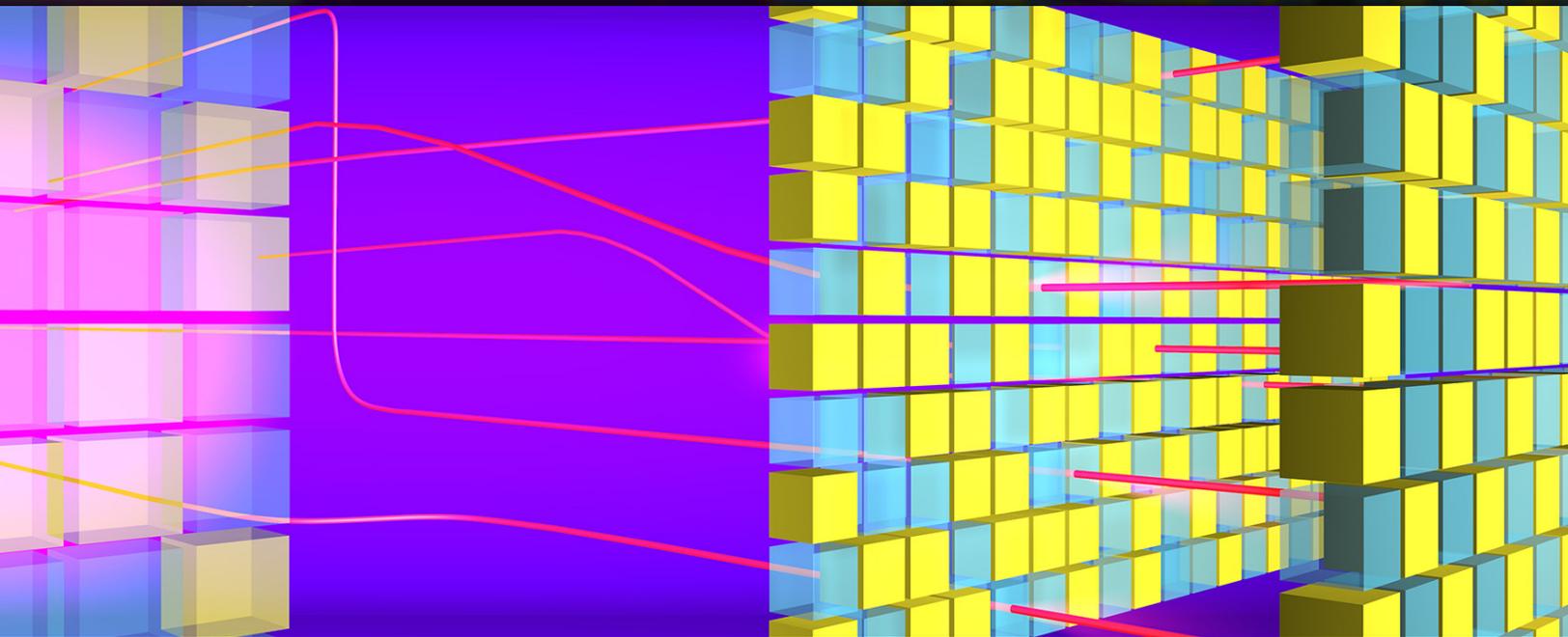


EPRI JOURNAL

Toward a New Risk-Informed Approach to Cyber Security



ALSO IN THIS ISSUE:

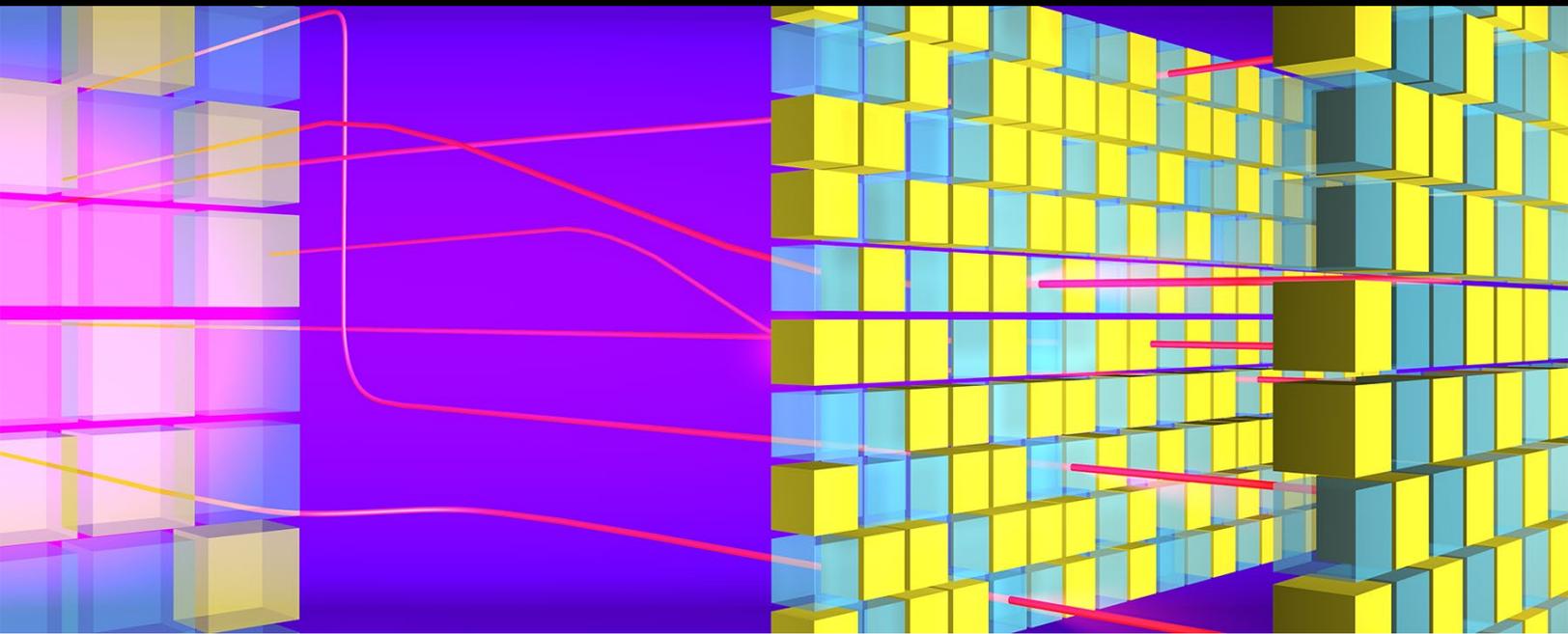
Utilities Abuzz

Can Blockchain Be a Blockbuster?

Nuclear Plant Modernization Advances in Utilities Large and Small

Table of Contents

Toward a New Risk-Informed Approach to Cyber Security.....	1
Utilities Abuzz	4
Can Blockchain Be a Blockbuster?.....	9
Nuclear Plant Modernization Advances in Utilities Large and Small	12
A New Motion Sensor to Fine-Tune Power Plant Operations.....	15
Active Efficiency: A Bold Step to Reimagine Energy Efficiency for the Digital Age	17
From Lithium to Potassium	19
A New Way to See Vibrations in Plant Equipment.....	21
Vehicle-to-Grid: \$1 Billion in Annual Grid Benefits?	22
Can Transmission Line Inspection Be Completely Automated?	23



Toward a New Risk-Informed Approach to Cyber Security

EPRI Guidelines Equip Electric Power Industry to Address Growing Risks and Vulnerabilities

By Chris Warren

A More Targeted Approach to Cyber Security

EPRI has developed step-by-step guidance for utilities to assess cyber security measures at power plants, informed by risk. The methodology enables users to allot more time and resources to protect the devices most critical to operations. “We made the business case for EPRI’s methodology with our senior management,” said Brad Yeates, Southern Nuclear’s manager of cyber security for Vogtle Units 3 and 4. “We concluded that this new approach was the most direct and cost-effective one.”

In a power plant, robust cyber security depends on safeguarding control system components. One critical component is a plant’s engineering workstation.

“It’s important to protect the engineering workstation because it’s connected to the programmable logic controllers in a power

plant,” said EPRI Senior Technical Leader Jeremy Lawrence. “It’s a prime target. If attackers get into it and inject malware, they could potentially compromise critical plant control functions and shut down the plant.”

The traditional “defense-in-depth” approach to protecting digital plant control components from attackers involves layering various security measures—a complex undertaking. It’s challenging to quickly determine the optimal types and number of layers.

Bulk power system operators in North America must comply with the North American Electric Reliability Corporation’s (NERC) Critical Infrastructure Protection (CIP) Standards. The NERC standards, along with cyber security regulations from the National Institute of Standards and Technology and the U.S. Nuclear Regulatory Commission, are sometimes known as the committed catalog approach because they direct the implementation of a catalog of security measures for all components. While this approach provides a

degree of security, power industry stakeholders are investigating the benefits of a more targeted approach—applying security measures to specific vulnerabilities in plant control systems.

“Standards and regulations have played an essential role in establishing a baseline of cyber security protections for the electric power industry—and in bringing stakeholders to the table to discuss how to secure critical assets,” said Lawrence. “Yet, compliance with standards and regulations doesn’t equal security. Power plant operators are raising the bar on cyber security to implement more sophisticated measures above and beyond the regulatory requirements.”

This is in line with growing cyber security risks. Last year, U.S. Department of Energy (DOE) Secretary Rick Perry told lawmakers that hundreds of thousands of cyber attacks on the American energy system take place each day. According to DOE’s Multiyear [Plan](#) for Energy Sector Cybersecurity, “The frequency, scale, and sophistication of cyber threats have increased, and attacks have become easier to launch. Nation-states, criminals, and terrorists regularly probe energy systems to exploit cyber vulnerabilities in order to compromise, disrupt, or destroy energy systems.”

“The threat only goes up,” said William Vesely, a project specialist in control systems engineering at Con Edison, the utility that serves New York City and Westchester County, New York. “Critical infrastructure in the power industry is a prime target, and staying ahead of the game is challenging and requires vigilance.”

RISK-INFORMED CYBER SECURITY

In collaboration with utilities, control system manufacturers, policymakers, and regulators, EPRI is developing new cyber security approaches to protect critical power plant assets.

As part of this research, EPRI has developed an advanced risk-informed [methodology](#) for utilities to assess cyber security measures. This step-by-step approach involves considering potential security breaches, their likelihood, and the consequences (such as radiological release, outages, and reputation damage) and then prioritizing mitigations.

Security standards and tools typically focus on company-level risk and may apply the same controls to every component. EPRI’s risk-informed guidance advances the state of the art through a systems engineering approach that enables users to assess specific cyber security risks at the component, system, and company levels.

“Not all components are created equal or serve the same function,” said Lawrence. “A limitation of the typical approach is that it doesn’t always differentiate among components. With our methodology, power plant operators can assess specific vulnerabilities with individual components and identify the best controls to mitigate the threats. They can spend more time protecting the devices most critical to operations—and prioritize application of standards and regulations. Standards provide the ‘what,’ and EPRI’s methodology provides the ‘how.’”

RISK-INFORMED APPROACH IN ACTION

The first step in EPRI’s methodology involves characterizing precisely the attack surface of each component in power plant control systems. An attack surface encompasses all the points at which a component can be attacked, including physical, network, and wireless access.

The next step: Identify the possible goals of an attack (such as stealing data or altering configuration files) and the possible exploit sequences (attack strategies), which vary depending on the goals and vulnerabilities.

With a comprehensive understanding of where, why, and how an attacker might strike, the plant operator can plan the most effective defenses.

The third step of the risk-informed approach is to assess each security measure’s ability to protect against, detect, respond to, and recover from the most likely attacks.

“There are lots of potential ways to mitigate each exploit sequence, and you want to apply the most effective combinations,” said Lawrence. “An engineering workstation may have anti-virus software already installed that can effectively detect malware and alert an operator of its presence. But it might not help much with response and recovery.”

A cumulative score is calculated for each security measure based on its effectiveness and ease of implementation. “The score tells you how well protected you are against each exploit sequence,” said Lawrence. “Whether that score is acceptable to a plant operator depends on the asset’s importance and the consequences of a successful attack. Staff at each plant must determine its acceptable risk threshold.”

The risk-informed approach provides a way to map security measures to regulatory requirements and to track compliance. While the path to achieving compliance varies depending on the regulatory body, regulators generally consider a risk-informed approach acceptable if it can be demonstrated to satisfy the regulations’ intent and objectives.

“The risk-informed approach can still meet regulatory requirements,” said Lawrence. “It’s a way to comply more efficiently and effectively.”

RISK-INFORMED CYBER SECURITY AT VOGTLE

As part of the construction of its [Plant Vogtle Units 3 and 4](#), Southern Nuclear adopted EPRI’s systems engineering approach to cyber security while complying with security regulations.

“We made the business case for EPRI’s methodology with our senior management,” said Brad Yeates, manager of cyber security for Vogtle Units 3 and 4. “We concluded that this new approach was the most direct and cost-effective one.”

Vogtle collaborated with EPRI to develop a risk-informed cyber security plan to help protect 16,000 digital plant components from attacks.

“We’re the first utility in the world to make a commitment to this approach to cyber security assessment and mitigation,” said Yeates. “We’re carving out a path for others to follow. Everybody that follows us is going to have a much easier time.”

Yeates worked with EPRI technical staff to develop the process to analyze the 16,000 digital assets, identifying approximately 400 distinct constituent components. “This is a manageable number of constituent elements that we can focus on during our initial technology assessment,” said Yeates. “Once these 400 are assessed, they become like a bag of LEGO® bricks that can be assembled into

larger digital systems and subsystems, with appropriate tailoring to their operational configurations. The technology assessment includes analysis of 89 critical systems.”

In using EPRI’s risk-informed methodology, Yeates is assessing each asset’s vulnerabilities, informing the selection of the best available protections. Yeates expects Units 3 and 4 to finalize their cyber security program by early 2020 and their assessments by the end of 2020.

“We must have the cyber program up and running in order to receive fuel,” he said. “Once we receive fuel, the units will go through a thorough testing phase before commercial operation.”

In 2019, EPRI is collaborating with vendors, manufacturers, and utilities on studies that document the implementation of EPRI’s advanced risk-informed approach and its benefits. Based on the results, these stakeholders are expected to provide EPRI with feedback, informing improvements to the approach.

Con Edison’s Vesely would like to see the electric power industry adopt this type of risk-informed cyber security approach, viewing it as a significant improvement to current practices.

The challenge for power companies is to balance the benefits of new digital technologies with security. “I think EPRI’s risk-informed approach is going to be a milestone in that direction,” he said. “I expect international standards to draw heavily on the concepts underlying EPRI’s approach.”

“EPRI has incorporated more engineering into the assessment of cyber risks in the electric power sector,” said EPRI’s Lawrence. “Our guidance equips power plant operators with the in-depth understanding of vulnerabilities they need to pinpoint the best protections and keep their facilities secure.”

KEY EPRI TECHNICAL EXPERTS

Jeremy Lawrence



Utilities Abuzz

EPRI Equips Utilities to Enhance Pollinator Habitats

By Brent Barker

A Tool to Prioritize Locations for Bee Conservation

Drawing on a database of land cover, soil types, and information about 4,000 U.S. bee species, EPRI's Wild Bee Habitat GIS Mapping Tool equips power companies to identify areas where they can have the greatest positive impact on wild bee pollination. "When EPRI asked us to test this new tool last year, we jumped at the opportunity," said Lewis Payne at the New York Power Authority. "We intend to integrate it with our GIS system to identify areas on our rights-of-way where we can enhance pollinator habitats."

When Lewis Payne began his career at the New York Power Authority (NYPA) in 2003, he was tasked with implementing the New York Public Service Commission requirement that the state's electric utilities develop long-range, systemwide integrated vegetation management plans. Such plans drive various actions in transmission rights-of-way to promote species diversity and healthy ecosystems.

Payne and his team manage vegetation on 25,000 acres along NYPA's 1,400 miles of transmission lines, which transport 37% of the state's bulk power.

As part of this work, Payne's team wanted to create good habitat for pollinators. "We removed tall trees and tall woody shrubs to promote and manage lower growing vegetation," said Payne. "This increased the biodiversity of the plant life, which in turn enhanced the habitat favorable to pollinators as well as to birds, mammals, and other fauna."

Maintaining pollinator-friendly habitat in NYPA's transmission line corridors has required sustained effort.

"To keep pollinators active in your habitat, you need a continuing source of food as well as nesting sites and water," said Payne. "Recent science has shown that the density of tall shrubs should be around 35–40% of a right-of-way's land area, and the shrubs should be intermingled with flowering species of forbs, perennials, ferns, and berry bushes that bloom in sequence through the growing season."

Every four years, Payne’s team inventories right-of-way vegetation on foot. “In addition to the vegetation survey, we’ve recently added a bee survey,” Payne said. “Crews walk a transect, record which plants are in bloom, count the number of bees on these plants, and input the information in our GIS system.”

A new EPRI tool could enhance these efforts. Drawing on a database of land cover, soil types, and information about 4,000 U.S. bee species, the Wild Bee Habitat GIS Mapping Tool equips companies to identify areas where they can have the greatest positive impact on wild bee pollination.

“When EPRI asked us to test this new tool last year, we jumped at the opportunity,” said Payne. “We intend to integrate it with our GIS system to identify areas on our rights-of-way where we can enhance pollinator habitats.”

EPRI’S POWER-IN-POLLINATOR INITIATIVE

The Wild Bee Habitat GIS Mapping Tool is a hallmark of EPRI’s [Power-in-Pollinators Initiative](#), a collaborative effort among more than 20 utilities to accelerate pollinator conservation. Utilities participate in workshops and webcasts, review the latest pollinator science, share lessons and

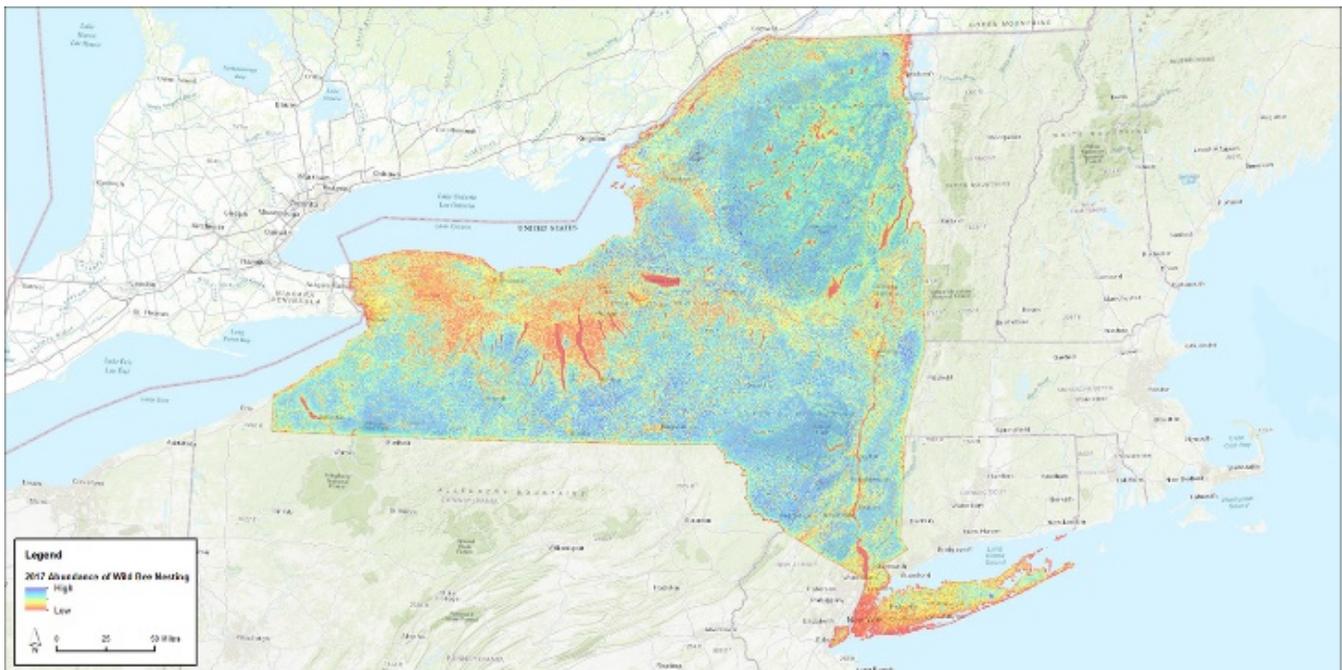
experiences, identify priorities and projects, and have access to analytical tools.

“It’s the world’s largest collaboration of its kind,” said EPRI Senior Program Manager Jessica Fox. “It has the potential to create pollinator habitat corridors that are more extensive than what any one company could create on its own.”

Pollinators include bees, birds, butterflies, bats, and other insects. Most flowering plant species need pollinators to reproduce, and plants representing about a third of global crop production depend on pollinators. Around the world, pollinator populations are in steep decline as a result of habitat loss, pollution, pesticide use, disease, and climate change.

“Documented declines in wild and domesticated pollinators have led to concerns about the future of our food systems and the health of our natural resources,” said Fox.

In addition to transmission corridors, utilities manage many other land parcels such as solar power plants and substations, which, when combined, present significant pollinator conservation opportunities.



Application of EPRI’s Wild Bee Habitat GIS Mapping Tool to New York state.

To keep pollinators active in your habitat, you need a continuing source of food as well as nesting sites and water. Recent science has shown that the density of tall shrubs should be around 35–40% of a right-of-way's land area, and the shrubs should be intermingled with flowering species of forbs, perennials, ferns, and berry bushes that bloom in sequence through the growing season.

“Power companies recognize that they have a unique opportunity to contribute to pollinator conservation while meeting core operational goals,” said Fox. An EPRI survey of utilities found that 76% are engaged in at least one pollinator conservation project.

The Wild Bee Habitat GIS Mapping Tool draws on years of pollinator-related research and habitat modeling. Through interviews with wild bee habitat experts and a literature review, EPRI identified the state of knowledge on bee habitat mapping and data analysis for conservation planning. To guide the tool's development, EPRI established a scientific advisory committee: Dr. Eric Lonsdorf (University of Minnesota), Dr. Claire Kremen (University of British Columbia), Dr. Jennifer Hopwood (Xerces Society), Jessica Fox (EPRI), and Kasey Allen (ICF).

Adapting part of the [InVEST Model](#) (an ecosystem services model developed by the Stanford National Capital Project), EPRI is building a new model more applicable to the operations and needs of electric power companies. Researchers compiled information from a national database of land cover and soil types, along with data on the location and abundance of those habitats that can be enhanced to support 4,000 wild bee species. Users can generate maps showing where wild bees are likely to be abundant and can benefit from more protection.

“The tool identifies where a company might want to allocate resources for the greatest impact on wild bee pollination,” said Fox. “It takes into account not only existing habitats, but also what is happening on adjacent parcels, such as housing, shopping centers, agriculture, and forests.”

The tool also considers habitat connectivity, a factor that has been challenging for conservationists to evaluate. Transmission corridors can provide pathways for wild bees to move between land parcels, helping them find food and water.

“In the future, we expect to research the feasibility of incorporating more local and state-level data into the national database to give us higher resolution and more accurate habitat mapping,” said Fox.

TRACKING CONSERVATION RESULTS

Successful utility pollinator conservation requires the use of metrics for tracking progress. Metrics should be aligned with specific goals such as sustainability planning, public outreach, habitat quality, and bee abundance.

“Similar to corporate sustainability commitments, it is important for companies to consider not only goals for pollinator conservation, but also how to measure and track progress toward those goals,” said Fox.

EPRI's Pollinator Metrics Database provides a first-of-its-kind reference for utilities to select appropriate metrics. It compiles metrics and maps them to various goals, drawing on results of peer-reviewed scientific literature and on resources from federal agencies, the Xerces Society, Wildlife Habitat Council, and other accredited sources.

“Pollinator abundance may be the wrong metric if your goal is to increase species diversity or to raise public awareness,” said Fox. “Utilities can filter the Pollinator Metrics Database for a specific goal (such as public communication) to select an appropriate metric (such as social media posts).”

FIELD STUDIES TO ENHANCE POLLINATOR HABITATS

Collaborating with utilities, EPRI is conducting longitudinal studies on pollinator abundance and diversity in sites in New York, Ohio, Alabama, and other states. Researchers are investigating the effectiveness of different plant species and seed mixes in attracting pollinators. They are tracking the benefits of vegetation management practices such as mowing, culling, and targeted herbicide application—which involves the use of “spot” spraying rather than aerial spraying. Goals include enhancing pollinator habitats and soil quality and reducing vegetation maintenance costs.

“We’ve tested different native seed mixes,” said EPRI Technical Lead Ashley Bennett. “In one study in Ohio with American Electric Power and the Dawes Arboretum, we reseeded previously forested and agricultural plots with native prairie plant seed mixes and are tracking their growth and flowering as well as the bee species they attract. We also looked at how well they held up against invasive plant species.”

Preliminary data from the Ohio study suggest that:

- The native plants increased the abundance and diversity of pollinators, including native bees, birds, and butterflies.
- Local pollinator populations shifted from being dominated by nonnative honeybees in the first year to native bumblebees in the second year.

“Utilities are excited about the benefits of using native plants,” said Bennett. “Standard practice after transmission line construction has been to apply turf grass seed mixes. Across the country, we’re finding that native plant mixes increase plant and pollinator diversity and require less mowing and maintenance. Because native plant communities have deep roots, they can slow water runoff and reduce erosion.”

At a 50-acre solar farm in Kentucky, EPRI is collaborating with LG&E and KU Energy to examine the effects of various seed mixes—including plants native to Kentucky—and the use of sheep grazing instead of mowing.

Bennett would like to study the unique role of transmission corridors in pollination. “I want to look at whether corridors facilitate the dispersal of pollinators across the landscape,” she said. “Do these corridors link otherwise isolated habitats together? Do they increase pollination services in adjacent agricultural fields? Answers to these questions have important implications for advancing large-scale pollinator conservation.”

A SHORT DOCUMENTARY FILM

Raising public awareness is instrumental in EPRI’s Power-in-Pollinators Initiative. In 2018, EPRI encouraged and facilitated utility participation in National Pollinator Week, an international event to educate and communicate about the importance of pollinators. Company activities included social media posts with pollinator stories and photos, public planting events, and displays at corporate headquarters. Companies reached nearly 700,000 people.

“This annual event is all about communications, outreach, education, and sharing experiences and research,” said Fox. “Only one utility in EPRI’s pollinator initiative had participated before. We introduced a huge swath of the electric power industry to the event, connecting utilities with significant pollinator resources, guidance, and support.”

EPRI is working with Tree Media to create a documentary film, *Power for Pollinators*, as part of an award-winning pollinator series, the first of which was narrated by Leonardo DiCaprio. *Power for Pollinators* will focus on the electric power industry’s unique opportunities to support pollinator conservation. It will explore the importance of pollinator conservation through:

- Rare, close-up, slow motion footage of bees in their natural settings
- Images of diverse bee species in North America
- Insights from internationally recognized pollinator scientists
- In-depth discussions about pollinator science and conservation

Fox and George DiCaprio are the executive producers. Release is anticipated in early 2020.

“Pollinators are critical to our well-being,” said Fox. “Our natural systems support us, and we need to

support them. Power companies are actively considering how to incorporate pollinator conservation in their day-to-day operations, and EPRI’s experts are honored to support them with robust science and credible approaches.”

Pollinator Collapse: Numerous Causes, Diverse Impacts

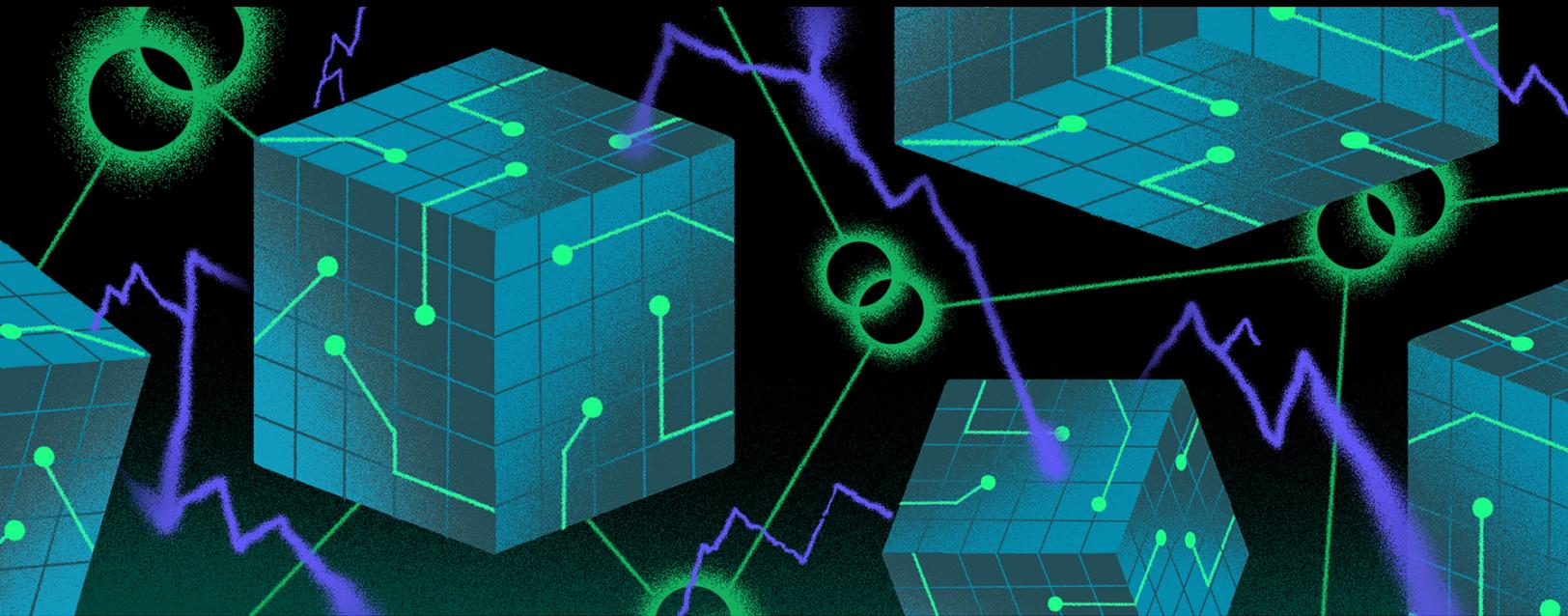
The causes and effects of pollinator declines around the world are not uniform among species. The collapse in honeybees has diminished agricultural productivity and is partly a result of an “external mite, an internal mite, as well as the fact that honeybees carry around a lot of pathogens and pests,” said EPRI Technical Lead Ashley Bennett.

For native bees, the causes of declines include loss of habitat, pesticide use, and impacts of climate change on the flowering plants needed to provide a continuous food supply.

“The overall trend appears to be a decline,” said Bennett. “But when you drill down into the data, there are some ‘generalist’ species holding their own or increasing. These are species that can feed on weedy species or do well in urban landscapes.”

KEY EPRI TECHNICAL EXPERTS

Jessica Fox, Ashley Bennett



Can Blockchain Be a Blockbuster?

Sorting Out the Hype and Reality of Distributed Ledger Technology in the Utility Industry

By Chris Warren

In late 2015, when the hype around blockchain was particularly intense, Diego Dal Canto dedicated many workday hours examining the technology's potential impacts on the electric power industry. Dal Canto works in the Innovation department at Italy-based utility Enel and is always on the lookout for disruptive technologies.

"It was really hard to make sense of all these big statements that everybody was making about blockchain and how it will change everything," said Dal Canto. "In 2017, the European Parliament published a [report](#) pointing to blockchain's potentially profound impacts across society. This was a very strong statement from a reliable institution."

In 2016, Enel formed an "Innovation Community" of 20 employees from different divisions to investigate blockchain and its potential benefits for the utility's operations and customers. Enel participated in a blockchain working group formed under the European industry association [Eurelectric](#) as well as in EPRI's [Utility Blockchain Interest Group](#)—involving

nearly 70 U.S. and international utilities to share lessons and best practices and identify possible applications.

Enel was among the first members of the [Enerchain](#) project, which brought together more than 40 utilities to launch a blockchain-based wholesale energy trading platform. In 2018, Enerchain facilitated the first wholesale energy transaction using blockchain, including a deal for 5.95 gigawatt-hours of natural gas-fired power generation between Enel's Spanish subsidiary, Endesa, and the utility Gas Natural Fenosa, now known as Naturgy.

Even with all this attention and activity, blockchain's future remains unclear. "In 2018, the Eurelectric working group published a couple of reports concluding that the technology is very immature and difficult to implement and scale in business applications," said Dal Canto. "In 2019, we are still in the same limbo, though we continue to scout blockchain and have well-trained staff who are ready to move fast on the technology if needed."

Enel's position reflects the attitudes of many utilities toward blockchain technology—intense interest in its transformative potential, yet persistent uncertainty about its use and benefits.

Blockchain, also known as distributed ledger technology, is a collection of continuously growing records (bundled together in blocks) that are linked together and secured using cryptography.

What makes it a potentially disruptive technology is its ability to record transactions between parties in a secure, transparent, cost-efficient, and unmodifiable way. Its distributed nature means that a single authority doesn't manage and control the transactions.

"In the past with smart contracts, participants were locked into using a particular vendor's system and needed to trust the vendor to keep the system secure," said EPRI Senior Program Manager Gerald Gray. "Blockchain is a peer-to-peer network. A contract facilitated by blockchain is executed automatically when the terms are met. You have a buyer, a seller, a payment, and an exchange of goods. The advantage of blockchain is that you're not locked into a vendor that may or may not be trustworthy. The potential downside is that you must trust a large, decentralized digital network to be secure. Blockchain networks may still be vulnerable to cyber attacks."

A recent EPRI [survey](#) of blockchain-related activities and attitudes among 15 European and U.S. utilities and one U.S. regional transmission operator reveals intense interest and ongoing challenges to developing compelling business cases. Key insights:

- Business model uncertainty and lack of standards are among the top reported barriers to blockchain investment.
- The respondents singled out transactive energy as the most promising application.

"Today, transactive energy is limited to homeowners and businesses selling generation from their rooftop solar to the utility at a price set by the utility or a regulator," said Gray. "Imagine a future where the price is set by the market, and you can buy from and sell to whomever you want. When these transactions occur at all levels of the grid, transmission system operators can sell to one

another and to distribution system operators while utility customers can sell to both types of companies as well as to their neighbors. Blockchain can potentially facilitate these diverse transactions."

Other survey results:

- There are more than 100 blockchain applications across electricity generation, transmission, and distribution, and more than 150 startups globally are working on energy-related blockchain applications.
- Three of the 5 European utilities surveyed have active blockchain projects.
- Five of the 16 respondents are engaged in research.
- Eight respondents have proof-of-concept or pilot projects.
- One respondent has no blockchain efforts underway.
- Blockchain-related staffing varies among respondents with respect to numbers and approach. Most reported cross-organizational teams from information technology, R&D, strategy, operations, and business development, with staff working part-time on blockchain issues.

Electric vehicle (EV) charging is also of interest. EV owners want the ability to charge anywhere at any time.

"Your home utility might be different from the utility where you shop or the utility where you work," said Gray. "Blockchain can potentially enable you to charge or discharge your EV in all jurisdictions by resolving variations in rate structures and payees in an instant, transparent way. In contrast, credit card payments go through several payment processors and then through the utility and its power suppliers in a way that's invisible to the customer. Like a credit card, you can carry blockchain in your pocket in the sense that you have a blockchain payment app on your smart phone that allows you to exchange Bitcoin or whatever digital currency you've signed up for."

But Gray adds that the value of this blockchain application is unclear. "Mobile wallet schemes such as Apple Pay and Google Pay have emerged as payment methods of choice," he said. "Consumers

may like the convenience of simply tapping their smart phones to an EV charger to make a payment via their credit or debit card.”

According to European respondents, grid asset provenance is particularly important for verifying carbon emissions related to the manufacture of transformers and other equipment made outside of Europe. “If a component is made in China using coal power, it will have a higher carbon intensity than the same component made in Denmark with wind power,” said EPRI International Executive Director Neil Hughes. “Blockchain can provide an irrefutable way to track where and how equipment is made.”

Launched in 2018, EPRI’s Utility Blockchain Interest Group is helping utilities sift through blockchain hype and identify the most promising applications.

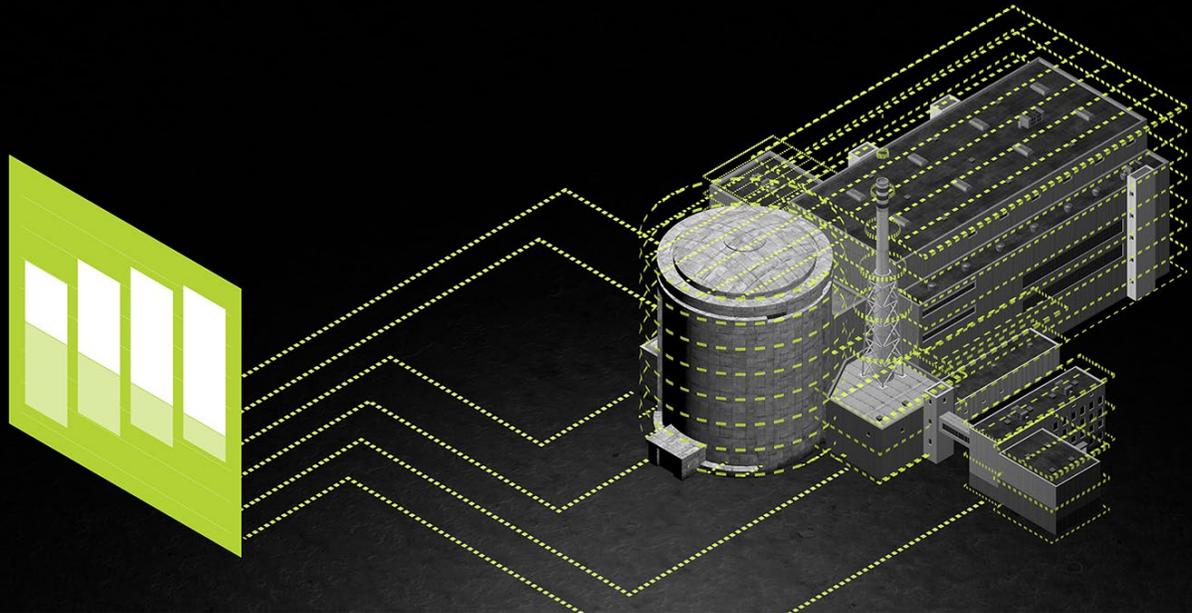
“Our monthly webcasts feature a utility presenter who describes their blockchain journey and the applications that are getting their attention,” said Hannah Davis, an EPRI analyst who leads the monthly webcasts.

“EPRI is educating vendors about how utilities do business today,” said Gray. “This information can equip them to develop blockchain technologies that are better, faster, or cheaper solutions.”

Stay tuned. As an independent research institute, EPRI will continue to work with vendors and utilities to help vet specific blockchain uses. “Blockchain could have value for the energy system, and our challenge is to establish exactly where that value is and quantify it,” said Hughes. “We are testing and refining ideas with our utility members to identify the most valuable possible uses.”

KEY EPRI TECHNICAL EXPERTS

Gerald Gray, Hannah Davis, Neil Hughes



Nuclear Plant Modernization Advances in Utilities Large and Small

Informed by EPRI Research, Exelon, Wolf Creek, and Callaway Expect Significant Cost Reductions

By Brent Barker

EPRI Guide Equips Nuclear Power Industry for Digital Modifications

EPRI's Digital Engineering Guide consolidates best practices for digital engineering and installing digital control technology at nuclear power plants. It helps further the aims of Delivering the Nuclear Promise, a U.S. industrywide initiative to enhance nuclear power's efficiency and long-term viability. "This guide could play a central role in driving digital modifications in the nuclear power industry," said John Connelly, senior engineering manager at Exelon Generation. "When all utilities are able to apply the same playbook, designs will become transportable and lead to significant reductions in implementation costs and improvements in plant performance."

Nuclear utilities big and small face financial challenges as electric load growth slows, renewable costs decline, and natural gas prices remain low.

Plant modernization is a potential countermeasure that could help revive the economic prospects of carbon-free nuclear power.

"For nuclear plants, the most viable path to long-term sustainability is deploying advanced technologies and harvesting the resulting efficiencies," said John Connelly, senior engineering manager at Exelon Generation, which operates 22 reactors in the United States.

"Modernization can equip nuclear plants with updated technologies and improved processes to deliver greater economic efficiency and reliability," said EPRI Senior Program Manager Rob Austin. "Our research has not revealed any technological barriers that would prevent nuclear plants from modernizing, and our initial estimates suggest that some U.S. plants could reduce their operations and maintenance costs by 50%."

In 2013, EPRI created the Digital Design Guide, which consolidated best practices for digital engineering

and installing digital control technology. EPRI in November 2018 updated and upgraded the guide, now called the [Digital Engineering Guide](#). It incorporates risk-informed decision making, which enables users to size digital controls and systems in proportion with the level of risk. It also draws on systems engineering in other high-reliability industries, such as petrochemicals and aerospace. The guide helps further the aims of [Delivering the Nuclear Promise](#), a U.S. industrywide initiative to enhance nuclear power's efficiency and long-term viability.

"This guide could play a central role in driving digital modifications in the nuclear power industry," said Connelly. "When all utilities are able to apply the same playbook, designs will become transportable and lead to significant reductions in implementation costs and improvements in plant performance."

Connelly expects that industry adoption of the Digital Engineering Guide could yield significant savings. A collaborative nuclear industry group (called the Design Oversight Working Group) conservatively estimated that a more consistent digital engineering process could reduce engineering costs by 20% to 40%. According to Connelly, a 20% cost reduction translates to an average annual savings of approximately \$500,000 per unit.

To coordinate a more directed modernization effort among global nuclear industry stakeholders, EPRI launched the [Nuclear Plant Modernization Initiative](#) in 2018. Austin is facilitating the sharing of technology demonstrations and potential standardized methods, tools, and designs to help inform stakeholder decisions on plant capital investments. Utilities are beginning to apply these solutions and see results.

EXELON GENERATION IMPLEMENTS EPRI GUIDE, REDUCES COMPONENT COUNT AND OUTAGE RATES

Since the 1990s, Exelon Generation has been a leader in applying digital control technology for nuclear power in the United States. Exelon Generation has developed and implemented standardized digital solutions for non-safety-related systems, such as feedwater, turbine, and reactor-level controls and generator voltage regulators. Exelon Generation implemented EPRI's Digital

Design Guide and developed an internal procedure to quantify the risks and consequences of every upgrade.

"Our procedure provides the 'what,' and EPRI's guide provides the 'how,'" said Connelly.

Exelon Generation recently replaced thousands of analog-based controls known as circuit cards with an advanced distributed control system.

"This enabled us to reduce the component count in the targeted systems by 80%, eliminating millions of dollars in future maintenance costs," said Connelly. "We now have far fewer components that can fail. The modification also eliminated every single-point vulnerability in the targeted systems and enables plants to run more efficiently."

In a fleetwide analysis of more than 500 unit-years of operations, Exelon Generation found that applying advanced digital technologies for turbine and feedwater controls reduced forced outage rates by as much as 95%.

WOLF CREEK AND CALLAWAY TAILOR EPRI QUICK GUIDES TO DEMONSTRATE COST REDUCTIONS

Plant operators at Wolf Creek (in Kansas) and Callaway (in Missouri) evaluated EPRI's series of [Quick Guides](#) for implementing continuous online monitoring for specific components. The guides equip operators to evaluate every degradation mechanism affecting a component, then recommend a combination of sensors, monitoring, and analytical methods to address the degradation.

"For us, a successful sensor-based equipment monitoring program can move a plant from time-based to condition-based maintenance with reduced costs," said Wolf Creek's manager of strategic projects, Matt Hall, who collaborates with Lorne Poindexter of Callaway on this initiative. "EPRI's guides are an excellent starting point, but because they are comprehensive, we found that implementing them in their entirety could be cost prohibitive in some cases. We revised the Quick Guide methodology and used that to demonstrate that condition-based maintenance can be implemented at a reasonable cost and with acceptable risk, while yielding a positive return on investment for those projects undertaken."

The full suite of component sensors recommended by a Quick Guide can help enable earlier detection of degradation. Working with EPRI, Wolf Creek and Callaway found that for them an optimal subset of sensors may allow some anomalies to progress—but to a stage that can be detected far in advance of component failure.

With support from EPRI, Callaway and Wolf Creek evaluated work order data for the condensate system and found that condition-based maintenance can reduce the plants' annual pump maintenance costs by \$15,000 and annual motor maintenance costs by \$35,000.

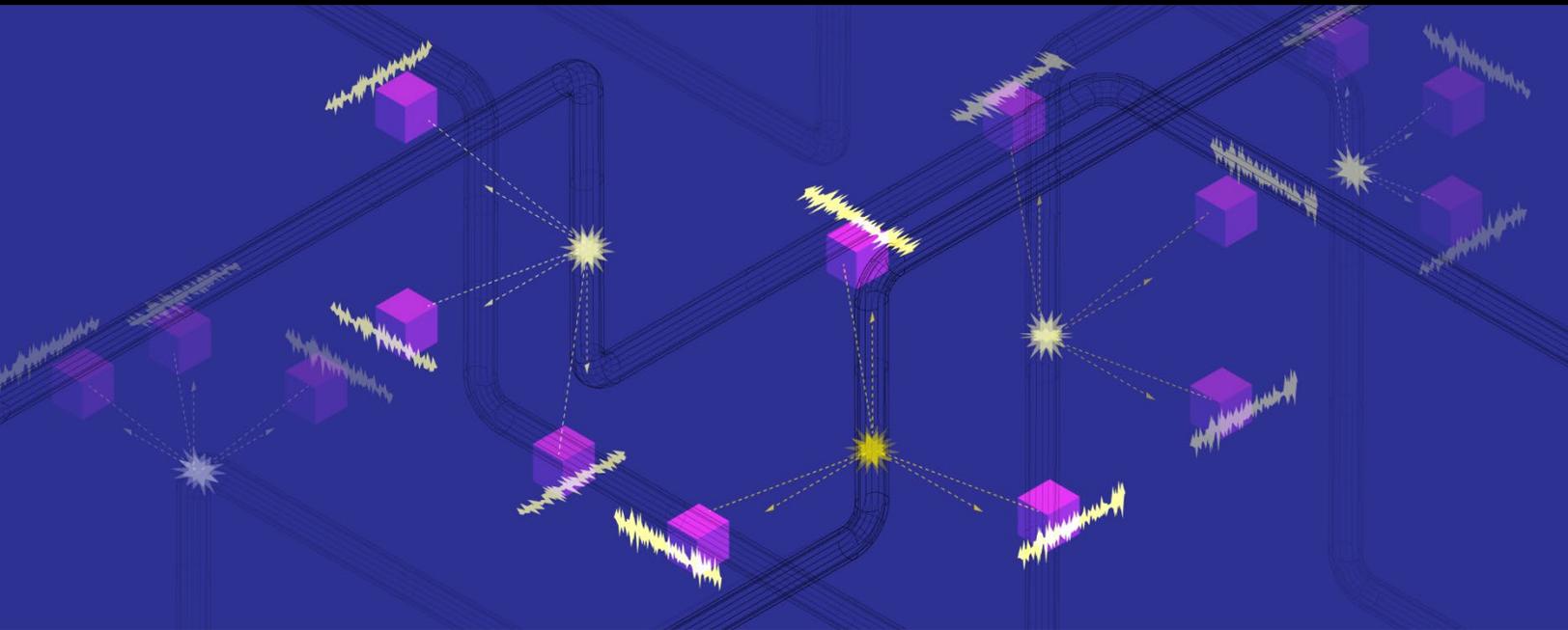
“For the condensate system, we found that the combination of vibration sensors and motor current signature analysis gives us the biggest bang for the buck,” said Hall. “They provide a solid return on investment for the chosen projects when accounting for implementation and operational costs as well as the 10-plus-year lifetime of the monitoring equipment. Because of economies of scale, we could expand this infrastructure to additional systems and components at a much lower price point.”

Callaway and Wolf Creek are working with EPRI to implement other parts of the revised Quick Guide methodology for several secondary systems. EPRI plans to incorporate the revised methodology into future guidance.

“These utility implementations show how plant modernization involves not just the core equipment controlling a nuclear site, but also how personnel monitor and maintain that equipment,” said Austin. “It will take this level of change across the entire plant to fully realize the benefits of modernization. That is the integrated approach of process improvement and technology we want to bring to the utilities.”

KEY EPRI TECHNICAL EXPERTS

Rob Austin



A New Motion Sensor to Fine-Tune Power Plant Operations

LIDAR Technology Enables ATCO Power to Minimize Pipe Damage as a Result of Flexible Operations

By Sarah Stankorb

ATCO Implements Innovative Approach to Address Pipe Damage

Informed by EPRI research demonstrating LIDAR as an effective tool to measure pipe displacement in power plants, ATCO Power used the technology at Sheerness Generating Station to determine that displacement varied depending on startup, shutdown, and ramping procedures. “As a result of the procedural changes implemented, we’ve seen a dramatic reduction in pipe displacement,” said ATCO Chief Inspector Derek Rasmussen. “Our technicians are aware that we’re using LIDAR to track pipe displacement, and that prompts them to take their time and adhere strictly to the revised procedures.”

What do archaeologists and power plant operators have in common?

In a recent breakthrough in archaeology, researchers used laser-based light imaging detection and radar

(LIDAR) technology to digitally erase trees from aerial images of a Guatemalan jungle and [locate the ruins](#) of thousands of Mayan houses, palaces, and roads. Now, ATCO Power’s Sheerness Generating Station in Alberta, Canada has applied the same tool to adapt plant operations to changing patterns of power generation.

With growing renewable generation, low natural gas prices, and other market forces, coal plants designed for continuous, high-output operation increasingly operate in flexible modes such as turndown (operating at reduced output), load-following (following the ups and downs of the daily load cycle), and cycling (turning off the plant daily, followed by a “hot start” in a few hours).

The resulting temperature changes can cause pipe systems to expand and contract, which can displace structural elements and shorten a piping system’s life. Operators at Sheerness Generating Station and other power plants in North America have observed damage in piping insulation and suspect that the cause is flexible operations.



The red box on the left is a LIDAR sensor. This device points a laser beam at the large pipe on the right and measures the time it takes for the reflected signal to return. A flat plate has been attached to this pipe to provide a good surface to reflect the laser and reduce measurement error. Photo courtesy of ATCO Power.



Movement of this power plant pipe resulted in damage to the steel insulation jacket on the right side. Photo courtesy of ATCO Power.

To research this theory, EPRI tested several methods and tools that measure displacement of pipe structures, including LIDAR, draw wire sensors, sonar, and stereo imagery. The research demonstrated LIDAR to be the most reliable, accurate, and cost-effective.

LIDAR determines distances by pointing a pulse laser beam at an object and measuring the time it takes for the reflected signal to return. The laser can pulse continuously to track a pipe's changing position during plant events such as shutdown and power-up. When LIDAR is used along with a system to transmit and collect the data, operators can assess how plant operations result in pipe displacement.

Informed by EPRI's findings, ATCO decided to deploy LIDAR at Sheerness along with a wireless communications system that enables users to easily store, transmit, and analyze the data. Historically at Sheerness, most pipe damage resulted from shutdown and startup associated with maintenance. Data showed that the extent of pipe displacement varied depending on adherence to the startup, shutdown, and ramping procedures.

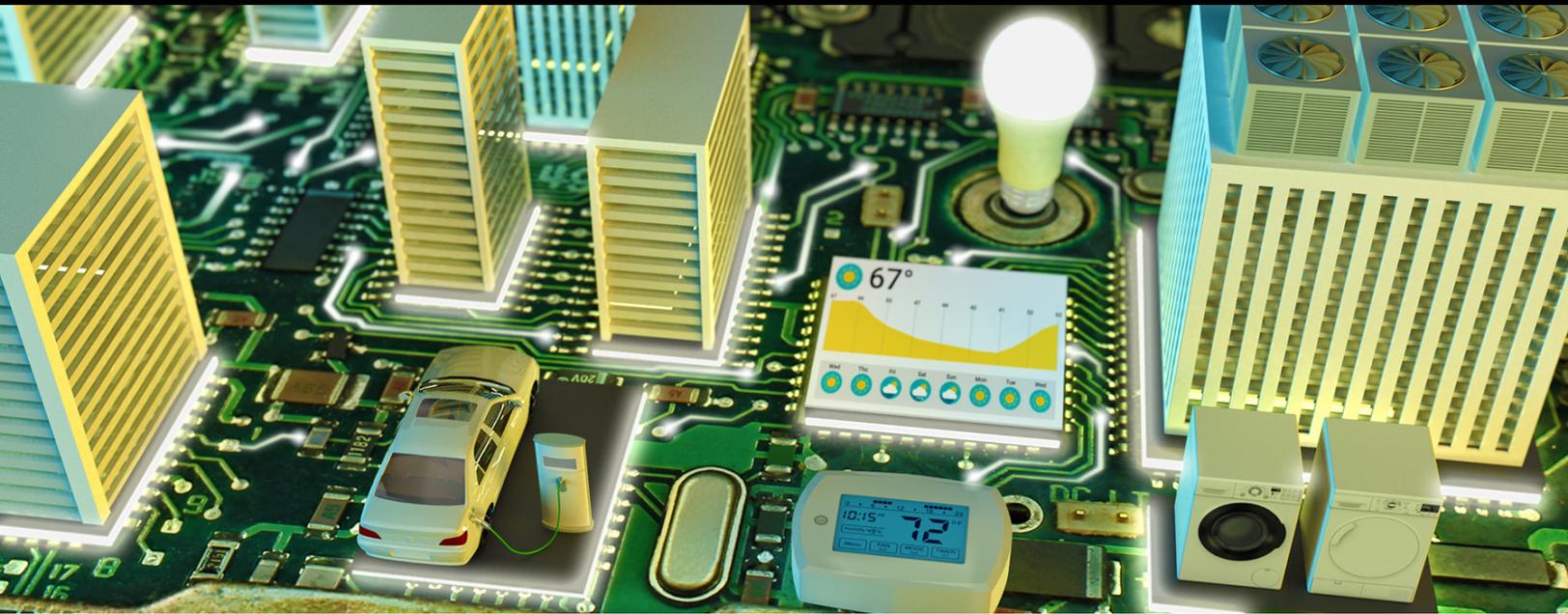
"We determined that operations teams that strictly follow procedures did not detect any pipe displacement," said Derek Hansen, who works in the thermal engineering group at the Sheerness plant. When displacement was detected, supervisors identified and corrected any steps or tasks that were omitted or delayed, such as verification of a valve opening and closing.

"As a result of the procedural changes implemented, we've seen a dramatic reduction in pipe displacement," said ATCO Chief Inspector Derek Rasmussen. "Our technicians are aware that we're using LIDAR to track pipe displacement, and that prompts them to take their time and adhere strictly to the revised procedures. It's kind of like having a speed camera in a playground zone."

Encouraged by ATCO's results, EPRI has launched a project to deploy LIDAR at power plants operated by seven other utilities and research the technology's potential applications and benefits.

KEY EPRI TECHNICAL EXPERTS

Stan Rosinski



Active Efficiency: A Bold Step to Reimagine Energy Efficiency for the Digital Age

By *Natasha Vidangos, Vice President for Research & Analysis at the Alliance to Save Energy*

We need to expand our understanding of energy efficiency—even reimagine it—using new tools in new ways through what we call *active efficiency*.

For decades, energy efficiency has focused on reducing energy consumption of components (like refrigerators and lightbulbs) to deliver cost savings. Such tools have saved Americans hundreds of billions of dollars a year. Today, information and communications technologies enable more sophisticated integration and automation, and we can make our energy system more efficient using tools traditionally considered outside the scope of energy efficiency. Important examples include:

- Fine-tuned and expanded demand response programs to increase grid stability and lower costs
- Greater flexibility and connectivity among buildings and the grid, with consideration of the grid’s time and locational needs
- Microgrids
- Optimized city designs that encourage multi-modal transportation and reduce congestion and idling
- Energy-efficient fuel switching
- District energy systems, combined heat and power, and waste heat recovery technologies
- Decarbonization of industrial facilities
- Water efficiency



Natasha Vidangos

Using these tools, we can define active efficiency as the rigorous deployment of technologies, practices, and policies that enable the most productive use of energy at a given place and time. The concept combines traditional and emerging efficiency tools (such as robust building envelopes and efficient devices and lighting) and non-traditional tools (such as new digital technologies).

Active efficiency recognizes that the impacts of energy efficiency investments are time-dependent and that coordinating these investments across systems may enable ever-greater energy savings.

As an example, consider a neighborhood in the Southeast United States in August. The houses have well-insulated building envelopes, smart thermostats, and two-way meters that connect to the neighborhood's electric vehicle (EV) charging stations. One morning, meteorologists predict record-breaking heat in the afternoon, and automated grid management systems trigger advance cooling of houses in the morning and cycling of air conditioners in the afternoon. Demand response programs—pre-set and automated to match the residents' preferences—make minor adjustments to water heater temperatures, air conditioning consumption at peak hours, and EV charging, earning residents extra dollars and flattening spikes in peak demand. Residents don't notice the changes, and the utility saves significant peak generation expenses.

Such automated, optimized coordination among building systems, EV charging systems, and the grid results in more efficient use of grid assets. Over time, this reduces energy use, electricity rates, outages, and greenhouse gas emissions.

In 2020, the Alliance to Save Energy will launch the Active Efficiency Collaborative—a coalition of private- and public-sector leaders—to promote this new vision and address barriers to its implementation.

It's no small task to optimize energy use across a much larger scale. The good news is that it's already happening. EPRI and many other stakeholders have laid important groundwork by developing concepts and strategies, such as the Integrated Grid, intelligent efficiency, electrification, demand flexibility, non-wires alternatives, the utility of the future, and grid-interactive buildings.

There is more to do. We need to fully understand the benefits of combining, coordinating, and automating strategies; establish strong policy and regulatory frameworks to enable active efficiency; build appropriate finance mechanisms; and create a coalition of champions. This is no time to be passive, and the Active Efficiency Collaborative is our first step on the path.

From Lithium to Potassium

Solution Shows Promise to Avoid Unexpected Shutdowns Due to a Vulnerable Supply of a Key Chemical

By Mary Beckman

EPRI Gears Up to Demonstrate a New Chemical for pH Control

A chemical used in Western nuclear plants for pH control is vulnerable to shortages, and EPRI is investigating its replacement with a more abundant chemical. Results to date are promising. “Good pH control is a key part of how we operate our plant,” said Jim Connolly, chief nuclear officer at South Texas Project. “EPRI is the perfect organization to help industry through this issue.”

One critical task for nuclear plant operators is to make sure that the water used to cool the reactor core doesn’t become acidic to the point of damaging plant materials and fuel. Early in the development of pressurized water reactors, engineers selected chemicals that could be added to the water to maintain the proper pH. For the Russian-made WWER type pressurized water reactors, they chose potassium hydroxide. For Western pressurized water reactors, they opted for lithium hydroxide enriched with the lithium-7 isotope.

The rationale for lithium-7 hydroxide was reasonable: Lithium-7 is produced during reactor operations when boron in the cooling water captures neutrons, so its use for pH maintenance simplified maintaining the optimal mix of chemicals in the water. In addition, the less common lithium-6 isotope in naturally occurring lithium produces radioactive tritium when hit by neutrons. The excess tritium could unacceptably increase radiation dose risk for staff in Western pressurized water reactors.

Fast forward many decades, and China and Russia are the only producers of enriched lithium-7. A 2013 U.S. General Accountability Office [report](#) flagged concerns about reliance on just two suppliers. In 2014, a mechanical malfunction at a Chinese production plant resulted in a global shortage of lithium-7 hydroxide.

Fortunately, no U.S. nuclear plants ran out of lithium-7 hydroxide, but the shortage raised concerns about the long-term viability of lithium-7 hydroxide use. Operators add lithium-7 hydroxide when they restart reactors after refueling, which usually occurs every 18 months. If lithium-7 hydroxide were not available, reactors could not be restarted. Operating a reactor without the use of lithium-7 hydroxide for pH control would result in significant corrosion of pipes and infrastructure.

“The shortage was a wake-up call for the industry,” said Scot Greenlee, senior vice president of engineering and technical services at Exelon Nuclear.

EPRI had already started investigating how to avoid shortages by replacing lithium-7 hydroxide with the far more abundant potassium hydroxide. Today, EPRI is nearly halfway through a 10-year research program to inform the switch, applying WWER experience with potassium hydroxide to Western plant designs.

“EPRI is responding to an industry need,” said Jim Connolly, chief nuclear officer at South Texas Project, a nuclear plant in Texas. “EPRI brings broad technical know-how to this issue.”

Led by EPRI Senior Technical Executive Keith Fruzzetti, researchers have conducted modeling and laboratory experiments to address technical gaps—and to determine whether potassium hydroxide replacement is safe enough to demonstrate in an operating nuclear reactor.

Results to date are positive, and EPRI and South Texas Project are planning a demonstration at the plant's Unit 1 for fall 2021. Pending approval by South Texas Project, the demonstration would span three refueling cycles.

"So far, there is no showstopper, so to speak," said Greenlee. "Everything is pointing to potassium hydroxide being able to be used in place of lithium-7 hydroxide."

Along with its abundance, potassium hydroxide offers other advantages. Because it's less expensive than lithium-7 hydroxide, its use could save \$100,000 per year per unit. Relative to lithium-7 hydroxide, potassium hydroxide requires less work to maintain a constant pH because its concentration in the coolant water is less variable. The radioactive byproducts of naturally occurring potassium isotopes are more readily managed than the radioactive byproducts of naturally occurring lithium isotopes.

Use of potassium hydroxide may also reduce the risk of unplanned distributions of power in the reactor core. Corrosion product deposits (known as crud) accumulate on fuel surfaces, and boron and lithium can precipitate within the crud to form lithium borate. Unplanned power distributions caused by these precipitates raise safety and operational concerns that may require dropping power output by as much as 25%.

EPRI modeling and laboratory studies demonstrated that because potassium hydroxide is more water-soluble than lithium hydroxide, its use can reduce lithium borate precipitation enough to cut fuel costs by as much as 2–3%. Based on preliminary EPRI calculations, this could translate to savings of \$1–2.5 million per unit per refueling cycle.

Crud can lead to corrosion in fuel cladding, which may require repairs or even fuel replacement at a cost of more than \$1 million. EPRI found that potassium hydroxide could reduce corrosion.

"The original motivator for potassium hydroxide was to eliminate the vulnerability to lithium-7 hydroxide shortages," said EPRI Senior Program Manager Lisa Edwards. "It's been a pleasant surprise to identify additional benefits that have nothing to do with the chemistry of pH control."

Prior to the demonstration, EPRI is addressing remaining technical gaps about potassium hydroxide use. For example, Western pressurized water reactors use nickel-based alloys that are not used in WWERs, and researchers are examining the performance of these alloys in the presence of potassium hydroxide. Another set of lab experiments is testing the effects of potassium hydroxide on fuel rods exposed to pressures, temperatures, and other conditions typical in operating reactors. The rods used in the experiments are the same as those used in nuclear plants except that they are heated electrically rather than with uranium fuel pellets.

As part of the plan for the South Texas Project demonstration, researchers would examine the effects on the fuel.

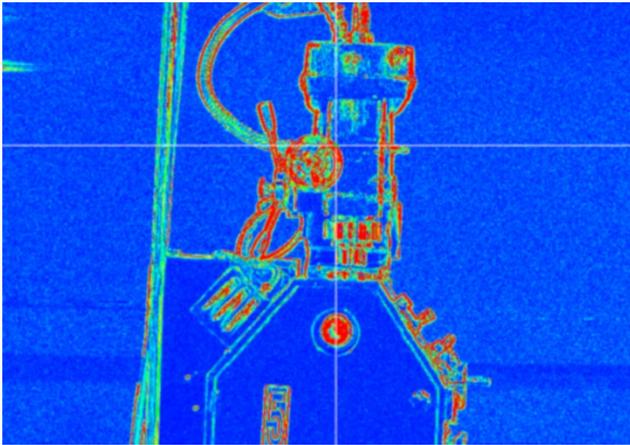
"If plants replace lithium-7 hydroxide with potassium hydroxide, they will need to make various operational changes," said EPRI's Fruzzetti. "Based on our experiments, we are developing a strategy to inform how operators could implement and manage these changes."

"Good pH control is a key part of how we operate our plant," said South Texas Project's Connolly. "EPRI is the perfect organization to help industry through this issue."

KEY EPRI TECHNICAL EXPERTS

Keith Fruzzetti, Dennis Hussey

A New Way to See Vibrations in Plant Equipment



A vibration imaging system may offer utilities a more comprehensive approach for detecting, characterizing, and tracking vibrations in power plant equipment, an EPRI [study](#) finds. Potentially, the technology can be applied in fossil, nuclear, hydropower, and wind power plants.

Over time, vibration in pumps, motors, rotors, and other power plant components can lead to degradation and even failure. Vibration monitoring can detect warning signs of failure, prompting maintenance and potentially preventing costly outages. Traditionally, vibration sensors such as accelerometers are attached to equipment, but these collect data only at individual points and cannot comprehensively assess vibration of components and systems. In addition, deploying these sensors may require component modifications, and the sensors may detach during operation.

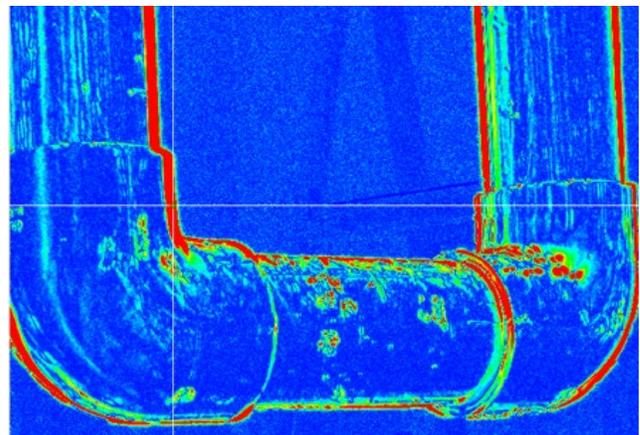
EPRI is investigating an imaging system that uses commercially available high-speed cameras and data-processing software to create vibrational maps of entire systems and components. Each pixel in the image is a data point. In the laboratory, the system successfully generated a comprehensive vibration analysis of various components. Researchers confirmed the data's accuracy by comparing them

with readings from a laser vibrometer (a technology commonly used to measure vibration).

When combined with a drone, the system can potentially evaluate components that are difficult to access or view. EPRI set up remote communications and onboard computing and made adjustments to minimize the drone's motor-induced vibrations. Researchers remotely controlled the integrated imaging system to complete the vibration analysis, and they found that the drone's vibrations did not adversely impact accuracy.

EPRI plans to collaborate with plant operators on field tests and publish a guide on lessons, best practices, technology improvements, and deployment.

Researchers report that the technology could potentially be integrated with systems for remote inspection and monitoring—such as crawlers, robots, and submersible vehicles.



A vibrational map (also known as a vibrogram) created during the EPRI study.

KEY EPRI TECHNICAL EXPERTS

Tony Cinson

Vehicle-to-Grid: \$1 Billion in Annual Grid Benefits?



An EPRI [study](#) finds that utilities and ratepayers can derive substantial value from large-scale deployment of electric vehicles (EVs) equipped to transmit power to the grid.

The [International Energy Agency](#) projects that by 2030 more than 130 million EVs will be on roads globally. Based on typical driving patterns, about 90% of EVs will be parked at any given time. These vehicles can potentially be grid-connected and available for dispatch to support grid operations. Many studies have documented grid benefits of *managed or smart charging*—systems through which a utility can remotely turn charging levels up, down, or off. But what is the value of taking smart charging a step further and deploying *vehicle-to-grid* (V2G) technologies that enable EVs to transmit power from their batteries to the grid? Such technologies can potentially lower grid operational costs by reducing peak demand, shifting load to off-peak times, and providing ancillary services.

EPRI researchers developed models to calculate the value of V2G-capable vehicles for California’s distribution systems. Key insights on what could happen:

- V2G technology can provide 2–3 times the value of managed charging.
- V2G technology can provide \$671 million in annual grid benefits, based on 3.3 million EVs in 2030 (medium EV forecast) with half of those EVs V2G-enabled.
- V2G technology can provide \$1 billion in annual grid benefits, given 5 million EVs in 2030 (aggressive EV forecast and a California goal) with half of those V2G-enabled.
- If half of California’s 600,000 EVs today were V2G-enabled, they could provide \$39 million in annual net value from peak shaving and ramping support.

This study builds on results from several years of [V2G technology development and demonstration by EPRI](#) along with major auto manufacturers such as Fiat Chrysler Automobiles and Honda R&D Americas. Funded by the California Energy Commission, the collaborative research is the first to combine evaluation of technology, valuation, and resource [planning](#) aspects of V2G.

KEY EPRI TECHNICAL EXPERTS

Sunil Chhaya

Can Transmission Line Inspection Be Completely Automated?



Two EPRI studies suggest that large-scale automation of transmission system inspection is feasible in the near future.

Increasingly, utilities inspect transmission systems by deploying drones to capture high-definition images of conductors, insulators, and other components. In most applications today, humans operate the drones and evaluate the images. By making drone-based inspections cheaper and less time-intensive, automation can drive widespread adoption.

In the first [study](#), EPRI tested several low-cost, commercially available drones at a Georgia field site with energized and non-energized transmission structures. The drones autonomously followed complex, three-dimensional flight plans and captured images without striking the structures. Existing LIDAR data on the structures proved critical to successful flight planning. However, improvements are needed in image perspective and navigation.

In the second [study](#), researchers examined the ability of nine machine learning technologies to evaluate thousands of images and identify defects in structures. Their performance was well above random prediction but well below human analysis. Larger image data sets are needed to train the technologies and improve their effectiveness, and researchers are collecting and curating additional images from utilities.

“To be successful, this research requires collaboration among utilities to pool and curate data and to test machine learning technologies,” said EPRI Senior Technical Leader Dexter Lewis. “Building an effective AI transmission and distribution inspection system is a challenge that is likely too large for any single utility, but together the industry can make a difference.”

EPRI plans to continue examining drone automation on energized transmission structures. EPRI has also established a broad [AI initiative](#) to facilitate collaboration among utilities, develop a research roadmap, collect and curate data sets for diverse applications, and educate electric power industry stakeholders.

KEY EPRI TECHNICAL EXPERTS

Dexter Lewis

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 electricity generated and delivered in the United States with international participation extending to nearly 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; Dallas, Texas; Lenox, Mass., and Washington, District of Columbia.

©2020 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute.

3002017739