ADVANCING CRITICAL INFRASTRUCTURE

With wide-ranging approaches to solving global problems, Lehigh researchers tackle key questions about the future of energy and infrastructure—and by extension, the future of modern society.

The countless man-made physical systems that keep us safe, comfortable and connected—buildings, roads, bridges, tunnels, transportation systems, the energy grid, water and sanitation systems, the Internet—are integral to modern life. And although they might go unnoticed or unappreciated in the day-to-day, we certainly notice them when something goes wrong: a train derailment, a bridge collapse.

In 2017 alone, severe weather events including Hurricanes Harvey, Irma and Maria pushed the infrastructure in those impacted areas to the very brink of—and sometimes beyond—their limits, often with dire consequences. And as infrastructure ages, the challenges and risks only grow more significant.

Lehigh researchers have long sought to meet infrastructure challenges. With an eye toward the interdependencies between these indispensable systems, researchers are working on a wide range of research that spans various fields of study to develop sustainable and resilient infrastructure and energy systems. Lehigh in April launched its new Institute for Cyber Physical Infrastructure and Energy, one of three inaugural Interdisciplinary Research Institutes (see sidebar on page 7), which will further strengthen and support this work.

MONITORING BRIDGE HEALTH

Pakzad uses data to assess the safety of the bridges that connect communities.

Ten years ago, while working toward his Ph.D. at UC Berkeley, Pakzad used fixed sensors to monitor the condition of San Francisco’s famed Golden Gate Bridge.

For our project, we spent $25,000 to attach 320 sensors to the bridge, creating a wireless sensor network,” says Pakzad. “Over a more than three-month deployment period, the amount of data we were able to collect was, for that time, unbelievable.”

As impressive as that was, the volume of data generated by the millions of connected mobile devices crossing the Golden Gate Bridge—inside the 100,000 vehicles, on average, that cross daily—dwarfs the amount of data that any fixed sensor network can obtain, either 10 years ago or today.

“How can we not use that data?” asks Pakzad. “It may not have the same quality as the dedicated, fixed sensor networks, but it still has value, and we want to extract all of the juice from it.”

SMARTER INFRASTRUCTURE

In 2017, America’s infrastructure received a grade of D+ by the American Society of Civil Engineers, which issues a report card every four years.

However, the communication infrastructure tends to be most up-to-date, says Shalinee Kishore, professor of electrical and computer engineering. “[It] can be used to help some of the other infrastructure systems work a little better, because in the end, those infrastructure systems are now going to be cyber-physical systems,” she says.

A “cyber-physical” system is, generally speaking, a physical system with cyber components that take measurements, gather information, and allow for automated changes and systems in the physical system. The application of digital communications technology to any physical system—the U.S. power grid, a manufacturing facility, a city’s transportation system, a bridge—is relatively cheap. Operators of these infrastructure systems use data collected from a variety of sources to make decisions about how to control the physical system or to determine what adjustments the system might require. Whether it is gathered from sensors physically attached to a structure, smartphones carried by users or customer comments posted on social media, the data can help develop a clearer understanding of how a system is functioning. This is particularly useful with aging infrastructure, says Kishore.

“The idea is to use the data to make all those aging infrastructure systems work better, to figure out what to upgrade, how to make it work with the retrograded parts of the system,” says Kishore. “And then infrastructure systems themselves are interconnected, so how you use the energy infrastructure and how you use the transportation infrastructure is very correlated. How does that data that you’re learning about one system versus the other tell you about both systems at once, and how could you make them jointly work better?”

The key question, says Shamim Pakzad, associate professor of civil and environmental engineering, is: “How can we use data to improve the quality of life in urban settings within the constraints that we have in the U.S. and in other industrial communities?”

Shalinee Kishore’s research interests are in communications theory, networks, and signal processing, with application to wireless systems and smart grid systems. She received her Ph.D. from Princeton University. Shamim Pakzad’s research interests include structural health monitoring, wireless sensor networks, damage detection, and probabilistic methods in civil engineering and structural reliability. She received her Ph.D. from the University of California, Berkeley.

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Illustration by Ryan Peltier
WATTS, BITS AND DOLLARS

Within the U.S. power grid lie three interdependent networks: power, communication and money—or, as the members of Lehigh’s Integrated Networks for Electricity (INE) research cluster like to say, watts, bits and dollars.

In 2011, the U.S. Department of Energy established the INE cluster, which includes faculty from a variety of disciplines focused on examining the electricity grid as an integrated “network of networks.” Since its inception, the group has produced significant research in the areas of cybersecurity for the electrical power grid as well as energy management systems, power system reliability, renewable energy integration and the development of ocean wave energy and other marine hydrokinetic energy systems. Nine cluster members are among the 532 recipients of $200 million multi-year university grant from the U.S. Department of Energy to develop an interdisciplinary approach to integratable, composable and evolvable cybersecurity in energy delivery systems. Two separate National Science Foundation grants have been awarded to teams of researchers to study ocean wave energy.

Kishore, along with Rick Blum, the Robert W. Wieseman Professor of Electrical Engineering, and Alberto Lamadrid, an assistant professor with a joint appointment in economics and industrial and systems engineering, are investigators on the DOE grant and are among the large group of Lehigh faculty working to make the U.S. power grid more sustainable and resilient.

“Everything depends on the grid,” says Blum. “And then, if you start thinking about it, the grid actually depends on other things as well. We need all of the various generation sources to supply this electrical energy to the grid.”

The grid network runs on a simple, automated principle: Energy is generated based on demand. When more demand is anticipated, generators can burn more coal or fuel to match that demand.

However, aging equipment, changing regulations and renewable generation such as wind and solar energy have added complexities to a system that has been mostly reliable over the years. Kishore says, “Decentralization at the wholesale and market levels has moved the energy industry away from the highly structured, vertically integrated monopolies that once dominated electricity production. Customers now have more options, and the competition between the various energy networks is more intense.”

As power flow conditions influence the communication between the power company and its customers, the type of communication shared can determine power flow. When customers have access to information about high-price times and low-price times, demand becomes more responsive. Customers can respond to prices as they make decisions about their energy consumption.

The three networks—watts, bits and dollars—work together connected and dependent upon one another.

EXPLORING INTERDEPENDENCIES

There is very small latency in the electricity system. Supply and demand have to be balanced in very short time scales, and there’s very little storage,” says Lamadrid. “So, what happens the moment that you start having more variable and uncertain energy?”

Many forms of renewable generation cannot be predicted easily—solar and wind, for example, depend upon weather conditions. This dependency makes the grid and solar a volatile proposition, requiring a form of backup generation to meet customer demand. In regions of the United States, that backup is natural gas: a clean, affordable, widely available resource.

The INE team is now examining the interaction between the electrical and natural gas networks.

“The problem is that the two systems are coupled, but we don’t fully understand or manage them that way,” says Blum. “We want to find a way that we can manage the electrical grid, we essentially ignore the natural gas network. We want to be able to take those networks into account during the planning of their operation,” says Blum.

In addition to electricity generation, natural gas is also used for heating in colder climates. As priority is given to heating customers, natural gas can become an unreliable resource for the power grid.

“If you’re in a place like New England, it’s probably more important to warm up your house than using natural gas in order to produce electricity,” says Lamadrid. “So, you end up in this situation in which you have very constrained pipeline capacity for natural gas, and therefore the system operator, which is already very reliant on that natural gas, may not have any fuel to start powering the system... It doesn’t happen very often, but you may end up with either very high prices or some curtailments. You’re going to be rationing this to that load because economically we cannot actually fulfill it.”

This affects the markets, says Lamadrid. “Despite their interdependency, the two systems are administered differently, and with its own incentives. The Lehigh team is interested in how to coordinate the markets across the two systems to reduce risk and vulnerability.

“There are some aspects of game theory here. In the case of natural gas, there may be some producers that want to maximize their profit. On the other hand, you have the system operator, whose interest is not in maximizing money but is in maximizing welfare. So, [the first] entity is going to be making a decision, and the [second] entity is going to be making the decision after they observe what the first one did. And then there will be some interaction between the two of them,” says Lamadrid.
**DANGEROUS CONNECTIONS**

The benefit of web-based interactions between systems are accompanied by some risks. Individuals who seek to exploit the interconnection between systems can compromise the grid, as well as any other systems dependent upon it.

"We can imagine hazards to infrastructure like hurricanes and earthquakes, terrorist attacks," says Richard Sause, the Joseph T. Stuart Endowed Chair of Structural Engineering and Architecture, and his Dumitru Ph.D. student, Kishore. "And they are of different types, and we need to think about how to defend against it." In the case of the power grid and natural gas, "if someone disrupts the natural gas sources or delivery network, that's going to affect the electrical grid since some generators in the grid run on natural gas." And the electrical grid itself provides electrical energy that's used to produce and transport the natural gas to the places needed. So, if the electrical grid goes down, that will also disrupt the natural gas network. These interdependencies can cause some serious problems," says Blum.

"In their latest research, Frangopol, the inaugural Fazlur R. Khan Professor of Structures and Extreme Events, and his research team at Lehigh, have been working to develop a comprehensive framework that combines models of individual and interdependent systems work together during and after a disaster. A framework that accounts for the randomness in it: planning for it, measuring it, optimizing it."

"As a Lehigh, I collaborate with people who are very easy to come to, but I try to have something more collaborative with experts different than me," says Kishore. "We're able to look at one problem and use our skills to solve the problem together. Then we use that experience to solve an even more significant problem between infrastructure systems. We build on the strengths of one to solve the problems in the second."}

**MANAGING RISK FROM NATURAL DISASTERS AND CLIMATE CHANGE**

Cyber-attacks aren't the only threats to our infrastructure systems. Natural disasters such as floods and hurricanes can have interesting effects. Lehigh researchers tackle these problems as well, studying a natural disaster connected systems might be hit by disasters, the difference between life and death. And, in the aftermath of such extreme weather events, bridges are also crucial for recovery efforts. Dan Frangopol and his research team, including students and postdocs, as well as advanced computer simulation, to assess the effects of natural disasters and other uncertainties on infrastructure during and after a disaster.

Dan Frangopol, associate professor of civil engineering, says: "Much of the modeling and research efforts to date have focused on designing buildings and infrastructure systems to avoid failures even under extreme events, and they have been quite successful," Bocchini says. "But in recent years the bar was raised. Our society not only asks the built environment to protect lives, but also to remain functional. Even after extreme events, we need our hospitals to be operational, our bridges to be safe, power and water in our homes, and functioning communication systems. Our system is far more complex than just the bridge. The recovery phase and the interdependencies among the systems involved. We start from the damage in every small structural component, and we zoom out to capture the recovery dynamics of the entire region. With good predictive models, we will be able to optimize mitigation and preparation."

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Through a $2.2 million NSF grant titled "Probabilistic Resilience Assessment of Interdependent Systems (PRAISys)—led by Lehigh and Lehigh researchers Snyder; Sause; Lamadrid; and Brian Davison, associate professor of computer science and engineering. The team focuses on the regional scale rather than the structural scale. How does an entire region recover from disaster? "Engineers have focused on designing buildings and infrastructure systems to avoid failures even under extreme events, and they have been quite successful," Bocchini says. "But in recent years the bar was raised. Our society not only asks the built environment to protect lives, but also to remain functional. Even after extreme events, we need our hospitals to be operational, our bridges to be safe, power and water in our homes, and functioning communication systems. Our system is far more complex than just the bridge. The recovery phase and the interdependencies among the systems involved. We start from the damage in every small structural component, and we zoom out to capture the recovery dynamics of the entire region. With good predictive models, we will be able to optimize mitigation and preparation."