an expensive new transformer at a substation?” Aligning battery technologies with applications and understanding recycling costs can help utilities make better decisions about energy storage.

This work can aid utilities as they plan for managing surging battery deployment, and help state and federal regulators formulate effective handling and recycling rules.

Going Beyond Recycling and Disposal

In 2016, EPRI will begin developing a model to assess the cradle-to-grave life cycle of lithium ion grid-scale batteries. Previous life cycle analyses conducted by EPRI, the U.S. Environmental Protection Agency (EPA), and Argonne National Laboratory focused on electric vehicle batteries and were limited to energy consumption during a few select phases of a product's life. Potentially sited near homes and businesses, grid-scale batteries are larger and subject to different regulations than vehicle batteries. A multi-disciplinary effort with EPRI's Environment and Power Delivery & Utilization research sectors, the new model will examine environmental impacts of grid-scale batteries comprehensively, including human and ecological health effects, energy and water consumption in mineral extraction, battery manufacturing, and recycling and disposal.

To guide model development, EPRI will first assess existing cradle-to-grave life cycle assessment tools and research on lithium ion batteries to identify knowledge gaps. EPRI will modify these tools to apply to different battery chemistries and technologies, then test the model and incorporate input from utilities, battery manufacturers, mining companies, and battery recyclers.

Along with the model, EPRI will publish a study summarizing existing knowledge about the various chemistries of grid-scale lithium ion batteries. By identifying and quantifying the range of environmental impacts of batteries, EPRI aims to provide utilities and society with information to decide when and where energy storage is a good choice.

Kamath believes that starting this work now is the best way to prepare for broader deployment of grid-scale battery storage. "We are at the front end of a very big opportunity in energy storage and looking at a new world unfolding before our eyes," he said. "Unexpected technical challenges and technologies will emerge. We are mapping the most likely futures so that we are prepared for the spectrum of environmental issues."

Key EPRI Technical Experts

Brittany Westlake, Haresh Kamath, Rachna Handa, Stephanie Shaw, Arnout ter Schure

First Person—Reinventing the Nation's Energy Systems: An "Unparalleled" Economic Opportunity

The Story in Brief

Lynn Orr is Under Secretary for Science and Energy at the U.S. Department of Energy. In this interview with *EPRI Journal*, Orr discusses his agency's recently released *Quadrennial Technology Review*, which examines the status of energy-related science and technology and R&D opportunities to advance them.

EJ: What is the significance of the recently released *Quadrennial Technology Review*?

Orr: As Under Secretary for Science and Energy, I look over the full range of fundamental science and applied energy research. My office led the effort to produce this Quadrennial Technology Review, though it involved a couple hundred people across the Department of Energy and about 500 outside experts helping with reviews and workshops. It was requested by the President's Council of Advisors on Science and Technology. They asked for the first one in 2010, and that was published in 2011, and this 2015 report is the next in the sequence.


Lynn Orr

We believe that the future of the United States depends on having a set of energy systems that are low-cost, secure, robust, and resilient, and that help us avoid climate change and other environmental impacts. The overall conclusion is that while we have made significant progress on all those fronts, there's a lot more to do. And there's a lot more we can do. There is a huge opportunity to invent the energy technologies and systems of the future, and our job now is to build and execute a portfolio of research that makes that possible. We need both the applied side and fundamental research. This is a time where we can put science and energy research to work in the interests of the nation.

The report's chapters look at six major energy sectors: the electricity grid, electric power generation, buildings, advanced manufacturing, fuels, and transportation. It also looks at these sectors from a systems standpoint, recognizing that individual energy technologies are important—and so are the systems in which they function. This perspective gives us some additional opportunities.

EJ: What are the next steps?

Orr: Translate this wide-ranging assessment of energy technologies and systems into the particular programs that we undertake. To decide where the best research opportunities are for us—and where there's an appropriate government role. Some of the work will be done by industry and other parts by us. The document is meant to be broader than just Department of Energy programs. We hope it will also be useful to others who are thinking about the energy system today and where it might go in the future—industry, research organizations, universities, and students around the world.

"We need both the applied side and fundamental research."

EJ: How does the report address the big changes and related challenges in the electric power sector?

Orr: This was the fun part of the assessment. There have been big changes in the electric power system since the last Quadrennial Technology Review, on both the supply and demand sides. There's a lot more wind and solar on the grid. There's been a shift in the mix of primary fuels that go into generating electric power. There are a lot of new phasor measurement units distributed around the nation, and there are a lot more smart meters. We have an opportunity to move the grid into an entirely new space. For example, having many more advanced sensors can tell us about the state of the grid, and advanced modeling can help us use that information to figure out where power should go. Advanced technologies and materials for power electronics and energy storage can help us manage deeper penetration of distributed generation and intermittent renewables, as well as microgrids. There is a big opportunity to provide better services, and to be more robust and resilient with new software and visualization tools to operate the transmission and distribution systems of the future.

EJ: What are the top three takeaways from the report?

Orr: I have four. The first is that the nation's energy systems—such as the electric power grid, pipeline systems, and transportation systems—are becoming much more connected with each other through communications and the Internet. These linkages give us opportunities previously not available by just working on individual systems. We can think about operating the linked systems in ways that balance loads and generation, and we can begin to optimize across these systems.

> "[The next steps are] to decide where the best research opportunities are for us—and where there's an appropriate government role. Some of the work will be done by industry and other parts by us."

The second is the diversification on both the supply side and the demand side. We have a richer set of energy resources being deployed for electric power generation, and we have diversified end uses. We're starting to think about electrifying transportation in a significant way. We've electrified a lot of our lives already, and that will continue in smart buildings and smart cities, so there's opportunity to provide better services there.

The third is energy efficiency. We have realized that we need to do energy efficiency everywhere in the system. It has immediate economic benefits, and it allows us to address climate change as well.

Fourth, we need to remember how important it is to have vigorous, fundamental scientific research underlying all these efforts—that takes advantage of our national laboratories and their user facilities. For example, it will be important to have ways to do advanced materials science, and high-performance computing can enable better control of very complex systems like the grid.

EJ: What might the convergence of all these energy systems look like? What do you see emerging to help them work in tandem?

Orr: There's both an opportunity and a challenge. The challenge is that all these systems have to communicate with each other to work effectively. That means that the communications need to be absolutely secure. Additional research is needed to achieve better cyber security, communications, and control systems.

In the 'how-cool-could-this-be' part of my answer, think about a city in the future. A unit for a city is a building. New energy-efficient buildings are complicated systems that require communications and sensors to figure out who's doing what and where, and what they need for heating, cooling, and other uses. In a neighborhood, there's a collection of buildings, and they might be connected by a microgrid that serves their needs. That microgrid links with the bigger grid, providing opportunities to manage heating, cooling, lighting, and power at the local and regional levels.

"We've electrified a lot of our lives already, and that will continue in smart buildings and smart cities, so there's opportunity to provide better services there."

Then there's the business of transporting yourself around the city. You'll use your Internet access to order your car with automatic, autonomous navigation, and that will get you where you need to go by avoiding the bad traffic spots and synchronizing with the traffic lights in the right way. You can imagine this as a set of linked, complex systems—systems of systems. There are plenty of challenges and opportunities to make this work in a way that will provide better services.

EJ: What is the role of research on breakthrough or "outside-the-box" technologies?

Orr: Sometimes breakthroughs will come because you backed up and tried to solve a problem in another way, and sometimes there is a new idea. Those are hard to schedule, but we can make sure that we take advantage of them when they happen. For example, particle accelerators were invented to allow us to understand the fundamentals of high energy and nuclear physics, and now we have 30,000 of them in use for applications in medicine, semiconductor manufacturing, security, and science.

Materials science offers opportunities for breakthroughs in almost all the areas in which we work, because many of the problems we need to solve require advanced materials. For example, wide bandgap semiconductor materials offer many opportunities for better transformers, active controls on power flow, and new design configurations that will enable better services.

"We are trying to reinvent the nation's energy systems, and we need all the tools we have now, plus more that we need to create. EPRI supports that work. EPRI can also help us communicate to the world why this is an important and necessary undertaking that is in all our interests. If we do this right, we have an economic opportunity for the United States that is quite unparalleled."

Another example: We can make many kinds of nanostructured materials now, and when you combine that with improved catalysts and the ability to make high-surface-area materials in the battery/fuel cell/energy conversion arena, that's a rich sandbox to play in, and we're trying to capitalize on that. That's a place where the fundamental science has an important role to play.

EJ: In light of the report's conclusions, how can EPRI help address DOE's R&D priorities over the next five years?

Orr: We've already taken advantage of EPRI and many of its member companies because there was such wide participation in preparing the report. But that was just the first step. We are trying to reinvent the nation's energy systems, and we need all the tools we have now, plus more that we need to create. EPRI supports that work. EPRI can also help us communicate to the world why this is an important and necessary undertaking that is in all our interests. If we do this right, we have an economic opportunity for the United States that is quite unparalleled. Just as electricity is woven through the fabric of modern society, a cost-efficient, robust, and resilient transmission and distribution system will underpin a globally competitive economy.

The assets of the energy system are, for the most part, privately owned, and there are myriad regulators at state and local levels. DOE helps to convene conversations among these groups to figure out ways to work together effectively. But to have a conversation, you have to have participants. We can count on EPRI to help us carry the conversation as we invent the electricity system of the future. That's a worthy endeavor.

EJ: The energy sector is transforming so rapidly that R&D needs may change in just a year. How does DOE plan R&D in such an environment?

Orr: We cheer. The fact that we can deploy the science and energy R&D resources that we have available, particularly in our 13 national labs that work on this area—that we can work in an agile way on the energy systems of the future—that's the most exciting thing that we can think of. We welcome the speed of change.

It is true that surprising changes have happened over the last four years, but they're the result of a lot of hard work to bring down the cost of things such as wind and solar. You're seeing utility-scale solar, and you're seeing individuals and businesses installing many solar panels. Wind is creeping up on 5 percent of electric power generation. Those are big changes, and they're an indication that the kind of research we've done in the past has paid off.

First Person—"Timely and in the Public Interest"

The Story in Brief

Sheryl Carter is co-director of the Natural Resources Defense Council's (NRDC) Energy Program and an EPRI Board member. In this interview with *EPRI Journal*, she discusses EPRI's public interest R&D role, R&D priorities, and policymaking in a rapidly changing industry.

EJ: How do you view EPRI's role in the electric power industry?


Sheryl Carter

Carter: We're facing a lot of challenges over the next 40 years and important goals we need to achieve—combatting global warming, modernizing the grid, addressing energy equity and affordability. We can make a lot of progress with the solutions we have in hand, but we need many new ones as well. Research fills the pipeline with those solutions. NRDC is a firm believer in research and development. We do not invest nearly enough in R&D, either by government or industry. Other countries invest much more. EPRI fills a critical role working with the industry to help provide the real solutions needed on the ground, as well as looking more broadly at the public interest for customers and the environment.

EJ: Can you point to recent examples of EPRI research that supports the public interest?

Carter: One great example is the whole "Integrated Grid" package of work. We're seeing big changes in the industry. On the customer side, you've got technologies such as rooftop solar, electric vehicles, and demand response, and on the industry side you've got increased large-scale renewables coming into the system with a more variable generation shape. The need to integrate these demand- and supply-side options has opened up a huge opportunity and many challenges. EPRI stepped in to address this issue with not just the industry, but also with technology providers and other stakeholders. It has provided a tool to utility commissions around the country to help them begin to assess what true integration could look like. That is both timely and in the public interest.

"EPRI fills a critical role working with the industry to help provide the real solutions needed on the ground, as well as looking more broadly at the public interest for customers and the environment."

EJ: What are the top three areas for EPRI to focus its R&D over the next five years?

Carter: One is energy efficiency. This is the cleanest and cheapest solution we've got, and we need to keep working to find increasingly efficient applications for electricity use. This is not necessarily just finding new technologies. It's figuring out how to better target energy efficiency to specific uses such as air conditioning that might make a difference on peak demand. It's also about better targeting efficiency in certain geographic regions to help relieve load in constrained areas, and ensuring that it is incorporated more fully into resource planning at all levels.

Number two: One potentially important way to decarbonize our economy is beneficial electrification—switching to electric alternatives of everyday technologies, such as automobiles, forklifts, and furnaces, when it reduces overall emissions and impacts at lower cost than fossil alternatives. Electrification is going to be increasingly important as our supply becomes cleaner, and EPRI has a big role to play there. Its work on heat pumps is a good start. But to be successful, EPRI must address the perception that electrification is just about load building. While EPRI works on these technologies, it needs to focus on the case that electrification is an overall environmental and efficiency improvement. NRDC and EPRI recently completed the second phase of research to help make the case to public utility commissions and other agencies that electric vehicles are a win for both the environment and the electric industry.

> "I want EPRI to carry the integrated grid concept one step further—not just work on integrating the distributed technologies we have now, but figuring out how to take fuller advantage of the benefits they can provide."

The third area is additional work on an integrated grid. EPRI has put together The Integrated Grid concept paper and a benefit-cost framework, which have been great contributions. I want EPRI to carry the integrated grid concept one step further—not just work on integrating the distributed technologies we have now, but figuring out how to take fuller advantage of the benefits they can provide. This involves strengthening the case that these technologies have a role to play to support the grid, and providing explicit guidance about what requirements they have to meet to benefit the grid and customers.

For example, for distributed rooftop solar, the case has been made that we need smart inverters. Germany found out after the fact that this was important. Now we need to know what smart inverters need to do to provide services to the grid, as well as have the grid provide services to the customer. EPRI has already done some work in this area, but more specific guidance is needed. Under what conditions would smart inverters provide benefits? What kinds of enabling technologies are needed to reduce the costs and increase the benefits? How do the answers to these questions vary depending on geographic location? This can equip regulators, utilities, providers, and customers to tap the capabilities of the technologies, help the overall system, and get the choices they want.

EJ: The electric power industry is changing rapidly, and no one knows exactly what the grid infrastructure or the customer will look like in 10 years. How does NRDC approach the task of identifying effective policies when the future is somewhat unknown?

Carter: With optimism and a focus on policies that support the cleanest and most efficient, reliable, and affordable electric system possible. The industry is moving to a low-carbon future, and is rapidly becoming a service-oriented and customer-focused business rather than a commodity-focused one. At the same time, it must make sure that it's providing affordable, reliable, environmentally responsible services. One of the first things we need to do is ensure that our regulations support movement in this direction. We don't need to know the exact future to do that.

> "Promising solutions are being added to the mix too rapidly to preordain the exact makeup of the grid…."

For example, traditional regulation penalizes utilities for not focusing on a commodity-intensive business because their cost recovery and financial health are dependent on kilowatt-hour sales. Regulation can be modified so they don't get penalized. For example, decoupling is a simple policy change that makes utilities indifferent to how much electricity they sell. It has been adopted in 16 states and is pending in another seven.

Breaking the link between sales and cost recovery is critical to ensuring a focus on service rather than commodity. But if the utility doesn't earn based on how much electricity it sells, you need to provide other earnings opportunities—linked to delivering clean, reliable, equitable, and affordable energy services, of course. Many utilities have been earning performance-based rewards for delivering on cost-effective energy efficiency savings, for example. Design and implementation of these performance-based rewards are going to be one of the more challenging things we face. New York's Reforming the Energy Vision proceeding is already talking about this.

Even if we don't know the complete future, there are actions we can take right now that will enable utilities to move forward with more freedom and flexibility, as long as we focus on moving toward a clean, reliable, and affordable end state. Promising solutions are being added to the mix too rapidly to preordain the exact makeup of the grid anyway.

Technology At Work

Change to Michigan Law Expands Use of Coal Combustion Products

Michigan Utilities Tap EPRI Research in Work with State Lawmakers

By Chris Warren

It's not as wide as the gulf separating ardent fans of the Wisconsin Badgers and Michigan Wolverines, but until recently a gap could be plainly seen between the two states' use of coal combustion products. For years, Wisconsin utilities such as We Energies have had a clear rule from state regulators for the use of fly ash, bottom ash, gypsum, and other coal combustion products in specified applications ranging from road base to wallboard to agricultural soil amendments (materials added to improve soil properties, reduce phosphorus loss in runoff, and promote crop growth).

Field application of gypsum

While Michigan didn't entirely prohibit the use of these and other industrial by-products, its laws and regulations governing such uses were more restrictive. As a result, applications such as soil amendments and road-base construction were impractical. This led We Energies, which also serves Michigan customers, to work with DTE Energy, Consumers Energy, Ford, General Motors, and other companies in a two-year effort to amend Michigan's Natural Resources and Environmental Protection Act. The outcome: in June 2014, Michigan Governor Rick Snyder signed legislation expanding permissible uses of industrial by-products, including coal combustion products.

Making the Case for Change

Although precedents for using coal combustion products have been considered and approved by other states and the U.S. Environmental Protection Agency, such a change in Michigan required thorough consideration. "The governor was interested, but it absolutely had to be legitimate," said Gary Dawson, Director of Land and Water Policy for Consumers Energy. "We had to prove that there were legitimate beneficial uses for these products that didn't hurt the environment."

The state's consideration drew from information provided in EPRI research. Particularly helpful, said Dawson, was years of research investigating environmental issues related to coal combustion products, their uses, and economic value. Prominent examples are an EPRI report that quantifies the benefits of using coal combustion products in sustainable construction projects and another on the use of flue gas desulfurization gypsum in agriculture. "There were dozens of papers," said Dawson. "We used the information in meetings with representatives of the state's Department of Environmental Quality and other agencies."

"The research helped demonstrate that these reuses are legitimate, beneficial, and safe for the environment," said Dawson.

Long-Term Benefits

Under the amended law, Michigan utilities can use coal combustion products to make stable roadway sub-bases, and gypsum can be sold to Michigan farmers for agricultural uses. With both applications, utilities can generate revenue from combustion products that otherwise would be shipped to landfills at significant expense. Their use can also reduce environmental impacts by replacing materials such as crushed stone and gravel that require resource-intensive mining processes. Another application now permitted is waste stabilizers at cleanup and landfill sites.

As the volume of coal combustion products grows with increasing numbers of scrubbers at coal plants, Michigan utilities could see additional opportunities for coal combustion products. The law's new provisions may encourage power companies to investigate and implement new uses for the materials.

Key EPRI Technical Experts

Ken Ladwig

Technology At Work

Protecting a Major Investment

EPRI Guidance Focused on Materials and Welds at the First U.S. Ultra-Supercritical Plant

By Chris Warren

Nick Akins was well aware of history—and he wanted to avoid repeating it.

In the mid-2000s, Akins and his colleagues at American Electric Power (AEP) began planning the design and construction of the $1.7 billion, 600-megawatt John W. Turk, Jr. coal plant in Fulton, Arkansas. Akins, who now is AEP's chief executive officer, knew how important it was to avoid the usual problems coal plants face early in their operating lives. "Typically, when these plants start up, the forced outage rate is high," said Akins.

For the Turk plant, the need was especially acute to protect against such outages. As the first ultra-supercritical plant in the United States, it would operate at temperatures above 1110°F and at a much higher efficiency than existing supercritical and subcritical coal plants with lower boiler temperatures. This would also result in lower fuel costs and substantially reduced carbon dioxide emissions.

This article is part of an *EPRI Journal* series exploring how collaborative R&D helps electric utilities manage various types of risk.

Read another article in this series about how We Energies reduced risk by transforming fly ash into asphalt.

But those benefits came with risks. High temperatures can adversely impact the durability of plant components, potentially leading to forced outages early in a plant's career and shortening its life. "If you subject materials to stress and high temperatures over time, they can age and degrade to the point where they are no longer useful," said Tim Riordan, AEP's vice president, engineering services. "When you consider a plant's materials, you have to balance how long a plant life you want and how much risk you're willing to take. We wanted to be sure to have an asset that has a 40-year life."

For Turk, the risks were substantial: a plant life shortened by five years as a result of component degradation could potentially mean a loss of tens of millions of dollars.

The John W. Turk, Jr. coal plant. Photo courtesy of American Electric Power.

To support Turk's reliable long-term operations, AEP collaborated with EPRI as the utility determined construction materials and maximum operating temperatures. AEP relied heavily on EPRI guidelines on materials for fossil power plants, covering topics such as fabrication of advanced steel components able to withstand higher temperatures and quality assurance steps during construction. "We used that as a basis for our plant materials and installation specifications," said Riordan.

AEP also applied EPRI research on filler metals used to connect dissimilar metal welds. In the 1980s, EPRI had determined that thermal stress was a main cause of filler metal failure and developed a filler metal to address this. (Ultimately, it was not commercialized because it tended to crack during welding.) When Turk was being planned, EPRI returned to the task and developed EPRI P87, a filler metal that could extend the life of dissimilar metal welds subjected to extremely high plant temperatures.

P87 was used in constructing Turk, and Akins said it provided the flexibility to design the plant for efficient operations at high and varying temperatures. "EPRI's guidelines and filler metal provided margins in the design that were necessary to manage the risk," said Akins. "It was clearly important to have a high level of confidence in the materials."

AEP and EPRI also addressed and mitigated the risk of exfoliation damage in advanced stainless steel superheater components. "The use of new advanced materials, steels, and alloys makes ultra-supercritical power plants possible," said John Shingledecker, EPRI program manager for fossil materials and repair. "A big part of EPRI's research is to improve our scientific understanding of these materials so we can ultimately provide AEP and others with the best guidance on procurement, fabrication, and long-term life management."

Keeping a Watchful Eye During Operations

The collaboration has continued since the Turk plant began operations in late 2012. EPRI is examining material samples from Turk to determine if their performance matches expectations. AEP will use the test results as it considers when and how to perform extensive plant inspections. "EPRI's tests look for early signs of degradation to make sure the plant is still expected to operate for its full design life," said Riordan. "Continually looking for signs of thermal damage in the components is helping us to outline an inspection protocol for the future."

Akins said that Turk's performance to date has been exceptional. He considers this good news—both for AEP in meeting its load demands, and for the industry in achieving carbon dioxide emissions reductions mandated by the U.S. Environmental Protection Agency's Clean Power Plan. "That is a big deal when you realize that this plant is 10 to 15 percent more efficient than nearly any other coal plant in the country."

Shaping the Future

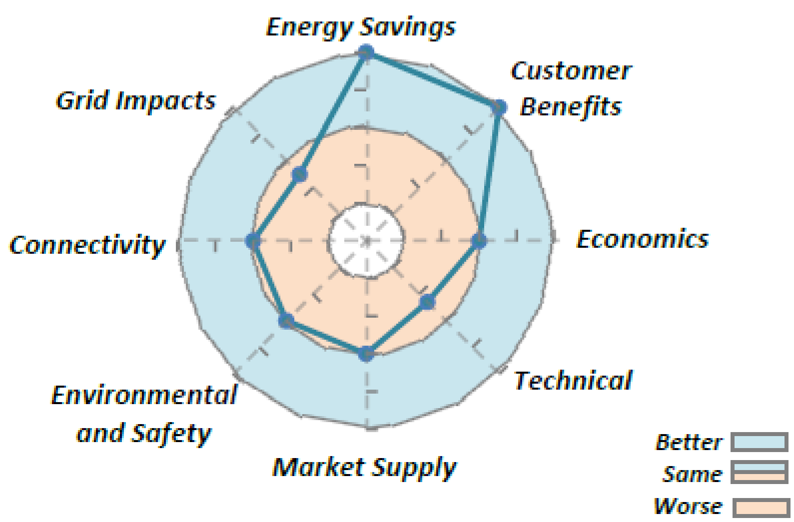
Tracking the Energy Efficiency Pipeline

EPRI Guide Helps Utilities Identify Technologies Best Positioned for Cost-Effective Deployment

By Garrett Hering

What is the cheapest, most environmentally benign electricity resource today? While most people first think of emissions-free wind and solar power, the answer is *energy efficiency*—the use of technologies that consume less energy to provide the same service.

Twenty-four U.S. states recognize the value of energy efficiency by setting mandatory or voluntary targets for electric utilities, which in turn encourage residential, commercial, and industrial customers to invest in energy-saving products such as LED (light-emitting diode) lamps, thermostat controls, and heat pumps. But with so many efficiency products, either new or under development, it can be daunting for utilities to identify the most promising ones for their energy-efficiency programs.



Charting progress: EPRI's Technology Readiness Guide scores energy efficiency technologies in a variety of categories. For each of these categories, the scores are plotted on a radial chart to compare performance of emerging and existing technologies. Very favorable technologies, such as LED lamps (shown in the chart), will have scores closer to or inside the blue ring. Scores closer to the center indicate that a technology is less favorable for a particular category.

In 2012, EPRI created its Energy Efficiency Technology Readiness Guide to help utilities determine the most cost-effective technologies with potential for broad deployment. Updated annually, the guide serves as a useful reference for utilities with long-standing and newly created efficiency programs. The 2015 update is available now.

"We provide a systematic assessment of technologies at different stages in the R&D pipeline, based on our own evaluations and drawing on input from utility program administrators and technology developers," said EPRI Project Manager Tom Geist.

The guide reviews dozens of technologies in five development phases:

1. **Technology scouting**. These early-stage technologies could become candidates for utility programs. Technologies often enter the pipeline through EPRI's Technology Innovation program, national laboratories, and universities.
2. **Assessment and lab testing**. Technologies advance to EPRI's End-Use Energy Efficiency and Demand Response program for laboratory testing and assessment.
3. **R&D field tests and demonstrations**. Based on laboratory performance, technologies graduate to field tests by EPRI and others, on a scale of tens to hundreds of units.
4. **Coordinated early deployments**. These larger-scale technology tests validate results from earlier stages and address challenges in supply chain and customer adoption.
5. **Full program rollout**. Technologies are deployed in utility energy efficiency programs.

"At some point in the pipeline, EPRI has supported each of the technologies through concept assessments, testing, case studies, or detailed cost-benefit analyses," said Geist. "This helps to move high-potential technologies through the pipeline and into efficiency programs."

The 2014 guidebook provides two-page briefings for 35 technologies, each with a short description of the device; testing results; technical information on cost, safety, environment, and grid impacts; images and graphics; requirements for advancing to the next stage of the pipeline; and an overall readiness score (see chart).

Technology readiness scores range from 0 to 100, with higher scores for devices further along in the pipeline. For example, electrochromic windows—which rely on layers of thin films on glass to control the amount of visible and infrared light entering buildings—are at the scouting stage with a technology readiness score of 10. Several types of residential and commercial heat pumps score from 40 to 75. LED lamps to replace incandescent bulbs are already included in many utility efficiency programs, scoring a 95.

Using this information, utilities can gain insights on those technologies best positioned to achieve cost-effective energy savings in their service territories now and in the future.

"We are working to fill the gap between the very detailed technical information of interest to engineers and more application-specific information," said Geist. "The Technology Readiness Guide is right in the middle."

Key EPRI Technical Experts

Tom Geist

Innovation

DERMS: Software and Communications for Grid Integration

Researchers Envision App Managing Millions of Distributed Energy Resources

By Matthew Hirsch

Who Knows What DERMS Is?

In a recent presentation about future grid innovations, EPRI Technical Executive Brian Seal gave the utility representatives in the audience a pop quiz. “I asked who had heard of DERMS,” said Seal, whose research addresses communication systems for distributed renewables. “Almost all the hands went up.” DERMS, or Distributed Energy Resources Management Systems, are new types of software and communication systems that manage distributed energy resources (DER) such as solar photovoltaic and battery storage systems. Such systems are envisioned to connect to thousands or someday millions of smart inverters, managing them in organized groups and simplifying their integration with distribution management systems and the rest of the utility enterprise.

DERMS are new types of software and communication systems that manage distributed energy resources such as solar photovoltaic systems.

Who Has DERMS on Their Systems?

“Then I asked who had DERMS, and no hands went up,” Seal said. “Utilities are aware that this need is coming soon and want to figure out how to fit it into their information and communications technology frameworks.”

“Connection of distributed energy resources to the distribution system is creating technical challenges, and increasingly utilities are using distribution management systems, or DMS, to improve reliability, optimize efficiency, and maintain power quality,” explained Seal. “These systems typically perform their duties by using a small number of relatively simple control devices. In their present form, they cannot manage large and growing numbers of grid-tied smart inverters with numerous complex functions, such as Volt-VAR control. DERMS supports distribution management by organizing the monitoring and management of these devices.”

What Will DERMS Do?

Industry stakeholders envision four primary roles for DERMS:

- **Aggregate**. Take the services of many individual distributed resources and aggregate them in a manageable number.
- **Simplify**. Handle the details of distributed resources’ settings and present simple, grid-related services.
- **Optimize**. Harness various distributed resources groups at minimal cost and maximum power quality.
- **Translate**. Diverse languages of various resources are presented and used cohesively.

Standards for DER Integration at Every Level

In recent years, Seal's team at EPRI worked with Sandia National Laboratories and the U.S. Department of Energy's (DOE) SunShot program to accelerate the development of international standards for communication interfaces from DERMS to individual inverters. As the DERMS' role is better understood, EPRI, DOE, and the National Renewable Energy Laboratory (NREL) are developing communication methods for groups of inverters, ensuring coordination with established interoperability standards. These standards can be used to integrate DERMS with other grid applications.

"We recognize that grouping DER and managing these groups must be possible at many levels: in a building management system, within a microgrid, at the feeder or circuit level, by the distribution utility, and by the system operator," said Seal. "This principle was previously applied in developing demand response standards and is now a key aspect of our DER integration strategy."

With respect to distributed resources, the urgency for DERMS depends on their number, characteristics, and location, along with distribution system design. In some regions, such as parts of Hawaii, smart inverters and DER management systems are needed now. Without them, maintaining grid stability and protecting grid assets become increasingly difficult.

Developing and Testing a Reference DERMS

NREL and EPRI recently tested newly developed DER group-management functions and messages at a workshop with software technology companies. To support testing, EPRI developed a reference DERMS software that can communicate upstream with enterprise applications and connect with and manage many smart inverters downstream. This enables the testing of algorithms to optimize dissemination of messages to various DER groups.

For the NREL workshop, EPRI built a tool for testing early-stage products, and vendors used it to demonstrate interoperability among DMS, DERMS, and utility distribution control systems. The successful demonstration helped build interaction among vendors, which continue to remotely access EPRI's test tool through an online server.

Bryan Palmintier, a senior research engineer in energy systems integration at NREL, said that eventually DERMS could be integrated into an *advanced distribution management system*—a mega-platform of all distribution management functions. "That's where I see the future and the excitement in this space," Palmintier said.

Key EPRI Technical Experts

Brian Seal

In The Field

Ultrasonic Device Sends Right Signals for HRSG Drains

By Garrett Hering

At a critical point in the post-apocalyptic movie, *Dawn of the Planet of the Apes*, one of Earth's last technicians uses an ultrasonic flowmeter to measure cooling and lubricating fluids inside pipes at a hydroelectric power plant. This enables a surviving remnant of humanity to restart the plant and deliver electricity to what is left of San Francisco.

Components of the EPRI-Flexim flowmeter solution attached to a drain pipe in a heat recovery steam generator.

EPRI turned to the same vendor—Flexim Americas—to test a modified version of its ultrasonic flowmeter in an innovative application to detect and purge condensation in heat recovery steam generators (HRSG), preventing costly damage. Since 2010, EPRI has assessed various condensation detection alternatives and in 2012 identified the Flexim flowmeter as a promising candidate.

During power plant startup and shutdown, condensation occurs in the high-pressure superheaters and reheaters of steam generators. As designed, drain systems at many of the world's more than 2,400 combined-cycle–natural-gas facilities do not adequately remove the condensate, which can result in severe fatigue and cracking on superheaters, reheaters, headers, and piping. It is a leading culprit in premature part failures, reduced plant availability, and increased maintenance costs. The problem is especially acute at horizontal-gas-path HRSGs, but it also can affect vertical-gas-path HRSGs.

In EPRI's solution, the flowmeter components are attached to drain pipes. Separately installed drain valves are synchronized with the flowmeter to automatically purge the identified condensate. The system differentiates between condensation and steam by sending ultrasonic signals into the pipes and timing their return. In field trials, the Flexim equipment immediately identified water in drain pipes and clearly indicated when drain valves opened and closed.

Since 2012, EPRI has successfully installed and tested this solution at Oglethorpe Power's Thomas A. Smith Energy Facility (a 1,250-megawatt plant in Murray County, Georgia) and at PSE&G's Bethlehem Energy Center in Albany, New York (which has a smaller, more tightly configured HRSG) and has validated it at other plants with different drain configurations and pipe sizes. It is available to be applied to the broader industry to provide for cheaper, more reliable production of electricity.

The technology could soon replace the conventional approach for detecting and removing condensation, which involves sealing moisture in large chambers called drain pots. In a 2007 report, EPRI found that most drain pots can be ineffective and high-maintenance, whether installed with new HRSGs or as retrofits. Most HRSG operators find them too large and expensive as retrofits and typically don't use them. This requires that drains be opened manually to purge moisture. With no way to detect moisture, operators have difficulty determining the right times to open and close drains. Closing drains too soon can severely damage pipes and headers, and opening them too often wastes energy and overuses components.

Ready for Primetime

“We are ready to go primetime in early 2016,” said EPRI Project Manager Bill Carson, adding that EPRI will assist Flexim’s rollout of the new ultrasonic flowmeter. “We have started presenting the technology to plant owners and operators. We plan to transfer this to industry next year, with commercial applications at different plants with a variety of drain configurations.”

Carson expects installation to cost less than $100,000 per plant, compared to more than $1 million for drain pots and other conventional solutions.

The two-year field demonstration at Oglethorpe Power’s unit included drain system modifications, installation of automated drain valves to purge condensate, and pressure measurements in drain pipes to confirm successful removal. “There are detailed installation and maintenance procedures, but the technology is still much cheaper than drain pots—and it is very effective at removing condensate,” said Carson.

Key EPRI Technical Experts

Bill Carson

In Development

Making Fiber Optics Work for Carbon Storage

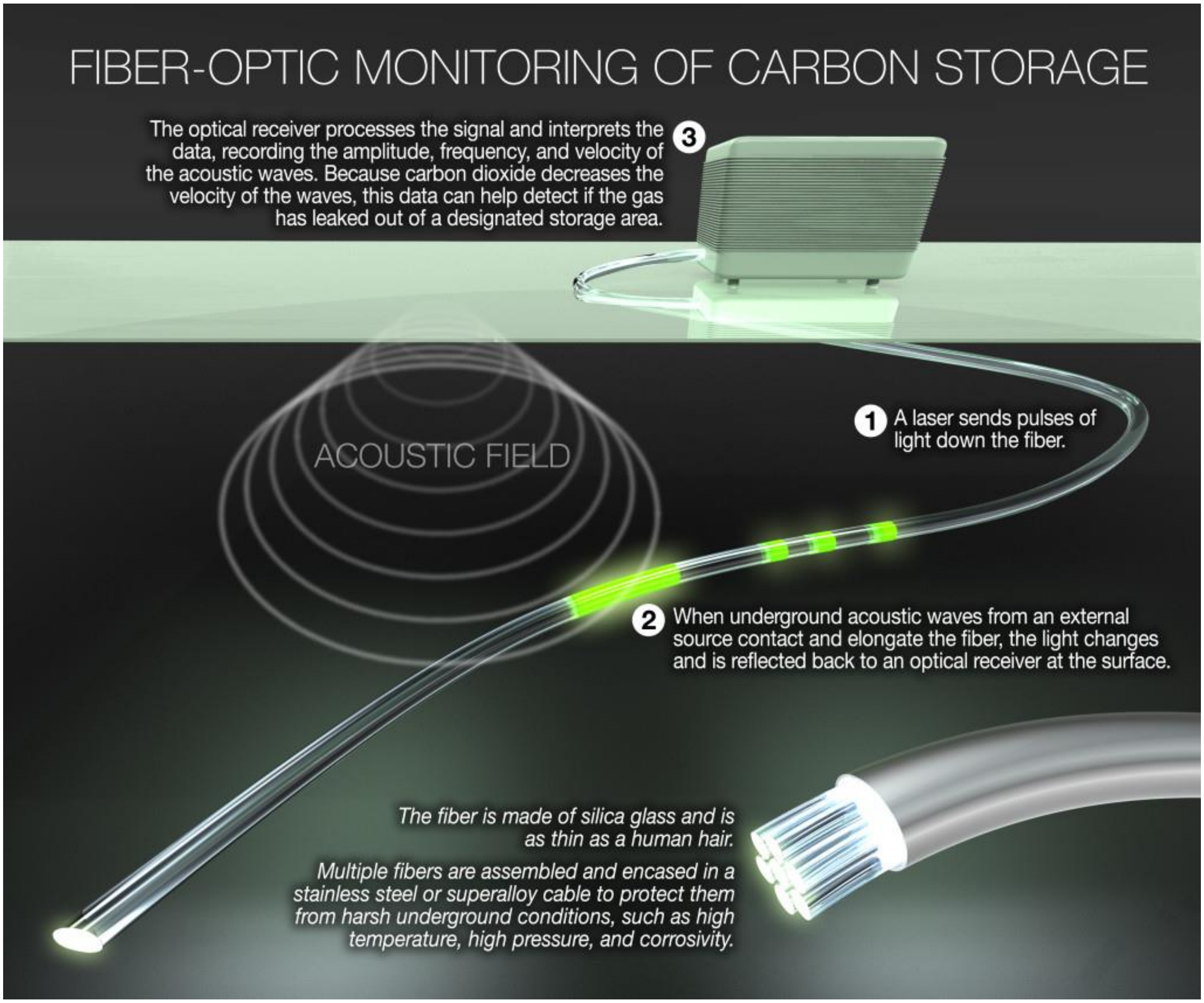
In Field Tests, Technology Demonstrates Potential for Cost-Effective, Accurate Monitoring of Underground Reservoirs

By Robert Ito

In Alabama field tests, EPRI has demonstrated the effective performance of fiber-optic arrays for monitoring carbon dioxide (CO_2) sequestration sites, creating an important application for this workhorse technology of the 1990s telecommunications boom. More field work is needed before commercialization.

Cost-effective, accurate monitoring of CO_2 flow, leakage, and distribution is needed to ensure safe, permanent storage in deep underground formations. Existing monitoring technology relies on an acoustic source—such as a heavy "thumper" truck that vibrates metal plates on the ground to send sound waves through the earth. The waves bounce off a reflective surface—for example, the bottom of a storage reservoir—and underground motion detectors called geophones measure the wave response, indicating the presence of CO_2. Geophones were first used by French soldiers during World War I to detect the presence of German tunnels. Today, geophones used for sophisticated time-lapse imaging of CO_2 plume positions must be set into place every time they are used to conduct underground surveys, which can result in inaccurate results if not placed in the same position every time. The devices are prone to mechanical failure, and their analog data transfer is slow.

Serving as both sensors and transmitters, fiber-optic cables can potentially provide more reliable data at a lower cost. Light pulses are sent down fibers and reflected back to the surface, with measurements made along the length of cables at any time. A data acquisition system gathers and interprets the sensor data. "With this approach, you can capture distributed data from 10,000 point-like measurements with 1-meter resolution along a 10,000-meter-long fiber-optic cable," said EPRI Principal Technical Leader Robert Trautz. "The spatial resolution on these fiber-optic arrays is about 10 times greater than standard geophones."



This graphic shows how fiber-optic monitoring of carbon storage works.

Unlike geophones, fiber-optic arrays can stay in the same place over a power plant's lifetime. They have no moving parts and are more durable. Cables are encased in protective materials such as stainless steel or Inconel (a nickel-based superalloy) to help them withstand the high temperatures, pressures, and salinity in deep underground environments. The arrays can transfer data at rates up to 16,000 samples per second.

With funding from the U.S. Department of Energy, EPRI has demonstrated how fiber-optic-based sensors can be used to identify dangerous, costly leaks and maximize CO_2 storage capacity—crucial to the successful implementation of carbon capture and storage technology. With continued testing, researchers believe that the commercial use of fiber-optic sensor arrays can revolutionize the emerging CO_2 storage industry.

Tests in Alabama

EPRI conducted initial tests at the Citronelle Oil Field in Alabama to compare the performance of geophones and fiber-optic arrays. Led by Trautz, researchers injected CO_2 into a storage reservoir 9,400 feet underground. Next, thumper trucks sent acoustic waves deep into the earth, and a crane raised and lowered a string of geophones to measure the reflected waves. Surveying the storage reservoir with this approach took about five days. Using a fiber-optic array, researchers completed the same survey in just one day. In addition to documenting the limitations of geophones—several were lost because of mechanical failure—researchers successfully used the fiber-optic sensors to create high-resolution seismic images of the storage reservoir.

The Citronelle tests comparing geophones and fiber-optic arrays will be completed in 2016. Researchers are looking for a site with a CO_2 injection well for further CO_2 flow and storage evaluations.

Temperature Sensing for CO_2 Storage

Because replacing water with CO_2 in deep underground wells and rock pores can change the thermal properties of these geological formations, temperature measurements can be used for monitoring CO_2 storage, distribution, and flow along a fiber-optic cable's length. EPRI researchers are looking for a site host to test the *heat-pulse monitoring method*, which uses fiber-optic-based distributed temperature sensing technology coupled with copper heater elements to measure subtle changes in thermal properties related to CO_2 movement into and through rock.

"With further testing, I can see this technology becoming fully commercial in less than five years," said Trautz.

Key EPRI Technical Experts

Robert Trautz

EPRI JOURNAL

The **Electric Power Research Institute, Inc.** (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

3002007152

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 | PO Box 10412, Palo Alto, California 94303-0813 | USA
800.313.3774 | 650.855.2121 | askepri@epri.com | www.epri.com