# RESILIENCY: THE ELECTRIC GRID'S ONLY HOPE

## HEARING

BEFORE THE

## COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
## HOUSE OF REPRESENTATIVES

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COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HON. LAMAR S. SMITH, Texas, *Chair*

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**October 3, 2017**

# RESILIENCY: THE ELECTRIC GRID'S ONLY HOPE

**Tuesday, October 3, 2017**

House of Representatives,
Committee on Science, Space, and Technology,
*Washington, D.C.*

The Committee met, pursuant to call, at 10:09 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Lamar Smith [Chairman of the Committee] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

# Congress of the United States
## House of Representatives
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

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Full Committee

## *Resiliency: The Electric Grid's Only Hope*

Tuesday, October 3, 2017
10:00 a.m.
2318 Rayburn House Office Building

**Witnesses**

**Dr. William Sanders,** Department Head, Department of Electrical and Computer Engineering, University of Illinois

**Mr. Carl Imhoff,** Manager, Electricity Market Sector, Pacific Northwest National Laboratory

**Dr. Gavin Dillingham,** Program Director, Clean Energy Policy, Houston Advanced Research Center

**Mr. Walt Baum,** Executive Director, Texas Public Power Association

# U.S. HOUSE OF REPRESENTATIVES
# COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

## HEARING CHARTER

September 28, 2017

**TO:** Members, Committee on Science, Space, and Technology

**FROM:** Majority Staff, Committee on Science, Space, and Technology

**SUBJECT:** Full committee hearing: "Resiliency: The Electric Grid's Only Hope"

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The Committee on Science, Space, and Technology will hold a full committee hearing titled *Resiliency: The Electric Grid's Only Hope* on Tuesday, October 3, 2017, at 10:00 a.m. in Room 2318 of the Rayburn House Office Building.

**Hearing Purpose:**

The purpose of the hearing is to define resiliency, examine electric resiliency from both physical and cyber threats, and to study the effectiveness of private and government coordination on resiliency across the electricity delivery sectors. This hearing will specifically discuss the recommendations made by the National Academies of Sciences, Engineering, and Medicine's July 2017 consensus study report, "Enhancing the Resilience of the Nation's Electricity System." This hearing will also highlight the Department of Energy's lead agency status for critical infrastructure in the energy sector, and the impact of early-stage applied research on the development of resilient grid technology, infrastructure, and operational strategies.

**Witness List**

- **Dr. William Sanders,** *Department Head, Department of Electrical and Computer Engineering, University of Illinois*
- **Mr. Carl Imhoff,** *Manager, Electricity Market Sector, Pacific Northwest National Laboratory*
- **Dr. Gavin Dillingham,** *Program Director, Clean Energy Policy, Houston Advanced Research Center*
- **Mr. Walt Baum,** *Executive Director, Texas Public Power Association*

**Staff Contact**

For questions related to the hearing, please contact Jimmy Ward of the Majority Staff at 202-225-0222.

Chairman SMITH. The Committee on Science, Space, and Technology will come to order. Without objection, the Chair is authorized to declare recesses of the Committee at any time.

Welcome to today's hearing entitled "Resiliency: The Electric Grid's Only Hope."

I'll recognize myself for an opening statement and then the Ranking Member.

Good morning. Today, the Committee on Science, Space, and Technology will examine the ongoing effort by federal agencies, industry, and the Department of Energy's National Labs to ensure that a resilient U.S. electric grid can deliver power to American homes, businesses, and essential services. This hearing specifically will consider the recommendations made by the National Academies of Sciences' in their July 2017 report identifying ways to enhance the resiliency of our electricity system.

This Committee has held hearings addressing physical and cyber threats to our power system, as well as technological solutions to stop or prevent damage from these attacks, but we often ignore the fact that damage to the power grid can and will continue to occur. We cannot predict when a cyberattack would threaten our power supply, and as we were reminded a few weeks ago with the impact of Hurricane Harvey, we don't know when the next devastating natural disaster will occur.

Instead of simply focusing on threats, we should prioritize improving the resiliency of our electric grid. The resiliency of the grid is the ability of system operators to prevent disruptions in power, limit the duration of a power disruption, and quickly repair potential damage. Resiliency is also increased by incorporating data analytics and anecdotal evidence to improve preparation for future disruptive events. Since it is not a question of "if" but a question of "when" the power grid will face significant physical and cyber threats, resiliency should be a priority for our electricity system.

Congress requested that NAS conduct a study on the resiliency of the Nation's electric system. The final report was authored by a group of academics and industry partners with a knowledge base in electrical systems, engineering, and cybersecurity. The author of this report, Dr. William Sanders, will testify today on the NAS report and its recommendations.

The report recommends government and industry collaboration and improved data-sharing as the primary strategy for improving the resilience of the Nation's electrical system. The NAS report also stresses the importance of the Federal Government's investment in the kind of long-term, early-stage applied research and technology development that is the mission of the DOE National Labs.

DOE maintains research infrastructure at National Labs that is vital to better understanding and operating our electricity system. High performance computing systems can conduct complex modeling and simulations that predict potential electricity outages and plan responses to attacks. And information-sharing programs like the Department's Cyber Risk Information Sharing Program facilitate industry communication on shared threats. By partnering with industry through the National Labs, DOE can provide critical knowledge and enable the deployment of new technology that improves grid resilience.

There are still challenges to improving resilience. The current federal programs to protect and preserve our electric grid are fragmented and complex. Within the Science Committee's jurisdiction alone, programs to improve grid security and resiliency are funded at the Department of Homeland Security, FERC, the Department of Energy, and the National Institute of Standards and Technology.

And incorporating utilities across the country, both large and small, adds even more complexity. Agencies will need to work together to simplify the information-sharing process for industry. Federal agencies, including DOE, must also prioritize the early-stage research that industry does not have the capacity to undertake. This will lead to the next-generation technology solutions.

I thank our witnesses today for testifying about their valuable efforts in research, and giving their insights about operations of the electric grid. I look forward to a productive discussion about how federal agencies can work with industry to secure a resilient electric grid and what role Congress should play in providing direction and oversight to this complex process.

[The prepared statement of Chairman Smith follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
October 3, 2017

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

## Statement from Chairman Lamar Smith (R-Texas)

*Resiliency: The Electric Grid's Only Hope*

**Chairman Smith:** Good morning. Today, the Committee on Science, Space, and Technology will examine the ongoing effort by federal agencies, industry, and the Department of Energy's (DOE) national labs to ensure that a resilient U.S. electric grid can deliver power to American homes, businesses, and essential services.

This hearing specifically will consider the recommendations made by the National Academies of Sciences' (N-A-S) in their July 2017 report identifying ways to enhance the resilience of our electricity system.

This Committee has held hearings addressing physical and cyber threats to our power system, as well as technological solutions to stop or prevent damage from these attacks.

But we often ignore the fact that damage to the power grid can and will continue to occur. We cannot predict when a cyberattack would threaten our power supply. And as we were reminded last week with the impact of Hurricane Harvey, we don't know when the next devastating natural disaster will occur.

Instead of simply focusing on threats, we should prioritize improving the resilience of our electric grid. The resiliency of the grid is the ability of system operators to prevent disruptions in power, limit the duration of a power disruption, and quickly repair potential damage.

Resiliency is also increased by incorporating data analytics and anecdotal evidence to improve preparation for future disruptive events.

Since it is not a question of "if" but a question of "when" the power grid will face significant physical and cyber threats, resiliency should be a priority for our electricity system.

Congress requested N-A-S conduct a study on the resiliency of the nation's electric system. The final report was authored by a group of academics and industry partners with a knowledge base in electrical systems, engineering, and cybersecurity.

An author of this report, Dr. William Sanders, will testify today on the N-A-S report and its recommendations.

The report recommends government and industry collaboration and improved data sharing as the primary strategy for improving the resilience of the nation's electrical system. The N-A-S report also stresses the importance of the federal government's investment in the kind of long-term, early-stage applied research and technology development that is the mission of the DOE national labs.

DOE maintains research infrastructure at national labs that is vital to better understanding and operating our electricity system. High performance computing systems can conduct complex modeling and simulations that predict potential electricity outages and plan responses to attacks.

And information sharing programs – like the Department's Cyber Risk Information Sharing Program – facilitate industry communication on shared threats. By partnering with industry through the national labs, DOE can provide critical knowledge and enable the deployment of new technology that improves grid resilience.

There are still challenges to improving resilience. The current federal programs to protect and preserve our electric grid are fragmented and complex.

Within the Science Committee's jurisdiction alone, programs to improve grid security and resiliency are funded at the Department of Homeland Security, FERC, the Department of Energy, and the National Institute of Standards and Technology (NIST). And incorporating utilities across the country, both large and small, adds even more complexity.

Agencies will need to work together to simplify the information sharing process for industry. Federal agencies, including DOE, must also prioritize the early-stage research that industry does not have the capacity to undertake, this will lead to the next generation technology solutions.

I thank our witnesses today for testifying about their valuable efforts in research, and giving their insights about operations of the electric grid.

I look forward to a productive discussion about how federal agencies can work with industry to secure a resilient electric grid and what role Congress should play in providing direction and oversight to this complex process.

###

Chairman SMITH. That concludes my opening statement, and the gentleman from Texas, Mr. Veasey, is recognized for his.

Mr. VEASEY. Good morning, and thank you, Chairman Smith, for holding this very important and timely hearing today. I really appreciate that. I'd also like to thank the distinguished panelists for being here this morning. I'd also like to thank Dr. Dillingham in particular. It's my understanding that your house was affected by the storm and hope that you and your family are doing okay now and recovering well.

And also I'd like to—I look forward to this hearing and—because I want to hear your professional findings and your firsthand account of what storms like this can cause to communities across the country. I'm also interested in learning what we can do to improve their ability to restore power and other essential services as quickly as possible.

Hurricanes Harvey, Irma, and Maria are very unfortunate examples of events that our world's leading scientific institutions many times here in this committee have warned us would happen more often. It is difficult to attribute any single storm to one specific cause but there is a strong scientific consensus that human activity is responsible for conditions that may lead to more frequent and intense hurricanes, and the severity of these events may continue to get worse unless we do something to change our trajectory. This is a major reason that resilience is so important, and I am glad that we are elevating our examination of this topic today.

With that said, I am very concerned again with how the Department of Energy may actually be using and redefining grid resiliency to accomplish a political agenda. Just last Friday, the Department of Energy submitted a proposed rule to FERC with the direct purpose of adjusting market rules to favor coal and nuclear plants because they may have several weeks of fuel on site. The Department asserted that this makes these plants more resilient than natural gas and renewables and therefore deserve extra compensation for this attribute.

And I would imagine, Mr. Chairman, that there are probably some people that drill in Texas for natural gas that will probably be—will probably disagree with that.

Now, to be clear I'm a very strong supporter of developing and incentivizing carbon capture methods and technologies. It will help us to—it will help us reasonably use the abundant fossil fuel resources our nation has at its disposal, including coal. I also support the development and deployment of next-gen nuclear technologies while doing what we can to safely extend the lifetime of our current fleet.

But that doesn't mean that we should unfairly favor coal and nuclear without a strong independently reviewed justification. The Department has leaned on its recently released report on the electric grid for its justification, but the lead author of that report, Alison Silverstein, pushed back against this mischaracterization of her work. According to the conversations she had with committee staff, the bulk of her work remained intact after she handed it to the Department. However, the final report's specific recommendations supporting coal and nuclear plants due to their resiliency characteristics was not justified by any research that she or her colleagues were aware of. In a piece she published in Utility Dive yesterday, Ms. Silverstein took issue with how DOE interpreted her technical work in the staff report.

And, Mr. Chairman, I would like to enter this article in the record.

Chairman SMITH. Without objection, so ordered.

[The information appears in Appendix II]

Mr. VEASEY. In it, she states the characteristics, metrics, benefits, and compensation for essential resilience and reliability services are not yet fully understood. Specifically, she concludes that, "At this point we could not say that coal and nuclear have unique characteristics that provide such resiliency benefits that they should receive special treatment in the market."

This conclusion is also echoed by a thorough analysis released by the conservative R Street Institute on Sunday, which found that this proposal is neither technically nor procedurally sound. R Street summarized it as an arbitrary backdoor subsidy to coal and nuclear plants that risk undermining the electrical competition throughout the United States.

And a story published in Energy and Environment News on Friday titled "Flooded Texas Coal Piles Dampen Reliability Arguments" is an example of why this proposed rule may not have been as rigorously developed as it should have been, never mind the fact that in addition to doing what we can to ensure the resiliency of the grid, the cost of unmitigated pollution from fossil fuels should also be incorporated into the cost. Propping up coal for one insufficiently justified reason without properly pricing a major cost of its development and use to our public health and the environment is not what I would call good policymaking.

And before I conclude, Mr. Chairman, I would like to note that while the natural disasters are considerable threat to our grid infrastructure, there are a number of other concerns to keep in mind, too: cybersecurity, physical attacks, our aging infrastructure, geomagnetic disturbances, all of those present unique challenges to grid resiliency. And I look forward to hearing all of these topics discussed today.

And finally, I would be remiss to not remind the majority of—the majority here on the panel that we are fast approaching the end of the year, and we have still not heard from Secretary Perry yet on this committee, and we need to hear from him. And I would think that with all the Texans that are on this committee that it would be like when he was with Randy Weber now in the State Legislature and he would feel fine coming on down here and talking to us. We've got east Texas, west Texas, the Houston area, Dallas-Fort Worth. We're all represented and I'm sure that Rick, as we used to call him when I was in the Texas Legislature, that he would feel fine coming on down here and talking to us and testifying.

So, Mr. Chairman, with that, I yield back my time.

[The prepared statement of Mr. Veasey follows:]

<u>OPENING STATEMENT</u>
**Ranking Member Marc Veasey (D-TX)**
**of the Subcommittee on Energy**

House Committee on Science, Space, and Technology
*Resiliency: The Electric Grid's Only Hope*
October, 3, 2016

Good morning and thank you, Chairman Smith, for holding this important and timely hearing today.

I would also like to thank this distinguished panel of witnesses for being here this morning. I'd like to thank Dr. Dillingham in particular, whose home and family, I understand, were directly impacted by Hurricane Harvey. Dr. Dillingham, I hope that you and your family are well on the road to recovery at this point. I look forward to hearing both your professional findings and your first-hand account of how storms like these can cause significant harm to communities across the country.

I'm also interested in learning what we can do to improve their ability to restore power and other essential services as quickly as possible. Hurricanes Harvey, Irma, and Maria are unfortunate examples of events that our world's leading scientific institutions have warned us would happen more often. If we are not able to sufficiently reduce the emissions that are the leading drivers of climate change, we are likely to see even more in the future.

It is difficult to attribute any single storm to one specific cause, but there is a strong scientific consensus that human activity is responsible for conditions that lead to more frequent and intense hurricanes. The severity of these events will continue to get worse unless we change our trajectory. This is a major reason that resilience is so important, and I am glad that we are elevating our examination of this topic today.

With that said, I am concerned with how the Department of Energy may actually be using and redefining grid resiliency to accomplish a political agenda. Just last Friday, DOE submitted a proposed rule to FERC with the direct purpose of adjusting market rules to favor coal and nuclear plants because they may have several weeks of fuel on site. The Department asserted that this makes these plants more resilient than natural gas and renewables, and therefore deserve extra compensation for this attribute.

Now, to be clear, I am a very strong supporter of developing and incentivizing carbon capture methods and technologies. It will help us responsibly use the abundant fossil fuel resources our nation has at its disposal, including coal. I also support the development and deployment of next generation nuclear technologies while doing what we can to safely extend the lifetime of our current fleet. But that doesn't mean that we should unfairly favor coal and nuclear without a strong, independently reviewed justification.

The Department has leaned on its recently released report on the electric grid for its justification. But, the lead author of that report, Alison Silverstein, pushed back against this mischaracterization of her work. According to conversations she had with Committee staff, the bulk of her work remained intact after she handed it to the Department. However, the final report's specific recommendation supporting coal and nuclear plants due to their resiliency characteristics was NOT justified by any research that she or her colleagues were aware of. In a piece she published in Utility Dive yesterday, Ms. Silverstein took issue with how DOE interpreted her technical work in the staff report.

I would like to enter this article in the record.

In it, she states, "The characteristics, metrics, benefits and compensation for essential resilience and reliability services are not yet fully understood." Specifically, she concludes that at this point we cannot say that coal and nuclear have unique characteristics that provide such significant resiliency benefits that they should receive special treatment in the market. This conclusion is also echoed by a thorough analysis released by the conservative R Street Institute on Sunday, which found that this proposal is "neither technically nor procedurally sound." R Street summarized it as "an arbitrary backdoor subsidy to coal and nuclear plants that risks undermining electrical competition throughout the United States."

And a story published in Energy and Environment News on Friday titled "Flooded Texas coal piles dampen reliability arguments" is a prime example of why this proposed rule may not have been as rigorously developed as it should've been. Nevermind the fact that, in addition to doing what we can to ensure the resiliency of the grid, the cost of unmitigated pollution from fossil energy plants should also be incorporated into its costs. Propping up coal for one insufficiently justified reason without properly pricing a major cost of its development and use to our public health and the environment is not what I would call good policymaking.

Before I conclude, I would like to note that while natural disasters are a considerable threat to our grid infrastructure, there are a number of other concerns to keep in mind. In particular, cybersecurity, physical attacks, aging infrastructure, and geomagnetic disturbances also present unique challenges to grid resiliency.

I look forward to the discussion on all of these topics today.

Finally, I would be remiss to not remind my Majority colleagues that we are fast approaching the end of the year and we have still not had the Secretary of Energy testify before the Committee – or any DOE leadership for that matter. With all the Texans here, I imagine Secretary Perry would feel right at home. It's our responsibility to provide Congressional oversight for the valuable research activities at the Department and I hope we will have the Secretary come testify soon.

Thank you, I yield back.

Chairman SMITH. That's a good pitch, Mr. Veasey, and a good statement as well. Thank you.

Let me introduce our witnesses. Our first witness today is Dr. William Sanders, Department Head of the Department of Electrical and Computer Engineering at the University of Illinois. Dr. Sanders received a bachelor's degree in computer engineering, a master's of science degree and a Ph.D. in computer science and engineering from the University of Michigan.

Our next witness is Mr. Carl Imhoff, Manager of the Electricity Market Sector at Pacific Northwest National Laboratory. With over 30 years of experience at PNNL, Mr. Imhoff has been involved with multiple electric power system organizations. He received a bachelor's degree in industrial engineering from the University of Arkansas and a master's degree in industrial engineering from Purdue University.

The third witness is Dr. Gavin Dillingham, Program Director for Clean Energy Policy at Houston Advanced Research Center. Additionally, Dr. Dillingham is the Director of the U.S. Department of Energy Southwest Combined Heat and Power Technical Assistance Partnership. He received a Ph.D. in political science from Rice University.

Our final witness today is Mr. Walt Baum, Executive Director of Texas Public Power Association. Previously, Mr. Baum was the Executive Vice President of the Association of Electric Companies of Texas. He received a bachelor's degree in economics from Austin College with concentrations in political science, regulatory policy, and land-use economics.

We welcome you all, look forward to your testimony today. And Dr. Sanders, if you will begin.

## TESTIMONY OF DR. WILLIAM SANDERS, DEPARTMENT HEAD, DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING, UNIVERSITY OF ILLINOIS

Dr. SANDERS. Thank you, Chairman Smith. Chairman Smith, Ranking Member Veasey, and Members of the Committee, I am honored to appear before you today. My name is Bill Sanders, and I'm the head of the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign.

I was a member of the committee that wrote the National Academies of Science's engineering and medicine consensus report entitled "Enhancing the Resiliency of the Nation's Electricity System."

The subject of this hearing is resiliency. Resiliency is a fundamental and different concept from other abilities such as reliability or cybersecurity. In the context of electric power, a key insight about resiliency is that it attempts to avoid an event—in this case a long-term blackout—but understands and admits that avoidance may not be possible and thus works to respond as quickly as possible, preserving critical individual and societal services and over time strives for full recovery and enhanced robustness to further impairments.

The reference studies focuses largely on the Nation's vulnerability to large-area, long-duration outages, those that span several service areas and last three days or longer. If found that much can be done to make these outages less likely, but they cannot be totally eliminated no matter how much money or effort is invested. To increase the resiliency of the grid, our report argues that the Nation must not only work to prevent and minimize the size of outages but must also develop strategies to cope with the outages when they happen, recover rapidly afterward, and incorporate lessons learned into future planning and response effort.

The offered report also recognizes that at least for the next two decades most consumers will continue to depend on the functioning of a large-scale, interconnected, tightly organized, and hierarchical structured electric grid for resilient electricity service.

In addition to many specific recommendations directed to particular organizations, the report makes seven overarching major recommendations. They're documented in detail in the report, and I'll just summarize them here. First, emergency preparedness exercises that include multisector coordination; implementing available grid resiliency technologies and best practices; supporting DOE research and grid resiliency; creating a stock pile of physical components, namely transformers, that enhance resiliency; developing a means for grid cyber resilience; continuous envisioning of possible impairments which could lead to large-scale grid failures; and ongoing efforts as needed to mandate strategies designed to increase the resiliency of the electricity system. In all of these efforts, the joint and collaborative involvement of government, industry, and academia is key to their success.

A new concern to the resiliency of the power cyber portion of the grid and how that cyber portion could affect overall grid resiliency, the electric power system has become increasingly reliant on its cyber infrastructure, including computers, communication networks, control system electronics, smart meters and other distribution-side assets. A compromise of the power grid control system or other portions of the grid cyber infrastructure can have serious consequences ranging from a simple disruption to—of service with no damage to physical components to permanent damage of hardware that can have long-lasting effects.

Over the last decade, much attention has been rightly placed on grid cybersecurity but much less has been placed on grid cyber resiliency. The sources of guidance on protection as a mechanism to achieve grid cybersecurity are numerous and documented in the report. It is now, however, becoming apparent that protection alone is not sufficient and can never be made perfect.

An experiment, for example, conducted by the National Rural Electric Cooperative Association and N–Dimension in 2014 determined that a typical small utility is probed or attacked every 3 seconds around the clock. Given the relentless attacks and the challenges of prevention, successful cyber penetrations are inevitable and there is evidence of increases in the rate of penetration in the past year. Serious risks are posed by further integration of operational technology systems with utility business systems, despite the potential for significant value and increased efficiency.

Given that protection cannot be made perfect and the risk is growing, cyber resiliency, in addition to more classical cyber protection approaches, is critically important. While some work done under the cybersecurity nomenclature can be used to support resiliency, the majority of the work today has been focused on preventing the occurrence of successful attacks rather than detecting and responding to partially successful attacks that occur.

As argued in the report and in our overarching recommendation number 5, further work is critically needed to define cyber resiliency architectures that protect against, detect, respond, and recover from cyber events that occur. So the title of this hearing, "Resiliency: The Electric Grid's Only Hope" is apt. The threat to grid resiliency is multifaceted and real, and the time to act is now.

Thank you for the opportunity to be with you here today. I would be happy to answer any questions you have.

[The prepared statement of Dr. Sanders follows:]

**TESTIMONY OF**

William H. Sanders

Donald Biggar Willett Professor of Engineering
Head, Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
Urbana, IL

**BEFORE THE**

United States House of Representatives
Committee on Science, Space, & Technology

**HEARING ON**

*Resiliency: The Electric Grid's Only Hope*

October 3, 2017

Rayburn House Office Building
Washington, DC

(Portions of this testimony were taken verbatim from the National Academies of Sciences, Engineering, and Medicine report "Enhancing the Resilience of the Nation's Electricity System, ISBN 978-0-309-46307-2 | DOI 10.17226/24836, available at http://nap.edu/24836 and the associated "Report in Brief")

**Introduction**

Chairman Smith, Vice-Chairperson Lucas, Ranking Member Johnson, members of the committee: I am honored to appear before you today to discuss the resiliency of the United States power grid.

I am a Donald Biggar Willett Professor of Engineering and the Head of the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign. I was the founding director of the Information Trust Institute at the University of Illinois, and served as director of the Coordinated Science Laboratory at Illinois. I am a professor in the Department of Electrical and Computer Engineering and in the Department of Computer Science. I am a fellow of the IEEE, the ACM, and the AAAS; a past chair of the IEEE Technical Committee on Fault-Tolerant Computing; and past vice-chair of the IFIP Working Group 10.4 on Dependable Computing.

I am an expert on secure and dependable computing with a focus on critical infrastructures. I have published more than 270 technical papers in those areas. I was the 2016 recipient of the IEEE Technical Field Award, Innovation in Societal Infrastructure, for "assessment-driven design of trustworthy cyber infrastructures for societal-scale systems." Since 2005, I have led or co-led major government-funded centers (TCIP, TCIPG, and CREDC) that work to make the grid secure and resilient. I was also a member of the committee that wrote the National Academies of Sciences, Engineering, and Medicine consensus report entitled "Enhancing the Resilience of the Nation's Electricity System" that is the subject of this hearing. In short, my experiences provide me with a unique perspective to offer the Committee insight and recommendations concerning the impairments to and approach for providing resiliency in the electric power grid.

In my remarks today, I will:

- Describe the concept of resiliency.
- Provide an overview of the report, why it is important, and the top recommendations from the report that should be implemented now and in the future.
- Describe the importance of resiliency on the cyber systems that control the grid and, because my personal expertise is cyber,

- Make specific recommendations to enhance the resiliency of the cyber portion of the power grid to cyberattacks and, in turn, the grid itself, while stressing that resiliency to other impairments is also very important.

Before doing so, I will provide a brief overview of the Trustworthy Cyber Infrastructure for the Power Grid (TCIPG) project which I led, and the Cyber-Resilient Energy Delivery Consortium (CREDC), which I currently co-lead.

**TCIP/TCIPG and CREDC**

I served as the Director and Principal Investigator (PI) of the DOE/DHS Trustworthy Cyber Infrastructure for the Power Grid (TCIPG) Center and currently serve as the co-PI of the Cyber-Resilient Energy Delivery Consortium (CREDC), which conducts research at the forefront of national efforts to make the U.S. power grid resilient.

The Trustworthy Cyber Infrastructure for the Power Grid (TCIP (2005-2010) and TCIPG (2009-2015) projects, a partnership of four academic institutions, were conducted to meet the challenge of making the electricity grid resilient. The TCIP Project was funded primarily by the National Science Foundation, with additional support by the Department of Energy's Office of Electricity Delivery and Energy Reliability, and by the Department of Homeland Security's Science and Technology Directorate, HSARPA, Cyber Security Division. The TCIPG project was funded by the Department of Energy's Office of Electricity Delivery and Energy Reliability with partial support from the Department of Homeland Security's Science and Technology Directorate, HSARPA, Cyber Security Division.

In these projects, we collaborated with national laboratories and the utility sector to protect the U.S. power grid by significantly improving the way the power grid infrastructure is designed, making it more secure, resilient, and safe. In both technology and impact, TCIP/TCIPG was a successful partnership of government, academia, and industry, creating multiple startup companies and transitioning multiple technologies to industry. The projects also had a significant positive impact on workforce education, delivering successful short courses, producing graduates, and providing the knowledge necessary to do interdisciplinary work of this type at other universities.

CREDC (funded by the Department of Energy Office of Electricity Delivery and Energy Reliability with support from the Department of Homeland Security's Science and Technology

Directorate, HSARPA, Cyber Security Division) is a partnership of 10 academic institutions and 2 national labs that performs research and development in support of the Energy Sector Control Systems Working Group's Roadmap of resilient Energy Delivery Systems (EDS) that focuses on the cybersecurity of EDS. In doing so, CREDC addresses the cybersecurity of power grids, as well as oil and gas refinery and pipeline operations. To do this, CREDC develops projects with significant and measurable sector impact, involving industry partners (asset owners, equipment vendors, and technology providers) early and often, with activities that range from helping to identify critical sector needs, to performing pilot deployment and technology adoption.

**Resiliency**

The subject of this hearing is "resiliency," which is a fundamental and different concept from other "-abilities," such as, for example, reliability or cybersecurity. The Random House Dictionary of the English Language defines resiliency as "the power or ability to return to the original form, position, etc. after being bent, compressed, or stretched . . . [the] ability to recover from illness, depression, adversity, or the like . . . [to] spring back, rebound." In the context of electric power, resiliency is not just about being able to lessen the likelihood that outages will occur, but also about managing and coping with outage events when they do occur. The goal is to lessen outage impacts, regrouping quickly and efficiently once an event ends, and in the process learning to better deal with other events in the future.

Flynn (2008) has outlined a four-stage framing of the concept of resilience: (1) preparing to make the system as robust as possible in the face of possible future stresses or attacks; (2) relying on resources to manage and ameliorate the consequences of an event once it has occurred; (3) recovering as quickly as possible once the event is over; and (4) remaining alert to insights and lessons that can be drawn (through all stages of the process) so that if and when another event occurs, a better job can be done on all stages. Our committee used that framing to organize our report.

A key insight about the concept of resiliency is that it attempts, to the greatest extent possible, to avoid the large-scale event (in this case a long-term blackout), but understands and admits that it may not be totally possible to avoid it, and thus works to respond as quickly as possible to the event once it occurs, preserving "critical" individual and societal services during the period of degraded operation and, over time, strives for full recovery and enhanced robustness to further impairments that could result in additional large scale events.

Because the power system is hierarchical, these same concepts apply at several different levels of the system, including across the high-voltage grid, the regional grid (some of which are operated by regional transmission organizations), local transmission and distribution systems (typically the domain of utilities), and the end-use level (on both the utility and customer side of the meter) and across the cyber and physical portions of the power grid. It is also clear that the resiliency of the power grid is critically dependent other interconnected infrastructures (e.g, oil and gas).

**National Academy Report Overview**

In its 2014 appropriations for the Department of Energy, Congress requested that the National Academies of Sciences, Engineering, and Medicine organize a study to identify technologies, policies, and organizational strategies to increase the resilience and reliability of the U.S. electricity system. The study focused largely on reducing the nation's vulnerability to large-area long-duration outages — those that span several service areas or even states and last three days or longer. It found that much can be done to make both large and small outages less likely, but they cannot be totally eliminated no matter how much money or effort is invested. To increase the resilience of the grid, our report argues that the nation must not only work to prevent and minimize the size of outages, but must also develop strategies to cope with outages when they happen, recover rapidly afterward, and incorporate lessons learned into future planning and response efforts. The report also recognizes that, at least over the next two decades, most customers will continue to depend on the functioning of the large-scale, interconnected, tightly organized, and hierarchically structured electric grid for resilient electric service. Recent and ongoing events, such as the hurricanes in the Southeast and wildfires in the West, make the consideration of grid resilience even more timely.

The Chair of the study was M. Granger Morgan, Carnegie Mellon University, and the committee members were Dionysios Aliprantis, Purdue University; Anjan Bose, Washington State University; Terry Boston, PJM Interconnection (retired); Allison Clements, GoodGrid LLC; Jeffery Dagle, Pacific Northwest National Laboratory; Paul De Martini, Newport Consulting Group; Jeanne Fox, Columbia University; Elsa M. Garmire, Dartmouth College (retired); Ronald E. Keys, United States Air Force (retired General); Mark F. McGranaghan, Electric Power Research Institute; Craig Miller, National Rural Electric Cooperative Association; Thomas J. Overbye, Texas A&M University; William H. Sanders, University Illinois at Urbana Champaign; Richard E. Schuler, Cornell University; Susan F. Tierney, Analysis Group; David G. Victor, University of California San Diego.

The report notes that when major electricity outages do occur, economic costs can tally in the billions of dollars and lives can be lost. It argues that resilience is not just about lessening the likelihood that these outages will occur. It is also about limiting the scope and impact of outages when they do occur, restoring power rapidly afterwards, and learning from these experiences to better deal with events in the future.

Large outages have happened in the past as a result of hurricanes, ice storms, and a variety of other causes. Even larger outages, extending across many states for periods of many days, are possible in the future. Chapter 3 of the report discusses over a dozen events that could cause widespread outages of long duration.

The central chapters of the report (Chapters 4, 5, & 6) are organized around three critical elements of building a secure power system:

1. Taking step to be better prepared, long before an outage occurs.
2. Taking steps to minimize the individual and social cost of a large-scale long-term outage.
3. Putting the system back together after an event and learning from the process so we are able to do a better job of making the system more resilient in the future.

**Report Recommendations**

In addition to many specific recommendations directed to particular organizations, the report makes seven overarching recommendations (see the report for a precise statement of each recommendation, and the report's recommendation on what organizations should be responsible for implementation):

1. Conduct more emergency preparedness exercises that include multisector coordination.
2. Rapidly implement resiliency-enhancing technical capabilities and operational strategies that are available today, and speed the adoption of new capabilities and strategies as they become available.

3. Sustain and expand the areas of research, development, and demonstration that are now being undertaken by the Department of Energy's Office of Electricity Delivery and Energy Reliability and Office of Energy Efficiency and Renewable Energy, with respect to grid modernization and systems integration, with the explicit intention of improving the resiliency of the U.S. power grid.
4. Through public and private means, substantially increase the nation's investment in the physical resources needed to ensure that critical electric infrastructure is robust and that society is able to cope when the grid fails.
5. Carry out a program of research, development, and demonstration activities to develop and deploy capabilities for the a) continuous collection of diverse (cyber and physical) sensor data; b) fusion of sensor data with other intelligence information to diagnose the cause of the impairment (cyber or physical); c) visualization techniques needed to allow operators and engineers to maintain situation awareness; d) analytics (including machine learning, data mining, game theory, and other artificial intelligence-based techniques) to generate real-time recommendations for actions that should be taken in response to the diagnosed attacks, failures, or other impairments; e) restoration of control system and power delivery functionality and cyber and physical operational data in response to the impairment; and f) creation of post-event tools for detection, analysis, and restoration to complement event prevention tools.
6. Establish and support a "visioning" process with the objective of systematically imagining and assessing plausible large-area long-duration grid disruptions that could have major economic, social, and other adverse consequences.
7. Establish small System Resilience groups, informed by the work of the Department of Energy/Department of Homeland Security "visioning" process, to assess and, as needed, to mandate strategies designed to increase the resilience of the U.S. bulk electricity system.

The joint and collaborative involvement of government, industry, and academia in implementing these recommendations is key to their success.

**Cyber Resiliency**

A relatively new concern, and the subject of my core expertise, is the resiliency of the cyber portion of the grid, and how it affects overall grid resiliency. The electric power system has become increasingly reliant on its cyber infrastructure, including computers, communication networks, other control system electronics, smart meters, and other distribution-side cyber assets, in order to achieve its purpose of delivering electricity to the consumer. A compromise of the power grid control system or other portions of the grid's cyber infrastructure can have serious consequences ranging from a simple disruption of service with no damage to the physical components to permanent damage to hardware that can have long-lasting effects on the performance of the system. Any consideration of improved power grid resiliency requires a consideration of improving the resiliency of the grid's cyber infrastructure.

Over the last decade much attention has rightly been placed on grid cybersecurity, but much less has been placed on grid cyber resiliency. The sources of guidance on protection as a mechanism to achieve grid cyber security are numerous, and documented in the report. It is now, however, becoming apparent that protection alone is not sufficient, and can never be made perfect. Cybercriminals are difficult to apprehend, and there are nearly 81,000 vulnerabilities in the NIST National Vulnerability Database making it challenging to use safe code (NVD, 2016). An experiment conducted by the National Rural Electric Cooperative Association and N-Dimension in April 2014 determined that a typical small utility is probed or attacked every 3 seconds around the clock. Given the relentless attacks and the challenges of prevention, successful cyber penetrations are inevitable, and there is evidence of increases in the rate of penetration in the past year.

Fortunately, the successful attacks to date have largely been concentrated on utility business systems as opposed to monitoring and control systems (termed operational technology or OT systems), in part because there are fewer attack surfaces, fewer users with more limited privileges, greater use of encryption, and more use of analog technology. However, there is a substantial and growing risk of a successful breach of operational technology systems, and the potential impacts of such a breach could be significant. These risks are growing partially because, as the grid is modernized, there is greater reliance on grid components with significant cyber controls. Serious risks are posed by further integration of operational technology systems with utility business systems, despite the potential for significant value and increased efficiency.

Given that protection cannot be made perfect, and the risk is growing, cyber resiliency, in addition to more classical cyber protection approaches, is critically important. Cyber resiliency aims to protect using established cybersecurity techniques, but acknowledges that such protections can never be perfect, and requires monitoring, detection, and response to provide continuous delivery of electrical service. While some work done under the cybersecurity nomenclature can support cyber resiliency (e.g. intrusion detection and response), the majority of the work to date has been focused on preventing the occurrence of successful attacks, rather than detecting and responding to partially successful attacks that occur.

A cyber resiliency architecture should implement a strategy for mitigating cyberattacks and other impairments by monitoring the system and dynamically responding to perceived impairments to achieve resiliency goals. The resiliency goals for the cyber infrastructure require a clear understanding of the interaction between the cyber and physical portions of the power grid, and how impairments on either (cyber or physical) side could impact the other side. By their nature, such goals are inherently system-specific, but should balance the desire to minimize the amount of time a system is compromised and maximize the services provided by the system. Often, instead of taking the system offline once an attack is detected, a cyber resiliency architecture attempts to heal the system while providing critical cyber and physical services. Based on the resiliency goals, cyber resiliency architectures typically employ sensors to monitor the state of the system on all levels of abstraction and detect abnormal behaviors. The data from multiple levels are then fused to create higher-level views of the system. Those views aid in detecting attacks and other cyber and physical impairments, and in identifying failure to deliver critical services. A response engine, often with human input, recommends the best course of action. The goal, after perhaps multiple responses, is complete recovery, i.e., restoring the cyber system to a fully operational state.

Further work is critically needed to define cyber resiliency architectures that protect against, detect, respond, and recover from cyber attacks that occur.

**Achieving Cyber Resiliency**

In addition to overarching recommendation number 5, the report makes a specific recommendation regarding cyber resiliency. Specifically, it states that:

"The Department of Energy should embark upon a research, development and demonstration program that makes use of the diverse expertise of industry, academia, and national labs that results in a prototypical cyber-physical-social control system architecture for resilient electric power systems. The program would have the following components: 1) A diverse set of sensors (spanning the physical, cyber, and social domains), 2) a method to fuse this sensor data together to provide situational awareness of known high quality, and 3) an ability to generate real-time command and control recommendations for adaptations that should be taken to maintain the resiliency of an electric power system."

**Physical Resilience is Equally Important**

Because my personal expertise lies in the area of information, communication, and control technologies I have elaborated on cyber resilience. However, in closing I should stress that Chapter 3 of our report identifies and discusses over a dozen events such as hurricanes, earthquakes, tsunamis, ice storms, terrorist attacks, and large solar storms, that could cause wide *physical* damage to the power system that could result in large outages. Putting the system back together after one of these extreme events could require many days or even weeks.

**Summary**

The title of this hearing "Resiliency: The Electric Grid's Only Hope" is apt. Unlike some, I don't believe "the sky is falling" or that we are on the brink of a major disaster. However, the threat to grid resiliency is real, and the time to act is now, so we don't reach that brink. To summarize the points that I made in this testimony:

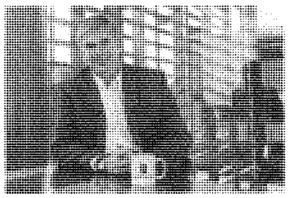
1) Grid resiliency is different than grid reliability, and requires a fundamentally new approach.
2) Grid resiliency attempts, to the greatest extent possible, to avoid long-term blackouts, but understands and admits that it may not be totally possible to avoid them, and thus works to respond as quickly as possible to the event once it occurs, preserving "critical" services during the period of degraded operation and, over time, strives for full recovery and enhanced robustness.
3) Efforts with appropriate funding must be put in place for:
   a) Emergency preparedness exercises that include multisector coordination,
   b) Implementing available technologies and best practices,

c) Supporting DOE research in grid resiliency,
d) Creating a stockpile of physical components that enhance resiliency,
e) Developing means for cyber resilience,
f) Continuous envisioning of possible impairments which could lead to large-scale grid failures, and
g) Ongoing efforts to assess and, as needed, to mandate strategies designed to increase the resilience of the electricity system.

4) The grid can only be resilient if its cyber infrastructure is resilient, so research and development are critically needed that provides assured mechanisms to ensure cyber resiliency.

Thank you for the opportunity to be here with you today. I would be happy to answer any questions that you have.

**William H. Sanders Biography**



William H. Sanders is a Donald Biggar Willett Professor of Engineering and the Head of the Department of Electrical and Computer Engineering (www.ece.illinois.edu) at the University of Illinois at Urbana-Champaign (illinois.edu). He is a professor in the Department of Electrical and Computer Engineering and in the Department of Computer Science. He is a fellow of the IEEE, the ACM, and the AAAS; a past chair of the IEEE Technical Committee on Fault-Tolerant Computing; and past vice-chair of the IFIP Working Group 10.4 on Dependable Computing. He was the founding director of the Information Trust Institute (www.iti.illinois.edu) at Illinois (2004-2011), and served as director of the Coordinated Science Laboratory (www.csl.illinois.edu) at Illinois from 2010 to 2014.

Dr. Sanders's research interests include secure and dependable computing and security and dependability metrics and evaluation, with a focus on critical infrastructures. He has published more than 270 technical papers in those areas. He served as the director and PI of the DOE/DHS Trustworthy Cyber Infrastructure for the Power Grid (TCIPG) Center (tcipg.org), which did research at the forefront of national efforts to make the U.S. power grid smart and resilient. He was the 2016 recipient of the IEEE Technical Field Award, Innovation in Societal Infrastructure, for "assessment-driven design of trustworthy cyber infrastructures for societal-scale systems."

## WILLIAM H. SANDERS

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**Education**

| Degrees | Field | Institution | Date Awarded |
|---|---|---|---|
| Ph.D. | Computer Science and Engineering | University of Michigan | 1988 |
| M.S.E. | Computer, Information and Control Engineering | University of Michigan | 1985 |
| B.S. | Computer Engineering | University of Michigan | 1983 |

**Academic Positions Held**

**Head, Department of Electrical and Computer Engineering, UIUC, 2014-Present.**
**Interim Head, Department of Electrical and Computer Engineering, UIUC, 2013-2014.**

Executive officer for department with approximately 105 faculty members and 60 staff; responsible for administrative, budgetary, hiring, and tenure decisions, and for leading the faculty and staff in the development of research, teaching, and public service programs. Oversees administrative and research expenditures of about $70M per year. Oversees and participates in extensive advancement activities as head, including managing and increasing the Dept. endowment of approximately $72M. Leads aggressive faculty hiring campaign that has hired 27 new tenure-track, 5 teaching, and 2 research faculty since Jan. 2014.

**Director, Coordinated Science Laboratory, UIUC, 2010-2014.**
**Acting Director, Coordinated Science Laboratory, UIUC, 2008-2010.**

Head of laboratory; responsible for research program with over 100 faculty members and 350 technical staff members. During Sanders's term as director, CSL's annual research expenditures rose from $17M to over $40M. It is a premier, multidisciplinary research laboratory that focuses on information technology at the crossroads of computing, control, and communications. During Sanders's tenure as director, it was composed of 3 institutes (the Advanced Digital Sciences Center, the Information Trust Institute, and the Parallel Computing Institute) and 7 national centers (Center for Exascale Simulation of Plasma-Coupled

Combustion; Center for People and Infrastructures; CompGEN; the Health Care Engineering Systems Center; the National Center for Professional & Research Ethics; SONIC Systems on Nanoscale Information fabriCs; and TCIPG, the Trustworthy Cyber Infrastructure for the Power Grid Center).

**Associate Director, Advanced Digital Sciences Center, UIUC, 2009-Present.**

Co-founded Center in 2009; is Illinois-based lead of the center, responsible (together with director) for its overall operation. ADSC is a bricks-and-mortar research laboratory in Singapore, with 14 participating Illinois faculty, 57 full-time technical staff members, and about $70M U.S. in research funding (over 7 years) from the government of Singapore.

**Donald Biggar Willett Professor of Engineering, Department of Electrical and Computer Engineering, UIUC, 2005-Present.**

This named professorship was given to Sanders in 2005 for his contributions in dependability/security evaluation, reliable and secure systems, and computer systems modeling and analysis.

**Director, Information Trust Institute, UIUC, 2004-2011.**

Was founding Director; established the Institute and grew it to include over 100 faculty from 28 departments, bringing in over $80M of external research funding and creating or helping create the TCIP and TCIPG (Trustworthy Cyber Infrastructure for the Power Grid) Centers, the Boeing Trusted Software Center, the Illinois Cyber Security Scholars Program, the Illinois Center for a Smarter Electric Grid, the Center for Assured Critical Application & Infrastructure Security (CACAIS), the Assured Cloud Computing University Center of Excellence, and an NSA Science of Security Lablet.

**Professor, Information Trust Institute, UIUC, 2004-Present.**

**Professor, Department of Electrical and Computer Engineering, UIUC, 1998-Present.**

**Professor, Coordinated Science Laboratory, UIUC, 1998-Present.**

**Associate Professor, Department of Electrical and Computer Engineering, UIUC, 1994-1998.**

**Research Associate Professor, Coordinated Science Laboratory, UIUC, 1994-1998.**

**Faculty Affiliate, Department of Computer Science, UIUC, 1994-Present.**

**Associate Professor, Dept. of Electrical and Comp. Engineering, University of Arizona, Tucson, AZ, 1994.**

**Assistant Professor, Dept. of Elect. and Comp. Engineering, Univ. of Arizona, Tucson, AZ, 1988-1994.**

## Other Professional Employment

Research Associate, Communications and Distributed Systems Laboratory, Industrial Technology Institute, Ann Arbor, Michigan, 1984-1988.
Teaching Assistant, Department of Electrical and Computer Science, University of Michigan, 8/83-12/83.
Digital Design Engineer, Optec, Inc., Lowell, MI, 1981-1983.

## Areas of Research

Dependability/Security Evaluation
Architecting Reliable and Secure Systems
Computer Systems Modeling and Analysis

**Consulting Activities**

SUNY Albany, 2014
Sterne, Kessler, Goldstein, and Fox, 2010-2012
WW Technology Group, 2006-2008
General Dynamics, 2006
Motorola Computer Group, 2000-2001
Motorola University, 1998-2001
IA Tech, Inc., 1998-Present
AT&T Bell Labs, 1996
Motorola Satellite Communications, 1993-2000
US West Advanced Technologies, 1991-1993
Bell Communications Research, 1990
Industrial Technology Institute, 1989

**Professional Societies**

Fellow, Institute of Electrical and Electronics Engineers
Fellow, Association for Computing Machinery
Fellow, American Association for the Advancement of Science
Past Vice-Chair, IFIP Working Group 10.4 on Dependable Computing
Eta Kappa Nu
Sigma Xi

**Awards and Honors, General**

***(See "Invited Talks and Seminars" for a list of keynote addresses presented; see "Service" for a list of advisory board memberships and distinguished professional service; see "Paper Awards" for scholarly paper awards.)***

**IEEE Technical Field Award, Innovation in Societal Infrastructure**, for "assessment-driven design of trustworthy cyber infrastructures for societal-scale systems," 2016.

Named on the **University of Illinois's Fall 2015 List of Teachers Ranked as Excellent by Their Students.**

Named on the **University of Illinois's Fall 2014 List of Teachers Ranked as Excellent by Their Students.**

**Named Fellow of the American Association of the Advancement of Science (AAAS)** for the development of fundamental theory and practical techniques to ensure that societal-scale distributed computing systems are trustworthy, 2014.

**NASA Tech Brief Award** for NTR no 42352: "A Performability-Oriented Software Rejuvenation Framework for Distributed Applications," 2006.

**Named Fellow of the Association for Computing Machinery** for "Outstanding contributions to the evaluation and design of dependable systems and networks," January 2004.

Named on the **University of Illinois's Fall 2003 Incomplete List of Teachers Ranked as Excellent by Their Students.**

Named on the **University of Illinois's Fall 2002 Incomplete List of Teachers Ranked as Excellent by Their Students.**

Recipient of one of the **2002 Engineering Council Awards for Excellence in Advising**, awarded to the top 10% of engineering advisors. (Selection is based on nominations from engineering students.)

Recipient of one of the **2000 Engineering Council Awards for Excellence in Advising**, awarded to the top 10% of engineering advisors. (Selection is based on nominations from engineering students.)

Named **Fellow of the IEEE**, for "Contributions to tools and techniques for performance and dependability evaluation of computer systems and networks," January 2000.

Made **Director of University of Illinois Motorola Center for High-Availability System Validation**, established by Motorola Inc. in December 1999 with funding of $1.1 million dollars for a 3-year period.

Recipient of one of the **1998 Engineering Council Awards for Excellence in Advising**, awarded to the top 10% of engineering advisors. (Selection is based on nominations from engineering students.)

**Elected member of IFIP Working Group 10.4 on Dependable Computing**, July 1992 (youngest member ever elected).

**Recipient of Faculty Award**, Digital Equipment Corporation, Incentives for Excellence, 1989, 1990, 1991. Twelve faculty members are selected nationally each year to receive this award. An individual can receive this award for a maximum of three years. ($75,000 cash prize, $105,000 in equipment).

**Member: Sigma Xi and Eta Kappa Nu academic honor societies.**

**Paper Awards**

Paper "A Quantitative Methodology for Security Monitor Deployment" won the Best Paper Award at the 46th Annual IEEE/IFIP International Conference on Dependable Systems and Networks, Toulouse, France, June 28-July 1, 2016.

Paper "ARIMA-Based Modeling and Validation of Consumption Readings in Power Grids" won the CIPRNet Young CRITIS Award (CYCA) at the 10th International Conference on Critical Information Infrastructures Security (CRITIS 2015), Berlin, Germany, Oct. 5-7, 2015.

Paper "PCA-Based Method for Detecting Integrity Attacks on Advanced Metering Infrastructure" won the Best Paper Award at the 12th International Conference on Quantitative Evaluation of Systems (QEST), Madrid, Spain, Sept. 1-3, 2015.

Paper "Enterprise Security Metrics with the ADVISE Meta Model Formalism" won a Best Paper award at SECURWARE 2015: The Ninth International Conference on Emerging Security Information, Systems and Technologies, Venice, Italy, Aug. 23-28, 2015.

Paper "Modeling the Fault Tolerance Consequences of Deduplication" won the Best Paper award at the 30th IEEE Symposium on Reliable Distributed Systems (SRDS 2011), Madrid, Spain, Oct. 5-7, 2011.

Paper "Blackbox Prediction of the Impact of DVFS on End-to-End Performance of Multitier Systems" won the award as Best Student Paper at the GreenMetrics 2009 Workshop, Seattle, Washington, June 15, 2009.

Paper "Detecting and Exploiting Symmetry in Discrete-State Markov Models" selected as one of the best papers at the 12th Pacific Rim International Symposium on Dependable Computing (PRDC'06); expanded version published in *IEEE Transactions on Reliability*.

Paper "Designing Dependable Storage Solutions for Shared Application Environments" selected as one of the best papers at the International Conference on Dependable Systems and Networks (DSN-2006); expanded version accepted for publication in *IEEE Transactions on Dependable and Secure Computing.*

Paper "Barbarians in the Gate: An Experimental Validation of NIC-based Distributed Firewall Performance and Flood Tolerance" selected as one of the best papers at the International Conference on Dependable Systems and Networks (DSN-2006).

Paper "Formal Specification and Verification of a Group Membership Protocol for an Intrusion-Tolerant Group Communication System" won the award as the Best Paper presented at the 2002 Pacific Rim International Symposium on Dependable Computing (PRDC 2002) Tsukuba, Japan, December 16-18, 2002.

Papers "The Möbius Modeling Tool" and "Möbius: Framework and Atomic Models" named as being among the best papers at the 9th International Workshop on Petri Nets and Performance Models, and then selected for publication (as a single paper) in an upcoming special issue of *IEEE Transactions on Software Engineering.*

Paper "On the Effectiveness of a Message-Driven Confidence-Driven Protocol for Guarded Software Upgrading" selected as one of the best papers at IEEE IPDS 2000 (expanded version published in *Performance Evaluation*), 1999.

Paper "Measure-Adaptive State-Space Construction" selected as one of the best papers at IEEE IPDS 2000 (expanded version published in *Performance Evaluation*), 1999.

Paper "State-Space Support for Path-based Reward Variables" selected as one of the best papers at IEEE IPDS '98 (expanded version to be published in *Performance Evaluation*), 1998.

Paper "An Efficient Disk-based Tool for Solving Very Large Markov Models" selected as one of the best papers at the 9th International Conference on Modelling Techniques and Tools (expanded version published in *Performance Evaluation*), 1997.

Paper "'On-the-Fly' Solution Techniques for Stochastic Petri Nets and Extensions" selected as one of the best papers at IEEE PNPM-7 (expanded version published in *IEEE Transactions on Software Engineering*), 1997.

Paper "Algorithms for the Generation of State-Level Representations of Stochastic Activity Networks with General Reward Structures" selected as one of the best papers at IEEE PNPM-6 (expanded version published in IEEE Transactions on Software Engineering), 1995.

**Instructional Activities**

Course Development

1. Developed ECE 577, Computer System and Network Evaluation, course on analytic methods for the evaluation of computer systems and networks, Univ. of Arizona, ECE Dept., taught 1989, 1990, 1991, 1992, 1993, 1994.

2. Substantially revised and updated ECE 578, Introduction to Computer Networks, undergraduate/beginning graduate course on computer networks and protocols, Univ. of Arizona, ECE Dept., taught 1988, 1989, 1990, 1991, 1992, 1993, 1994.

3. Course Director for ECE 311, Microcomputer Laboratory, University of Illinois, ECE Dept., 1994-.

4. Developed and taught ECE 497WHS, Analytic Techniques for Computer System and Network Evaluation, Univ. of Illinois, ECE Dept., Spring 1995, Fall 1997.

5. Substantially revised and taught ECE/CS 441, Computer System Analysis, with Ravi Iyer, University of Illinois, ECE Dept., 1996.

6. Developed 16-hour short course for Motorola University entitled "Validating High-Availability Systems," 1998.

7. Developed 24-hour short course for Motorola University entitled "*UltraSAN*: Modeling, Analyzing, and Simulating High-Availability Systems," 1999.

Short Courses

"Network Protocol Interoperability and Performance/Dependability Evaluation," May 31-June 2, 1989 (with R. Martinez).

"Performance/Dependability Evaluation of Internetwork Environments," May 15-17, 1990 (with R. Martinez).

"Protocol Performance Evaluation," presented to a class at Ft. Huachuca, AZ, Aug. 1991.

"Performability Modeling with Stochastic Activity Networks," for US West Advanced Technologies, Aug. 17-19, 1992.

"Performability Evaluation using Stochastic Activity Networks," for Motorola Satellite Communications, Jan. 1994.

"*UltraSAN* Training Seminar," for Motorola Satellite Communications, August 1998.

"Validating High-Availability Systems," for Motorola University, October 1998, December 1998, July 1999, September 1999, February 2000, May 2000, June 2000, August 2000, Sept. 2000, October 2000, and March 2001.

"*UltraSAN* Training Seminar," for Motorola University, February 1999.

"*UltraSAN*: Modeling, Analyzing, and Simulating High-Availability Systems," for Motorola University, November 1999, February 2000, May 2000, and Sept. 2000.

"Validating High-Availability Systems," for SUN Microsystems, Nov. 2000.

Short course at the Department of Information Engineering at the University of Pisa, Italy, April 2006.

"Möbius: Modeling, Analyzing, and Simulating Systems," at General Dynamics, Aug. 2006.

"Quantitative Evaluation of Security Metrics" tutorial presented at 2010 International Conference on Quantitative Evaluation of SysTems (QEST).

"Cyber-Security in the Electrical Power Grid," short course taught along with Himanshu Khurana and David Nicol at the 44th Hawai'i International Conference on System Sciences, Kauai, Hawaii, Jan. 4, 2011

Undergraduate Advising

1. Served as representative for Computer Engineering at University of Illinois ECE Undergraduate Advising Fair, October 1995.

2. Served as computer engineering representative at Coordinated Science Laboratory Orientation, Fall 1996.

3. Served as computer engineering representative at Graduate School Opportunities Seminar, Fall 1996.

4. Served as computer engineering representative at ECE Advising Fair, Spring 1997.

5. Served as judge at ECE Undergraduate Research Symposium, April 1997.

6. Served as computer engineering representative at ECE Advising Fair, Fall 1998.

7. Served as computer engineering representative at ECE Advising Fair, Spring 1999.

**Research, Creative, and Other Scholarly Activities**

Books Edited

M. Dal Cin, C. Meadows, and W. H. Sanders (eds.), *Dependable Computing for Critical Applications 6*, vol. 11 of *Dependable Computing and Fault-Tolerant Systems* (ed. A. Avizienis, H. Kopetz and J. C. Laprie), Los Alamitos, CA: IEEE Computer Society Press, 1998.

P. Kemper and W. H. Sanders (eds.), *Computer Performance Evaluation: Modeling Techniques and Tools, Lecture Notes in Computer Science*, No. 2794 (ed. G. Goos, J. Hartmanis, and J. van Leeuwen), Berlin, Germany: Springer-Verlag, 2003.

G. Norman and W. Sanders (eds.), *Proceedings of the 11th International Conference on Quantitative Evaluation of Systems (QEST 2014), Lecture Notes in Computer Science*, vol. 8657, Springer, 2014.

Chapters in Books

W. H. Sanders and J. F. Meyer, "Performance Variable Driven Construction Methods for Stochastic Activity Networks," in *Computer Performance and Reliability* (ed. G. Iazeolla, P. J. Courtois, and O. J. Boxma), Amsterdam: North-Holland, 1988, pp. 383-398.

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E. Van Ruitenbeek, K. Keefe, W. H. Sanders, and C. Muehrcke, "Characterizing the Behavior of Cyber Adversaries: The Means, Motive, and Opportunity of Cyberattacks," FastAbstract in the *2010 International Conference on Dependable Systems and Networks Supplemental*, Chicago, Illinois, June 28-July 1, 2010, pp. 17-18.

W. H. Sanders, "Quantitative Security Metrics" (Keynote 1), *Proceedings of the 2010 IEEE International Symposium on Modeling, Analysis & Simulation of Computer and Telecommunication Systems (MASCOTS)*, Miami Beach, Florida, Aug. 17-19, 2010, p. xv.

W. H. Sanders, "Quantitative Evaluation of Security Metrics," *Proceedings of the 7th International Conference on the Quantitative Evaluation of Systems (QEST)*, Williamsburg, Virginia, Sept. 15-18, 2010, p. 306.

W. H. Sanders, "Building Resilient Infrastructures for Smart Energy Systems (Abstract)," *Proceedings of the 3rd IEEE PES Conference on Innovative Smart Grid Technologies (ISGT 2012)*, Washington, D.C., Jan. 16-20, 2012.

W. H. Sanders, "TCIPG: Trustworthy Cyber Infrastructure for the Power Grid Overview," *Proceedings of the 3rd IEEE PES Conference on Innovative Smart Grid Technologies (ISGT 2012)*, Washington, D.C., Jan. 16-20, 2012.

Bulletins or Reports

J. F. Meyer, K. H. Muralidhar, and W. H. Sanders, "LAN Protocol Validation," *ITI Technical Report ITI-TR-87-26*, Communications and Distributed Systems Laboratory, Industrial Technology Institute, Ann Arbor, MI, Oct. 1987.

W. H. Sanders and C. N. Thurwachter, "The Effect of Slot Time on the Performability of Token Bus Networks," *GAINS Technical Report,* Communications and Distributed Systems Laboratory, Industrial Technology Institute, Ann Arbor, MI, Feb. 1988.

J. F. Meyer, K. H. Muralidhar, and W. H. Sanders, "Model-Based Performability Evaluation of Local Area Networks," *Technical Report ITI-TR-88-7*, Communications and Distributed Systems Laboratory, Industrial Technology Institute, Ann Arbor, MI, May 1988.

W. H. Sanders, "Construction and Solution of Performability Models Based on Stochastic Activity Networks," *Technical Report CRL-TR-9-88,* Computing Research Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI, Aug. 1988.

W. P. Delaney, M. P. Kaplan, S. M. Mahoney, W. H. Sanders, and S. C. West, "Experiences in Porting *UltraSAN* from Unix to AIX and the RISC SYSTEM/6000," *Tucson Technical Report, TR-82.0531*, IBM ADSTAR, Tucson, AZ, Sept. 1992.

A. P. A. van Moorsel and W. H. Sanders, "Adaptive Uniformization: Technical Details," *PMRL Technical Report 93-4*, Dept. of Electrical and Computer Engineering, University of Arizona, Tucson, AZ, Jan. 1993. (Also Memoranda Informatica 93-22, Computer Science Dept., University of Twente, The Netherlands).

L. M. Malhis, W. H. Sanders, B. P. Shah, and S. C. West, "Modeling OAM Using Stochastic Activity Networks and *UltraSAN*," *PMRL Technical Report 93-1*, Dept. of Electrical and Computer Engineering, University of Arizona, Tucson, AZ, Mar. 1993.

L. M. Malhis, W. H. Sanders, B. P. Shah, and S. C. West, "*UltraSAN* Models for OAM Modeling Project," *PMRL Technical Report 93-2*, Dept. of Electrical and Computer Engineering, University of Arizona, Tucson, AZ, Mar. 1993.

L. A. Kant, L. M. Malhis, W. H. Sanders, B. P. Shah, and S. C. West, "*UltraSAN* Models for Recycle Modeling Project," *PMRL Technical Report 93-18*, Dept. of Electrical and Computer Engineering, University of Arizona, Tucson, AZ, Dec. 1993.

L. A. Kant, L. M. Malhis, W. H. Sanders, B. P. Shah, and S. C. West, "Modeling Recycle Using Stochastic Activity Networks and *UltroSAN*," *PMRL Technical Report 93-19*, Dept. of Electrical and Computer Engineering, University of Arizona, Tucson, AZ, Dec. 1993.

V. Gupta, V. Lam, H. V. Ramasamy, W. H. Sanders, and S. Singh, "Stochastic Modeling of Intrusion-Tolerant Server Architectures for Dependability and Performance Evaluation," University of Illinois at Urbana-Champaign Coordinated Science Laboratory technical report UILU-ENG-03-2227 (CRHC-03-13), December 2003.

H. V. Ramasamy, A. Agbaria, and W. H. Sanders, "Semi-Passive Replication in the Presence of Byzantine Faults," University of Illinois at Urbana-Champaign Coordinated Science Laboratory technical report UILU-ENG-04-2202 (CRHC-04-02), February 2004.

D. Daly, P. Buchholz, and W. H. Sanders, "An Approach for Bounding Reward Measures in Markov Models Using Aggregation," University of Illinois at Urbana-Champaign Coordinated Science Laboratory technical report UILU-ENG-04-2206 (CRHC-04-06), July 2004.

D. Daly, P. Buchholz, and W. H. Sanders, "A Preorder Relation for Markov Reward Processes," IBM Research Report RC23827 (W0512-025), December 6, 2005.

S. Gaonkar, E. Rozier, A. Tong, and W. H. Sanders, "Scaling File Systems to Support Petascale Clusters: A Dependability Analysis to Support Informed Design Choices," University of Illinois at Urbana-Champaign Coordinated Science Laboratory technical report UILU-ENG-08-2202 (CRHC-08-01), January 2008.

S. Singh, W. H. Sanders, D. M. Nicol, and M. Seri, "Automatic Verification of Distributed and Layered Security Policy Implementations," University of Illinois at Urbana-Champaign Coordinated Science Laboratory technical report UILU-ENG-08-2209 (CRHC-08-05), July 2008.

S. Chen, K. R. Joshi, M. A. Hiltunen, W. H. Sanders, and R. D. Schlichting, "Link Gradients: Predicting the Impact of Network Latency on Multi-Tier Applications," University of Illinois at Urbana-Champaign Coordinated Science Laboratory technical report UILU-ENG-08-2214 (CRHC-08-08), August 2008.

S. Gaonkar and W. H. Sanders, "Simultaneous Simulation of Alternative Configurations of Markovian System Models," University of Illinois at Urbana-Champaign Coordinated Science Laboratory technical report UILU-ENG-09-2203 (CRHC-09-02), March 2009.

E. W. D. Rozier and W. H. Sanders, "Dependency-Based Decomposition of Systems Involving Rare Events," University of Illinois at Urbana-Champaign Coordinated Science Laboratory technical report UILU-ENG-11-2203 (CRHC-11-03), January 2011.

U. Thakore, G. A. Weaver, and W. H. Sanders, "An Actor-Centric, Asset-Based Monitor Deployment Model for Cloud Computing." University of Illinois at Urbana-Champaign Coordinated Science Laboratory technical report UILU-ENG-14-2202, July 2014.

Publications in above categories that have been submitted for publication but not yet accepted

K. Keefe, B. Feddersen, M. Rausch, R. Wright, and W. H. Sanders, "Stochastic Cybersecurity Model Generation with the Möbius Ontology Framework," submitted to the ACM/IEEE 20th International Conference on Model Driven Engineering Languages and Systems (MODELS 2017), Austin, Texas, September 17-22, 2017.

V. Badrinath Krishna, R. Macwan, C. A. Gunter, and W. H. Sanders, "Integrity Attacks on Renewable Energy Generators," submitted to the ACM Conference on Computer and Communications Security (CCS), Dallas, Texas, October 30-November 3, 2017.

Patents

Matti Hiltunen, Richard Schlichting, Kaustubh Joshi, and William Sanders, U.S. patent 7,536,595: "Systems, Devices, and Methods for Initiating Recovery," issued May 19, 2009.

Shuyi Chen, William Sanders, Matti Hiltunen, Kaustubh Joshi, and Richard Schlichting, U.S. patent 8,073,655: "Quantifying the Impact of Network Latency on the End-to-End Response Time of Distributed Applications," issued December 6, 2011.

D. M. Nicol, W. H. Sanders, S. Singh, and M. Seri, U.S. patent 8,209,738: "Analysis of Distributed Policy Rule-Sets for Compliance with Global Policy," issued June 26, 2012.

Invited Talks and Seminars (unpublished)

"Construction and Solution of Performability Models Based on Stochastic Activity Networks," presented at the Computer Science Colloquium, Computer Science Dept., University of Arizona, Tucson, AZ, Sept. 21, 1989.

"Efficient Modeling Methods for Stochastic Activity Networks," presented at the Computer Group Seminar, Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ, Oct. 6, 1989.

"Efficient Modeling Methods for Stochastic Activity Networks," presented at the Systems and Industrial Engineering Seminar, Department of Systems and Industrial Engineering, University of Arizona, Tucson, AZ, Nov. 9, 1989.

"Applications of Stochastic Activity Networks to Performance/Dependability Evaluation," presented at the 3rd International Workshop on Petri Nets and Performance Models, Kyoto, Japan, Dec. 11-13, 1989.

"Performance Evaluation of Interconnection Networks for ISDN Switching Applications," presented at Italtel, Milan, Italy, June 19, 1990.

"Performance Evaluation of Computer Systems and Networks," presented at Technology '90, Mesa, AZ, Dec. 5, 1990.

"Performability Evaluation of Computer Networks Using Stochastic Activity Networks," presented at the Hartford Graduate Center, School of Engineering and Science, Hartford, CT, Jan. 18, 1991.

"Performability Modeling with *UltraSAN,"* Research Report presented at the 19th IFIP Working Group 10.4 and 11.3 Joint Meeting, Grand Canyon, AZ, Feb. 22-24, 1991.

"Performability Evaluation of CSMA/CD and CSMA/DCR Protocols under Transient Fault Conditions," Research Report presented at the 20th IFIP Working Group 10.4 Meeting, Quebec City, Canada, June 28 - July 1, 1991.

"Evaluation of Computer Networks Using *UltraSAN*," presented at Computer Science Dept. Seminar, University of Twente, The Netherlands, Oct. 4, 1991.

"Performability Modeling with *UltraSAN*," presented at Siemens Research Center, Munich, Germany, Oct. 7, 1991.

"Dependability Evaluation Using Composed SAN-Based Reward Models," Research Report presented at the 21st IFIP Working Group 10.4 Meeting, Maui, Hawaii, Feb. 20-24, 1992.

"Evaluation of Media Access Control Protocols under Transient Fault Conditions," presented at the 21st IFIP Working Group 10.4 Meeting, Maui, Hawaii, Feb. 20-24, 1992.

"Performability Evaluation: Models, Algorithms, and Applications," presented at the Systems and Industrial Engineering Seminar, Dept. of Systems and Industrial Engineering, University of Arizona, Tucson, AZ, Feb. 27, 1992.

"Reward Models with Impulse and Rate Rewards: An Algorithm and Numerical Results," Research Report presented at the 22nd IFIP Working Group 10.4 Meeting, Cape Cod, MA, July 9-14, 1992.

"A Model-Based Foundation for Evaluating Large Scale Telecommunications Systems," presented at US West Advanced Technologies, Boulder, CO, Dec. 14, 1992.

"Analytic Performability Evaluation of a Group-Oriented Multicast Protocol," presented at Computer Science Dept. Seminar, University of Twente, The Netherlands, July 2, 1993.

"Analytic Performability Evaluation of a Group-Oriented Multicast Protocol: A Case Study in the Use of Reduced Base Model Construction Methods," presented at ECE Dept. Seminar, Dept. of Electrical and Computer Engineering, University of Illinois, Urbana-Champaign, IL, Sept. 20, 1993.

"Performability Evaluation of Psync," presented at the Institute Informatik, TU Wien (Technical University Vienna), Wien, Austria, Oct. 18, 1993.

"Analytic Performability Evaluation of a Group-Oriented Multicast Protocol," Research Report presented at the IFIP Working Group 10.4 Meeting, San Diego, CA, Jan. 7-8, 1994.

"Adaptive Uniformization," Research Report presented at IFIP Working Group 10.4 Meeting, Horseshoe Bay, TX, June 18-19, 1994.

"The *UltraSAN* Project," presented at Electrical and Computer Engineering Dept., University of California at Irvine, Oct. 1994.

"SAN-Based Importance Sampling Methods," Invited Lecture at Dagstuhl Seminar on Performance and Dependability Modeling with Stochastic Petri Nets, Dagstuhl, Germany, May 22-25, 1995.

"New Methods for Performance/Dependability Evaluation," Invited Seminar, Siemens Corporate Research and Development, May 29, 1995.

"The *UltraSAN* Project," presented at Dept. of Systems and Computer Engineering, Carleton University, Ottawa, Canada, Sept. 25, 1995.

"An Analytic Performability Evaluation of a Group-Oriented Multicast Protocol," Carleton University, Ottawa, Canada, Sept. 26, 1995.

"Transient Solution of Markov Models by Combined Adaptive and Standard Uniformization," IFIP 7.3 Workshop, Lambertville, NJ, May 27-28, 1996.

"Transient Solution of Markov Models by Combined Adaptive and Standard Uniformization," 30th Meeting of IFIP WG 10.4, Appi, Iwate, Japan, June 27-July 1, 1996.

"Uniformization Methods for Markov Models," ICASE Colloquium, NASA Langley Research Center, July 17, 1996.

"A Changepoint Algorithm for Parallel Simulation," NASA ICLASS Review, NASA Langley Research Center, October 1, 1996.

"Largeness-Tolerant Methods for Markov Models," Performance '96 Hot Topic Session Presentation, Lausanne, Switzerland, October 7-11, 1996.

"Issues in Modeling Distributed System Software with Stochastic Activity Networks: A Case Study: Modeling Psync Communication Software," Performance '96 Hot Topic Session Presentation, Lausanne, Switzerland, October 7-11, 1996.

"A New Algorithm to Compute the Distribution of Reward Accumulated Over a Finite Interval," WG7.3 Workshop on Performance Evaluation, Lausanne, Switzerland, October 11-12, 1996.

"Unified Performance/Dependability Assessment Environments," Department Seminar, Electrical Engineering and Computer Science Department, University of Michigan, April 21, 1997.

"Unified Performance/Dependability Assessment Environments," Departmental Seminar, Department of Computer Science, Dartmouth University, April 28, 1997.

"AQuA: Adaptive Quality of Service for Availability," presented at IFIP WG 10.4 meeting, Honolulu, Hawaii, January 10-15, 1999.

"Dependability Management of Distributed Objects in AQuA Using Proteus," presented at a Computer Science Department Seminar, University of Arizona, February 2, 1999.

"Möbius: An Integrated Performance/Dependability Evaluation Environment," presented at the 4th DARPA Fault-Tolerant Computing Workshop at JPL, Pasadena, CA, March 23-25, 1999.

**Keynote speaker** at the 1999 International Workshop on Petri Nets and Performance Models (Sept. 1999).

**Keynote speaker** at MASCOTS '99, the Seventh International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (Oct. 1999).

"Integrated Frameworks for Multi-Level and Multi-Formalism Modeling," presented at the Workshop on Modeling of Heterogeneous Networks, University of Maryland, October 25, 1999.

"Integrated Frameworks for Multi-Level and Multi-Formalism Modeling," Distinguished Seminar Series, ECE Department, Washington State University, March 2, 2000.

"AQuA: An Infrastructure for Building Dependable Distributed Systems," Seminar Series, ECE Department, University of Wisconsin, April 14, 2000.

"AQuA: An Infrastructure for Building Dependable Distributed Systems," Seminar Series, EE Department, University of Pennsylvania, April 17, 2000.

"Model Construction in *UltraSAN*," Formal Methods and Performance Analysis: The First EEF-Summerschool on Trends in Computer Science, Nijmegen, the Netherlands, July 3-7, 2000.

"Building Dependable Distributed Systems Using the AQuA Architecture," invited talk presented at Microsoft Research, August 24, 2000.

"AQuA - Adaptive Quality of Service for Availability," invited talk presented at the International SRDS Workshop on Dependable System Middleware and Group Communication, Nürnberg, Germany, October 2000.

"Integrated Frameworks for Multi-level and Multi-formalism Modeling," invited talk presented at AT&T Research, November 17, 2000.

"Enabling and (in my Humble Opinion) Essential Technologies for Dependability Benchmarking," 39th IFIP Working Group 10.4 Meeting, March 1, 2001.

"Design and Validation of Highly Available Systems," IBM Manageability Workshop, May 8, 2001.

"The Möbius Framework - With an Application to Stochastic Process Algebras," 40th IFIP Working Group 10.4 Meeting, Stenungsund, Sweden, July 2001.

"Multi-level and Multi-formalism Modeling of Ultra-large Networks," Workshop on Modeling and Simulation of Ultra-Large Networks: Challenges and New Research Directions, Tucson, AZ, November 19-20, 2001.

"Strategy for a Dependable Information Society: Creating a Science/Engineering to Validate the Critical Information Infrastructure," EU-US Workshop on RCD Strategy for a Dependable Information Society, December 1, 2001.

"Dealing with Largeness and Complexity in System Models," invited talk at the Universität Dortmund, Germany, December 2001.

"Designing and Assessing Adaptive Dependable Distributed Systems: Putting the Model in the Loop," invited talk presented at the 41st Meeting of IFIP Working Group 10.4, Saint John, Virgin Islands, USA, January 5, 2002.

"The Möbius Performance Engineering Framework," NSF Next Generation Software Workshop, Austin, Texas, February 28, 2002.

"The Möbius Performance/Dependability Evaluation Framework," invited talk presented at CNR, Pisa, Italy, March 21, 2002.

"The Möbius Framework and Tool," invited talk presented at the University of Twente, The Netherlands, May 23, 2002.

"Building and Validating Intrusion-Tolerant Distributed Systems," presented at HP Labs, Palo Alto, CA, February 11, 2003.

"Multi-formalism and Multi-solution Frameworks for Dependability and Performability Evaluation," presented at Dagstuhl-Seminar 03201 on Probabilistic Methods in Verification and Planning, May 11-16, 2003.

**Keynote talk** on "Cooperative Research in Multi-Formalism, Multi-Solution Modeling: Opportunities and Challenges" at the Workshop on Stochastic Petri Nets and Related Formalisms (ICALP 2003 Satellite Workshop), Eindhoven, The Netherlands, June 28-29, 2003.

"Design, Implementation, and Validation of an Intrusion-Tolerant Publish and Subscribe System," Department Seminar, University of Erlangen-Nuremberg, October 3, 2003.

Participated in panel on "Trustworthiness of Open Information Systems: How Should It Be Achieved?" at the 22nd IEEE Symposium on Reliable Distributed Systems, Florence, Italy, October 6-8, 2003.

Participated in panel on "Dependability Benchmarks - Can You Rely on Them?" at the 1st Latin American Symposium on Dependable Computing, São Paulo, Brazil, October 21-24, 2003.

"Design, Implementation, and Validation of an Intrusion-Tolerant Publish and Subscribe System," Department Seminar, Universidade de Lisboa, Portugal, February 16, 2004.

"Design, Implementation, and Validation of an Intrusion-Tolerant Publish and Subscribe System," IFIP Research Report Presentation, Moorea, French Polynesia, March 9, 2004.

**Keynote talk** at Petri Nets 2004: 25th International Conference on Application and Theory of Petri Nets, Bologna, Italy, June 21-25, 2004.

**Keynote speaker** at the Windber Research Institute Showcase for Biotechnology, Johnstown, Pennsylvania, August 15, 2005.

**Keynote speaker** at LADC'2005: 2nd Latin-American Symposium on Dependable Computing, Bahia, Brazil, October 25-28, 2005.

"Protecting the Power Grid in Cyberspace," ACDIS Seminar at the University of Illinois Program in Arms Control, Disarmament, and International Security, March 29, 2006.

"Infrastructure Reliability & Security Management using Partially Observable Markov Decision Processes," IFIP 10.4 Working Group Meeting, June 29-30, 2006.

"Automatic Recovery Using Bounded Partially Observable Markov Decision Processes," IBM Research Seminar, Zurich, July 13, 2006.

"Probabilistic Validation of Computer System Security," Invited Tutorial at 2006 Quantitative Evaluation of Systems Conference, Sept. 2006.

"TCIP: Trustworthy Cyber Infrastructure for the Power Grid," DOE Office of Electricity Delivery and Energy Reliability Visualization and Controls Program Peer Review, Oct. 2006.

"TCIP: Trustworthy Cyber Infrastructure for Power," IFIP 10.4 Workshop, Jan 2007.

"Implementing Sound Access Policy with the Access Policy Tool," I3P Control Systems Security Workshop, Feb. 15, 2007.

"Dealing with Largeness and Complexity in System Models: The Möbius Approach," Virginia Tech, February 26, 2007.

"TCIP: Trustworthy Cyber Infrastructure for Power," Department Seminar, Agricultural Engineering Dept., University of Illinois, March 2007.

"Probabilistic Validation of Computer System Security," Department Seminar, University of Erlangen, Germany, March 19, 2007.

**Keynote speaker**, "Probabilistic Validation of Computer System Security," at First Open Workshop of the ReSIST European Network of Excellence (Resilience for Survivability in Information Society Technologies), Budapest, Hungary, March 21-22, 2007.

**Keynote speaker**, "Automatic Recovery from Failures and Attacks Using Bounded Partially Observable Markov Decision Processes," at the Workshop on Recent Advances in Intrusion-Tolerant Systems (WRAITS 2007), held in conjunction with the European Conference on Computer Systems (EuroSys 2007), Lisbon, Portugal, March 23, 2007.

**Keynote speaker**, "TCIP: Trustworthy Cyber Infrastucture for Power," at the Cyber Security and Information Infrastructure Research Workshop (CSIIR), Oak Ridge, Tennessee, May 14-15, 2007.

Participated in panel on "Architecting Critical Infrastructures" at the DSN 2007 Workshop on Architecting Dependable Systems, Edinburgh, Scotland, June 27, 2007.

"Dealing with Largeness and Complexity in System Models: The Möbius Approach," Department Seminar, University of Edinburgh, UK, June 2007.

"Probabilistic Validation of Computer System Security," Department Distinguished Seminar, Computer Science Department, College of William & Mary, Williamsburg, VA, Nov. 1, 2007.

"Möbius: A Flexible, Extensible, Environment for Dependability, Safety, and Security Evaluation," U.S. Army Engineering and Support Center, Huntsville, AL, Nov. 27, 2007.

**Keynote speaker**, "Probabilistic Quantification of Security," at the 2007 Pacific Rim Dependable Computing Conference, Melbourne, Australia, Dec. 17, 2007.

**Keynote speaker**, "RRE: A Game-Theoretic Intrusion Response and Recovery Engine," CeDICT Workshop on Dependable ICT Systems, Hoog Brabant, Utrecht, The Netherlands, Apr. 24, 2009.

**Keynote speaker**, "RRE: A Game-Theoretic Intrusion Response and Recovery Engine for Process Control Applications," 4th International CRIS Conference on Critical Infrastructures, Linköping, Sweden, Apr. 28, 2009.

Participant on panel on "Research Challenges in Failure Diagnosis," Workshop on Failure Diagnosis at the 58th IFIP WG 10.4 Meeting, Chicago, IL, June 26, 2010.

**Keynote speaker**, "Quantitative Security Metrics," 18th Annual Meeting of the IEEE International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS 2010), Miami Beach, FL, Aug. 17-19, 2010.

"Trustworthy Cyber Infrastructure for the Power Grid," Department of Electronic Systems, Aalborg University, Denmark, Nov. 16, 2010.

"Cyber-security in the Electrical Power Grid," Tutorial, Hawaii International Conference on System Sciences, Jan 4, 2011.

"Smarter Power Grids: Challenges and Research Directions," IFIP 10.4 Workshop on Workshop on Dependability Issues for a Smarter Planet, Snowmass, CO, Jan. 12-16, 2011.

Securing the Grid Panel, 2011 National Electricity Forum, Washington DC, Feb. 16-17, 2011.

"Smart Grid Security Efforts @ Illinois," SANS 2011 North American SCADA and Process Control Summit, Orlando, FL, Feb. 28 – Mar. 1, 2011.

"Making Sound Cyber Security Decisions Through a Quantitative Metrics Approach," Dept. Seminar, City University, London, March 9, 2011.

Congressional Briefing on Power Grid Infrastructure and Security and Resiliency, Washington, D.C., Mar. 30, 2011.

"RRE: A Game-Theoretic Intrusion Response and Recovery Engine," TRUST Seminar, University of California, Berkeley, Mar. 31, 2011.

Panel chair and participant, "Perspectives from Industry," Innovation Summit: Building Bridges to Interdisciplinary Learning at Illinois Integrating Education and Research, Apr. 13-14, 2011.

**Keynote speaker**, "Making Sound Cyber Security Decisions through a Quantitative Metrics Approach," 1st International Workshop on Resilience Assessment of Critical Infrastructures, São José dos Campos, Brazil, Apr. 25, 2011.

**Keynote speaker**, "Making Sound Cyber Security Decisions through a Quantitative Metrics Approach," 11th Annual Conference on High Confidence Software and Systems, Annapolis, Maryland, May 1-6, 2011.

"Building Resilient Infrastructures for Smart Energy Systems," TCIPG Summer School on Cyber Security for Smart Energy Systems, Q Center, St. Charles, Illinois, June 13-17, 2011.

"TCIPG Highlights," NITRD Tailored Trustworthy Spaces: Solutions for the Smart Grid Workshop, Arlington, Virginia, July 18-20, 2011.

"Challenges and Approaches for a Trustworthy Power Grid Cyber Infrastructure," Distinguished ECE Department Seminar, Vanderbilt University, Sept. 13, 2011.

"Challenges and Approaches for a Trustworthy Power Grid Cyber Infrastructure," University of Texas at Dallas, Sept. 26, 2011.

"Analysis of Enterprise and Control Network Firewall Configurations for Compliance with Global Policy," Honeywell, Minneapolis, Minnesota, Oct. 3, 2011.

"Making Sound Design Decisions Using Quantitative Security Metrics," CyLAB Seminar, Carnegie Mellon University, Pittsburgh, Penn., Nov. 14, 2011.

"Making Sound Design Decisions Using Quantitative Security Metrics," TCIPG Seminar Series on Technologies for a Resilient Power Grid, University of Illinois at Urbana-Champaign, Jan. 6, 2012.

"Intrusion Detection for AMI," EPRI Workshop, Huntington Beach, CA, Feb. 13, 2012.

"Making Sound Design Decisions using Quantitative Security Metrics," FY12 NSF Distinguished Lecture Series in Computer Information Science & Engineering, National Science Foundation, Arlington, Virginia, Feb. 15, 2012.

"CPS Challenges for a Trustworthy Power Grid Cyber Infrastructure," NIST Foundations for Innovation in Cyber-Physical Systems, Chicago, IL, Mar. 13, 2012.

"The Path to a Secure and Resilient Power Grid Infrastructure," Cybersecurity and Smart Infrastructure: Ensuring Resilience and Deterrence, American Chemical Society Hill Briefing, Rayburn House Office Building, Washington DC, April 19, 2012.

**Keynote speaker** at the 3rd ACM/SPEC International Conference on Performance Engineering (ICPE 2012), "Assuring the Trustworthiness of the Smarter Electric Grid," Boston, Massachusetts, Apr. 23, 2012.

"Understanding the Role of Automated Response Actions to Improve AMI Resiliency," NIST Cyber-Physical Systems Workshop, Gaithersburg, MD, April 24, 2012.

**Keynote speaker**, "Ensuring System Resilience at Design Time: A User and Attacker Oriented Approach," Designed-In Security Workshop at the 2012 High Confidence Software and Systems Conference (HCSS), Annapolis, Maryland, May 6-11, 2012.

"CPS Challenges for a Trustworthy Power Grid Cyber-Physical Infrastructure," CTO Roundtable on Cyber-Physical Systems: Building Safety, Security, Reliability, and Robustness into the Smart System Technologies of the Future, Washington, DC, June 18, 2012.

"Quantitative Evaluation of System Security using ADVISE," Workshop on the Science of Humans and Cyber-Security, Dartmouth College, Dartmouth, NH, June 19, 2012.

"Trustworthy Cyber Infrastructure for the Power Grid (TCIPG)," DOE Cybersecurity for Energy Delivery Systems Peer Review, Washington, DC, July 24-26, 2012.

**Keynote speaker**, "Assuring the Trustworthiness of the Smarter Electric Grid," 11th IEEE International Symposium on Network Computing and Applications (IEEE NCA12), Cambridge, Massachusetts, Aug. 23-25, 2012.

"Analysis of Enterprise Network Firewall Configurations for Compliance with Global Policy," School of Electrical Engineering and Computer Science Seminar, Washington State University, Pullman, Washington, Sept. 6, 2012.

Distinguished Lecture speaker, "Building Resiliency into the Smarter Electric Grid," Department of Computer Science, Wayne State University, Detroit, Michigan, Sept. 11, 2012.

**Keynote speaker** at the Workshop on Research and Use of Multiformalism Modeling Methods (WRUMMM), London, UK, Sept. 17, 2012.

**Keynote speaker**, "Building Resiliency into the Smarter Electric Grid," Association of Illinois Electric Cooperatives Annual Meeting, Springfield, IL, Oct. 3, 2012.

"Building Resiliency into the Smarter Electric Grid," Electrical and Computer Engineering Dept. Seminar, Univ. of Miami, Miami, FL, Oct. 8, 2012.

"Attack Prevention and Detection," at the IEEE Central Illinois Section's Technical Workshop: Cyber Security with Application on Electric Power Grids, Urbana, Illinois, Nov. 17, 2012.

"Challenges and Approaches for a Trustworthy Smart Grid Infrastructure," Department of Computing seminar, Imperial College London, London, UK, Dec. 10, 2012.

"Science of Security Lablets Propose a Hard Problems Structure That Can Be Used to Organize Their Current and Potentially Future Research," 2012 Science of Security Community Meeting, National Harbor, Maryland, Nov. 29-30, 2012.

"Cybersecurity Needs for the Smart Grid," NIST Smart Grid Advisory Committee Meeting, Gaithersburg, MD, Dec. 19, 2012.

"Challenges and Progress Toward a Resilient Electric Grid," Research Report at IFIP 10.4 Working Group on Dependable Computing, Tavira, Portugal, Jan. 21, 2013.

"Challenges and Approaches for a Trustworthy Power Grid Cyber Infrastructure," College of Computing and Informatics Seminar, University of North Carolina – Charlotte, Charlotte, NC, Feb. 6, 2013.

"Securing the Grid," Tech Council of Maryland, Bethesda, MD, Feb. 7, 2013.

"TCIPG Center Overview: Trustworthy Cyber Infrastructure for the Power Grid," FREEDM Center Industry Workshop, North Carolina State University, Raleigh, NC, Feb. 13, 2013.

**Plenary speaker**, "Analysis of Process Control Network Firewall Configurations for Compliance with Global Policy," at the 2nd IEEE INFOCOM Workshop on Communications and Control for Smart Energy Systems (CCSES 2013), INFOCOM'13, Turin, Italy, Apr. 19, 2013.

"Security through Resilience," United Technologies Research Center, East Hartford, CT, Sept. 23, 2013.

**Keynote speaker**, "Building Resilience into the Smart Grid," 3rd Great Lakes Symposium on Smart Grid and the New Energy Economy, Chicago, IL, Sept. 25, 2013.

"Challenges and Approaches for a Trustworthy Power Grid Cyber Infrastructure," Institutionen för Datavetenskap IDA-30 lecture, Linköpings Universitet, Linköping, Sweden, Nov. 11, 2013.

"Challenges and Opportunities in Modeling the Power Grid Cyber-Physical Infrastructure," invited lecture at Schloss Dagstuhl Seminar 14031: Randomized Timed and Hybrid Models for Critical Infrastructures, Dagstuhl, Germany, Jan. 12-17, 2014.

"Challenges and Approaches for a Trustworthy Power Grid Cyber Infrastructure," Cyber Seminar Series, Department of Homeland Security, Washington, D.C., Apr. 14, 2014.

**Semi-plenary keynote speaker**, "Making Sound Design Decisions using Quantitative Security Metrics," Resilience Week 2014, Denver, CO, Aug. 19-21, 2014.

"Making Sound Security Decisions using Quantitative Security Metrics," presentation to SCORE Working Group, Office of the Director of National Intelligence, Baltimore, MD, Oct. 3, 2014.

"Challenges and Approaches for a Trustworthy Power Grid Cyber Infrastructure," presented at the U.S. Department of Energy, Washington, DC, Dec. 15, 2014.

"Challenges and Approaches for a Trustworthy Power Grid Cyber Infrastructure," School of Electrical Engineering and Computer Science Colloquium talk, Oregon State University, Corvallis, OR, Jan. 12, 2015.

Panel speaker, "Department Heads Panel," ECEDHA Annual Conference and ECExpo, Hilton Head, SC, Mar. 14, 2015.

**Keynote speaker**, "Cyber Security of Power Grids," JST-NSF-DFG-RCN Workshop on Distributed Energy Management Systems, Washington, DC, Apr. 20, 2015.

"Challenges and Approaches for a Trustworthy Power Grid Cyber Infrastructure," ECE Spring 2016 Colloquium Series, Rutgers University, Piscataway, NJ, Mar. 9, 2016.

**Afternoon keynote speaker**, "Engineering in Cyber Resiliency: A Pragmatic (But Not Perfect) Approach," October 2016 C3E Workshop, Atlanta, GA, Oct. 17, 2016.

"Engineering in Cyber Resiliency: A Pragmatic (But Not Perfect) Approach," Computer Systems Colloquium, Stanford University Department of Electrical Engineering, Stanford, CA, Oct. 19, 2016.

"Engineering in Cyber Resiliency: A Pragmatic (But Not Perfect) Approach," SnT Distinguished Lecture, Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, Nov. 11, 2016.

Participated in panel on "Security and Privacy of Big-data Applications," 22nd IEEE Pacific Rim International Symposium on Dependable Computing (PRDC 2017), Christchurch, New Zealand, Jan. 24, 2017.

Title TBD: Invited talk at the Workshop on Data Mining for Cyber-physical and Industrial Systems (organized in association with the International Conference on Data Mining (ICDM 2017), New Orleans, LA, Nov. 18, 2017.

Software Demonstrations at Technical Conferences

Presented at 4th International Workshop on Petri Nets and Performance Models, Melbourne, Australia, Dec. 2-5, 1991. (*UltraSAN* Version 0.1)

Presented at ICASE Workshop on Software Tools and Techniques for Performance and Reliability Estimation, June 17-18, 1993. (*UltraSAN* Version 1.1.3)

Presented at 23rd Annual International Symposium on Fault-Tolerant Computing, Toulouse, France, June 22-24, 1993. (*UltraSAN* Version 1.1.3)

Presented at Performability Modeling of Computer and Communication Systems, Mont St. Michel, France, June 28-30, 1993. (*UltraSAN* Version 1.1.3)

Presented at 12th Symposium on Reliable Distributed Systems, Princeton, NJ, Oct. 6-8, 1993. (*UltraSAN* Version 2.0)

Presented at 4th International Workshop on Petri Nets and Performance Models, Toulouse, France, Oct. 20-22, 1993. (*UltraSAN* Version 2.0)

Presented at 7th International Conference on Modelling Techniques and Tools for Computer Performance Evaluation, Vienna, Austria, May 3-6, 1994. (*UltraSAN* Version 2.0.1)

Presented at 1995 International Workshop on the Numerical Solution of Markov Chains, Raleigh, NC, January 16-18, 1995. (*UltraSAN* Version 3.0)

Presented at IEEE International Computer Performance and Dependability Symposium, Erlangen, Germany, April 1995. (*UltraSAN* Version 3.01)

Presented at 5th IFIP Working Conference on Dependable Computing for Critical Applications, Urbana, IL, Sept. 27-29, 1995. (*UltraSAN* Version 3.01)

Presented at 6th International Workshop on Petri Nets and Performance Models, Durham, NC, Oct. 3-6, 1995. (*UltraSAN* Version 3.01)

Presented at IEEE International Computer Performance and Dependability Symposium, Urbana, Illinois, Sept. 1996. (*UltraSAN* Version 3.1)

Presented at International Workshop on Petri Nets and Performance Models/International Conference on Modelling Techniques and Tools for Computer Performance Evaluation, June 1997. (*UltraSAN* Version 3.3)

Presented at 27th International Symposium on Fault-Tolerant Computing, Seattle, Washington, June 24-27, 1997. (*UltraSAN* Version 3.3)

Presented at DARPA Quorum/High Confidence Computing PI Meeting, San Diego, California, July 12-17, 1998. (AQuA Architecture 1.0)

Presented at 4th DARPA Fault-Tolerant Computing Workshop, Jet Propulsion Laboratory, Pasadena, California, March 23-25, 1999. (Möbius Version 1.0)

Presented at PNPM'99: 8th International Workshop on Petri Nets and Performance Models, Zaragoza, Spain, Sept. 8-10, 1999. (Möbius Version 1.0)

Presented at DARPA Quorum Technology Demonstration Event, Crystal City, VA, February 7-11, 2000. (AQuA Architecture 2.1)

Presented at IEEE International Computer Performance and Dependability Symposium /International Conference on Modelling Techniques and Tools for Computer Performance Evaluation, Schaumburg, IL, March 27-30, 2000. (Möbius Version 1.0)

Presented at the DARPA OASIS PI meeting, Santa Fe, New Mexico, July 24-27, 2001. (ITUA Group Communication System Version 1.0)

Presented at the International Workshop on Petri Nets and Performance Models, Aachen, Germany, September 11-14, 2001. (Möbius Version 1.1)

Presented at the DARPA Oasis PI Meeting, Hilton Head Island, South Carolina, March 12-15, 2002. (ITUA Architecture 1.0)

Presented at DARPATech 2002 (DARPA's 22nd Systems and Technology Symposium), Anaheim, CA, July 31, 2002. (ITUA Architecture 3.0)

Presented at DARPA DISCEX III, Washington, D.C., April 23, 2003. (ITUA Architecture 3.1)

**Grants, Contracts and Gifts received for Research and Teaching**

| Year | Brief Title | Source of Funds | # of PI's |
|---|---|---|---|
| 1990-1992 | Model-Based Evaluation of Manufacturing Networks and Systems, $160,000, PI Sanders. | Intel Corp. | 1 |
| 1990-1992 | SAN-Based Performability Tools for Evaluating Large-Scale Telecommunication Systems, $43,090, PI Sanders. | Bellcore | 1 |
| 1990-1993 | Picture Archiving and Communications Systems: System-Level and Modeling Issues, $75,000, PI Sanders. | Toshiba Corp | 1 |
| 1991-1992 | A Model-Based Foundation for Evaluating Large-Scale Telecommunications Systems, $12,700, PI Sanders. | UA Adv. Telecom. Research Project | 1 |
| 1991-1993 | SAN-Based Performability Tools for Evaluating Large-Scale Telecommunication Systems, $239,775, PI Sanders. | US West Adv. Tech. | 1 |
| 1992-1994 | SAN-Based Performance Modeling of Distributed-System Software, $322,995, PI Sanders. | IBM Corp. | 1 |

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|---|---|---|---|
| 1992-1999 | Algorithm Development in Support of Computer-Based Performance-Dependability Evaluation, $520,000, PI Sanders. | Motorola Corp. | 1 |
| 1993-1996 | Massively Parallel Simulation of Large-Scale, High Resolution Ecosystem Models, $900,000, PI Zeigler. (left project in Aug. 1994, when I moved to UI) | Nat'l Science Found. | 6 |
| 1995 | Methods for Performability Evaluation, $10,000 unrestricted gift, PI Sanders. | Vysis Corp. | 1 |
| 1995 | Equipment in Support of Performance/Dependability Evaluation, PI Sanders. | Intel Corp. | 1 |
| 1995-1996 | Algorithms for Performance, Dependability, and Performability Evaluation using Stochastic Activity Networks, $75,000, PI Sanders. | NASA Langley Res. Ctr. | 1 |
| 1996 | Methods for Performability Evaluation, $10,000 unrestricted gift, PI Sanders. | Nat. Media Labs (3M) | 1 |
| 1996 | Routing and Robust Transport of Multi-Class Applications Subject to QOS Constraints, $35,000 unrestricted gift, PI Sanders. | Bellcore | 1 |
| 1996-1997 | Acquisition of Research Equipment for High-Speed Computing and Networking Initiative, $750,000 (NSF) plus matching funds (total: $1,601,738), PI Iyer. | NSF and matching funds | 5 |
| 1996-1999 | A Quality of Service Approach to Survivability, $726,086 (Amount of subcontract to UI from BBN; Total amount of DARPA contract to BBN $1,981,642), PI Sanders. | DARPA (BBN prime) | 1 |
| 1996-2000 | Rapid Analysis and Recovery Techniques for Critical Defects and Failures in Command and Control Applications, $1,437,632, PI Sanders. | DARPA | 1 |
| 1997 | Performability Modeling of Embedded Systems, $20,000 unrestricted gift, PI Sanders. | Interstate Electronics | 1 |
| 1997-2000 | Survivability of Large-Scale Information Systems, $300,000 (amount of subcontract from BBN; total amount of DARPA contract to BBN is $1,644,301), PI Sanders. | DARPA (BBN prime) | 1 |
| 1999-2002 | An Integrated Framework for Performance Engineering and Resource-Aware Compilation, $1,949,330, PI Sanders. | NSF | 3 |
| 1999-2002 | Motorola Center for High-Availability System | Motorola | 1 |

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| | Validation, $850,000, PI Sanders. | | |
| 2000-2001 | Distributed Object Integration for the Quorum Integration Effort, $850,000, PI Sanders. | DARPA (BBN prime) | 1 |
| 2000-2003 | Intrusion Tolerance by Unpredictable Adaptation, $514,977 (subcontract amount; total award $1,994,657), PI Sanders. | DARPA (BBN prime) | 1 |
| 2000-2003 | ITR: Experimental Validation of Large-Scale Networked Software Systems, $1,800,000, PI Sanders. | NSF | 4 |
| 2001-2003 | Validation of Intrusion-Tolerant Systems, $327,170, PI Sanders. | DARPA (BBN prime; add-on to the Intrusion Tolerance project) | 1 |
| 2002-2004 | Survivability of CECOM SMS Services: An ITUA Approach and Probabilistic Quantification of Security Metrics in Cyberspace, $150,000, PI Sanders. | DARPA (BBN prime) | 1 |
| 2002-2005 | Designing Protection and Adaptation into a Survivability Architecture: Demonstration and Validation (DPASA-DV), $1,285,437, PI Sanders. | DARPA (BBN prime) | 1 |
| 2003-2005 | US-Germany Cooperative Research: Analysis of Multi-Paradigm Möbius Models Using Kronecker-Based Techniques, $19,666, PI Sanders. | NSF | 1 |
| 2003-2006 | Creating an Integrated Modular Environment for the Modelling, Analysis, and Verification of Embedded Hybrid Systems, $255,000, PI Neogi. | NSF | 2 |
| 2004-2005 | Applications of Stochastic Modeling to Biological Systems gift, $240,000, PI Sanders. | Pioneer Hi-Bred | 1 |
| 2004-2006 | Information Trust Institute funding, $500,000, PI Sanders. | State of Illinois Dept. of Commerce and Economic Opportunity | 1 |
| 2004-2006 | On-Line Model-Based Adaptation Research, $70,000, PI Sanders. | AT&T | 1 |
| 2004-2008 | NGS: A Compiler-Enabled Model- and Measurement-Driven Adaptation Environment for Dependability and Performance, $1,200,000, PI Sanders. | NSF | 4 |
| 2004-2012 | Cyber Situational Awareness and Network Defenses ($1,094,640), PI Sanders initially, then later Kalbarzcyk. | Boeing | 7 |
| 2004- | Boeing Trusted Software Center, $6,584,000 ($484,000 of which is allocated to Sanders), PI Sanders initially, | Boeing | 1 |

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| | later transitioned to Nicol. | | |
| 2005-2006 | Information Trust Institute funding, $986,643, PI Sanders. | US Commerce Dept. | 1 |
| 2005-2007 | Unifying Stakeholders and Security Programs to Address SCADA Vulnerability and Infrastructure Interdependencies, $535,000 ($267,500 allocated to Sanders), PI Sanders. | DHS (I3P prime) | 2 |
| 2005-2010 | CT-CS: Trustworthy Cyber Infrastructure for the Power Grid, $7,125,000, PI Sanders. | NSF | 6 |
| 2006 | EU-US Summit Series on Cyber Trust: Workshop on System Dependability & Security, $61,127, PI Sanders. | NSF | 1 |
| 2006-2007 | Adoptability Evaluation of SPI Technologies, $325,000, PI Nicol. | SAIC-DEMACO | 3 |
| 2006-2007 | Sandia-Trustworthy Cyber Infrastructure for the Power Grid, $125,000, PI Sanders. | Sandia National Laboratories | 1 |
| 2006-2008 | Information Trust Institute funding, $987,228, PI Sanders. | US Commerce Dept. (SBA) | 1 |
| 2006-2009 | Detecting and Preventing Attacks with Vulnerability Signatures, $412,000, PI Borisov. | NSF | 3 |
| 2006-2010 | CSR-PDOS: Improving System Reliability via Delta Execution, $762,000 ($168,449 allocated to Sanders), PI Zhou. | NSF | 4 |
| 2006-2011 | CRI-A Configurable Application-Aware High-Performance Platform for Trustworthy Computing, $500,000, PI Hwu. | NSF | 4 |
| 2007-2009 | Policy Assessment and Verification in Survivable Process Control Systems, $500,000 ($250,000 allocated to Sanders), PI Nicol. | DHS (I3P prime) | 2 |
| 2007-2009 | Assessable Identity and Privacy Protection: End-to-End Assessment of Identity & Privacy Protection, $600,000 ($200,000 allocated to Sanders), PI Nicol. | DHS (I3P prime) | 3 |
| 2007-2012 | MLS Computing Platform Based on COTS and Open Source Technology, $610,000, PI Nicol. | Rockwell Collins | 2 |
| 2008 | 2008 Summer School on "Cyber Security for Process Control Systems," $30,000, PI Sanders. | Battelle Energy Alliance | 1 |
| 2008 | unrestricted research support, $100,000, PI Sanders. | Raytheon | 1 |
| 2008 | A Simulation Emulations Testbed for SS7 Networks, | Raytheon | 2 |

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|---|---|---|---|
| | $70,000, PI Nicol. | | |
| 2008 | unrestricted research support, $30,000, PI Sanders. | Deere & Co. | 1 |
| 2008-2009 | Helmet Integrated Nanosensors Signal Processing and Wireless Real Time Data Communication for Monitoring Blast Exposure to Battlefield Personnel, $203,280, PI Watkin. | Army | 5 |
| 2008-2010 | Trustworthy Communication Architecture for Converged SCADA Applications, $249,056, PI Khurana. | Pacific Northwest Nat'l Lab | 3 |
| 2008-2012 | Quality of Information Assurance: Assessment Management and Use (QIAAMU), $201,999, PI Sanders. | BBN Technologies | 1 |
| 2008-2014 | Illinois Cyber Security Scholar Program, $6,571,180, PI Campbell. | NSF | 3 |
| 2009 | National Cyber Range Program, $197,738, PI Sanders. | SAIC | 2 |
| 2009 | DURIP: Timing Traffic Analysis Testbed, $83,800, PI T. Coleman. | U.S. Air Force | 4 |
| 2009 | unrestricted research support, $20,000, PI Sanders. | AT&T | 2 |
| 2009 | IBM Faculty Award, $75,000, PI Sanders. | IBM | 1 |
| 2009-2010 | Design and Development of TCIP Education Applets for Integration of Renewable Resources in the Power Grid, $100,000, PI Sanders. | Pacific Northwest Nat'l Lab | 2 |
| 2009-2011 | Research and Experimentation with PMU Data and Delivery Network, $150,000, PI Sanders. | Pacific Northwest Nat'l Lab | 2 |
| 2009-2011 | Cyber Security Risk Metrics for DHS (TTA03), $125,000, PI Sanders. | AF (Cyber Defense Agency prime) | 1 |
| 2009-2012 | Prediction and Provenance for Multi-Objective Information Security Management, $223,900, PI Sanders. | Hewlett-Packard | 1 |
| 2009-2012 | unrestricted research funds, $37,500, PI Sanders. | Rockwell Collins | 2 |
| 2009-2015 | TCIPG Trustworthy Cyber Infrastructure for the Power Grid, $18,753,340, PI Sanders. | U.S. Dept. of Energy (NETL) | 2 |
| 2010 | IBM Faculty Award, $75,000, PI Sanders. | IBM | 1 |
| 2010 | Design of Trustworthy Automated Off-Road Vehicles, $40,000, PI Bretl. | Deere & Co. | 3 |
| 2010-2011 | Methods to Quantify the Cyber Security Smart Grid | GE Global Research | 1 |

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|---|---|---|---|
| | System Architectures and Applications, $151,477, PI Sanders. | | |
| 2010-2011 | gift, $100,000, PIs Nicol and Sanders. | Northrop Grumman | 2 |
| 2010-2012 | Center for Assured Critical Application & Infrastructure Security (CACAIS), $1,192,650, PI Nicol. | Office of Naval Research (ONR) | 2 |
| 2010-2013 | Design Development and Demonstration of Wide-Area PMU Data Sharing System for Entergy, $600,000, PI Sanders. | DOE (Entergy prime) | 1 |
| 2010-2015 | Illinois Center for a Smarter Electric Grid (ICSEG), $5,000,000, PI Overbye. | IL Dept. of Commerce and Economic Opportunity | 4 |
| 2011-2012 | gift, $40,000, PI Sanders. | Fujitsu | 1 |
| 2011-2013 | Assured Cloud Computing University Center of Excellence (ACC-UCoE), $6,000,000, PI Campbell. | Air Force | 4 |
| 2011-2013 | Secure Information Exchange Gateway for Electric Grid Entities, $1,175,000, PI Sanders. | DOE (GPA prime) | 4 |
| 2011-2013 | Tools and Methods for Hardening Communication Security of Energy Delivery System (EDS), $750,000, PI Sanders. | DOE (Telcordia prime) | 3 |
| 2012 | Scalable Intrusion Detection Systems for Advanced Metering Infrastructures, $114,111, PI Sanders. | Electric Power Research Institute | 2 |
| 2012-2016 | Science of Security Administration, $391,319, PI Nicol. | National Security Agency (CMU prime) | 3 |
| 2012-2016 | Program in Digital Forensics (PDF), $548,721, PI Campbell. | National Science Foundation | 5 |
| 2012-2016 | A Game-Theoretic Approach to Building Resilient Cyber Systems, $2,183,464, PI Sanders. | National Security Agency | 1 |
| 2013-2015 | Quantitative Security Metrics for Cyber-Human Systems, $275,000, PI Sanders. | National Security Agency (CMU prime) | 2 |
| 2013-2015 | Quantitative Assessment of Access Control in Complex Distributed Systems, $280,568, PI Nicol. | National Security Agency (CMU prime) | 2 |
| 2013-2016 | Applied Resiliency for More Trustworthy Grid Operation (ARMORE), $975,000, PI Sanders initially, then Yardley. | Dept. of Energy (GPA prime) | 4 |
| 2013-2016 | Practical Metrics for Enterprise Security Engineering $1,899,995, PI Sanders. | Dept. of Homeland Security | 1 |
| 2013-2016 | Collaborative Defense of Transmission and Distribution | Dept. of Energy | 5 |

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|---|---|---|---|
| | Protection and Control Devices against Cyber Attacks $1,273,000, PI Valdes. | (ABB prime) | |
| 2013-2016 | Secure Policy Based Configuration Framework, $930,000 PI Yardley. | Dept. of Energy (EPRI prime) | 4 |
| 2013-2016 | SDN (Software Defined Network) Project $1,100,000, PI Bobba. | Dept. of Energy (SEL prime) | 4 |
| 2013-2017 | Illinois Cyber Security Scholar Program, $5,071,180, PI Campbell. | NSF | 5 |
| 2014-2016 | Science of Security for Systems, $6,474,953, PI Nicol. | National Security Agency | 3 |
| 2014-2016 | Data-Driven, Model-Based Decision-Making based on Quantifiable Security Metrics, $803,787, PI Sanders. | National Security Agency | 1 |
| 2015 | Design and Evaluation of Methods to Detect Electricity Theft in Advanced Metering Infrastructure, $25,000, PI Sanders. | Siebel Energy Institute | 2 |
| 2015-2020 | Cyber Resilient Energy Delivery Consortium (CREDC), $28,099,258, PI Nicol | Dept. of Energy | 3 |

**b. For Instruction**

| | | | |
|---|---|---|---|
| 1998-1999 | Development of Short Courses for Motorola Univ. $431,800 | Motorola, Inc. | 2 |

**Graduate Thesis Research Advising**

M.S. Degrees Granted

George Lin, May 1990, *Performance Evaluation of Interconnection Networks for ISDN Switching Applications.*
Manish Rai, July 1990, *Design and Implementation of a Reduced Base Model Construction Technique for Stochastic Activity Networks.*
Yasser Alsafadi, Aug. 1990, *Definition and Evaluation of the Data Link Layer of PACnet.*
Roberto Freire, Dec. 1990, *A Technique for Simulating Composed SAN-Based Reward Models.*
Janet Tvedt, Dec. 1990, *Solution of Large-Scale Stochastic Process Representations of Stochastic Activity Networks.*
Kevin Prodromides, Jan. 1991, *Performability Evaluation of Two Collision-Resolution Schemes for Carrier Sense Multiple Access Protocols.*
Hemal Shah, Dec. 1991, *Performance Evaluation of Manufacturing Systems using Stochastic Activity Networks.*
M. Akber Qureshi, Aug. 1992, *Reward Model Solution Methods with Impulse and Rate Rewards: An Algorithm and Numerical Results.*
Bruce D. McLeod, May 1993, *Performance Evaluation of N-Processor Time Warp using Stochastic Activity Networks.*

W. Douglas Obal II, Aug. 1993, *Importance Sampling Simulation of SAN-Based Reward Models.*
Bhavan P. Shah, Aug. 1993, *Analytic Solution of Stochastic Activity Networks with Exponential and Deterministic Activities.*
John Diener, July 1994, *Empirical Comparison of Uniformization Methods for Continuous-Time Markov Choins.*
Anand Kuratti, July 1994, *Analytical Evaluation of the RAID 5 Disk Array.*
Fransiskus Krisnadi Widjanarko, Dec. 1994, *Evaluation of an Adaptive Checkpointing Scheme for Multiprocessor Systems.*
George Wilkey Richardson, Dec. 1995, *Evaluation of a Parallel Chaos Router Simulotor.*
Raman Krishnan, Dec. 1995, *The Impact of Workload on the Dependability of Microprocessors Used in Control Applications.*
Brian Melcher, Dec. 1995, *A Methodology for Evaluating the Availability of Computer-Integrated Manufacturing Management Systems.*
Daniel D. Deavours, May 1997, *Solutions to Lorge Markov Chains Produced by Stochastic Petri Nets.*
David Henke, August 1998, *Loki–An Empirical Evaluation Tool for Distributed Systems: The Experiment Analysis Framework.*
G. P. Kavanaugh, August 1998, *Design and Implementation of an Extensible Tool for Performance and Dependability Model Evaluation.*
Jessica Pistole, August 1998, *Loki–An Empirical Evaluotion Tool for Distributed Systems: The Run-Time Experiment Framework.*
Brijbhushan Sabnis, August 1998, *Proteus: A Software Infrastructure Providing Dependability for CORBA Applications.*
John Sowder, August 1998, *State-Space Generation Techniques in the Möbius Modeling Framework.*
Alex Williamson, August 1998, *Discrete Event Simulation in the Möbius Modeling Framework.*
Aaron Stillman, October 1999, *Model Composition within the Möbius Modeling Framework.*
Jay M. Doyle, May 2000, *Abstract Model Specification Using the Möbius Modeling Tool.*
Paul G. Rubel, October 2000, *Passive Replication in the AQuA System.*
Amy Christensen, October 2000, *Result Specification and Model Connection in the Möbius Modeling Framework.*
Ramesh U.V. Chandra, January 2001, *Loki: A State-Driven Fault Injector for Distributed Systems.*
David Daly, May 2001, *Analysis of Connection as a Decomposition Technique.*
Prashant Pandey, September 2001, *Reliable Delivery and Ordering Mechanisms for an Intrusion-Tolerant Group Communication System.*
Harigovind Venkatraj Ramasamy, April 2002, *A Group Membership Protocol for an Intrusion-Tolerant Group Communication System.*
Patrick Gerald Webster, October 2002, *Design of Experiments in the Möbius Modeling Framework.*
Salem Derisavi, May 2003, *The Möbius State-Level Abstract Functional Interface.*
Ryan Michael Lefever, May 2003, *An Experimental Evaluation of the Coda Distributed File System Using the Loki State-Driven Fault Injector.*
Kaustubh Raghunandan Joshi, May 2003, *Evaluoting Unavailability Caused by Group Membership Using Global-State-Based Foult Injection.*
Vishu Gupta, May 2003, *Intrusian-Tolerant State Transfer for Group Communication Systems.*
James Patrick Lyons, August 2003, *A Replication Protocol for an Intrusion-Tolerant System Design.*
Sankalp Singh, December 2003, *Probabilistic Validation of an Intrusion-Tolerant Replication System.*
Fabrice Stevens, May 2004, *Validation of an Intrusion-Tolerant Information System Using Prabobilistic Modeling.*
Michael A. Ihde, July 2005, *Experimental Evaluations of Embedded Distributed Firewalls: Performance and Policy.*
Mark Griffith, May 2006, *Dynamic Partitioning of Stochastic Networks of Molecular Interactions.*
Elizabeth Van Ruitenbeek, July 2007, *Madeling Mobile Phone Virus Propagation to Quantify Response Mechanism Effectiveness.*

Michael Graham McQuinn, December 2007, *Solution of Graph-Composed Markov Models Using Symmetry Detection and Symbolic Data Structures.*
Shuyi Chen, 2008, *Link Gradients: Predicting the Impact of Link Latency on Multi-tier Applications.*
Michael D. Ford, May 2012, *A Generalized Adversary Decision Algorithm and Analytic Solution Methods for ADVISE Models.*
Sobir Bazarbayev, May 2013, *Content-Aware Resource Scheduling for Commercial and Personal Clouds.*
Ahmed Mohamad Fawaz, May 2013, *A Response Taxonomy and Cost Model for Advanced Metering Infrastructures.*
David Raymond Grochocki Jr, May 2013, *Deployment Considerations for Intrusion Detection Systems in Advanced Metering Infrastructure.*
Craig Thomas Buchanan, May 2014, *Simulation Debugging and Visualization in the Möbius Modeling Framework.*
Carmen Cheh, December 2014, *The Cyber-Physical Topology Language: Definition and Operations.*
Ronald Joseph Wright, December 2014, *A Job Server for Parallel and Concurrent Execution of Möbius Simulators.*
Uttam Thakore, July 2015, *A Quantitative Methodology for Evaluating and Deploying Security Monitors.*
Benjamin E. Ujcich, July 2015, *An Attack Model, Language, and Injector for the Control Plane of Software-defined Networks.*
Varun Badrinath Krishna, December 2016, *An Energy-Efficient P2P Protocol for Validating Measurements in Wireless Sensor Networks.*
Michael J. Rausch, December 2016, *Determining Cost-Effective Intrusion Detection Approaches for an Advanced Metering Infrastructure Deployment Using ADVISE.*

M.S. Students Currently Supervised

Atul Bohara

Ph.D. Degrees Granted

Luai Malhis, January 1996, *Development and Application of an Efficient Method for the Solution of Stochastic Activity Networks with Deterministic Activities.*
Akber Qureshi, April 1996, *Construction and Solution of Markov Reward Models.*
Latha Arun Kant, August 1996, *Analysis of Cell-Loss Processes and Restoration Schemes in ATM Networks.*
Anand Kuratti, September 1997, *Improved Techniques for Parallel Discrete Event Simulation.*
Douglas Obal, August 1998, *Measure-Adaptive State-Space Construction Methods.*
Yansong (Jennifer) Ren, May 2001, *AQuA: A Framework for Providing Adaptive Fault Tolerance to Distributed Applications.*
Daniel Deavours, August 2001, *Formal Specification of the Möbius Modeling Framework.*
Sudha Krishnamurthy, October 2002, *An Adaptive Quality of Service Aware Middleware for Replicated Services.*
David Daly, May 2005, *Bounded Aggregation Techniques to Solve Large Markov Models.*
Salem Derisavi, May 2005, *Solution of Large Markov Models Using Lumping Techniques and Symbolic Data Structures.*
HariGovind Venkatraj Ramasamy, 2005, *Parsimonious Service Replication for Tolerating Malicious Attacks in Asynchronous Environments.*
Kaustubh Raghunandan Joshi, 2007, *Stochastic-Model-Driven Adaptation and Recovery in Distributed Systems.*
Shravan Gaonkar, 2008, *Exploring Design Configurations of System Models: From Simultaneous Simulation to Search Heuristics.*
Vinh V. Lam, 2011, *A Path-based Framework for Analyzing Large Markov Models.*
Ryan M. Lefever, 2011, *Diverse Partial Memory Replication.*
Saman Aliari Zonouz, 2011, *Game-Theoretic Intrusion Response and Recovery.*

Elizabeth LeMay, 2011, *Adversary-Driven State-Based System Security Evaluation.*
Shuyi Chen, 2011, *Gradient Techniques for Performance Prediction and Control in Multitier Systems.*
Eric William Davis Rozier, 2011, *Understanding the Fault-Tolerance Properties of Large-Scale Storage Systems.*
Sankalp Singh, 2012, *Automatic Verification of Security Policy Implementations.*
Douglas C. Eskins, 2012, *Modeling Human Decision Points in Complex Systems.*
Ahmed M. Fawaz, 2017, *Achieving Cyber Resiliency against Lateral Movement through Detection and Response.*

Ph.D. Thesis Students Supervised at Present

Varun Badrinath Krishna
Carmen Cheh
Ahmed Fawaz
Mohammad Noureddine
Michael Rausch
Uttam Thakore
Benjamin Ujcich
Ronald Wright

## Editorships of Journals

Guest Co-Editor, *Performance Evaluation* journal special issue on Modelling Techniques and Tools for Computer Performance Evaluation, vol. 63, no. 6, June 2006.
Member of the Editorial Board of *IEEE Security and Privacy* magazine, 2005-2006.
Member of the Editorial Board of the journal *Performance Evaluation*, 2004-2011.
Area Editor for Simulation and Modeling of Computer Systems for the *ACM Transactions on Modeling and Computer Simulation*, 2002-2010.
Associate Editor of *IEEE Transactions on Reliability*, 1999-2005.
Associate Editor of *IEEE Transactions on Software Engineering*, 1996-2000.
Guest Co-Editor, Special Section on Petri Nets and Performance Models, *IEEE Transactions on Software Engineering*, vol. 25, no. 2, March/April 1999.
Guest Co-Editor, Special Section on Dependable Computing for Critical Applications, *IEEE Transactions on Software Engineering*, vol. 25, no. 5, Sept./Oct. 1999.

## Post-doctoral Associates

Aad van Moorsel, May 1994 – Jan. 1996, of The Netherlands, now at the University of Newcastle upon Tyne.
Michel Cukier, Nov. 1996 – Nov. 2001, of France, now at the University of Maryland.
Adnan Agbaria, Oct. 2002 – July 2005, of Israel, now at Toga Networks (Huawie Research) and Haifa University.
Robin Berthier, Oct. 2009 – Feb. 2012, of France, now at the University of Illinois and Network Perception.
Eric W. D. Rozier, Jan. – June 2012, of the U.S., now at Iowa State University.
Sankalp Singh, July 2012 – Dec. 2012, of India, now at Google.
Gabriel Weaver, Jan. 2013 – Feb. 2014, of the U.S., now at the University of Illinois.

## Other Scholarly Activities

Conference Organization

Executive Committee Member, IEEE 10th Annual International Phoenix Conference on Computers and Communications, 1991.

Local Arrangements Chairperson, Second IFIP International Conference on Dependable Computing for Critical Applications, 1991.

Publication Chair, IEEE International Computer Performance and Dependability Symposium, 1995.

Co-Vice-Chair, Illinois Computer Affiliates Conference, 1995.

Industrial Relations Chairperson, 1995 Pacific Rim International Symposium on Fault-Tolerant Systems, Dec. 1995.

Co-Organizer, IFIP 10.4 Workshop on Tools for Dependable System Design and Evaluation, June 1995.

General Chair of Illinois Computer Affiliates Program (ICAP) Meeting, April 1996.

Vice-General Chair, IEEE International Computer Performance and Dependability Symposium, 1996.

Co-Organizer, Third International Workshop on Performability Modeling of Computer and Communication Systems (PMCCS3), 1996.

Program Co-Chair, Sixth IFIP International Working Conference on Dependable Computing for Critical Applications, 1997.

Software Tools Chairperson, IEEE 7th International Workshop on Petri Nets and Performance Models, 1997.

Software Tools Chairperson, International Conference on Modelling Techniques and Tools for Computer Performance Evaluation (TOOLS'97), 1997.

Software Tools Co-chairperson, IEEE 27th Annual Fault-Tolerant Computing Symposium, 1997.

Publications Chair, IEEE 28th Annual Fault-Tolerant Computing Symposium, 1998.

Program Co-chair, IEEE 29th Annual Fault-Tolerant Computing Symposium, 1999.

Co-organizer, International Workshop on Performability Modeling of Computer and Communication Systems (PMCCS), 2001.

Member, Advisory and Publicity Committee, 7th IEEE International Workshop on Object-oriented Real-time Dependable Systems (WORDS 2002).

Program Co-chair, Sigmetrics 2003: International Conference on Measurement and Modeling of Computer Systems, 2003.

General Chair and Program Co-chair, PNPM-03 (the 11th International Workshop on Petri Nets and Performance Models), 2003.

General Chair and Program Co-chair, Performance Tools 2003: 13th International Conference on Modelling Tools and Techniques for Computer and Communication System Performance Evaluation, 2003.

General Chair, 2003 Illinois Multiconference on Measurement, Modelling, and Evaluation of Computer-Communication Systems, 2003.

Ad Hoc Steering Committee Chair, QEST '04: 1st International Conference on Quantitative Evaluation of SysTems, 2004.

Publicity Co-Chair, SRDS 2004 (23rd Symposium on Reliable Distributed Systems).

Steering Committee Chair, QEST (International Conference on Quantitative Evaluation of Systems), 2004-2008.

International Liaison Chair, European Dependable Computing Conference (EDCC-5), 2005.

Local Organizing Committee member, 6th Symposium on Understanding Complex Systems (UCS 2006), 2006.

Fundraising co-Chair for North America, 40th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN 2010), 2010.

IEEE Symposium on Reliable Distributed Systems (SRDS), Best Paper Co-Chair, 2013.

Permanent member, Steering Committee of the IEEE Symposium on Reliable Distributed Systems (SRDS), 2013-present.

Co-organizer, Schloss Dagstuhl Seminar 14031: Randomized Timed and Hybrid Models for Critical Infrastructures, 2014.

Program Committee Co-Chair, QEST: International Conference on Quantitative Evaluation of SysTems, 2014.

Panel moderator, "The Science of Security" panel, the Cybersecurity Innovation Forum, 2014.

Conference Program Committee Service

IEEE 9th Annual International Phoenix Conference on Computers and Communications, 1990.

IEEE 4th International Workshop on Petri Nets and Performance Models, 1991.
IEEE 12th International Conference on Distributed Computer Systems, 1992.
IEEE 5th International Workshop on Petri Nets and Performance Models, 1993.
IEEE 12th Symposium on Reliable Distributed Systems, 1993.
IEEE 23rd Fault-Tolerant Computing Symposium, 1993.
IEEE Workshop on Fault-Tolerant Parallel and Distributed Systems, 1994.
IEEE 13th Symposium on Reliable Distributed Systems, 1994.
28th Annual Simulation Symposium (SCS and IEEE), 1995.
IEEE 15th International Conference on Distributed Computing Systems, 1995.
IEEE International Computer Performance and Dependability Symposium, 1995.
IEEE 25th Fault-Tolerant Computing Symposium, 1995.
IEEE 6th International Workshop on Petri Nets and Performance Models, 1995.
Joint 8th International Conference on Modelling Techniques and Tools for Computer Performance Evaluation and 8th Conference on Measuring, Modelling, and Evaluating Computing and Communication Systems, 1995.
5th IFIP Working Conference on Dependable Computing for Critical Applications, 1995.
IEEE 26th Fault-Tolerant Computing Symposium, 1996.
SCS Conference on Analytical and Numerical Modeling Techniques, 1996.
International Conference on Performance Theory, Measurement and Evaluation of Computer and Communication Systems (PERFORMANCE'96), 1996.
IEEE 15th Symposium on Reliable Distributed Systems, 1996.
29th Annual Simulation Symposium (SCS and IEEE), 1996.
IEEE International Workshop on Dependability in Advanced Computing Paradigms, 1996.
IEEE International Workshop on Embedded Fault-Tolerant Systems, 1996.
6th IFIP Working Conference on Dependable Computing for Critical Applications, 1997.
IEEE 7th International Workshop on Petri Nets and Performance Models, 1997.
International Conference on Modelling Techniques and Tools for Computer Performance Evaluation (TOOLS'97), 1997.
3rd International Conference on Reliability, Quality and Safety of Software-Intensive Systems (ENCRESS'97), 1997.
SIGMETRICS '97, 1997.
30th Annual Simulation Symposium (SCS and IEEE), 1997.
IEEE 28th Fault-Tolerant Computing Symposium, 1998.
Workshop on Software and Performance (WOSP98), 1998.
International Conference on Modeling Techniques and Tools for Performance Evaluation (Tools '98), 1998.
3rd IEEE High-Assurance Systems Engineering Symposium (HASE), 1998.
20th International Conference on Applications and Theory of Petri Nets (ICATPN '99), 1999.
32nd Annual Simulation Symposium, 1999.
International Conference on the Numerical Solution of Markov Chains (NSMC '99), 1999.
8th International Workshop on Petri Nets and Performance Models (PNPM '99), 1999.
7th International Workshop on Parallel and Distributed Real-Time Systems (WPDRTS), 1999.
7th International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS '99), 1999.
4th IEEE Symposium on High Assurance Systems Engineering (HASE '99), 1999.
IEEE International Computer Performance and Dependability Symposium (IPDS 2K), 2000.
33rd Annual Simulation Symposium, 2000.
TOOLS 2000 (Int'l Conf. on Techniques and Tools for Computer Performance Evaluation), 2000.
DSN-00: International Conference on Dependable Systems and Networks (FTCS-30 & DCCA-8), 2000.
Pacific Rim International Symposium on Dependable Computing (PRDC 2000), 2000.
SIGMETRICS/Performance, 2001.
21st IEEE International Conference on Distributed Computing Systems (ICDCS-21), 2001.

DSN-01: International Conference on Dependable Systems and Networks, 2001.
2001 IEEE CS Workshop on Object-oriented Real-Time Dependable Systems (WORDS 2001), 2001.
Internet Performance Symposium (IPS-2001) at Globecom 2001.
PRDC 2001: IEEE Pacific Rim Dependable Computing Conference.
IPDS (Computer Performance and Dependability) track of DSN (International Conference on Dependable Systems and Networks), 2002.
Sigmetrics 2002.
Internet Performance Symposium (IPS 2002) in conjunction with Globecom 2002.
Performance Tools 2002: 12th International Conference on Modelling Tools and Techniques for Computer and Communication System Performance Evaluation, 2002.
10th IEEE/ACM Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS 2002), 2002.
4th IEEE International Workshop on Advanced Issues of E-Commerce and Web-Based Information Systems (WECWIS 2002), 2002.
PAPM-ProbMiV: 2nd Joint International Workshop on Process Algebra and Performance Modelling, Probabilistic Methods in Verification, 2002.
Pacific Rim International Symposium on Dependable Computing (PRDC 2002), 2002.
International Workshop on Self-Repairing and Self-Configurable Distributed Systems, 2002.
23rd IEEE International Conference on Distributed Computing Systems (ICDCS), 2003.
Middleware 2003: 4th IFIP/ACM/USENIX International Conference on Distributed Systems Platforms, 2003.
Latin American Symposium on Dependable Computing (LADC), 2003.
3rd DARPA Information Survivability Conference and Exposition (DISCEX 3), 2003.
MASCOTS 2003, the 11th IEEE/ACM Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems, 2003.
DSN Dependable Computing and Communications Symposium, 2003.
DSN IPDS (Performance and Dependability Symposium), 2003.
ACM Workshop on Survivable and Self-Regenerative Systems, 2003.
25th International Conference on Applications and Theory of Petri Nets (ICATPN), 2004.
International Conference on Dependable Systems and Networks (DSN-04), 2004.
PDS (Computer Performance and Dependability) track of the International Conference on Dependable Systems and Networks (DSN-04), 2004.
2nd Workshop on Mobile Distributed Computing (MDC04), held in conjunction with the 24th International Conference on Distributed Computing Systems (ICDCS'04).
International Service Availability Symposium (ISAS), 2004.
1st International Conference on Quantitative Evaluation of Systems (QEST), 2004.
5th International Workshop on Software and Performance (WOSP 2005).
International Conference on Application and Theory of Petri Nets 2005.
PDS (Performance and Dependability Symposium) track of the 2005 International Conference on Dependable Systems and Networks (DSN 2005).
DCCS (Dependable Computing and Communications Symposium) track of the 2005 International Conference on Dependable Systems and Networks (DSN 2005).
Latin American Symposium on Dependable Computing (LADC 2005).
Performance 2005: IFIP WG 7.3 International Symposium on Computer Performance, Modeling, Measurements and Evaluation.
Second International Service Availability Symposium (ISAS '05), 2005.
PRDC-11: The 2005 Pacific Rim International Symposium on Dependable Computing (PRDC 2005).
RAID 2005: 8th International Symposium on Recent Advances in Intrusion Detection, 2005.
4th IEEE International Symposium on Network Computing and Applications (IEEE NCA05), 2005.
24th Symposium on Reliable Distributed Systems (SRDS 2005), 2005.
2nd International Conference on Quantitative Evaluation of Systems (QEST), 2005.
IFIP Conference on Biologically Inspired Cooperative Computing, 2006.

Performance and Dependability Symposium (PDS) track of the 2006 International Conference on Dependable Systems and Networks (DSN 2006), 2006.
26th IEEE International Conference on Distributed Computing Systems (ICDCS-26), 2006.
25th IEEE International Symposium on Reliable Distributed Systems (SRDS 2006), 2006.
SIGMETRICS/Performance 2006.
3rd International Conference on Quantitative Evaluation of Systems (QEST), 2006.
Performance and Dependability Symposium (PDS) track of the 2007 International Conference on Dependable Systems and Networks (DSN 2007).
PERFORMANCE 2007, the 26th IFIP WG 7.3 International Symposium on Computer Performance Modeling, Measurement and Evaluation.
ACM SIGMETRICS 2007, the International Conference on Measurement and Modeling of Computer Systems.
4th International Conference on Quantitative Evaluation of Systems (QEST'07), 2007.
1st Annual IFIP WG 11.10 International Conference on Critical Infrastructure Protection, 2007.
IEEE International Symposium on Network Computing and Applications, 2007.
Performance and Dependability Symposium (PDS) at the 38th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN 2008), 2008.
3rd Workshop on Recent Advances in Intrusion-Tolerant Systems (WRAITS), 2009.
Performance and Dependability Symposium (PDS) at the 39th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN 2009), 2009.
International Workshop on Security Measurements and Metrics (MetriSec 2009), 2009.
Performance and Dependability Symposium (PDS) at the 40th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN 2010), 2010.
7th International Conference on the Quantitative Evaluation of SysTems (QEST), 2010.
6th International Conference on the Numerical Solution of Markov Chains (NSMC), 2010.
ACM SIGMETRICS 2010: International Conference on Measurement and Modeling of Computer Systems, 2010.
4th Workshop on Recent Advances in Intrusion-Tolerant Systems (WRAITS), 2010.
International Workshop on Security Measurements and Metrics (MetriSec 2010), 2010.
5th International Workshop on Critical Information Infrastructures Security (CRITIS 2010), 2010.
1st Workshop on Smart Grid Networking Infrastructure (SGNI 2010), 2010.
IEEE SmartGridComm Symposium on Architectures and Models for the Smart Grid, 2010.
Performance and Dependability Symposium (PDS) at the 41st Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN 2011), 2011.
Fault Tolerance and Dependability track for the 31st International Conference on Distributed Computing Systems (ICDCS 2011), 2011.
1st International Workshop on Resilience Assessment of Critical Infrastructures, 2011.
International Workshop on Security Measurements and Metrics (MetriSec), 2011.
International Conference on Critical Information Infrastructure Security (CRITIS), 2011.
Performance and Dependability Symposium (PDS) at the 42nd Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN 2012), 2012.
9th International Conference on the Quantitative Evaluation of SysTems (QEST), 2012.
1st International Conference on High Confidence Networked Systems (HiCoNS), 2012.
Workshop on Open Resilient human-aware Cyber-physical Systems (WORCS-2012), 2012.
IEEE SmartGridComm Symposium - Cyber Security, 2012.
IEEE SmartGridComm Symposium - Smart Grid Communication Networks, 2012.
Winter Simulation Conference (WSC), 2012.
International Workshop in Quantitative Aspects in Security Assurance (QASA), 2012.
ICT for Energy Symposium of the 2nd IEEE International Energy Conference and Exhibition (EnergyCon), 2012.
Performance and Dependability Symposium (PDS) at the 43rd Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), 2013.

Fault Tolerance and Dependability track of the 33rd IEEE International Conference on Distributed Computing Systems (ICDCS), 2013.
10th International Conference on the Quantitative Evaluation of SysTems (QEST), 2013.
Risk Management Embedded Topical Meeting (part of the 2013 American Nuclear Society Winter meeting), 2013.
"Smart Grid Cyber Security and Privacy" symposium for SmartGridComm, 2013.
2nd International Workshop on Quantitative Aspects in Security Assurance (QASA), 2013.
IEEE International Workshop on Measurements and Networking (M&N), 2013.
44th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), 2014.
Fault Tolerance and Dependability track, International Conference on Distributed Computing Systems (ICDCS), 2014.
International Workshop on Graphical Models for Security (GraMSec), 2014.
IEEE International Conference on Smart Grid Communications (SmartGridComm): Cyber Security and Privacy Symposium, 2014.
45th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), 2015.
1st Workshop on Safety and Security of Intelligent Vehicles, 2015.
4th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS), 2015.
IEEE International Conference on Smart Grid Communications (SmartGridComm): Cyber Security and Privacy Symposium, 2015.
HotSoS Symposium and Bootcamp on the Science of Security, 2016.
2nd Workshop on Safety and Security of Intelligent Vehicles, 2016.
SmartGridComm2016-Security (2016 IEEE International Conference on Smart Grid Communications (SmartGridComm): Cyber Security and Privacy for the Smart Grid), 2016.
4th Annual Symposium and Bootcamp for Hot Topics on Science of Security (HoTSoS), 2017.
20th Symposium on Research in Attacks, Intrusions and Defenses (RAID), 2017.
8th IEEE International Conference on Smart Grid Communications (SmartGridComm), Cyber Security and Privacy Track, 2017.
SAFECONFIG 2017: Applying the Scientific Method to Active Cyber Defense Research Workshop, 2017.
48th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), 2018.

Conference Session Chairs

IEEE 8th Annual International Phoenix Conference on Computers and Communications, 1989.
IEEE 4th International Workshop on Petri Nets and Performance Models, 1991.
IEEE 12th Annual International Phoenix Conference on Computers and Communications, 1993.
IEEE 12th Symposium on Reliable Distributed Systems, 1993.
1995 AIAA Conference, San Antonio, TX, March 1995.
Joint 8th International Conference on Modelling Techniques and Tools for Computer Performance Evaluation and 8th Conference on Measuring, Modelling, and Evaluating Computing and Communication Systems, 1995.
Performance '96, 1996.
IEEE 27th Fault-Tolerant Computing Symposium, 1997.
IEEE 28th Fault-Tolerant Computing Symposium, 1998.
2002 Pacific Rim International Symposium on Dependable Computing (PRDC2002), 2002.
1st Latin American Symposium on Dependable Computing, 2003.
2004 Pacific Rim International Symposium on Dependable Computing (PRDC 2004), 2004.
18th IFIP World Computer Congress, 2004, session on "Further Challenges and Perspectives" in Fault Tolerance for Trustworthy and Dependable Information Infrastructures Topical Day.
1st International Conference on the Quantitative Evaluation of Systems (QEST) 2004, session on "Scheduling and Optimization."

DSN-05, the International Conference on Dependable Systems and Networks, 2005, session on "Intrusion Detection and Tolerance."

Session Chair, "Expanding the Research Horizon," GridWise Global Forum, September 2010.

SmartGridComm: 2nd IEEE International Conference on Smart Grid Communications, 2011, session on "Cyber and Physical Security and Privacy."

Paper Reviews

Review papers for numerous journals and conferences.

**Service**

Professional Society

Vice-Chairperson of IFIP Working Group on Dependable Computing, 1999-2005.

Executive Committee of the IEEE Technical Committee on Dependable Computing and Fault Tolerance, 2000-present.

Elected Vice-Chair and then Chair of IEEE Technical Committee on Fault-Tolerant Computing. Served as Vice-Chair 2000, and as Chair 2001-2003.

Elected member of the Board of Directors, ACM Sigmetrics, served 2001-2003, 2005-2007.

IEEE Computer Society Smart Grid Vision Project (SGVP), cyber security topic area leader, 2011-.

IEEE CS Fellows Evaluation Committee, 2014 and 2016.

Federal

Participated in NSF/DARPA workshop on Performance Engineering, Sept. 1996. Gave advice to NSF and DARPA officials that resulted in a new DARPA research program on performance engineering.

Participated in DARPA ISAT Study Group on Complex Systems, January 1997-August 1997. In doing so, I helped establish priorities for and create research directions for work in the area of representation and analysis for system modeling, specification, design, prediction, control and assurance of large scale, complex systems.

Participated in National Science Foundation panel evaluating pre-proposals (for Group Projects) submitted to the ITR program, Feb. 2001.

Participated in National Science Foundation panel evaluating proposals submitted to the NGS Program, March 2001.

Participated in National Science Foundation workshop on Information Technologies for Security, Nov. 2001.

Participated in National Science Foundation panel evaluating proposals to NSF I/UCRC Planning Grant Program, Nov. 2001.

At the request of the National Science Foundation, participated in the EU-US meeting and workshop entitled "R&D Strategy for a Dependable Information Society: EU-US Collaboration," Dec. 2001.

Participated in National Science Foundation panel evaluating proposals to Federal Cyber Service: Scholarship for Service (SFS) program, Jan. 2002.

Participated in National Science Foundation panel evaluating proposals to Trusted Computing program, March 2002.

Served on NSF Panel on Next Generation Software Program, 2003.

Served on NSF Panel on medium ITR proposals, May 2003.

Served on NSF Panel on the Highly Dependable Computing Program, July 2003.

Served on NSF Panel on CyberTrust, June 2004.

Served on NSF CCFST-HEC Panel, August 2004.

Served on NSF Computer System Research proposal review panel, March 2005.

Member, Networking and Information Technology Technical Advisory Group (TAG) of the President's Council of Advisors on Science and Technology (PCAST), 2006-2007.

Served as an NSF reviewer for FREEDM Center, 2009, 2010, 2011, 2012, 2013.

Served on a smart grid panel for the U.S. Government Accountability Office (GAO), May 25-27, 2011.

Participated in SECURE GRID 2010 Table Top Exercise at government request, USAF Academy Falcon Club, Colorado, July 13-14, 2010.

National Institute of Standards and Technology (NIST) Smart Grid Advisory Committee (SGAC), three-year term starting August 2010.

DHS steering committee to develop a roadmap for securing control systems in the nuclear sector, 2011-present.

Participated in Grid Security Panel discussion at the 2011 DOE-NARUC National Electricity Forum, February 16, 2011.

Member of the Intelligence Science and Technology Experts Group (ISTEG) of the National Academies of Sciences, Engineering, and Medicine, supporting the Office of the Director of National Intelligence, 2015-present.

University Committees

Member, Network Manager's Committee, University of Arizona, Sept. 1990-Aug. 1993.
Member, College of Engineering Committee on Computational Science, University of Arizona, Dec. 1991-Aug. 1993.
Member, Arizona Advanced Telecommunications Research Project, Technical Steering Committee, Sept. 1991-Aug. 1993.
Member, College of Engineering Computer Policy Committee, University of Arizona, Sept. 1991-Aug. 1994.
Member, University Telecommunications Advisory Committee, University of Arizona, Sept. 1992-Aug. 1994.
Member, University of Illinois Library Committee, 1995-2000.
Senator, University of Illinois Faculty Senate, 1996-1998.
Member, Stewarding Excellence @ Illinois Beckman and IGB Project Review Team, 2010-present.
Member, University of Illinois Entrepreneurship Roundtable, 2011-present.

Member, Grainger Big Data Committee, University of Illinois College of Engineering, 2013-present.
Member, UI Labs Campus Committee, 2014-present.
Member, UI College of Engineering Zhejiang University partnership committee, 2014-present.
Member, ZJU-UIUC Institute (Zhejiang University and the University of Illinois at Urbana-Champaign) Operating Committee, 2016-present.
Member, Search Committee, Vice Chancellor for Advancement, 2016-present.
Member, Chancellor's Transition Advisory Committee, 2016-present.

Departmental Committees

Co-Chairman, Computer Engineering Distinguished Lecture Series Committee, 1991-1992.
Member, Department Computer Policy Committee, Dept. of Electrical and Computer Engineering, University of Arizona, Sept. 1989 - Aug. 1992.
Member, Department Graduate Policy Committee, Dept. of Electrical and Computer Engineering, University of Arizona, Sept. 1990 - Aug. 1992.
Chairperson, Computer Engineering Faculty Search Committee, Dept. of Electrical and Computer Engineering, University of Arizona, Spring 1994.
University of Illinois, Co-Chairperson, Illinois Computer Affiliates Program, 1994-1996.
Member, University of Illinois ECE Dept. Fellowship Committee, 1994-1997.
Member, University of Illinois ECE Dept. Curriculum Committee, 1995-1998.
Member, University of Illinois ECE Dept. Qualifying Examination Committee, 1995-1996.
Elected Member, University of Illinois ECE Dept., Dept. Advisory Committee, 1996-1998, 1999-2001.
Elected Member, Coordinated Science Laboratory Policy and Planning Committee, 1998-2000.
Member, University of Illinois, ECE Dept. Graduate Committee, 1998-2000.
Member, University of Illinois, ECE Dept. Graduate Recruitment Committee, 1999-2000.
Member, University of Illinois, ECE Dept. ABET Preparation Committee, 1999-2001.
Chairperson, University of Illinois, ECE Dept. Computer Engineering Area Committee, 1999-2001.
Member, University of Illinois, ECE Dept. Faculty Search Committee, 2000-.
Member, University of Illinois, ECE Dept. Public Relations Committee, 2005-.
ECE Alternate Alumni Coordinator, 2005-.

Other Outside Service

External reviewer, College of William and Mary's Department of Computer Science, winter 2018.
Member of the External Advisory Council of the Santa Fe Community College's proposed NSF for ATE project INTEGRATE (Interdisciplinarity Network for Trustworthy Energy Grid Resiliency Through Advanced Technological Education), 2017-.
Member at Large of the Board of Directors of the Electrical and Computer Engineering Department Heads Association (ECEDHA), 2017-2019.
Member of the Jean-Claude Laprie award committee, 2017.
Member of the National Academies' Panel on "Enhancing the Resilience of the Nation's Electric Power Transmission and Distribution (T&D) System, 2016-present.
Member of the National Academies' Forum on Cyber Resilience, 2015-present.
Member of the 2014 Visiting Committee, Department of Electrical & Computer Engineering, National University of Singapore, 2014.
Member of the Advisory Group for SRI International and USC/ISI's collaborative NSF project on "The Road to Tomorrow: Cybersecurity Experimentation of the Future," 2013-2014.
Member of the Scientific Advisory Board (SAB) for the Forschungszentrum Telekommunikation Wien (FTW) Telecommunications Research Center Vienna, 2012-2015.
Member of the Cyber Security Research Alliance (CSRA) Advisory Board, 2012-present.

Member of the Advisory Committee for the Computing and Computational Sciences Directorate of Oak Ridge National Laboratory, 2011-present.

Served on panel on "The Most Promising New Control System Research Projects" at the 2011 North American SCADA and Process Control Summit.

Served on Academic Review Panel for the Center for Information Technology Research in the Interest of Society (CITRIS).

Served on Economist "Smart Grid Tour" panel in the Economist Intelligent Infrastructure Series, September 2010.

Served on National Academy of Sciences panel on "Shifting Power: Smart Grid Energy 2010," August 2010.

Member of the TRUST Distinguished External Advisory Board, University of California at Berkeley, 2006-present.

Member, Advisory Board for the European Union Integrated IRRIIS (Integrated Risk Reduction of Information-based Infrastructure Systems), 2006-present.

Member of the Advisory Committee for the Computational Sciences and Engineering Division (CSED) for Oak Ridge National Laboratory, 2005-present (renewed 2010).

Named member of the Motorola Research Visionary Board (RVB), 2005 (re-invited 2007).

Member of the University of Michigan EECS Department National Advisory Committee, 2004-present.

Acted as mentor to Univ. of Arizona Flinn Scholar Program, 1989-1990.

Administered Univ. of Arizona ECE Department Master's Exam, Spring 1989.

**Improvement Activities**

Took University of Illinois Course on "Teaching College," Fall 1994.

Chairman SMITH. Thank you, Dr. Sanders. And, Mr. Imhoff.

**TESTIMONY OF MR. CARL IMHOFF, MANAGER, ELECTRICITY MARKET SECTOR, PACIFIC NORTHWEST NATIONAL LABORATORY**

Mr. IMHOFF. Thank you, Chairman Smith, Ranking Member Veasey, and Members of the Committee today, for the opportunity to join this important conversation. My name is Carl Imhoff, and I lead the Grid Research Program in DOE's Pacific Northwest National Laboratory in Washington State. For more than two decades, PNNL has supported power system resilience, reliability, and innovation for DOE and utilities across the Nation. I also chair DOE's Grid Modernization Laboratory Consortium, a team of 12 National Labs that support DOE's grid modernization initiative with—along with over 100 partners from industry and academia such as ERCOT and Texas A&M and the University of Illinois.

Today, I offer three main points regarding grid resilience. Point 1, substantial opportunity exists to leverage fundamental science and applied research to enhance the Nation's options for modernizing the grid in ways that enhance overall resilience, and I'll share five examples.

Point 2, the national laboratories have delivered important new approaches to enhance grid resilience, and I'll share some recent accomplishments and some emerging new efforts that were just recently announced.

And point 3, state and federal regulatory stakeholders need resilience valuation tools in addition to the science and technology innovation so that they can better enable the required investment to actually deliver the science and technology innovations.

Let's start with science and technology opportunities themselves. The definition of a resilient grid addresses both avoiding and resisting outages before an incident occurs, as well as rapidly responding to an incident and recovering as quickly as possible afterwards, two sides of the coin. Science and technology can contribute on both sides, avoidance before events and recovery afterwards.

Specific S and T topics we think are vital to the future include the following: enhanced, real-time, predictive operational tools to detect problems early and steer around them; enhanced precision planning tools to better predict risk and design accordingly to make systems more resilient; advanced grid architecture, coordination, and control of the grid to pinpoint new structural risks and options on how to control the system and recover it more quickly; number 4, advanced data and visual analytic tools for better situational awareness across all hazards whether it's physical, weather, cyber; and then number 5, energy storage at an affordable price point to provide a new grid flexibility option for the future.

For the hearing objective of improved cyber resilience, advanced data analytics and new grid architectures and controls would substantially improve the situational awareness of cyber threats and provide more resilient control options to present—to prevent further system damage. And advanced predictive operation tools and energy storage would help operators limit the spread of cyber-induced outages.

For the hearing objective of physical resilience, an important emerging tool is the development of design basis threat assessments to frame the physical threat scenarios of highest priority to individual utilities. These systematic threat assessments, linked with enhanced planning tools, would better guide resilience investments for utilities and other stakeholders.

Switching now to progress in the national laboratory grid modernization efforts, a foundational project in that effort is developing metrics to support government and industry efforts in grid modernization. Grid resilience is one of those six metrics. It's one that's still under debate in terms of its definition, and it's closely related to the traditional metric of grid reliability, as well as emerging metric called grid flexibility.

Other projects include dynamic contingency analysis tools to help planners better avoid white area cascading outages like we experienced in the Northeast in 2003. This tool was developed in partnership with DOE and ERCOT and soon will become part of ERCOT's regular planning efforts.

Grid analysis and design for resilience was another recent GMLC project delivered for New Orleans to help coordinate microgrids and other critical functions like water pumping, et cetera, to help them ride through emergencies.

Finally, DOE awarded $32 million last month to fund seven resilient distribution public-private projects around the country to validate the performance of new resilience innovations emerging from the GMLC portfolio.

My third point is that science and technology advances must be complemented by new tools to help utilities and regulators chart the investment strategies to improve grid resilience. Utilities at all levels, consumer-owned and, must have the capacity to understand the value of alternatives to improve their system, and state regulators need the same tools to provide the regulatory incentives to deliver the resilience improvements at scale. The National Labs are developing such evaluation framework with state and industry participation.

So I conclude that science and technology innovation can enable a modernized grid that we can see, control, and protect like never before. Big data management, new data analytics, machine learning, and exascale computing will be central to delivering this modern grid and maintaining U.S. leadership. Grid resilience is intricately linked to other attributes such as reliability and flexibility, and new tools to value and simulate grid resilience concepts in concert with public-private field validation will accelerate national grid modernization efforts.

I look forward to answering any questions.

[The prepared statement of Mr. Imhoff follows:]

Statement of Carl Imhoff
Manager, Electricity Market Sector
Pacific Northwest National Laboratory
Before the
United States House of Representatives
Committee on Science, Space and Technology

October 3, 2017

Good morning. Thank you, Chairman Smith, Ranking Member Johnson, and Members of the committee. I appreciate the opportunity to appear before you today to discuss U.S. electric infrastructure resilience issues and opportunities.

My name is Carl Imhoff, and I lead the Grid Research Program at the Pacific Northwest National Laboratory (PNNL), a Department of Energy (DOE) national laboratory located in Richland, Washington. I also serve as the Chair of DOE's Grid Modernization Laboratory Consortium, a team of national labs that, along with industry, industry groups such as the Gridwise Alliance and Electric Power Research Institute (EPRI), and university partners, supports the Department's Grid Modernization Initiative. The consortium members include PNNL, the National Renewable Energy National Laboratory, Sandia National Laboratories, Oak Ridge National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, Idaho National Laboratory, Argonne National Laboratory, the National Energy Technology Laboratory, Savannah River National Laboratory, Lawrence Livermore National Laboratory and the National Accelerator Laboratory at Stanford.

Today I will address three main points:

1. Substantial opportunity exists to leverage fundamental science and applied research to enhance the nation's options for modernizing the grid in ways that enhance overall resilience.

2. The national laboratories have delivered important contributions in new approaches to enhance grid resilience. I will discuss the importance of research and development to ensuring a resilient, reliable and flexible grid, share recent accomplishments delivered in partnership with industry, and highlight emerging resilience research activities.

3. State and federal regulatory stakeholders need innovative tools and data sets to improve valuation of power system resilience so that they can better enable the investment required to deliver a modern grid that is resilient, reliable and flexible.

**Background**

For more than two decades, PNNL has supported power system reliability, resilience and innovation for the State of Washington, the Pacific Northwest, and the nation. Over this period, the laboratory has:

1. Led DOE-industry collaborations in developing and deploying synchrophasor technology to help avoid blackouts. Phasor measurement unit networks are designed to enhance situational awareness of wide area systems. This new grid tool has demonstrated value by detecting impending system control and equipment faults for system operators, thus avoiding major outages. California estimates $360 million annual savings to customers due to avoided outages, plus $90 million annual savings in improved utilization of existing generation and delivery systems. In east Texas, phasor measurement units enabled Entergy to respond to major storm outages by synchronizing a temporary electrical island to reduce outages during the recovery. At the Columbia Generating Station, an 1100-megawatt nuclear reactor in Washington State, the Bonneville Power Administration has demonstrated savings of $400,000, on average, for testing generator controls settings without requiring a plant shutdown.

2. Led a public-private collaboration with utilities and vendors to develop and demonstrate transactive control concepts on the Olympic Peninsula in Washington and for the Pacific Northwest Smart Grid Demonstration project—the largest of its kind—to validate smart grid benefits and new control approaches that engage demand and distributed resources at scale. Example outcomes include Avista Corporation implementing distribution automation and smart metering pilots that delivered a 10-percent reduction in customer outages, reduced consumer outage durations by 21 percent, and resulted in 1.5 million avoided outage minutes between April 2015 and April 2016. Avista also saved 42,000 megawatt hours in 12 months. Idaho Falls Power implemented transactive control of end uses and utilized the concept to minimize customer outages during an extreme winter storm when the western system operators were calling for emergency reductions in load.

3. Delivered the first applications of high performance computing to grid tools such as interconnection-scale contingency analysis, reducing run times from days to under two minutes. PNNL also applied high performance computing and phasor measurement unit data to deliver the first real-time dynamic state estimation to open the door to the future world of predictive grid tools. This parallelized state estimator tool enabled PNNL to meet an ARPA-E challenge to reduce dynamic line rating calculations from 24 hours to 10 minutes, creating the potential to operate the system with much higher asset utilization.

These examples illustrate the high return on investment possible by utilities and national labs across the country when combining new electric infrastructure innovation with public-private validation and deployment.

The DOE Grid Modernization Initiative is an important source of innovation for national efforts to modernize the energy infrastructure. Improved grid resilience is a major objective of the overall effort. The Initiative is a DOE-wide effort across multiple program offices to accelerate the development of technology, modeling analysis, tools, and frameworks to enable grid modernization adoption. As a key component of this Initiative, the Grid Modernization Laboratory Consortium is working closely with partners in industry, academia, and cities and states to deliver on the objectives outlined in DOE's Grid Modernization Multiyear Program Plan. These integrated efforts will deliver new concepts, tools, platforms, and technologies to better measure, analyze, predict, and control the grid of the future to improve resilience, reliability and productivity. Public/private collaboration in field validation accelerates the development of lessons learned and data that support states and utilities to develop business cases for their grid modernization efforts. I respectfully request that the appended fact sheet on the Grid Modernization Laboratory Consortium be entered into the record along with my written testimony.

**Emerging Science and Technology Opportunities to Enhance Power System Resilience**

The definition of a resilient grid addresses both avoidance and resistance to outages before an incident, as well as to the ability to rapidly respond to an outage and achieve full recovery as quickly as possible. Science and technology provide substantial contributions to avoidance and resistance to outages, as well as to the post-event assessment and recovery. New digital sensing, measurement, and control concepts, often termed "smart grid", are enabling system operators to "see" and "control" the grid with exceptional precision and speed. These new concepts, combined with new distributed energy resources such as energy storage, local generation sources, or microgrids, are paving the way for enhanced grid performance that is more resilient, reliable and flexible. Selected examples of significant science and technology advances include:

1. **Enhanced real-time, predictive operational tools:** High-precision fast sensor networks linked to utility control centers enable operators to predict grid system behavior, anticipate dangerous oscillations, and optimally adjust power flows and power transfer limits. These tools leverage advanced computing and mathematical algorithms to deliver modeling and simulation tools that dramatically enhance resilience hy helping avoid outages in the first place. They also help operators adapt to outages and recover system operations faster. These modeling and simulation tools are examples of the tools recommended in the National Academies report on grid resilience.

2. **Enhanced precision planning tools:** The nation invests substantial capital in grid infrastructure, and these investments typically have multi-decade lifetimes. Recent advances in computation and simulation tools promise to improve the accuracy and speed of system planning tools that can better assess complex risk scenarios and improve system designs that will improve resilience for future decades. DOE teamed with PNNL and ERCOT to develop a new dynamic contingency modeling tool that helps grid planners explore larger, more complex cascading failure scenarios. Successful testing with ERCOT has led to broader

industry use of this tool that promises to support the design of systems that are more resilient to increasingly complex "all hazards" threats to the system. This effort is consistent with the National Academies grid resilience recommendations for improved "visioning" of future resilient grid system outcomes and the modeling tools to validate cost effective system designs to deliver the desired resilience.

3. **Advanced grid architecture, coordination and control:** Technology and business model evolution are driving substantial change to power systems and related critical infrastructures such as communications, fuel supply, markets and control. DOE is working with states and industry to envision how the new aspects of a modern grid will change and fit together in the future. This effort will then frame where changes in coordination and control of utility systems and consumer systems must occur to ensure a resilient and reliable grid. Success will lead to new control concepts that ensure modern, distributed power systems will be more resilient and secure. These new paradigms of grid structures and control will be a fundamental element in the National Academies recommended "visioning" processes to chart new approaches for grid resilience.

4. **Advanced data and visual analytic tools:** Trends in e-commerce, digital grid technologies, and consumer devices and services are creating a dramatic increase in data on the power system, much of which flows at very high speed. GE Digital Energy testified earlier this year that the grid has approximately two billion "edge devices" today, estimated to grow to more than 20 billion in 2025. Substantial opportunities exist for "big data" management, advanced data analytics, machine learning, network science, and research to ensure security of the grid and effective use of the data generated by the grid. Fundamental advances will be required in high performance computation, mathematics, statistics, and communications networks to deliver on the potential for full system observability and control. PNNL, in partnership with Argonne National Laboratory and the National Renewable Laboratory, has launched the first grid application of exascale computing for the grid as part of the DOE Exascale Computing program.

5. **Energy storage at an affordable price point to provide a new grid element:** Large complex systems typically require the flexibility to decouple supply and demand to maintain reliability. Examples include warehouses for logistics and storage tanks for water systems. The equivalent for power systems is energy storage. The power system of the future will greatly benefit from increased use of energy storage to serve this "shock absorber" role as loads become more complex and generation becomes more variable. Energy storage systems will reduce the risk of outage, enhance emergency operations of local microgrids during emergencies, and improve the recovery of failed systems. Early GMLC research indicates that affordable grid-scale storage, linked with smart power electronics and new control theory, offers significant potential to improve grid resilience to all hazards. Materials science is vital to driving the grid-scale price points down, and advanced theory for coordination and control linked with storage is important to delivering increased grid flexibility and resilience.

With regard to the Hearing objective of improved cyber resilience, advanced data analytics (item 4 above) and new grid architecture and controls (item 5 above) would substantially improve situational awareness of cyber threats and provide more resilient control options to mitigate the impact from attacks. And the advanced predictive, real-time operational tools (item 1 above) would give operators precise tools to limit the spread of a cyber-induced outage and speed recovery. Energy storage (item 5 above) would provide more flexibility in how operators mitigate any cyber outage and speed recovery. In addition to technology innovations, small and mid-sized utilities could substantially improve their cyber readiness through implementation of existing cyber security maturity self-assessment tools and vulnerability assessments. The challenge small utilities face is limited engineering staff and financial resources to systematically conduct cyber vulnerability assessments and cyber maturity self-assessments.

For the Hearing objective of physical resilience, an important emerging tool is the development of "design basis threat" assessments to frame the physical threat scenarios of highest priority to individual utilities. PNNL recently developed the first design basis threat assessment for NERC targeting physical resilience. This approach is consistent with the National Academies grid resilience report recommendation to systematically "vision" the emerging threat profiles and define priorities for improved resilience. With a prioritized plan for reducing physical security risk, the predictive real-time operation tools (item 1 above), enhanced planning tools to mitigate the risk of cascading outages triggered by physical attack (item 2 above), and sources of flexibility to cushion the system and speed recovery (e.g., energy storage in item 5 above or adaptive controls in item 3 above) would provide a path to improving physical attack resilience.

In summary, advances in science and technology concepts, conducted and validated in the field with public-private partnerships, offer substantial potential to improve grid resilience to cyber threat, physical attack and other sources of threat to the grid.

**National Laboratory Collaborative Efforts To Improve Power System Resilience**

DOE convened a consortium of 13 national laboratories—the Grid Modernization Laboratory Consortium (GMLC)—in 2014 to support its Grid Modernization Initiative in a coordinated, collaborative manner. A foundational element of this effort has been to frame metrics to support government and industry efforts in grid modernization. Grid resilience is one of the six metrics; it is closely related to the traditional metric of grid reliability, as well as an emerging metric called grid flexibility.

The National Academies grid resilience definition is similar to the definition in the GMLC Metrics effort. The challenge, however, is that metrics for resilience depend upon the type of threat or risk being addressed. And the attribute of "grid flexibility" is an emerging grid attribute that will be important to providing improved grid resilience in the future grid. Definitions and perspectives for these three metrics are described below.

| GMLC Grid Modernization Metrics Research Related to Resilience | | |
|---|---|---|
| **GMLC Definition** | **Current Status** | **Next Steps** |
| **Resilience**: The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions, deliberate attacks, accidents, or naturally occurring threats or incidents. | Widely-accepted metrics for resilience do not exist currently. Existing metrics do not focus on impacts resulting from individual events or on individual critical sectors, especially resilience events, which are generally infrequent yet have large consequences. | With key stakeholders, GMLC is piloting new metrics through case studies:<br>• Electrical service<br>• Critical electrical service<br>• Restoration cost and time<br>• Monetary impacts |
| **Reliability:** Maintain the delivery of electric services to customers in the face of routine uncertainty in operating conditions. For distribution systems, focus is on interruptions in the delivery of electricity in sufficient quantities and quality. For bulk power system reliability, metrics focus on near-term operations and longer term planning. | Existing metrics are mature but focus on distribution networks. They gauge the frequency and duration of outages averaged over all customers within a service territory over a specific time period. This approach masks the wide variance among outages in terms of size, duration and economic impact on customers. | For distribution, the GMLC is developing more granular, value-based metrics that enable utilities to estimate the likely costs to customers in specific locations so that investment dollars can be allocated to reduce the likelihood of the most costly interruptions. These are being developed and demonstrated through a partnership with the American Public Power Association. Bulk power efforts include working with the North American Electric Reliability Corporation new transmission metrics to gauge overall reliability of the three North American interconnections. |
| **Flexibility:** The ability to respond to future uncertainties that stress the system in the short term and may require the system to adapt over the long term. For near-term operations, flexibility refers to the agility of electrical networks to adjust to known or unforeseen short-term changes, such as abrupt changes in load conditions or sharp ramps due to errors in renewable generation forecasts. For longer-term investment perspectives, flexibility refers to the ability to respond to major regulatory and policy changes and technological breakthroughs without incurring stranded assets. | Widely accepted metrics for flexibility do not exist. | Industry feedback indicates the highest priority for flexibility metrics pertain to coping with short-term fluctuations in the availability of generation from wind and utility-scale solar facilities. The GMLC is evaluating more than 20 separate metrics that could quickly identify the nature of a given fluctuation or estimate the likely effectiveness of alternative options for dealing with that fluctuation.<br><br>The GMLC will also examine how to build more flexibility into long-term system planning. |

The GMLC research portfolio includes projects focused on improved power system resilience. Some highlights of recent results include the following (fact sheets attached):

- **Transactive Campus Testbeds for Local and Regional Grid Resilience and Flexibility:** Corporate, university, and government campuses represent a substantial resource for microgrid and load coordination to support emergency response and deliver power system flexibility at local and regional levels. In Washington State, three campuses (PNNL, the University of Washington, and Washington State University) are establishing transactive controls of responsive distributed energy resources, major loads and energy storage to coordinate at the local campus and to collectively deliver resilience and flexibility to the regional grid. These testbeds will deliver design and operational strategies and lessons learned to support wider adoption across the nation.

- **Grid Analysis and Design for Energy and Infrastructure Resiliency for New Orleans:** Coastal cities like New Orleans, Louisiana, often experience extended disruption of electric grid operations, resulting in impacts to other energy intensive infrastructures vital to recovery, including flood control operations, water supply and treatment, transportation, emergency response, and banking. A recently completed GMLC project developed strategies with stakeholders to effectively use local distributed generation, microgrids, and renewable energy resources as well as cost-effective grid resilience enhancements to reduce the severity of power outage impacts and enhance community resilience for U.S. coastal communities. It delivered an integrated strategy engaging city emergency response officials, utility representatives and others to deliver a more robust city response that supported flooding management and emergency services in addition to power restoration to city neighborhoods.

- **Microgrid Enhancements for Grid Resilience in Kentucky and Alaska:** Two projects addressed how to enhance resiliency of power grids supporting critical loads and remote communities, respectively, through advanced microgrid controls, as well as informing investment decisions to reduce risks to extreme storms and other threats. These projects have delivered enhanced microgrid toolsets available to industry microgrid designs, and strategies for system planning and financing to expand the availability of microgrids to support improved grid resilience.

- **Threat Detection and Response with Data Analytics:** The nation's power grid faces dynamic and complex threats from cyber-attacks, physical attacks, and storms. This research brings together six laboratories to develop an all-hazards approach to protect the grid through advancements in three key areas of technology development: sensors, data analytics, and a response/mitigation framework. Industry partners are advising the research and will ultimately be candidates for field validation of these emerging analytic concepts.

- **Southeast Regional Consortium for Improving Distribution Resiliency through Advanced Sensors and Controls:** GMLC labs have teamed with multiple utilities in the Southeast to deploy and test advanced sensor platforms and analytic tools to enhance power system monitoring and recovery in the face of increasing extreme events (e.g., hurricanes). Through the development of an advanced sensing, communication, and control ecosystem, increased situational awareness technologies have been deployed for field validation that will improve overall storm resilience and response.

Finally, DOE recently awarded seven new resilient distribution systems projects in September. These public-private efforts will validate emerging GMLC resilience concepts in utility and community environments.

**Innovation in Valuation Tools and Data Sets to Advance State and Federal Regulatory Consideration of Investment for Power System Resilience**

Science and technology efforts are critical to modernize the grid for resilience, reliability and flexibility, but alone cannot achieve the end state goal. Utilities at all levels—consumer-owned, investor-owned, municipalities—must have the capacity to understand the value of alternatives to improve their system resilience and performance. State regulators need the same tools and data sets with which to evaluate modernization plans and provide the regulatory incentives to achieve prudent modernization that delivers affordable resilience improvements to product offerings that enable modernization at scale. Finally, vendors must be able to define market opportunities to ensure rapid innovation in their product offerings.

The GMLC portfolio includes research projects to develop a framework for valuation of the new grid technologies and concepts so that government and industry stakeholders can work together to assess the benefits and costs of resilience improvement strategies. This partnership between DOE, states, and industry is an important collaboration in charting a timely path to a more resilient U.S. power system.

**Conclusion**

In conclusion, science and technology innovation offer the capacity to deliver a resilient and modernized grid that we can "see and control and protect" like never before. Big data management, new data analytics and fundamental advances in machine learning, and exascale computing will be central to delivering this modern grid and maintaining U.S. leadership. Grid resilience is intricately linked to other grid attributes such as reliability and flexibility. And new tools to value and simulate grid resilience concepts, in concert with public/private field validation, will accelerate national grid modernization efforts.

I appreciate the opportunity to discuss this important issue with you today, and I am happy to answer your questions. Thank you.

GRID
MODERNIZATION
LABORATORY
CONSORTIUM
U.S. Department of Energy

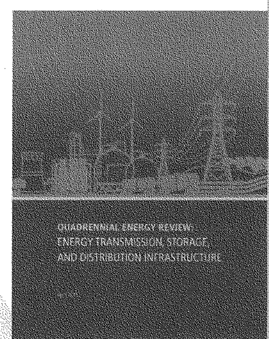
# Delivering a Power Grid for the $21^{st}$ Century

The United States power system is a strategic investment for our nation, and new paradigms for designing, operating and securing our grid are critical for our national economic and security goals. To meet this challenge, the U.S. Department of Energy established the Grid Modernization Initiative. Through this Initiative, DOE is working with public and private stakeholders to develop the concepts, tools, and technologies needed to measure, analyze, predict, protect, and control the grid of the future.

In support of this Initiative, the DOE launched the **Grid Modernization Laboratory Consortium** to engage the national laboratories working on DOE grid programs to frame a new integrated approach for planning and delivering innovations and thought leadership in support of grid modernization. This new, crosscutting approach ensures that DOE research and development investments and capabilities are fully coordinated to enable a modern U.S. power system.

Comprised of 65 leading scientists and engineers from across the DOE national labs, the technical teams are aligned with **six technical thrust areas**:

- **sensing and measurements**
- **devices and integrated systems**
- **system operations, power flow, and control**
- **design and planning tools**
- **security and resilience**
- **institutional support.**




Released in April 2015, the Quadrennial Energy Review (QER) highlighted fundamental challenges and new opportunities for transforming the grid to meet new demands of U.S. energy and economic priorities of the 21st century. The QER recommended focused investment in Grid Modernization research and development as a national imperative.

## IMPACT

By 2025, grid modernization is expected to help industry substantially improve the performance and security of the U.S. electric system by delivering the following grid qualities:

- Improved reliability for customers
- Enhanced resilience against all hazards
- Continued affordability in the face of change
- Enhanced environmental performance delivering a clean supply of electricity
- Fundamental security of the delivery of the nation's electricity needs

## THE CHALLENGE

For the next several decades, the Grid Modernization Laboratory Consortium will coordinate grid modernization activities to address the following challenges:

- increasing the grid's digital capacity
- enabling two-way power flow for distributed generation (renewables)
- improving security and resilience to all hazards—cyber, physical and other risks
- developing tools and control paradigms that leverage the capabilities of new digital grid technologies to deliver improved reliability and economic productivity.

## STAKEHOLDER INVOLVEMENT AND OUTREACH

Modernization of the U.S. electric grid entails dramatic transformations, with close collaboration required across industry, states, federal agencies, regulators and numerous other stakeholders. In addition to leading the lab-to-lab technical teams to best leverage intellectual and scientific assets, the labs also play a key role in engaging regional stakeholders in new concepts.

For example, the labs are providing institutional support to states, local communities, tribes, and others to develop new regulations needed to unleash the potential of the modern grid. The labs will also engage in the development and implementation of regional and local demonstrations, co-funded by industry, to accelerate the rate of impact of the new innovations emerging from the DOE Grid Modernization efforts.

## CONTACTS

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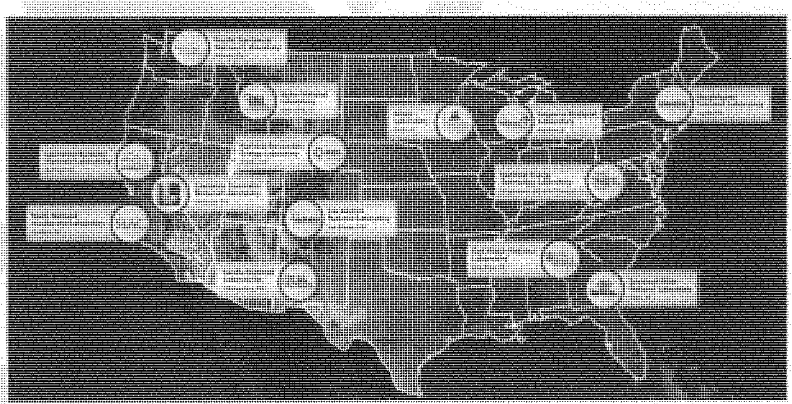
303.275.3994

## MULTI-YEAR PROGRAM PLAN

[illegible]



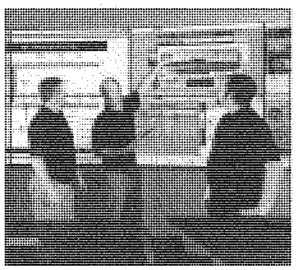
GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy



# Clean Energy & Transactive Campus

## CHALLENGE

Vast opportunities for improved reliability, consumer benefits, and energy efficiency exist at the buildings-to-grid nexus. Realizing those benefits, however, requires research, development, and testing of transactive controls for energy management. Greater understanding and implementation of transactive controls at the single building, single campus, multi-campus, and community microgrid scale will help lead to a more reliable, resilient grid.



*On PNNL's campus, the Building Operations Control Center tracks building energy use and serves as the "nerve center" for the multi-campus project.*

## APPROACH

Pacific Northwest National Laboratory (PNNL) is leading a three-site project with Washington State University (WSU) and the University of Washington (UW). This is the first time researchers will test the use of demand-side transactive controls ("behind the meter") at this scale, involving multiple buildings and devices. Primary activities at each campus include the following:

- PNNL – multi-campus network operations; transactive campus/building response applications; transactive/advanced buildings controls testbed
- WSU – microgrids as a resilience resource/smart city; solar and battery in microgrid operations; flexible loads; thermal storage
- UW – energy efficiency applications, leveraging transactive network; smart solar inverter integration with distribution; transactive grid controls.

Another key objective is the establishment of a transactive energy system testbed. The partners will examine how the testbed can be operated as both a flexibility resource to help manage electricity loads and bring intermittent renewable energy onto the power grid, and as a platform for future research and development in the emerging buildings-grid discipline. A second phase of this project expands to new partners Case Western Reserve University and the University of Toledo in 2017.

## At-A-Glance

### PROJECT LEAD

- [illegible]
  Pacific Northwest National Laboratory
  [illegible]

### PARTNERS

- Washington State University
- University of Washington
- Case Western Reserve University
- University of Toledo

### TECHNOLOGY

- VOLTTRON™
- Transactive Controls
- Microgrids
- Smart Solar Inverter
- Energy Storage

### BUDGET

[illegible]
- [illegible]
  U.S. Department of Energy
- [illegible]
  Washington State Clean Energy Fund

### DURATION

[illegible]

### TECHNICAL AREA

[illegible]
- [illegible]
  Pacific Northwest National Laboratory
  [illegible]

## EXPECTED OUTCOMES

Using transactive controls to manage devices, data, and decision making, buildings will automatically adjust energy loads based on pre-determined criteria such as cost, essential services, and comfort levels.

Knowledge gained from this activity informs responsive load management, energy conservation, and future grid modernization decision making, regionally and nationally. This is a key step forward in achieving a more modern, efficient, and reliable power grid.

## LAB TEAM

[illegible]

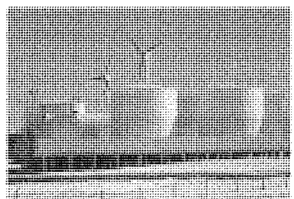
Devices and Timing | Sensing and Measurement | System Operations and Control
Design and Planning | Security and Resilience | Institutional Support

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

PROJECT 1.3.21 | FACT SHEET

# Alaska Microgrid Partnership

## CHALLENGE



*Two of three wind turbines can be seen over the bulk fuel tanks of the Kasigluk Power Station, a vision of what could be possible in the future.*

Alaska—perhaps more than any other region in the country—faces unprecedented challenges in modernizing its rural energy infrastructure. Across the state, approximately 200 isolated microgrid systems are not connected to larger grids, and most of these systems rely almost exclusively on imported fuel (primarily diesel) to meet electrical, space/water heating, and transportation requirements. These communities have populations ranging from 50 to 6,000 people, are composed primarily of native Alaskans, and have some of the highest energy costs in the nation (up to ~10 times the national average).

Alaska has extensive renewable energy resources, access to advanced diesel and load control technologies, and significant opportunities to improve energy efficiency. Despite this potential, relatively few energy projects have been completed with most of these projects being funded by grants. Rural Alaska likely has the lowest reliability and least resilient power systems in the country.

## APPROACH

This project involves creating a development pathway for islanded microgrids that emphasizes leading by example, then testing the pathway using two pilot projects, and making the pathway data and other useful information available for other communities to follow. Key project activities include the following:

- developing a consistent assessment pathway to reduce total imported energy usage in a holistic way, working to address electrical, heating, and transportation energy needs;
- pulling together largely existing analytical tools to coordinate technical and financial methods that support full development assessments, allowing expanded public and private sector engagement;
- integrating more robust financial pro-forma assessment into the analysis of energy options, facilitating private sector investment in energy system improvements;
- implementing the pathway with two pilot communities, providing a workable example for other, non-pilot communities; and

## At-A-Glance

### PROJECT LEADS

[illegible]

### PARTNERS

[illegible]

### BUDGET

[illegible]

### DURATION

[illegible]

### TECHNICAL AREA

[illegible]

- developing new data sources and sharing information with project developers—via the Alaska Energy Data Gateway—that details the human, financial, and technical capacity of communities across Alaska to undertake new energy infrastructure projects.

## EXPECTED OUTCOMES

The over-arching goal of the Alaska Microgrid Partnership is to significantly reduce the use of imported energy sources in Alaska's remote microgrids without increasing system lifecycle costs, while improving overall system reliability, security, and resilience. Expected outcomes from this project include the following:

- documenting the full techno-economic development process for reducing imported energy consumption by at least 50% in remote microgrids in Alaska, using a combination of energy efficiency, building energy improvements, power system upgrades, and transportation options analysis;
- identifying investment opportunities (i.e., the business case) to attract the funding needed to implement these types of projects on a wide scale;
- creating an implementation methodology for other communities to follow by documenting and publicizing the community assessment, data collection, project analysis, and development process; and
- implementing the methodology in two pilot communities to serve as models to position the communities to seek private and public funding to implement project recommendations.
- making Alaska Mircrogrid Partnership project and community information and data more readily available through an expansion of the Alaska Energy Data Gateway: https://akenergygateway.alaska.edu/

The potential worldwide market and impact are significant: 400 diesel microgrids in Canada, 70 in Greenland, and more than 1,000 in Indonesia. The International Energy Agency estimates that more than 700 million people currently without electricity access could be most cost-effectively served by mini-grids or microgrids.


*Pathway for Holistic Community Microgrid Development*

## LAB TEAM

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy



# Industrial Microgrid Analysis and Design for Energy Security and Resiliency

## CHALLENGE

Industrial utility customers have a unique opportunity to support a modern energy economy and a stronger, more reliable grid. They typically need reliable, secure power in high quantities, and many facilities have their own backup generators and redundant electrical feeds to bolster their reliability. However, many of the generators are only used for routine testing and for their intended purpose only a few hours a year. If these backup assets could be used as a microgrid for both blue-sky and contingency cases, then the microgrid could provide both reliability to the customer and services to the grid. Some utilities are not familiar with some of the emerging grid technologies and how they can be incorporated into their operations to increase grid resilience for their customers. The perceived risk associated with new technology adoption can present a significant barrier to modernizing the grid.

Addressing utility hesitation head-on by involving utilities in the entire development of grid modernization technologies and providing hard evidence of benefit to both customers and utilities could be the key to unlocking utility modernization efforts across the country.

## APPROACH

Advanced microgrid control schemes are one way to increase the reliability and strength of the grid. Oak Ridge National Laboratory (ORNL), in partnership with Sandia National Laboratories (SNL) and Fortune 10 company United Parcel Service (UPS), is investigating, developing, and analyzing the risks, costs, and benefits of a microgrid at the UPS World Port and Centennial Hub facilities in Louisville, Kentucky. This processing hub, the crown jewel of UPS's company, is the most technically advanced facility of its kind in the world, and UPS is very interested in the development of an industrial microgrid to serve its 50-megawatt power needs.

This partnership will keep the utility engaged in the project and aware of how industry customers want to use microgrids, and how microgrids will affect the larger electric grid.

## At-A-Glance

### PROJECT LEADS

- [illegible]
  Oak Ridge National Laboratory
  [illegible]
- [illegible]
  Sandia National Laboratories
  [illegible]

### PARTNERS

- United Parcel Service
- [illegible]
- Burns & McDonnell
- [illegible]
- Louisville Gas & Electric
- [illegible]

### BUDGET

[illegible]

### DURATION

[illegible]

### TECHNICAL AREA

Security and Resilience
[illegible]
National Renewable Energy Laboratory
[illegible]

## EXPECTED OUTCOMES

Technical documents developed from this project will provide a roadmap and set of open-source tools for UPS and other industries interested in microgrid technologies. The institutional and regulatory challenges associated with development of an industrial microgrid will be spelled out. The methods and open-source tools used in this project can be directly applied to other interested industries. The project will also highlight the interaction between an industrial customer interested in pursuing a microgrid and a utility that may be unfamiliar with adopting such a technology—a scenario that industries across the country are highly likely to face.

## LAB TEAM

Oak Ridge National Laboratory | Sandia National Laboratories

Launched in November 2014 under the U.S. Department of Energy's Grid Modernization Initiative, the GMLC is a strategic partnership between DOE Headquarters and the national laboratories, bringing together leading experts and resources to collaborate on national grid modernization goals. The GMLC's work is focused in six technical areas viewed as essential to modernization efforts.

Devices and Testing | Sensing and Measurements | Systems Operations and Control
Design and Planning | Security and Resilience | Institutional Support

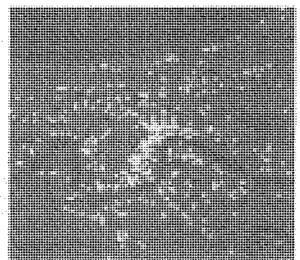
GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy



# Grid Analysis and Design for Energy and Infrastructure Resiliency for New Orleans

## CHALLENGE

The heightened risk coastal cities like New Orleans, Lousiana (NOLA) encounter from hurricanes, floods, and other natural disasters is never farther than the memory of Hurricane Katrina. During such events, extended disruption of electric grid operations exacerbate interruption of energy intensive infrastructures vital to recovery, including flood control operations, water supply and treatment, transportation, emergency response, and banking. The resilience of communities is dependent on grid resilience.



*This color-coded schematic of New Orleans indicates where critical infrastructure in the area does not exist (red); exists but is less than required by users (yellow); or exists and meets user-defined requirements (green).*

## APPROACH

Identifying approaches to effectively use local distributed generation and renewable energy resources as well as cost-effective grid resilience enhancements can help reduce the severity of power outage impacts and enhance community resilience for many U.S. coastal communities subject to similar threats and risks. This project will support the development of priority electrical distribution system upgrades and advanced microgrid pilot projects that can help bolster community-level resilience for NOLA and other coastal U.S. cities. This project will provide detailed information and conceptual models that can help NOLA and other coastal cities prepare for, prioritize, and execute grid resilience projects. Data will be available to stakeholders from the following efforts:

- Infrastructure Impact Modeling and Analysis
- Resilient Power Distribution Modeling and Analysis
- Integration of Distributed, Renewable, Energy Storage, and Energy Efficiency Options
- Cost/Benefit Analysis.

## At-A-Glance

### PROJECT LEADS

[illegible]

### PARTNERS

[illegible]

### TECHNOLOGY

[illegible]

### BUDGET

[illegible]

### DURATION

[illegible]

### TECHNICAL AREA

[illegible]

Rev. 2, June 2017

## EXPECTED OUTCOMES

NOLA, the local electric utility Entergy, and relevant stakeholders will have a set of risk-informed, cost-effective recommendations for grid resilience enhancement. NOLA, Entergy, and state and federal agencies can use these recommendations to rank energy infrastructure improvement options and set improvement implementation and funding priorities. This effort will produce a template for other communities to use for increasing grid and community resilience.

## LAB TEAM

Los Alamos National Laboratory

Sandia National Laboratories

Launched in November 2014 under the U.S. Department of Energy's Grid Modernization Initiative, the GMLC is a strategic partnership between DOE headquarters and the national laboratories, bringing together leading experts and resources to collaborate on national grid modernization goals. The GMLC's work is focused on six technical areas viewed as essential to modernization efforts.

Devices and Testing | Sensing and Measurements | Systems Operations and Control
Design and Planning | Security and Resilience | Institutional Support

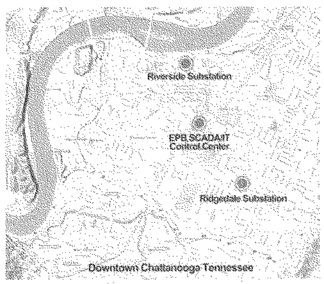
GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy



# Southeast Regional Consortium

## CHALLENGE

Different geographical regions across the United States face specific electric grid challenges, such as recurring weather extremes, integration of distributed energy resources (DERs), and an aging electricity infrastructure. On the hurricane-prone Southeast Coast of the United States, damage to electrical infrastructure is not merely inconvenient—it can cause loss of life and millions to billions of dollars in economic losses. Advancing the state of the grid in the Southeast to improve overall system resiliency will reduce the impact of these weather events. Engaging regional stakeholders is crucial to effectively developing new technologies to address the unique regional challenges they face. This involvement will help overcome barriers in transitioning modern, new grid technologies to industry.




*Time-sensitive network testing locations.*

## APPROACH

The Southeast Regional Consortium is conducting collaborative research to enhance responsiveness, enable faster restoration of power, and increase the concentration of DERs for overall system resiliency. Led by Oak Ridge National Laboratory (ORNL), Savannah River National Laboratory, the University of Tennessee, the Center for Advanced Power Energy Research, and the Clemson 20 MVA Electrical Grid Laboratory—along with critical industry partners, such as Duke Energy, Tennessee Valley Authority, Southern Company, Chattanooga Electric Power Board (EPB), and Santee Cooper—this effort includes four technical projects:

1. Development and testing of distributed control technologies and algorithms for the future EPB distribution center microgrid through hardware-in-the-loop testing at ORNL. ORNL's distributed control framework—Complete System-Level Efficient and Interoperable Solution for Microgrid Integrated Controls—will be applied to a detailed model of the future EPB microgrid that includes photovoltaics, inverters, communications, storage, and loads to accurately simulate

## At-A-Glance

### PROJECT LEADS

- Savannah River National Laboratory
- Oak Ridge National Laboratory

### PARTNERS

- Electric Power Board
- Santee Cooper
- Clemson University
- Southern Company
- Tennessee Valley Authority

### BUDGET

### DURATION

### TECHNICAL AREA

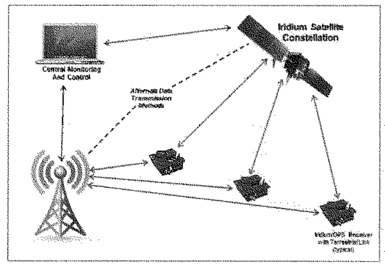
System Operations and Control
Pacific Northwest National Laboratory

the EPB microgrid from bits to electrons. This will be done using ORNL's Distributed Energy Communications and Controls laboratory low-voltage hardware-based microgrid simulator and Real-time Digital Simulator.

2. Development and validation of a cyber-resilient dual-mode, terrestrial and satellite-based wireless sensor/control network—applicable not only to the Southeast, but any region in the United States due to the use of satellite networks.
3. Testing of new time-sensitive network technologies using dark fibers on the EPB fiber-optic data network.
4. Development of step distance protection for distribution systems using passive optical sensors.

   Step distance protection is currently only applied at the transmission level.

In addition, the consortium is convening a workshop to connect regional stakeholders, foster shared understanding of the technical challenges facing utilities in the Southeast, and discuss the new technologies emerging from DOE grid modernization efforts.




## EXPECTED OUTCOMES

Distributed control technologies will improve distribution system resiliency while increasing the concentration of DERs, and dual-mode wireless networks will allow rapid detection of cyber-attacks. Time-sensitive networks will provide the information needed for fast digital control over networks and transient monitoring in distribution systems.

The increased resolution of optical sensors will provide increased visibility, opportunities for new more resilient protection schemes at the distribution level, improved fault localization, and bi-directional power flow. Dual wireless sensing/control will create weather-independent information networks that will help restore power to critical loads more quickly during storms.

Building on existing collaborations, the consortium will foster new engagements with the University of Tennessee, Clemson, Duke University, The University of North Carolina, EPB, Santee Cooper, Southern Company, Dominion, SRNL, and ORNL to assure that these and other emerging technology developments to create a modern resilient grid are more rapidly moved from laboratories to industry implementation.

## LAB TEAM

Oak Ridge National Laboratory | SRNL Savannah River National Laboratory

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy



# Threat Detection and Response with Data Analytics

## CHALLENGE

Large amounts of data related to regional outages, cyber health, distribution sensors, and advanced metering infrastructure (AMI) are gathered from the electrical grid. However, it is difficult to identify cyber-attacks and differentiate them from non-cyber incidents. Furthermore, degradation of the grid can come in many forms, including failure of materials, equipment, and information infrastructure resulting from natural or malicious events. Consequences from any of these scenarios can affect the reliability, maintainability, and availability of data required for decision making at numerous levels.

## APPROACH

This project will develop advanced analytics using operational technology (OT) cyber data to detect complex cyber threats. Analytics will be developed that can assist in differentiating between cyber and non-cyber-caused incidents using available cyber data. To this end, the project team will conduct the following activities:

- Evaluate which sensor data are most valuable and could provide the biggest positive impact (in terms of grid resiliency/security) if an event is successfully detected. Possible data sources are phasor measurement units (PMUs) in electrical distribution systems, renewable generation and distributed energy resources (photovoltaics/inverters), demand response data for energy dispatch on the bulk electric system or electric vehicles on the consumer side, AMI data, and building automation data.
- Develop analytics to identify emerging cyber incidents on the electric grid using OT data identified in the previous objective.
- Attempt to differentiate cyber grid incidents from other grid hazard incidents, such as physical attacks, natural hazards, etc.
- Test analytics with industry and asset owner partners.

## At-A-Glance

### PROJECT LEADS

- [illegible]
  Lawrence Livermore National Laboratory
  [illegible]
- [illegible]
  Lawrence Berkeley National Laboratory
  [illegible]

### PARTNERS

- [illegible]
- [illegible]
- Schweitzer Engineering Laboratories

### BUDGET

[illegible]

### DURATION

[illegible]

### TECHNICAL AREA

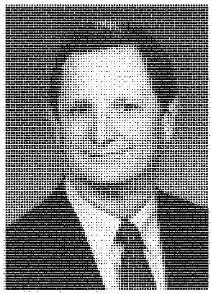
Security and Resilience
[illegible]
National Renewable Energy Laboratory
[illegible]

## EXPECTED OUTCOMES

The project will identify "cyber-physical" signatures that will allow us to quickly differentiate between cyber events and non-cyber events on the grid. By differentiating between cyber-related and non-cyber-related/operational events, determinations can be made about the type of incident and its root cause. We will partner with a U.S. utility to obtain sensor data and validate prototype analytics against the data.

Research results will lead to development of commercial tools that will improve a utility's ability to differentiate between cyber and non-cyber incidents so that they can make the most appropriate response during an event.

## LAB TEAM



Carl Imhoff

Manager
Electricity Market Sector

Pacific Northwest National Laboratory

## Biography

Mr. Imhoff manages the Electric Infrastructure market sector within Pacific Northwest National Laboratory's Energy and Environment Directorate. The market sector conducts advanced electric infrastructure research and product development with the U.S. Department of Energy, state governments, vendors, and commercial energy firms. In this role he is responsible for PNNL's research and development programs on innovations in the areas of advanced power transmission reliability concepts, demand response, development of improved integration concepts for renewable energy generation technologies, policy and strategy for smart grid concepts, and cross-cutting grid analytic tools in visualization and high performance computing.

As leader of PNNL's Laboratory Objective for a Secure and Efficient Grid, Mr. Imhoff is accountable for Lab-level strategy and execution of strategic development for grid strategy, capabilities, and partnerships, ensuring continued leadership by PNNL in grid modernization over the next decade. In November 2014, Mr. Imhoff was selected by DOE as Laboratory Integrator Team Chair for the DOE Grid Modernization Laboratory Consortium. This Consortium is charged with increasing integration among DOE offices and national laboratories working to transform the U.S. power grid to meet the consumer, economic, environmental, and security priorities of the 21st century.

During his 30-plus years at PNNL, Mr. Imhoff has conducted and managed a broad range of energy research. His technical work emphasizes systems engineering and operations in the areas of power system reliability, smart grid, energy efficiency, energy storage and clean power generation. He has been actively involved in a number of electric power system organizations and bodies, including the North American Synchrophasor Initiative, the GridWise Alliance, the Consortium for Electric Reliability Technology Solutions, and the Western Electric Coordinating Council.

Chairman SMITH. Thank you, Mr. Imhoff.
And, Dr. Dillingham.

**TESTIMONY OF DR. GAVIN DILLINGHAM, PROGRAM DIRECTOR, CLEAN ENERGY POLICY, HOUSTON ADVANCED RESEARCH CENTER**

Dr. DILLINGHAM. Good morning. Chairman Smith, Ranking Member Veasey, and Members of the Committee, thank you for the opportunity to appear before you today. I'm Gavin Dillingham, Program Director of Clean Energy Policy at HARC. We're a nonpartisan research institute in the Woodlands, Texas. I'm pleased to provide testimony on the resiliency of the United States' power infrastructure, particularly in respect to risks posed by extreme weather events.

Thank you for the opportunity to discuss the findings of the latest NAP report on resilience. It's very timely and important. It pushes forward the discussion that we must have to ensure a more resilient power system.

A key area of interest for me is the discussion on the increasing intensity of extreme weather and the impact on the electric system. The systems must be designed and constructed for a multitude of extreme weather events, and I wanted to provide one example and specific to Texas. Texas has experienced multiple extreme weather patterns resulting in significant power outages in the last few years.

First of all, there was the statewide drought of 2011/2012. This multiyear drought placed considerable pressure on power generation, which is highly dependent on water for cooling. During the drought, there was not enough water to cool the plants or the water was too warm for cooling. There was a significant concern by ERCOT about losing millions of potentially several thousand megawatts of power if the drought did not end.

A recent Argonne National Labs study finds—that looked at the drought situation finds that the Texas grid could face severe stress due to lack of water availability, as well as derating of thermal electric plants due to high water temperatures. The stress on the power system due to this drought is not only limited to Texas. It's an issue across the entire western United States, particularly in the arid States.

And Texas, beyond drought, we've had three 500-year-plus flood events in the last three years, the most recent being Hurricane Harvey, which dumped about 27 trillion gallons of water along the Gulf Coast. If you're familiar with Texas and the eighth wonder of the world, that's 68,000 Astrodomes'—or 86,000, I'm sorry, Astrodomes' worth of water. If you actually added that out, it'd be about 400 square miles about 128 feet high, I mean, a huge amount of water at one point, left close to one million utility customers without power.

The other two floods we've had was the tax day flood of 2016, and the 2015 Memorial Day flood. Flooding can cause significant damage to transmission and distribution systems, particularly substations, and the potential long-term duration of floods can significantly delay the restoration of power to communities.

I'd be remiss not to mention Hurricane Ike, which happened in 2008. During Hurricane Ike, 2.1 million customers lost power. Many of them were out of power for over two weeks. which is actually fairly small when you look at what just happened with Hurricane Irma where there were over 9 million customers that lost power. And then you look at the Hurricane Maria, which essentially took out the entire island of Puerto Rico. Texas also deals on average with 146 tornadoes per year, wildfires and ice storms, and most recently, the Texas panhandle, January 2017 ice storm that cut power to 31,000 customers.

This is one example of one State. Similar stories of extreme weather events can be found across all States. For more info, you could check out the Department of Energy's U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather.

Natural disasters will increase in number and have already increased in intensity, and this puts our existing grid at risk. It's very difficult to determine the timing, location, and intensity of these events. With this level of uncertainty and when financial resources are limited, it is challenging to make the appropriate investment decisions. When decisions are not made, infrastructure is not built, and our systems are not prepared. This will result in significant damage and loss.

Uncertainty is the enemy of action. Fortunately, we're seeing the deployment of downscaled regional climate models that provide improved certainty of the likelihood of extreme weather events. Texas Tech University Climate Science Center is a great example of doing some of this work. Better visibility into future climate patterns will improve planning for power systems and decision-making, and the—more investment must go into these models to reduce further uncertainty.

Some of the solutions we'd like to discuss, first of all, in the United States, the power portfolio is very highly water-dependent. Approximately 85 percent of our power generation requires water. Fortunately, systems not requiring water being deployed across the country largely in the form of wind and solar generation systems, battery storage, and microgrid. However, the speed at which these systems are being deployed does not look to significantly shift the grid away from water dependency. Projections differ significantly, but regardless of what projection you look at, both—most of them look at over 60 percent of the power system dependent on water out to 2050.

The technology and capability is available to quickly deploy these systems. Unfortunately, policy and regulations have not kept up. It should hearten the Committee to know that the recently released DOE grid reliability study finds increased deployment of renewable resources has not and will not negatively impact the operation of the grid. This should remove some of the policy and regulatory headwinds here.

A key issue is availability of funding. Two funding mechanisms that could increase the deployment of renewable energy is to allow renewables to participate in master limited partnerships, similar to what fossil fuel assets are allowed to participate in, and allowing the deployment of green bonds to fund renewable infrastructure. These are two market-based funding solutions.

Other hindrances are the patchwork of grid interconnection standards, old utility models that do not account for the benefits of DER. We should also start looking into PEER, performance excellence electricity renewable—renewal. These are voluntary power resilience standards that should be considered to improve the reliability and resilience and operational effectiveness of our grid. And then also looking at microgrids and microgrids with combined heat and power. These are proven systems to improve—increase the resilience of critical infrastructure. It's estimated that 3.7 gigawatts of microgrid systems will be deployed by 2020, which is small in comparison to other resources. But a very important resource as we look for systems that are resilient and have demonstrated their efficacy through a wide number of natural disaster events, most recently being the UTMB in Galveston during Hurricane Harvey.

The DOE has actively worked to increase deployment of CHP through its Better Buildings Initiative Resiliency Accelerator and Combined Heat and Power Technical Assistance Partnership. It is recommended this technical assistance continue.

To conclude, the tendency is to count the number of hurricanes and extreme weather events and make that the key climate metric. The numbers are increasing. There is uncertainty when exactly there'll be a material increase, but that is largely irrelevant as the intensity of these storms increase. There's considerable agreement by climate models that they will continue to do so. We are not prepared for this growing intensity.

Natural disasters threats are real and now directly impact the operation of our grid. If we continue business as usual, systems will become more vulnerable, the economic and social—societal disruption cost will increase, and recovery will be less sustainable to growing demand on constrained resources. The technology and systems exist that are being deployed now to limit this risk. However, barriers exist with funding, regulations, and utility models that hinder deployment of these resilient systems.

Thank you for the opportunity today. Sorry for going long.

[The prepared statement of Dr. Dillingham follows:]

HARC

**Testimony of:**

Gavin Dillingham, PhD - Program Director at HARC

**On behalf of:**

HARC

**Before the:**

House Committee on Science, Space and Technology

October 3, 2017

HARC
8801 Gosling Dr
The Woodlands, TX 77381

HARC

Chairman Smith, Ranking Member Johnson, and members of the committee, thank you for the opportunity to appear before you today. I am Gavin Dillingham, Program Director for Clean Energy Policy at HARC and I am pleased to provide testimony on the resilience of the United States' power infrastructure, particularly in respect to the risks posed by the increasing number of extreme weather events.

HARC is a non-partisan research institute in The Woodlands, TX. We were founded by George Mitchell in 1982. The organization was founded to conduct research and analysis that can be shared with communities to help with their decision making. Our researchers focus on areas of water quality and supply, air quality, ecosystem services, and energy, both clean energy deployment, as well as research to reduce the environmental impact and improve the health and safety of upstream oil and gas operations. HARC is an inter-disciplinary organization so many of us work across these disciplines to improve the resilience and adaptive capacity of our communities.

I appreciate the opportunity to discuss the findings of Enhancing the Resilience of the Nation's Electricity System report. This report is very timely and important. It pushes forward the discussion that we must have to ensure a more resilient power system. A key area of interest for me is the discussion related to the increasing number and intensity of extreme weather and their current and future impact on national electric power system. These systems must be designed and constructed for a multitude of extreme weather events. To give you a Texas example, in recent years, Texas has experienced some pretty extreme weather patterns resulting in significant power outages and disruption to communities.

First, there was the state wide drought in 2011 and 2012. This multi-year drought placed considerable pressure on power generation. Most power generation is dependent on water for cooling. During the drought there was either not enough water to cool the plants or water was too warm for cooling. During 2011, ERCOT, the organization that manages the Texas grid, was concerned about losing "potentially several thousand megawatts" if the drought did not end[1]. There were also plants during this time curtailing operation at night so they would have plenty of water to provide power during the day, as well as plants that were piping water from other sources to ensure they could operate. A recent paper by Argonne National Lab "Impact of Future Climate Variability on ERCOT Thermoelectric Power Generation" considered the drought implications for the ERCOT grid. The findings indicate that out to 2030, unless we become less dependent on water, the Texas grid could face severe stress due to lack of water availability both in drought and non-drought scenarios, as well as derating of thermoelectric plants due to high water temperatures[2]. This stress on the power system due to water supply is not limited to Texas. It is an issue particularly across the western United States.

Most recently we have had to manage extreme flooding events, three five hundred year plus flood events in the last three years. The most recent being two weeks ago with the arrival of Hurricane Harvey. Harvey dumped about 27 trillion gallons of water along the Gulf Coast, about 86,000 Astrodomes[3] worth of water, and left close to one million utility customers without power. The other two floods were the Tax Day Flood of 2016 and the 2015 Memorial Day flood. The Memorial Day Flood

[1] https://www.texastribune.org/2011/09/16/drought-could-post-problems-texas-power-plants/
[2] http://www.ipd.anl.gov/anlpubs/2013/03/75723.pdf
[3] http://www.houstonchronicle.com/life/article/Hurricane-Harvey-by-the-numbers-12172287.php

flooded communities stretching from the Texas Hill Country to the Gulf Coast. Flooding can cause significant damage to transmission and distribution infrastructure, particularly substations. The potential long-term duration of floods can significantly delay the restoration of power to communities where substations and other power infrastructure are inaccessible.

I would be remiss not to mention Hurricane Ike in 2008. Ike caused power losses for over 2.1 million customers in a service territory of 2.2 million people. Many of these customers did not have power for over two weeks[4]. This is a fairly small number when you consider the power outages from Hurricane Irma, at over 9 million and Hurricane Maria cutting power to nearly the entire island of Puerto Rico.

Beyond droughts, hurricanes and floods, Texas also deals with on averages 146 tornadoes per year, more than any other state,[5] and has had to deal with two of the largest fires in recent history, the Bastrop Fire in 2011, small in acreage but with a large price tag of $325 million[6] and the 2017 fire in the Texas panhandle which scorched 750 square miles. Not only did 2017 bring Harvey and the Panhandle fire, a large ice storm blew through the Texas Panhandle in January cutting power to 31,000 customers.

This is just an example of one state that has had significant stress placed on its power system due to extreme natural disaster events. Similar stories of extreme weather events can be told across all states. The Department of Energy published a report in 2013, titled "US Energy Sector Vulnerabilities to Climate Change and Extreme Weather"[7] that goes into significant detail concerning the problems power systems have experienced and will experience due to extreme weather.

The events listed above very much parallel the findings of the report. Natural disasters are increasing in number and intensity and this puts our existing grid at considerable risk. A problem faced by the power industry is that there is not just one type of natural disaster placing stress on the power system. There are multiple pending disasters. Further this does not include cyber or physical attacks to these system. The problem with all of these pending threats is that it is very difficult to determine the timing, the location and intensity of these events. With this level of uncertainty and when resources are limited, it is very challenging to make the appropriate investment decisions.

My expertise is not with cyber or physical threats, I can only speak to natural disaster threats. Due to the multitude of natural disaster threats, we have seen the development and growth of what is called the adaptation gap. Due to uncertainty of timing and intensity of natural disaster events, decision making can be hampered. When decisions are not made, infrastructure is not built. When the natural disaster events occur our systems are not prepared. The result is significant damage and loss to our communities, environment and economy. Unfortunately, most of the US is largely in a reactive mode of loss recovery, rather than focusing on loss mitigation and resilience. This is not to say there are not some efforts underway, particularly on the east coast with the aftermath of Superstorm Sandy, but there is considerable work that still must be done.

[4] http://www.chron.com/business/energy/article/Outages-dwindling-across-Texas-but-many-still-12165137.php
[5] http://www.ustornadoes.com/2016/04/06/annual-and-monthly-tornado-averages-across-the-united-states/
[6] https://en.wikipedia.org/wiki/Bastrop_County_Complex_Fire
[7] https://energy.gov/sites/prod/files/2013/07/f2/20130710-Energy-Sector-Vulnerabilities-Report.pdf

HARC

Uncertainty is the enemy of action. Fortunately, we are seeing the development and deployment of down scale regional climate models that can provide significantly improved information on the likelihood of future extreme weather events. Texas Tech University Climate Science Center is doing great work in developing down-scaled models that are being shared with key decision makers as they conduct resilience planning. Better visibility into future climate patterns will improve planning and decision making across all critical infrastructure, particularly our power generation systems.

There are two key areas I would like to discuss a bit further. First, the potential lack of water supply available to existing and future power systems and one solution, microgrids and their current deployment.

The NAP report suggests there will be an increased likelihood of water stress across the United States. This is due not only to drought, but increasing competing demands by communities, agriculture and industry. The ANL report mentioned above provides a nice explanation of water constraints.

At present, the United States current power generation portfolio is highly water dependent; approximately 85% of power generation requires water to operate[8]. This does not include hydropower, rather this is water to cool coal, natural gas, and nuclear based power generation systems[9]. Fortunately, systems that do not require water to produce power are being actively deployed across the country, largely in the form of wind and solar generation systems and to a growing extent, battery storage, micro-grid and micro-grid combined heat and power (CHP) systems. However, to date, the speed to which these systems are being deployed does not look to significantly shift the grid away from water dependent power generation resources in the near future. This has been well illustrated in the Department of Energy's 2017 Annual Energy Outlook (AEO)[10]. Some argue the AEO is too conservative[11] and place projections of solar and wind at 35% of total installed capacity by 2050. Regardless of what projection you accept, both still have over 60% of the power system dependent on water.

The highly anticipated DOE Grid Reliability which considered the impact of renewable energy on grid reliability finds that increased deployment of solar and wind does and will not negatively impact the operation of the grid. The technology and capability is available to quickly deploy these systems, unfortunately, policies and regulations do not. As with any infrastructure system a key issue is the availability of funding. Two key funding mechanisms that could increase the deployment of renewable energy is to allow renewables to participate in master limited partnerships, similar to fossil fuel assets. Second, accelerating the deployment of green bonds to fund renewable infrastructure. Although there has been a growing number of green bonds issued for green infrastructure, there is still some hesitancy due to what defines a green bond, what can be funded by these bonds and how they can be positioned in the financial markets. Two other key issues are the lack of interconnection standards across many states and an old-utility model that still largely cannot account for the benefits provided by distributed energy resources (DER). Granted, there are some utilities that are doing great work and actively working

[8] https://750astrodomes.com/2017/07/14/electric-power-sector-you-have-a-water-problem/
[9] https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf
[10] https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf
[11] http://thehill.com/blogs/pundits-blog/energy-environment/322442-the-trouble-with-underestimating-clean-energy

on valuing and deploying DER. However, the current patchwork of activity does not allow for a rapid deployment of DER and/or utility scale systems. Finally, federal and state policy makers should consider the development and deployment of power resilience standards such as PEER (Performance Excellence in Electricity Renewal). PEER is a rating process designed to measure and improve sustainable power system performance[12]. Very similar to the LEED building rating program. PEER is a voluntary program that utilities and power providers can work toward. A PEER rated power system meets strict criteria for reliability and resilience, operational effectiveness and environmental standards.

One final note on DER concerns the growing deployment of microgrids. These are mini-power systems for a building, campus, neighborhood, that typically have a variety of generation resources working together including a combined heat and power system, solar panels, and/or batteries. Microgrids and particularly microgrids with CHP are being considered more often to increase the resilience of critical infrastructure, such as hospitals, wastewater and water treatment plants, police and fire stations, data centers, emergency centers, etc. It is estimated that approximately 3.7 GW of microgrid systems will be deployed by 2020.[13] Small in comparison to other resources, but a very important resource as we look for systems that are resilient and have demonstrated their efficacy through a wide number of natural disaster events. Microgrid CHP systems have on multiple occasions demonstrated their ability to stay online during and after significant natural disaster events[14], with the most recent example being the new CHP system at the University of Texas Medical Branch in Galveston during Harvey. The deployment of these systems have seen a significant level of support from, the Department of Energy. The DOE has been actively working to increase the deployment of CHP through its Better Buildings Initiative Resiliency Accelerator[15] and the Combined Heat and Power Technical Assistance Partnership[16]. It is recommended this technical assistance continue.

To conclude, the tendency is to count the number of hurricanes and extreme weather events and make that a key climate metric. The numbers are increasing, there is uncertainty when exactly there will be a material increase, but that is largely irrelevant as the intensity of these storms increase, which they have. There is considerable agreement by the climate models that they will continue to do so[17]. We are not prepared for this growing intensity, much less an increasing number and intensity.

Natural disaster threats are real and are now directly impacting the operation of our grid. If we continue business as usual, systems will become only more vulnerable. The economic and societal disruption costs will continue to increase and recovery will become less sustainable due to growing demand on constrained resources. The technology and systems exists that are being deployed now to limit this risk. However, significant barriers still exist, particularly funding, regulations and utility models that hinder the deployment of theses resilient systems.

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[12] http://peer.gbci.org/faq
[13] https://www.greentechmedia.com/articles/read/u-s-microgrid-growth-beats-analyst-estimates-revised-2020-capacity-project
[14] https://www1.eere.energy.gov/manufacturing/distributedenergy/pdfs/chp_critical_facilities.pdf
[15] https://betterbuildingssolutioncenter.energy.gov/accelerators/combined-heat-and-power-resiliency
[16] https://energy.gov/eere/amo/chp-technical-assistance-partnerships-chp-taps
[17] https://www.gfdl.noaa.gov/global-warming-and-hurricanes/

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**Gavin Dillingham, PhD Bio**

Dr. Gavin Dillingham is Program Director for Clean Energy Policy at HARC and Director of the US DOE's Southwest Combined Heat and Power TAP. Dr. Dillingham joined HARC in 2012 where he leads research and program efforts focusing on improving the climate resilience of the electric power infrastructure and built environment.

Dr. Dillingham has worked in the clean energy industry for the last twenty years in both the private and public sector. Much of this work focused on climate action planning, greenhouse gas mitigation strategies and strategic energy management for large institutions and cities.

His current work at HARC includes studying and developing climate risk mitigation strategies for the public and private sector, climate action decision making and planning, and clean energy finance. Specific projects Dr. Dillingham is leading includes research on decision making in regards to the deployment of critical power infrastructure across the United States; a study on the deployment of climate resilience standards for the built environment; and research on corporate operational decisions in regards to climate vulnerability and risk.

Dr. Dillingham's programmatic activity includes directing the Department of Energy's Southwest Combined Heat and Power Technical Assistance Partnership which is tasked with improving community resilience and reducing energy waste through increased investment in CHP. He also leads HARC's efforts with the Texas State Energy Conservation Office which is working on improving energy data access and the deployment of PACE financing.

Dr. Dillingham received his PhD in Political Science from Rice University in 2008 where he studied policy diffusion and adoption of natural resources policies across U.S. states.

# Gavin Dillingham, PhD

Program Director, Clean Energy Policy and Director of DOE's Southwest CHP TAP at Houston Advanced Research Center (HARC)

gavin.dillingham@gmail.com

## Summary

Program Director for research institute focusing on climate adaptation with specific focus on investment in resilient power infrastructure and the adoption of clean energy policies at the local, state and federal level.

Highlights Include:

- Expert in Electric Power Resilience - Lead the DOE's Southwest CHP Technical Assistance Partnership with the responsibility of increasing investment in combined heat and power (CHP) and microgrid applications across the region. The focus is largely on improving community resilience and reducing energy consumption by providing technical assistance to end-users, as well as conducting education and outreach to potential investors and policy makers.

- Predictive Modeling and Quantitative Analysis - Conduct research developing predictive models with event history analysis to better understand state and city adoption of clean energy policies

- Accomplished in grant research, writing, management and evaluation; securing and managing over $30 million in grants in the past 8 years

- Expert in City-level Clean Energy Policy and Sustainability Best practices - authored multiple best practice case studies for energy management for large and mid-sized Texas cities; Technical Advisor to the City of Houston for its City Energy Project, a joint project of NRDC and IMT, which will work to develop energy efficiency policies for the city.

- Lecturer at Rice University in Policy Studies Department teaching a class on public policy planning.

## Experience

**Program Director, Clean Energy Policy; Senior Research Scientist at Houston Advanced Research Center (HARC)**

January 2016 - Present

HARC is a research hub providing independent analysis on energy, air, and water issues to people seeking scientific answers. We are focused on building a sustainable future that helps people thrive and nature flourish.

- Lead research efforts focusing on policy adoption and innovation of clean energy policy at local, state and national levels.
- Lead market analysis and program design efforts for utility incentive and rebate programs
Conduct policy design and analysis for local and state clean energy programs.
- Direct federal and state grant funded programs focusing on the identification of regulatory and policy barriers barriers to clean energy implementation.
- Technical Advisor to local government - provide advice on clean energy policy development and design; conduct cost-benefit analysis and life-cycle cost analysis to assess policy feasibility.

**Director - Southwest CHP Technical Assistance Partnership at HARC**
October 2015 - Present

Lead the Southwest CHP Technical Assistance Partnership at the Houston Advanced Research Center. The Center's mission is to improve community resilience and reduce energy consumption by promoting combined heat and power and microgrid applications through technical assistance and project qualification screenings, education and outreach to end-users and policy.

**Lecturer - Public Policy Planning - Adoption and Innovation**
January 2013 - Present

Teaching a class on the public policy process with a specific focus on policy adoption and innovation using event history and survival analysis modeling. Presented a variety of key policy process topics including the advocacy coalition framework, punctuated equilibrium, network analysis and policy diffusion via economic competition and social learning. Discussed topics related to energy efficiency, climate change, oil and gas exploration and production, gun control, public health and public education.

**Research Scientist, Clean Energy Policy at Houston Advanced Research Center**
August 2012 - December 2015 (3 years 4 months)

- Acting as Technical Advisor to the City of Houston for the City Energy Project; lead effort in developing and deploying strategy to implement CEP program in Houston; identify best practices around proposed policies, determine applicability and feasibility for Houston and incorporate best practice information into outreach and education documents, as well as in policy language; conduct data analysis regarding policy cost benefit, energy savings, emissions reductions, and economic impact to help with drafting policy; provide technical assistance, editing and review for drafting of each policy;
- Working SECO and SPEER on the City Efficiency Leaders Project; conduct research and analysis on best practices and lessons learned for public sector energy efficiency policies and initiatives; develop case studies based on research.
- Lead efforts for SECO's DOE SEP 2013 grant award for removing barriers to combined heat and power and industrial energy efficiency; lead stakeholder engagement efforts and developing action plan with stakeholders to overcome barriers.

• Lead the development and drafting of the City of Houston's Sustainability Action Plan; the action plan provides a way forward for the City to reach is 50% GHG reduction goal by 2020.
• Conduct research regarding the development of predictive models to better understand the diffusion and innovation of energy efficiency and renewable energy policy across state and local governments; considering how networks, learning, competition and state characteristics affect the adoption of policy; Assessment of existing micro-grid policies influencing the deployment of CHP, solar and storage in micro-grid setting

**Manager, Energy and Sustainability at Houston ISD**
November 2010 - July 2012 (1 year 8 months)
-Lead the development and implementation of a 30 million square foot energy efficiency retrofit with an expected yearly energy savings of $12 million per year upon project completion;
-Manage the procurement of electricity and natural gas contracts for 300 campuses;
-Develop and deploy the Green School Challenge. A District wide behavioral change program to reduce energy and water consumption at District campuses;
-Implementing single stream recycling program for District, secured $300,000 in funding for program development;
-Lead the development of renewable energy projects at District; secured grant for solar installation at Wilson Elementary School.

**Lecturer - Energy Efficiency Policy at Rice University**
August 2010 - December 2010 (4 months)
Taught public policy seminar related to energy efficiency and the built environment.

**Director of Sustainable Growth**
February 2009 - November 2010 (1 year 9 months)
- Implemented a $75 million energy performance contracting project, resulting in over $6 million energy savings per year. The retrofit included City Hall, the Hobby Center for Performing Arts, the City's Admin Building, Police Headquarters, Courthouse, parks, libraries, health facilities and police stations; the project also including a feasibility study to implement a district cooling/heating system for City administration facilities in Downtown Houston;
- Participated in the feasibility study of a combined heat and power installation at two of the City's waste water treatment plants. This was a $30 million project that would install gas fired turbine generators on each site and utilize waste heat for sludge drying purposes;
- Led energy efficiency, renewable energy and sustainability grant development writing efforts for City securing over $53 million in grants from the Department of Energy, State Energy Conservation Office and the Environmental Protection Agency;
- Led Texas' largest weatherization assistance program;leading a team to weatherize over 8,000 residence in Houston;
-Led the development and publication of the City's emission reduction plan;
-Assisted in the procurement of electricity contracts.

**Senior Business Consultant**
June 2008 - February 2009 (8 months)
- Conducted financial analysis to determine suitability of business life-cycle management (BLCM) solution for upstream oil and gas companies;
- Built business case for Human Resource transformation initiative at a $6B petroleum engineering and construction company;
- Conduct research and analysis on the affect federal government policy has on upstream exploration and production behavior.

**Staff Analyst - Public Policy Land Use Planning at City of Houston**
January 2007 - May 2008 (1 year 4 months)
- Acted as a liaison between city council members, the Mayor's office and the Planning and Development Department; worked to establish effective policies pertaining to annexation, land development and extra-territorial jurisdiction issues;
- Worked jointly with Public Works' Public Utilities Division on analyzing the feasibility and applicability of municipal utility district (MUD) creation and MUD annexations;
- Conducted legislative review and analysis for all Texas State Legislature bills concerning planning, land-use and economic development.

**PhD Candidate at Rice University**
August 2002 - January 2007 (4 years 5 months)
-PhD student at Rice University in Political Science - Doctorate earned end of January 2007.
-Conducted research on land use public policy analysis, development and adoption; institutional effectiveness and civic participation in environmental issues
-Taught classes in statistics and American Politics;
-Project manager for a National Science Foundation grant studying the effects of Hurricane Katrina on evacuees from New Orleans.

**Environmental Specialist**
November 1998 - August 2002 (3 years 9 months)
- Actively worked with Chief Environmental Officer to develop Enron's renewable energy position and policy strategy toward state and federal legislation, specifically focused on with greenhouse gas and air quality issues;
- Conducted analysis of alternative energy legislation and collaborated with energy traders to determine bio-fuel market plays and opportunities
- Participated in the development of the Enron Corp. greenhouse gas inventory utilizing the IPPC guidelines and global climate change policy;
- Participated in the design, content and publication of company's Corporate Responsibility and Sustainability report following Ceres transparency guidelines;

- Managed the design, development and implementation of Web-based environmental health and safety performance management system resulting in more efficient, effective and accurate reporting by global assets.

## Education

**Rice University**

PhD, Political Science - Public Policy Adoption and Analysis, 2002 - 2007

**Texas Tech University**

B.A, Psychology - Summa Cum Laude, 1995 - 1997

**Activities and Societies:** Psi Chi, Treasurer; Golden Key International Honor Society; Research Assistant with Psychology Department;

## Honors and Awards

Leadership in Action for Environmental ImprovementEnergy Efficiency, Renewable Energy, Public Policy, Economic Development, Running, Cooking and Reading

## Gavin Dillingham, PhD

Program Director, Clean Energy Policy and Director of DOE's Southwest CHP TAP at Houston Advanced Research Center (HARC)

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Chairman SMITH. Thank you, Dr. Dillingham. That is fine.
Mr. Baum.

**TESTIMONY OF MR. WALT BAUM, EXECUTIVE DIRECTOR, TEXAS PUBLIC POWER ASSOCIATION**

Mr. BAUM. Thank you, Mr. Chairman, Ranking Member Veasey. I appreciate the opportunity to testify today. My name's Walt Baum, and I'm the Executive Director of the Texas Public Power Association. TPPA represents the 72 municipally owned utilities in the State of Texas. We represent about 15 percent of the customers. In Texas you also have electric co-ops that serve another 15 percent of the customers, and then the investor-owned utilities serve the rest. TPPA is also a proud member of American Public Power Association, APPA.

I'm here today to talk about the real world—a real world example of a resilient grid and that is how ERCOT, the grid the serves most of Texas, recovered from Hurricane Harvey. I don't have to tell any of you about the devastation that Hurricane Harvey caused. Many—all of you have seen it; many of you experienced it firsthand. It was an incredible storm that Dr. Dillingham talked about, all the water and wind that was dropped. It really was two different storms when it hit Texas. It was a wind event in the Corpus area where first made landfall as a category 4 hurricane, and a lot of transmission was damaged, but then, as it moved on to the coast and into the Houston and the Beaumont, Port Arthur areas, it became much more than just a rain event. And utilities there were dealing with flooded substations and other issues.

In the Corpus area, AEP, the utility which serves the Corpus area, they alone had over 550 transmission structures that were damaged and 5,700 distribution poles that were hurt by the storm. And, as we said, then in the Houston and Beaumont and Port Arthur areas you had flooded substations. We actually had to bring in some temporary mobile substations to replace those flooded substations, which was—which is newer technology that probably wasn't available 10, 15 years ago. We're proud of that.

It was a tough storm, but the story is largely good in Texas. There were about—right at about 1–1/2 million customers were affected but not at any time. Because of the way that the storm was very slow-moving, we never had more than about 300,000 customers out at any one time. And all customers were restored—96 percent of the customers were restored within 14 days when the storm first made landfall. There were a few others that took a little bit longer to restore just because of flooding and high water. But as of—20 days after the storm originally made landfall, all customers who could take power were back and receiving power. And we're really proud of that work and the tireless work of linemen and line workers to repair the grid.

Reliability and resiliency are really closely intertwined concepts in the electric grid. Reliability is when you turn on that switch is—are the lights going to come on? And resiliency is when those lights don't come—turn on when you flip that switch, how long does it take to get them back on. Our goal is always 100 percent reliability, but because we can't prevent weather or other manmade emergencies, a reliable grid must have built-in resiliency.

Every storm's different and Harvey's historic. And because I'm from Texas, this is where I'm contractually obligated to say this wasn't our first rodeo. Utilities nationwide plan and coordinate to prepare for these types of events, and plans address how crews will be deployed and how information will be shared with customers and when to call for additional help. Grid resiliency is really part of day-to-day operations in the electric utility industry from going out and doing tree trimming and vegetation management to when you're planning the grid, planning it with redundancy in mind, and grid operators and utilities with generation plan for reserve margins to make sure there's ample power during our peak times, even if large generation units go off-line. Transmission and distribution systems are always designed with redundancy, and ERCOT actually conducts annual Black Start training which is done to simulate the total loss of our grid and bringing it back up from zero.

Mutual aid is also a key important part of resiliency. Just as firefighters, police officers, and other emergency responders combine forces to help rebuild communities, line workers and other personnel do that as well. Crews from all across Texas and other areas of the country shared in our restoration efforts. Utilities that were most affected called in crews from other areas. In our systems, municipally owned utilities went to go help out the investor-owned utilities after getting there systems back online. CPS Energy sent crews to help AEP Texas and CenterPoint. And not just electric workers, they also sent IT personnel to help them get their networks back up and running. APPA, the American Public Power Association, has its own mutual aid network, and they coordinate with EEI, the investor-owned trade associations, and NRECA, the electric co-ops associations.

During Harvey, we did daily calls with APPA to talk about how the municipally owned utilities were affected and then moved on to calls that DOE ran in which all of the different sectors of the electric industry got together to help. And similar coordination was in place for Irma.

Once restoration was complete in Texas, we sent many crews to Florida and CPS Energy, Austin Energy, Denton, Garland and other Texas utilities were all out there helping Florida. And we have our own mutual assistance group in Texas as well to first respond to our different systems.

While the story is positive, each event is also a way for individual utilities to learn and be better prepared for the next round of storms. Our new Public Utility Commission Chair had a hearing last week in which she identified several issues for the industry and government partners to work together to prepare for the next storm. My members' Public Power utilities and the entire electric industry are committed to sharing information, technology crews, and equipment to continue to keep the lights on.

I especially want to thank all the crews and personnel in our industry. The tireless work of the line workers and support staff behind them is truly inspirational. It's also serious and dangerous business. Unfortunately, the industry lost a young lineman last month who is helping to restore power near Victoria.

Thank you very much for the opportunity to testify, and I'm happy to answer any questions.

[The prepared statement of Mr. Baum follows:]

**Testimony of**

**Walt Baum**

**Executive Director**

**Texas Public Power Association**

**Submitted to the**

**HOUSE SCIENCE, SPACE AND TECHNOLOGY COMMITTEE**

**for the October 3, 2017, Hearing**

**"Resiliency: The Electric Grid's Only Hope"**

Chairman Smith, Ranking Member Bernice Johnson, and members of the Committee, thank you for inviting me to testify at the hearing today, "Resiliency: The Electric Grid's Only Hope."

My name is Walt Baum. I am the Executive Director of the Texas Public Power Association (TPPA). TPPA represents the 72 municipally owned electric utilities (MOUs) in Texas, along with other public electric providers such as river authorities, joint action agencies and some electric cooperatives. MOUs serve more than 5.1 million Texans. TPPA is also a proud member of the American Public Power Association (APPA), the voice for not-for-profit, community-owned utilities that serve 49 million people in 2,000 towns and cities nationwide.

**Hurricane Harvey Recovery Update**

I am here today to give a real world example of a resilient grid and how Texas electric utilities are recovering from Hurricane Harvey.

I don't have to tell you about the devastation caused by Hurricane Harvey. Some of you have seen and experienced it firsthand. The combination of high winds, historic rainfall and torrential flooding led to over 1.5 million electric customers being temporarily affected by the storm. However, because it was such a slow storm that lasted several days the number of customers outages at any one given time was far less than 1.5 million, peaking at just over 300,000. Coastal utilities were primarily affected, but areas that were over 100 miles inland experienced 100 mph gusts leading to damage to electric distribution systems throughout the state.

Fortunately, restoration efforts are complete for all customers who can take power. Within 14 days after the storm hit there were less than 30,000 customers without power.

The investor owned utilities that serve the majority of the coastal areas of Texas were most affected. AEP Texas serves the Corpus Christi and Victoria areas, where the storm first came onshore on the evening of Friday August 25th as a category 4 hurricane. They had 220,000 customers affected at the peak and restored power to 96% of them within 14 days. AEP brought in over 5600 resources from across the state and country. Crews are concentrated the largest effort in the Aransas Pass, Rockport, Victoria and Refugio areas, which were most devastated by the storm. AEP service territory had 549 transmission structures and 5700 distribution poles downed or damaged.

CenterPoint serves Houston and surrounding area. CenterPoint restored service to 1.27 million customers in about 10 days. Some of those outages were controlled in order to protect equipment (or for safety reasons). They did not suffer significant wind damage, but lost several substations due to flooding. A temporary mobile substation was constructed near a severely flooded substation to serve area distribution load while the permanent substation was repaired. CenterPoint brought in 1500 crews from 7 states to assist in restoration efforts.

Entergy Texas serves the area east of Houston and the Beaumont/Port Arthur areas. They had 192,000 customers affected by the storm. On September 8th power has been restored to all other customers impacted by Hurricane Harvey except for customers served by flood damaged equipment and areas that are still flooded. Many customers experienced multiple outages as conditions changed from wind to rain to flooding. Temporary mobile substations were also brought in while severely damaged substations are rebuilt and repaired.

TNMP (which serves several communities up and down the coast) restored power to almost 80,000 customers, including 22,000 customers out during their peak. All customers were restored within 10 days. They suffered no outages to their transmission system or industrial customers. The imported about 400 additional crews to help restore power.

Electric cooperative members in Texas also worked tirelessly since September 25, when Hurricane Harvey made landfall. There were a total of 179,016 outages and they were down to less than 1,000 outages within 10 days. Some of the biggest obstacles in getting folks turned back quickly included limited access due to high water and issues in East Texas with Entergy transmission. Co-op employees from across Texas assisted other co-ops hardest hit by the storm.

Municipally owned systems did not suffer the worst impacts of the storm. Overall we had about 160,000 customers affected, and had service restored to nearly everyone within three days. Robstown, which is located close to Corpus Christi, suffered wind damage but had crews out working on their lines the day after the storm passed and restored power to 95 percent of their customers within two days. Some East Texas systems lost power due to transmission outages in the area, but did not suffer large distribution damage.

**ERCOT**

ERCOT, the Electricity Reliability Council of Texas, is the grid operator for most of Texas affected by the storm. ERCOT's System Operations team worked 24/7 at ERCOT's System Control Center, which is built to withstand hurricane-force winds, to monitor the situation and protect overall system reliability. Extra engineering staff supported their efforts throughout the storm. ERCOT sent out several operation notices to market participants before and during the storm and was in constant communication with transmission and generation owners regarding hurricane preparations.

The ERCOT system experienced a number of transmission outages. Six 345 kV lines, ninety-one 139 kV lines and one hundred and thirty eight 69 kV lines were affected. Over 10,000 MWs of generation was also affected at some point, primarily due to floodwaters but also some due to transmission outages and some facilities that were impacted because they couldn't be reached by employees. ERCOT did instruct 2 generation facilities to run under their "Reliability Unit Commitments" program to provide voltage support and system reliability. ERCOT did have sufficient generation resources available throughout the storm and recovery and did not have to shed load or import power.

At the South Texas nuclear plant near Bay City, over 250 operators, engineers, maintenance and other support staff were stationed at the 2,700-megawatt plant throughout the storm. That plant continued to produce power safely at 100 percent capacity throughout the event.

**Electric Grid Resiliency**

The electric utility industry strives to maintain a reliable and resilient grid. A reliable grid is one where you can count on the light coming on when you flip the switch. A resilient grid is one that can bounce back quickly from an adverse event. They are closely intertwined concepts: a reliable grid is one with built- in resiliency. Our goal is one hundred percent reliability. But because we cannot prevent Acts of God or all manmade emergencies, a reliable grid must have built- in resiliency to allow for as quick as of recovery as possible.

Every storm is different and Harvey was historic, but this is not the first storm to hit Texas. Electric utilities nationwide plan and coordinate to prepare, mitigate, and safely restore power in a wide variety of emergency events. Plans address how crews will be deployed, how information will be shared with customers, and when to call for additional help.

Grid resiliency is part of day-to-day operations in our industry. Tree-trimming and vegetation management are part of normal utility operations. Our utilities are designed with redundancy in mind. Grid operators and utilities with power plants plan for reserve margins annually to ensure ample power during weather events or other grid emergencies. Transmission and distribution systems are designed with redundancy in mind. ERCOT conducts annual "blackstart" training which simiulates proper restoration of the ERCOT system in the event of a system wide black out.

Mutual aid is an important component of resiliency. Just as firefighters, police officers, and other emergency responders combine forces to help rebuild communities devastated by natural disasters, lineworkers and other electric utility personnel come together in an emergency to turn the lights back on. Crews from all across Texas and other areas of the country have shared in the restoration efforts. The utilities that were most affected called in crews from around the country. After dealing with their outages CPS Energy, Austin Energy, New Braunfels and others went to go help other MOUs, and helped out coops and IOUs as well. CPS Energy sent crews to help AEP Texas in the Victoria and Bloomington areas and in addition to over 50 lineworkers they also sent IT professionals to help with network and infrastructure work. Over 1500 mutual assistance crews from other parts of Texas as well as Louisiana, Mississippi, Missouri, Florida, Kansas, Alabama and Tennessee assisted CenterPoint in their recovery efforts.

APPA has its own mutual aid network, which also coordinates with the Edison Electric Institute and the National Rural Electric Cooperative Association, the trade associations for investor-owned utilities and rural electric cooperatives, respectively. During Harvey, there were daily calls set up through APPA for MOUs in Texas and Louisiana to coordinate needs and recovery efforts. There were also daily calls run by the Department of Energy that APPA, EEI, NRECA, Nuclear Energy Institute the Department of Homeland Security, and others participated in to coordinate efforts between sectors and also CEO level calls hosted by Secretary Perry to discuss any specific needs. Similar coordination was in place for Hurricane Irma. Once restoration was complete in Texas, CPS Energy, Austin Energy, Denton, Garland and other Texas utilities sent crews to help Irma restoration efforts.

Texas also has a Texas Mutual Assistance Group made up of the larger utilities that coordinate mutual aid agreements and efforts. Texas Public Utility Commission staff worked with the State Emergency Operations Center during the storm to provide a contact point for utilities and their needs. The Public Utility Commission also issued emergency orders after the storm giving the Executive Director discretion over disconnect, reconnect, billing estimation and customer disconnection rules. They also Retail Electric Providers to offer deferred payment plans for customers in affected areas.

While the story is largely positive, each event is also a way for individual utilities to learn and be better prepared for the next round of emergency conditions. The new Public Utility Commission Chair held a meeting on September 28th and identified several issues for industry and government partners to review.

My members, public power utilities, and the entire electricity industry are committed to sharing information, technology, crews, and equipment to continue to keep the lights on. I especially want to thank all of the crews and personnel in our industry. The tireless work of the lineworkers and the support staff behind them is truly inspirational. But this is a serious and dangerous business; unfortunately the industry lost a young lineman last month when he was working to restore power near Victoria, TX.

Thank you for the opportunity to testify. I'm happy to answer any questions you may have.

TPPA
Texas Public Power Association

## WALT BAUM

**Executive Director**
***Texas Public Power Association (TPPA)***

Walt Baum is the Executive Director of the Texas Public Power Association (TPPA). Texas Public Power Association represents the interests of public power providers in the state of Texas including the municipally owned electric utilities, river authorities, joint action agencies, and some electric cooperatives. The 72 municipally owned electric utilities in Texas provide power to more than 4 million Texans over some 1.8 million meters. As a spokesperson and advocate he serves as the voice of the Public Power industry in Texas.

Walt has over 20 years of experience managing the interactions between State Government and the electric power industry and has lead teams in the passage of multiple pieces of legislation that have defined the Texas electric market. Prior to TPPA Walt served as the Executive Vice President of the Association of Electric Companies Texas (AECT) and as Chief Clerk of the Texas House of Representatives State Affairs Committee.

A native of Amarillo, Walt holds a BA in Economics from Austin College in Sherman, TX. He is a member of the Advisory Committee of the American Public Power Association and serves on the Board of Directors of the Association of Women in Energy.

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Chairman SMITH. Thank you, Mr. Baum.

Thank you all for your testimony, and I'll recognize myself for five minutes for questions. And let me direct my first question, Dr. Sanders, to you.

You will be challenged, by the way, to give a brief answer to my question, which is what are the short-term and long-term steps that need to be taken to protect the electric grid from cyber attacks?

Dr. SANDERS. You're right. Professors are not known for being brief, but I'll do my best.

Chairman SMITH. Okay. And if you have to pick, choose the short-term as opposed to long-term.

Dr. SANDERS. Okay.

Chairman SMITH. Yes.

Dr. SANDERS. So, first, let me say that there's a large effort underway today much different than there was at the turn of the century to protect the grid against cyber attacks. Since the early 2000s the Department of Energy, the National Science Foundation, the National Labs, and others have been working in this area, and substantial progress has been made. So, in a sense, what needs to be done and I think what we are doing is taking a concerted approach where industry, government, and academia come together to work on this problem.

Many ideas, technical ideas and technical solutions, have been developed, and a short-term challenge and maybe the most important short-term challenge is to find ways within the very multifaceted landscape that includes regulation, that includes issues with cost, that includes States and Federal Governments to find ways to implement those solutions. We've made substantial progress there, but there are many things that still have been developed that need to be implemented to make our grid secure.

Chairman SMITH. Okay. Thank you, Dr. Sanders.

And, Mr. Imhoff, what can the government do to encourage innovation that will promote resiliency?

Mr. IMHOFF. Another short answer. I think the key is to provide leadership, to encourage the combination of fundamental advances in mathematics, in control theory, and data analytics and advanced computing and link those closely with industry through bodies such as NERC, the Electric Subsector Coordinating Council, which is a strong government industry body, work with NRECA and APPA and others to help move those fundamental advances to practice and implementation within industry. Step one would be field validation. Most of those are cost-shared. I think most industry members would argue that they've been very productive. So I think from the federal standpoint, leadership to help drive forward the fundamental knowledge to help us innovate and stay in front of the wave is a fundamental contribution.

Chairman SMITH. Okay. Thank you, Mr. Imhoff.

And, Mr. Baum, in what way does the Texas electric grid—in what way does it differ from other grids and why?

Mr. BAUM. Well, the Texas electric grid is—we talk a lot about—you know, Texas is very different and Texas has its own grid. ERCOT covers 85 percent of the area of the State and about 90 percent of the load. It doesn't cover the entire State. Areas in the

Panhandle and the corners of Texas aren't part of the grid, but we are our own grid. Power that is generated in Texas largely stays in Texas. Of about 70,000 possible megawatts of generation, at any time we can only import or export under 1,000 megawatts. So, you know, we truly—we're—I like to say that Texas is an island a lot in electricity. That sounds a little calloused now with what's going on with Puerto Rico, but we pretty much are on our own, and so, you know, that—we are different from the rest of the country in terms of that goes.

Chairman SMITH. Okay. But in positive ways that you just mentioned because the coverage and so forth. Okay.

Mr. BAUM. Yes.

Chairman SMITH. Thank you, Mr. Baum.

Dr. Sanders, one last question for you. Would we benefit from simplifying our structure having fewer government agencies and departments involved? I guess it depends on how you simplify, but do you think that's a direction we should go? And I think that's one of your recommendations anyway.

Dr. SANDERS. So the committee report was neutral on the actual government structure to be used. The committee felt very strongly that this is a complicated issue, that there are different issues, for example, the interaction between DHS and DOE that are working well, and—but these need to be correlated.

Chairman SMITH. Okay. Thank you, Dr. Sanders. And that concludes my time, and the gentleman from Texas, Mr. Veasey, is recognized for his questions.

Mr. VEASEY. Thank you, Mr. Chairman.

I wanted to ask Dr. Dillingham a couple of questions particularly as it relates to climate change and rising global temperatures. I know that there are a lot of people including oftentimes on this committee we hear that—we don't know human involvement as it relates to climate change or some people that outright deny that climate change is happening even though there's a lot of consensus within the scientific community that there is some manmade contributions as it relates to climate change.

And I wanted to ask you, as we consider potential infrastructure investments, do you think that States and utilities should consider climate change as it relates to the resiliency of the systems?

Dr. DILLINGHAM. Yes, thank you for that question. Yes. And what we seem to find is that when we talk about climate change, there's usually like a specific type of event that's pointed to like hurricanes or to floods or just one particular type of weather phenomenon. And when you look at climate change, there's a significant number of weather phenomena that are happening here for what I mentioned, from drought to floods to hurricanes to ice storms, and all of these are events that are becoming more intense and more extreme. And the—you know, we've seen that actually personally, and we've also seen that within the future climate models that are being deployed.

One of the things that, you know, needs to be considered and we've been discussing this a lot more at HARC and across the State is, you know, now that these climate models, the downscaled regional climate models are becoming a lot more accurate in understanding the intensity and likelihood of these events happening. It needs to be at least part of the conversation here. We have projections for—in ERCOT, for example the amount of solar and wind that are going to be deployed. That does not take into—that takes into account historical weather patterns but that does not take into account future weather patterns or future weather phenomena. And so if we have models that were getting greater—we're feeling more comfortable with and feel like they have better accuracy, it is important that we start including those within our projections and understanding on how the grids operate for the future so we can start developing in that regard.

Mr. VEASEY. Well, thank you very much. That sounds reasonable. What about insurance companies? Do you think that they need to consider changing environmental factors when engaging with potential clients?

Dr. DILLINGHAM. The insurance companies are way ahead of us on this. They already are doing this. They have their catastrophe models and now they're bringing in the downscaled climate models. And many of their decisions now are based on potential future climate factors that they're looking into and what's the risk of us funding this infrastructure into the future. And so what you're seeing now is actually development of resilience bonds that are actually being coupled with catastrophe bonds. And these resilience bonds are largely put in place by the insurance companies to mitigate risk. The Brookings Institute had a nice report on this a couple years ago discussing the opportunity to bring the—in resilience bonds into the market to bring in another kind of funding source essentially, bring in the financial market to help better develop more resilient infrastructure. And so the insurance companies are way ahead in this regard.

Mr. VEASEY. This is again for you, Dr. Dillingham, and Walt. As you know, Hurricane Harvey was not the first hurricane to damage Texas and won't be the last. This is, you know, something that we've had experience with and will continue to have experience with. One—and communities are trying to look for ways they can harden their infrastructure to deal with future catastrophes. One notable example in Houston is the wall that was built after Hurricaine Allison to protect the substation that provides power to the medical center.

I wanted to ask you how have communities adapted to the changing conditions that we are experiencing as a result of climate change?

Dr. DILLINGHAM. There has been—I'll just speak specific to the Houston region. There has been some significant activity or growing activity in this regard. UTMB Galveston is an example that was flooded out during Hurricane Ike. They had to essentially close that down, and there was questions whether or not it'd even become operational again.

But what they've done since then is they've put in a combined heat and power system, which is an onsite natural gas-generated system that operated great during Hurricane Harvey. They also built that above grade. It's up on the second floor, so it prevents floodwaters from getting in there and they also build a flood wall around it. So there's steps happening especially within critical infrastructure, hospitals particularly, wastewater treatment plants that are going into place, and a lot of it is focused on distributed generation and—which is typically a combined heat and power type system being put in place.

As far as just in the community in general when you look at the parts of the community that have started taking action to be more resilient—so Meyerland is a neighborhood in Houston that has flooded multiple times. The homes that are starting to build above grade, the homes that are taking these—you know, starting to put in these resilience standards to make sure that they're above grade, none of those flooded. So—and they're—and those homes are in good shape.

And so it's a matter of starting to put in place these voluntary resilience standards, educating communities, educating project developers, engineers, architects to understand what is the way to start building more—in a more resilient fashion but do it in a cost-effective manner. You can't do it in Texas if you're going to mandate regulations, and you're not going to do it if it's expensive. We built ourselves on low cost of business and low cost of living.

And so what the important piece is is how do you implement this stuff and how do you build capacity within our building community to allow them to do this in a cost-effective way?

Mr. VEASEY. Thank you. Thank you, Mr. Chairman.

Chairman SMITH. Thank you, Mr. Veasey.

And the gentleman from California, Mr. Rohrabacher, is recognized for questions.

Mr. ROHRABACHER. Thank you very much, Mr. Chairman, and thank you, Mr. Chairman, for holding this hearing today. And it is something I just think that we have not given serious attention to this. I know we've had several Members over the years who have made it their crusade to talk to us about EMP and other threats, but it just—nothing seems to be—get done and there doesn't seem to be a national strategy that actually coincides with how vital this could be to the well-being of the American people.

If we have something go crazy with the sun, I understand it could knock out all of our grid. I mean, you'd knock out 75 percent of the people's electricity in the United States of America. I mean, this is a tremendous threat that—and again, we're talking today about reliability and resilience.

Let me talk to you about some real specifics rather than having the experts get together and talk about it, all right? What about a more diversified power system that we would then target that would be a much more diversified power source for the American people? Would that be a major step towards dealing with this potential threat? Anybody want to say anything about that?

Dr. SANDERS. You can go first. I'll go second.

Mr. IMHOFF. Thank you for the question, and I think that diversity, whether it's in diversity of fuel mix, diversity of generation and other things provides resilience and robustness to the system.

Mr. ROHRABACHER. Well——

Mr. IMHOFF. And from the standpoint of EMP and space weather or——

Mr. ROHRABACHER. Right.

Mr. IMHOFF. —geomagnetic activities, there are differences. The higher risk is at the further northern latitudes and the southern latitudes. I think the good news, sir, is that over the last year, both DOE has put in place an initial program plan dealing with the space weather issues. The Electric Power Research Institute has actually begun working on standards and operational approaches for component purchase and installation that would begin to deal with these issues. NERC has actually set two standards that are the beginning of a journey that would help utilities better plan for and defend and operate through these storm events.

Mr. ROHRABACHER. Well, let me get real clear on this. We now depend on big, huge electric plants, and it seems to me that we could have, for example—let me ask you whether this would have been one solution—if we would have determined 20 years ago or 30 years ago that we're going to build small modular nuclear reactors which are now we are told we are very capable—have been capable of building, would that in some—would that type of diversification help us solve this or deal with this issue?

Mr. IMHOFF. So I think diversity, regardless of the type, regardless of whether it's natural gas or nuclear, can provide some resilience, but any device is going to be—has some risk in terms of electromagnetic fields. They would need to have——

Mr. ROHRABACHER. Right.

Mr. IMHOFF. —the protection, the shielding, et cetera, on critical components regardless of the type of generation. So nuclear itself is not more or less robust.

Mr. ROHRABACHER. So—but if we—so we have smaller nuclear power plants in various communities, for example, which I understand we're capable of doing in very—which are, by the way, safer from what I understand than light-water reactors, that that would not protect—give us more protection than to have it in one major power plant?

Dr. SANDERS. So let me follow up a bit on this. As Mr. Imhoff said, diversity in the source of generation, both in the type and in the geographical distribution of the generation, can be helpful. With regard to the kind of solar events that you talk about, the same issues, whether we're diversified or—to different degrees or not will apply with regard to the resiliency of the transmission and distribution system of the overall grid. There are very interesting strategies that are talked about in the report. These include microgrids. These include——

Mr. ROHRABACHER. Right. Let me ask you this. Would it be easier to fix if you've got a major source versus many smaller sources, a big nuclear power plant versus small modular nuclear power plants? No?

Dr. SANDERS. I'm not an expert enough to know that.

Mr. IMHOFF. I can't speak to that either, sir.

Mr. ROHRABACHER. Okay. Well, let me just note that we also have solar panels that—you know, would that be affected as well, if a house—you go down right to the greatest diversification which is individual homes, would this be more resilient and have more protection?

Mr. IMHOFF. I can't speak to the inherent robustness of solar panels themselves per se, and I don't think the outcome is to move to completely distributed energy. There are some values of some of the large centralized plants as well, so I think it's really an issue at each region, at each electrical region, whether it's Texas or the Western Coordinating Council or the Southeast, they need to look at their fuel diversity, they need to look at their prices, they need to look at their vulnerability to things like geomagnetic storms and figure out what's that right balance between centralized and decentralized activities.

The one challenge, sir, what's changing at the edge in terms of today's grid is there's an explosion of new devices and new services and new innovations coming at the edge, many of which are outside the boundary of the utilities. Microsoft is providing its own power. Walmart is generating its own renewables on rooftops in their stores all around the country, so these are dramatic shifts in how we plan the system, as opposed to how we did it 20 and 30 years ago, so I think it's regional and local. I think they each need to figure out what's the right balance of distributed versus centralized generation and supply, and that's part of what I think is so important about regional planning activities across the country, doing what makes sense for them locally.

Mr. ROHRABACHER. Okay. Thank you very much.

Chairman SMITH. Thank you, Mr. Rohrabacher.

The gentleman from California, Mr. Takano, is recognized.

Mr. TAKANO. Thank you, Mr. Chairman.

On Friday, the Secretary of Energy submitted a proposed rule to the Federal Energy Regulation Commission, otherwise known as FERC, with the explicit purpose of adjusting market rules to favor coal and nuclear power plants. The justification that they provided was for—for this was that these sources have several weeks of fuel onsite and therefore are inherently more resilient than natural gas or renewable energy generators.

However, this assertion, along with the overall proposal, has received widespread criticism not only from the renewable and natural gas industries but from respected independent and even conservative experts on power markets. For example, Utility Dive just published a point-by-point refutation of this misguided effort by Alison Silverstein, who is the lead author—who is lead author that DOE hired to draft the grid report that the agency used to justify the new proposal.

The conservative R Street Institute also released a thorough analysis on Sunday, which concluded that this proposal is, quote, "an arbitrary backdoor subsidy to coal and nuclear power plants that risks undermining electrical competition throughout the United States, end quote". And Nora Mead Brownell, a former Republican FERC commission said in an Energy & Environment News article posted yesterday that she, quote, "has never seen a credible argument, not one, that there is a problem with resiliency and reliability," end quote, due to coal and nuclear power plant retirements.

On the contrary, a story published in E&E News on Friday titled, quote, "Flooded Texas Coal Piles Dampen Reliability Arguments," end quote, is—and it's a clear example of how poorly justified this proposed rule really is.

Now, each—gentlemen, I need to get through—I want to get to several questions. Do you think subsidizing the coal industry is an efficient and cost-effective way to make the grid more resilient? I would prefer a yes or no answer.

Dr. SANDERS. So I think, first and foremost, we have to remember that resiliency is a system issue. No single source of generation can determine the resiliency of the grid. It depends on having enough generation in a distributed fashion, having the transmission and distribution infrastructure to deliver the power to the consumer——

Mr. TAKANO. Excuse me, Mr. Sanders, I've got to get through——

Dr. SANDERS. Okay.

Mr. TAKANO. —a few questions. Can you kind of give me a yes or no, I mean, as far as—I mean, my question is pretty simple. Do you think subsidizing the coal industry is an efficient and cost-effective way to make the grid more resilient knowing all we know about coal and competition——

Dr. SANDERS. Right. Right. The report did not find that to be true.

Mr. TAKANO. Okay. Thank you. Mr. Imhoff?

Mr. IMHOFF. So, just quickly, resilience is a system activity, and what I think is more important is what are those plans replaced with? If they're replaced with combined-cycle natural gas or other things, those have equal and sometimes better resilience capabilities than the coal plant. I am not a markets person, so I can't really speak to the issue of subsidy.

Mr. TAKANO. All right. Thank you. Dr. Dillingham?

Dr. DILLINGHAM. I would have to answer no. Being from the State of Texas, we're not a big fan of subsidies and especially in this case.

Mr. TAKANO. Thank you. Thank you for that. Mr. Baum?

Mr. BAUM. The key, as has been mentioned is, you know, multiple fuel sources and redundancy on the grid, but I don't think any special subsidies is needed.

Mr. TAKANO. So subsidizing coal industry is not an efficient and cost-effective way to make the grid more resilient? Probably not? Would that be fair to say, Dr. Baum?

Mr. BAUM. Probably not.

Mr. TAKANO. Okay. Thank you. Thank you. Mr. Imhoff, in your testimony you discuss how energy storage could provide more flexibility in how operators might mitigate cyber outage and improve recovery. Can you expand more in the specifics about energy storage is able to accomplish such a task?

Mr. IMHOFF. Yes, thank you, Mr. Takano, and thank you for your leadership on the advanced battery grid caucus.

Mr. TAKANO. You're welcome.

Mr. IMHOFF. The issue around energy storage is it fundamentally decouples supply from demand. It's like a shock absorber for your truck that you drive down your ranch road. The shock absorbers help smooth it out and enable you to keep from spilling the coffee in your lap. Energy storage will help decouple supply from demand, and what that adds to the grid is flexibility. So if there's a cyber attack that takes out a certain substation or certain supply sources, having that added flexibility in terms of energy storage linked with advanced control and power electronics that are smart power electronics give the operator more degrees of freedom for how they steer around that problem. So that's the role it will play, adding more flexibility to the system to respond to an outage.

Mr. TAKANO. Well, and it's also energy-source neutral, so if we found—in the case of Mr. Rohrabacher—small nuclear power plants were more efficient than gas—than the gas-powered plants, I mean, this still would be a tremendous addition to the resilience of the system.

Mr. IMHOFF. It is source-neutral, correct.

Mr. TAKANO. Thank you, Mr. Chairman. I yield back.

Chairman SMITH. Thank you, Mr. Takano.

The gentleman from Florida, Mr. Posey, is recognized.

Mr. POSEY. Thank you very much, Mr. Chairman, and thank you, gentlemen, for appearing today.

Have any of you read the book *One Second After*? It's a novel by William Forstchen. It was a New York Times bestseller. Well, it was obviously written from a report about the EMP, electromagnetic pulse, threat our nation faces, and if you're in the energy business, I would really recommend the book to you to read.

A little over a year ago, the Earth's orbit missed by about one week a solar eruption which seems would have taken out all our satellite communications and probably destroyed our power grid. My question to you is what you think we should be doing to protect our citizens against that threat? About 60 seconds each would be appreciated with Dr. Sanders first.

Dr. SANDERS. So, first, let me say that I am not personally an expert on this topic, but we did have expertise on our committee and I've—on this matter Tom Overbye from the University of—or from Texas A&M University is an expert on this topic. I talked with him about this issue, and this is an issue of intense research. This is an issue of intense study, and there are solutions that are beginning to emerge but they're in the early stages. They include raising awareness to the potentially severe impacts of GMDs. There is software now to plan for the impacts of GMD on systems, and people are using that to do studies.

We're at the stage really where engineers are getting down to looking at what the real issues are. There are magnetometers that are being installed across the country to measure these kinds of disturbances. In fact, the University of Illinois has one on some land that my department owns right off site. And research is ongoing with groups like NERC and EPRI helping in this effort.

So in summary, we don't have all the solutions we need now, but progress is being made.

Mr. POSEY. Thank you, sir.

Mr. IMHOFF. To follow up, nor am I an expert but I will say the following. We have a number of disparate activities in the country related to electric magnetic pulse. We have a spread of tools, but what we don't have is an integrated toolset, nor do we have a common reflection across the three different waveforms, E1, E2, and E3, and we need to get to that so that we can provide guidance to industry to—for them to better shield and protect the new devices that are being produced for the grid for which we are modernizing and investing heavily each year.

So there is work underway. There are coordinating groups trying to drive that, but I think we need a more focused national effort to move towards a common set of integrated tools that reflect all three of those E1, E2, E3 waveforms. And the challenge is—and some of the solutions for geomagnetic sometimes might interfere or confound the solutions for the EMP waveform, so that's why we need this integrative view of the waveform so we can get a common voice to industry on how to design around this issue.

Mr. POSEY. Thank you.

Dr. DILLINGHAM. I would have to say Dr. Sanders and Mr. Imhoff are the experts here, and they did a good job in as far as explaining stuff. I learned something there, but I cannot speak to this issue.

Mr. BAUM. And I would say, you know, this is an issue that is being studied right now. EPRI, the Electric Power Research Institute, is conducting a multiyear study on this where they are also releasing what they find every few months and all different types of utilities, investor-owned, municipally owned, co-ops are participating in that EPRI report.

I know there are—my feeling is the first thing we need to do is study and figure out what if any technical changes needs to be made to the grid, but I think you need to do the study and research first. There are people out there saying we've got this quick fix that if you buy this type of Faraday cage or this type of new equipment, you know, then you'll fix your problem, but I think you need—I think we need more study first and then decide what if any new equipment needs to be made.

Mr. POSEY. Thank you. Which agency do you see having taken the lead in this or do you think should be taking a lead in it? We've had hearings on this before, and I found the industry had very little interest in this.

Mr. IMHOFF. So, my understanding is a group called the Mission Executive Council is actually working on this, and I believe that that council has represented some Department of Energy and from the Department of Defense and other agencies that are linked to the satellite systems, et cetera. So I would start with Mission Executive Council. I don't know a lot about them, but I believe there already is some coordination across the key involved agencies.

Mr. POSEY. Okay. Thank you, Mr. Chairman. I see my time is expired.

Chairman SMITH. Okay. Thank you, Mr. Posey.

The gentleman from New York, Mr. Tonko, is recognized.

Mr. TONKO. Thank you, Mr. Chair, and thank you to our witnesses for being here today. Obviously, this hearing was rescheduled due to the recent natural disasters. In light of those disasters, I believe it's an appropriate time for this committee to consider how to strengthen our grid. I would hope as we invest in the comeback for all the States that have been impacted by these natural disasters and also areas like Puerto Rico, the Virgin Islands, and the various territories, I would hope we build a grid of the future.

We've learned many lessons from Mother Nature. Following the devastation from major disasters, people begin to think and plan for all possibilities. In New York, the REV initiative, borne by the New York State Public Service Commission, came in the aftermath of Superstorm Sandy. It was inspired by Superstorm Sandy. That disaster showed the value of distributed generation and encouraged the State to invest in microgrid R&D and consider barriers to deployment.

So, Dr. Dillingham, you mentioned microgrids paired with combined heat and power systems. Can you describe the value these systems add to our grid system in general?

Dr. DILLINGHAM. Yes, absolutely. So, a microgrid system with combined heat and power is typically a natural gas-based system, and so what these combined heat and power systems do is they produce power onsite and then also provide thermal services if it's for hospital sterilization, domestic hot water, steam for industry manufacturing, and such.

And so what we typically find is that the natural gas infrastructure is significantly—can be significantly more robust than a transmission distribution infrastructure. It seems to withstand a lot of the severe weather events. And so what we're seeing now is a greater deployment of these CHB microgrid systems particularly in the hospitals—in Texas and in kind of most of our region in hospitals, wastewater treatment plants, first responder-type facilities, data centers, and you're seeing a greater growing of flexibility in application of these.

At one point, combined heat and power was largely seen as kind of an industrial type of approach. Now, you can get them down to very small even residential size to build even community microgrid systems. And in many cases these are fairly diverse systems to where you have maybe the CHP or a natural gas generator as your base system, and then you have solar and batteries there as well, so you have an additional—other types of generation components.

But it's largely, you know, a system that allows you to potentially island from the grid so if the power does go down, you would want to island from the grid. And if you do have that, you also need to have Black Start capability, so there's plenty of other types of components that go into a more resilient type microgrid system there that have been demonstrated and proven to work time and time again. And it adds to the diversity that we've been talking about of a power system.

Mr. TONKO. Okay. Thank you. I would add that school systems where you might have a swimming pool as part of the phys. ed. infrastructure are also opportune——

Dr. DILLINGHAM. Right. And filters are used quite a bit for—or high schools, schools use them quite a bit for shelters as a last resort, and that's a very good application for that.

Mr. TONKO. Absolutely. How important is federal funding for the development of these systems?

Dr. DILLINGHAM. At this point, it's a fairly mature system as far as the combined heat and power piece goes here. These have been around for quite a while. The diversity of applications now, most of the issues we find is there's just a lack of knowledge as far as how these systems can be used beyond, say, a gas refinery or beyond a natural gas processing plant, and how do we move this into a diversity of other groups.

And so most of the work that we do has to do with kind of educating and kind of capacity-building among those that have not had a lot of experience with this. It's like when you talk with someone about solar and they still think it's, you know, $5 a watt, and right now, it's down to 60 cents a watt. People still think the economics are not there, but they are now, and so you just need that education piece of that, as well as some early technical assistance.

Now, as far as microgrids in general, you know, there's still some significant work that can be done especially when you look at the communication devices, the sensors, how these are coupled together, how to do the appropriate optimization models. You know, there's some—still some significant work that needs to be supported at the R&D level, but the basic component of like a CHP, combined heat and power system is largely there and just needs to continue to be built out.

Mr. TONKO. Thank you. The National Academies of Science's July report on resiliency suggested that distributed energy resources, and I quote, "may help avoid or defer the need for new generation transmission or distribution infrastructure to address congestion localized, reliability, or resilience issues." So, Dr. Sanders, if integrated properly, can distributed generation contribute to making a resource generation mix more resilient?

Dr. SANDERS. To give you a simple answer, yes. We believe that putting together distributed generation sources, together with an appropriately engineered grid, can add to resiliency.

Mr. TONKO. And if we include other investments such as storage and microgrids, does that offer new opportunity?

Dr. SANDERS. Definitely, they are all possibilities. It's hard to predict the future, and in one of the chapters, we talk about various features and how the grid would have to adapt to those futures, but they're all things that could be part of the mix.

Mr. TONKO. Thank you. Mr. Chair, I yield.

Chairman SMITH. Thank you, Mr. Tonko.

The gentleman from Texas, Mr. Weber, is recognized for questions.

Mr. WEBER. [Presiding] Thank you, Mr. Chairman.

My district 14 in Texas, the three coastal counties starting at Louisiana and coming southwest, arguably ground zero for Harvey flooding. It's just unbelievable. I have learned more about restoration, recovery, and all of the efforts that have gone on than I ever wanted to know about disasters, and I hope I never get to—have to use it again.

So with that as a backdrop, Beaumont lost water because their electrical boxes went—lost their city water system because their electric boxes went underwater, and a lot of the infrastructure there, had it been raised above ground six, eight, ten feet or more, it could have been protected. We're talking about infrastructure.

Walt knows that I was on the Environmental Reg Committee in the Texas House and dealt with energy there that session so this is very—and I was an air-conditioning contractor before I sold my company, so this is very near and dear to my heart. A great, great discussion.

A couple things I did want to follow up on. The gentleman from California, Mr. Rohrabacher, talked about EMPs and SMRs. Of course the SMRs are going to be more expensive to buy up front, so there's a cost factor there, but when you talk about EMP protection, I don't know probably which one of you guys can answer this is—does EMP affect only a magnetic field that is in operation at the time, or is it all electrical devices?

Mr. IMHOFF. Again, it's not my area of expertise, but I believe it would affect all because it's going to create currents that will tend to overheat and cause issues in various electrical devices, but again, I'm not an expert in this area.

Mr. WEBER. So you're—that is to suppose that a jet engine in an energy plant built by GE or whoever, this turbine that's not spinning—in other words, if we had redundancy, if we had a plant sitting there that wasn't operating, wasn't active, EMP, solar flare, choose whatever method you want, you were thinking that that would destroy the windings in that engine. Dr. Sanders?

Dr. SANDERS. So once again, not being an expert but talking with experts about this, my understanding is potentially yes if they are connected to the grid in a way that that current can get to them, but I think the important point is is that potentially, particularly when this is a solar-generated event, there is some warning, and so if we have appropriate detectors on the Earth, then we may be able to reconfigure parts of the grid——

Mr. WEBER. You would have a main switch you could throw——

Dr. SANDERS. In a sense.

Mr. WEBER. —disconnect it?

Dr. SANDERS. In a sense. It's probably not as simple as one main switch, but there are ways in which we could build protection according to the understanding——

Mr. WEBER. Okay.

Dr. SANDERS. —I have.

Mr. WEBER. Let me—you know, reading through this and going back through this brings up some really interesting questions. I think there's about five ways that we can help make our grid more resilient, and I'll just name them real quick. We need to have portable deployable assets. We talked about SMRs. We talked about other systems. Mr. Dillingham, you called it a microgrid of sorts I guess. I don't know how you have a natural gas pipeline that's capable of running that kind of facility, high-pressure pipeline. That's one of the challenges.

You have to have preapproved—in other words, FERC, all these agencies have to have preapproved these in emergencies. You have to have multiple assets. You have to have more than one you can bring in. They have to be close. You have to have trained personnel. And I know in ERCOT—Mr. Baum, you and I talked about this—we really have a good—like I said, I've learned more about all of the collaboration that goes on after a disaster—a network of first responders. If you've got preapproved, if you've got portable assets, if you've got them close by, and you've got a network of trained responders that's cooperating, that will help harden our grid.

Now, you get to the transportation part, the lines and stuff, Fukushima taught us something over in Japan, their nuclear plant, their backup power was too low. If we had our way, we would raise everything up eight, ten feet in the air at least to get everything above groundwater.

Harvey was the single largest flooding event in United States history, so, you know, I don't know if we can come in and fix all of those problems and raise all of those things up.

Mr. Baum, I'm going to come to you with a question. What kind of technology is available in your experience to stop a domino effect of power outages from moving region to region?

Mr. BAUM. In Texas, our grid operator, you know, is—as Dr. Dillingham talked about earlier, we deal with weather events all the time, nothing as extreme as Harvey normally, but our grid operators are used to dealing with loss of certain lines or loss of certain generation. During Harvey, ERCOT did have—they have certain power plants that they have under contract to provide emergency power when needed, and when we lost some transmission lines due to the storm, they were able to call those reliability unit commitments into play, and a couple of power plants spun up to provide voltage support for that area. So that type of coordination needs to continue.

One of the things you mentioned earlier, the staging and the moving of equipment, having ways to, you know, before—you know, before Harvey and especially before Irma, being able to stage crews and equipment and already have polls on the way to help out, you know, is very key.

And, you know, like you said with the, you know, having modular equipment, you know, I mentioned earlier the mobile substations that we are able to bring in and keep power on the grid, and those type of activities need to continue.

And it's like you said earlier, design changes do need to happen. The—you know, in Houston where you lost a big substation due to flooding, the Memorial substation, that had been there for 15 years——

Mr. WEBER. Right.

Mr. BAUM. —and—I'm sorry, for 50 years and had never had water inside it. But with this storm it was flooded and was underwater for over 10 days. So that is now—that substation is being rebuilt with, you know, the new normal to be prepared if we have another flood event——

Mr. WEBER. Right.

Mr. BAUM. —and being raised and doing walls and other things like that, you know, our—we need to look—you know, we need to take what we've learned from this storm and be prepared to do those design changes.

Mr. WEBER. Absolutely. Well, I appreciate that. Like I said, I've learned a lot. I hope I never have to use it again, but it is—it will be very, very important information to have.

I'm going to now recognize the gentleman from California, Mr. McNerney.

Mr. MCNERNEY. Well, I thank the sitting-in Chairman for recognizing me. I thank the panelists.

A moment of self-promotion, I care a lot about resiliency and reliability, and that's why, with Mr. Latta, we formed the bipartisan congressional caucus on grid innovation, and we've produced some bills that are now working their way through the system to answer some of these questions.

My first question goes to Mr. Dillingham. Is there a significant difference in terms of reliability and resiliency with regard to microgrids versus distributed systems, or do they pretty much look the same in terms of those two questions?

Dr. DILLINGHAM. It's largely the same. I mean, it just depends on how you're defining a microgrid. Out there, there's still a considerable amount of definitions on what a microgrid would be, but it's largely distributed energy resources. You know, typically, if you look at solar rooftop, it's distributed energy. If you look at a microgrid, it's—typically has multiple resources associated with it, if it's solar, battery, CHP, or the like.

Mr. MCNERNEY. Okay. Thank you. You mentioned the adaption gap. Can you describe why that's a challenging problem?

Dr. DILLINGHAM. That's been—starting to be discussed quite a bit more and just generally infrastructure issues as far as how do we best prepare for climate change issues and if that's water treatment or stormwater mitigation or our transportation infrastructure or power infrastructure. But the concern is and the issue that we face is that, due to the multitude of potential weather events that are being faced, taking one action in one area may not necessarily solve other action. So if we deal with drought within our power system, does that necessarily solve high wind, ice storm, flooding, hurricane-type issues.

And when you are limited—financially limited, as we are, you know, within cities and with kind of—just within our infrastructure budgets, you kind of have this difficulty of making the appropriate decision, which way do I go as far as investing in the right piece of infrastructure. If I go and prepare for droughts and then all of a sudden I have ten years of floods, I look like I've really made a mistake here.

And so that's one of the—when the expectations with these downscaled climate models, they're becoming so precise now, you can actually start putting likelihood estimates associated with potential storm intensity, as well as number of events, and those should start at least being considered being incorporated in our planning as we go forward and that should potentially reduce that uncertainty.

Mr. MCNERNEY. Very good. Mr. Imhoff, your testimony touches on the effort in framing metrics to support grid modernization. What role can the Federal Government play in developing metrics for the grid?

Mr. IMHOFF. Thank you, sir, for the question. The Federal Government is involved. As part of the Grid Modernization Laboratory Consortium, we are framing a set of metrics for the next generation grid, three of which are the traditional usual suspects of reliability and affordability and environmental profile, but the new ones of resilience and flexibility are kind of challenging and under debate but they're very essential as we go forward.

So I think the Federal Government is providing some of the innovation to help frame and recast some of these activities, and they've established the opportunity then to work with States and the—at the regulatory bodies and the vendor community and others to help test and validate these, and they're part of the current GMLC research portfolio.

Mr. McNERNEY. I've been in standards committees, and they're a pain, but it's worth it. It's worth the effort.

Mr. Sanders, is enough being done regarding the interconnectedness of the grid with oil, gas, and other natural resources?

Dr. SANDERS. That's definitely an area in which more work needs to be done. Much of the work to date has been focused on the resiliency of the grid, but as I think many of us agree and as the report notes, that interconnectedness is important, so more work should be done.

Mr. McNERNEY. Well, how would you rank cybersecurity issues with the grid resiliency?

Dr. SANDERS. Cybersecurity, if I understand your question correctly, is a very important impairment to grid resiliency, a very real impairment, and one of the important things we should consider. The report takes an all-hazards approach. In fact we talk about about 12 different impairments of the grid. They're all important, can't leave them out. What we need to understand is to what extent can we build protections that can protect against multiple of these impairments, and to what extent do we need to build specific mitigations for them?

Mr. McNERNEY. Well, then how does knowledge of previous cyber attacks prepare for future attacks? Is——

Dr. SANDERS. Great question. Clearly, knowledge is very important. On one hand, knowledge can be used through appropriate information-sharing in order to alert others that this particular vulnerability, which is being exploited, may be exploited in another location and in a very close period of time. On the other hand, there are always new kinds of attacks, so-called zero-day attacks, and so we cannot rely purely on history to think about the future.

In a sense what we need to do—and this is where resiliency is very important—is we need to build systems that, rather than protecting against very specific cyber attacks, protect against whole classes of effects those cyber attacks may bring on the grid. So by thinking about the effects and through resiliency, through that resiliency cycle, mitigating those effects, then we can begin to protect against zero-day attacks that we haven't seen before.

Mr. McNERNEY. All right. Thank you, Mr. Chairman. I yield back.

Mr. WEBER. I thank the gentleman.

The gentleman from Indiana, Mr. Banks, is recognized for five minutes.

Mr. BANKS. Thank you, Mr. Chairman.

What an incredibly important subject for us to tackle today, so I appreciate the Committee diving deeply into these issues.

And when I continue to talk about the cyber-related aspect of this subject as the growing number of—the growing threat of cyber attacks is something that concerns me as a policymaker and does a number of my colleagues as well. And these are no longer hypothetical threats. We've seen two threats to the electrical grid in Ukraine, for example. And with the systems relying more and more on computers and information technology, we need to do everything, as you know, that we can to counter potential cyber threats.

So with that, Dr. Sanders, could we take a step back and maybe give us more specifically how often is the cyber—is there a cyber attack or an attempt of a cyber attack on our national grid? And have we seen that number rise over the past five years?

Dr. SANDERS. Thank you very much for that important question. First, let me say that it's a very difficult question to answer. Different people have different bits of knowledge, some of that knowledge in the open, some of that knowledge classified, some of that knowledge in the hands of other countries, so it's a difficult question to answer.

Having said that, what we're seeing is an increase in the rate of observed cyber attacks, right? We now have documented cyber attacks that are known in the public. We didn't have that just a few years ago. And we're seeing that the frequency of lower-grade probing and attacks on both the operational technology and on the information technology, both on the—if you will, the online part of the grid and the offline control of the grid, those kinds of attacks increasing.

Mr. BANKS. How do we monitor those attacks? I mean, how do you—can you give us sort of a dummied-down version of how we monitor—how do we know that those attacks occur and exist?

Dr. SANDERS. Sure. So some of them are big and we read about them in the news, right, the Ukraine attack and these kinds of things. Some of them we can monitor for. The lower-grade, more frequent ones we can monitor for using online technology. There are systems called intrusion detection systems first popularized in our corporate information technology systems that can look for packets, that can look for behavior that tends to be abnormal and flag those as possible attacks. There have been specific versions of those intrusion detection systems that have been built for the power grid both on the side of smart meters, for example. One was developed at the University of Illinois that's been prototyped and used at FirstEnergy, for example, and other aspects of grid-specific kind of networks.

Now, the trouble is is those signals are not always clear. We get a lot of noise in those, and so we have to fuse that information together, and we have to create higher-level intelligence that we then can make those determinations, and work to do that is ongoing.

Mr. BANKS. So these might seem like obvious questions, but what do we know about these adversaries who carry out attacks like these? What are their motives? Where are they coming from? Can you talk a little bit—we haven't talked enough about that today. Can we talk a little bit about——

Dr. SANDERS. Sure. Sure.

Mr. BANKS. —what we know about these adversaries?

Dr. SANDERS. Sure. I think we know a lot, but we know pieces of the whole story. We know that they come in all forms. We know that they come from kiddie scripters up to potentially nation-states, right? The evidence is pretty strong that nation-states are involved. We know that they're coordinated, we know that they're deliberate, we know that they will wait, they will insert code into a system and they may wait months until they activate that code. So the real challenge is to gain that understanding and to understand how to react to these things when the adversaries may be willing to wait months to gain their information.

Mr. BANKS. An incredibly important subject, and hopefully, Mr. Chairman, we'll have many more opportunities to examine these issues. I appreciate all of you being here very much. With that, I yield back.

Dr. SANDERS. Thank you very much.

Chairman SMITH. Thank you, Mr. Banks.

The gentleman from Illinois, Mr. Foster, is recognized.

Mr. FOSTER. Thank you, Mr. Chairman. And this is a technical question here. A lot of the really destructive scenarios that people, you know, worry about have to do with phase imbalances, resonant conditions, this sort of stuff, frequency mismatches that make it really hard to control the grid. These don't occur in a DC. grid, and there—I was wondering what studies may have been done about the potential resiliency differences on DC. grids versus A.C. grids which, you know, have just a number of advantages I can think of just in terms of being able to, you know, passively protect them with things like diode clamps from—and the interface is a much simpler one. You have—simply, are you delivering the voltage and current or are you not, and opening up the circuit. It's just—from a number of ways, it seems to me it's a lot easier to protect. I was wondering what work has been done on trying to quantify that difference and that may actually cause us to think over time of actually switching to a DC. grid, which gets mooted from time to time. Yes.

Mr. IMHOFF. So I'll start but defer to the professor. The—as you know, the history of our system being an A.C. system is long, and it started 2 centuries ago I guess, but there's substantial experience with DC. interties mainly today focused on movement of large amounts of power over long distance. They are more efficient and you can—actually, right above the A.C. system and not have to deal with a lot of the reliability oscillatory control and other things underneath in that A.C. system.

Mr. FOSTER. Correct. Right.

Mr. IMHOFF. But it all gets down to cost, and so the planners—we don't—have not seen a lot of DC. activity here in the United States over the last decade until the offshore wind issues became emergent, and so there is more direct-current activity in Asia and in Europe than in the United States. I think here is just an artifact of the economics of the current system where we have a flat demand. We have a lot of inexpensive natural gas, and I don't think that the economics have really tripped it in the favor of more DC. activities going forward.

I will say that, as part of the grid modernization consortium portfolio, there is a study that's being coordinated with various ISOs, Midwest ISO, Southwest Power Pool, Bonneville, and the Western Interconnection looking at seams issues in terms of how my DC. overlays enable capacity-sharing beyond the current interconnection boundaries and what value would that provide and what sort of cost performance would that offer. So I think there's an emerging body of knowledge and analytic tools that might look to the next generation of the modernized grid and re-examine this issue of what might be the relationship between A.C. and DC. systems at the bulk system-level. And that study should be wrapping up in January, I believe.

Mr. FOSTER. Well, the other thing that's changed is essentially all power that goes out certainly at the consumer level goes through an A.C. to DC. converter, and so at some point, you know, we've been just converting more than we might necessarily have to. And the pure DC. system may have advantages just in terms of—you know, if we were to start over from scratch, I think we'd seriously consider a DC. system.

Also, if you add the requirement of EMP hardness, which is a very expensive thing but may prove necessary, and cross your fingers that Rocket Man doesn't do what he's been talking about, but if that is a requirement added to this, then I think protecting a DC. system against that will be, my guess, significantly easier than an A.C. system where you have phase and frequency to worry about.

So is there any work, you know, at the lower end in Europe or anywhere looking at—you know, at the distribution-level DC. system?

Mr. IMHOFF. There is consideration of this notion of avoiding the transform—and the inherent losses in the transformers to go to more DC. I think some of the large data farms and others are emerging are very high consumers of electricity actually do some of that because they're inherently D.C.-oriented inside and so they're avoiding some of those issues. But it's more kind of localized and off—one-off evaluations, I believe. I'm not aware of anything substantial in the United States.

Mr. FOSTER. Yes, well inside big data centers, for example, I believe they are switching to DC. power. It is where they have got, you know, many megawatts. And so there's another big vulnerability that gets worried about, which is just how long it would take us to remanufacture many, many high-powered transformers, whereas it probably would be easier to rebuild the fraction of D.C.-to-D.C. converters that got wiped out in an EMP pulse. And so if you add that as a requirement, it may again tip the balance when you add the hardness requirement.

Anyway, if there's anything specific that can be talked about either, you know, publicly or not publicly about efforts along that direction, I'd be interested.

Mr. IMHOFF. I'd be happy to take that for the record.

Mr. FOSTER. Thank you. I yield back.

Chairman SMITH. Thank you, Mr. Foster.

And the gentleman from Illinois, Mr. LaHood, is recognized.

Mr. LAHOOD. Thank you, Mr. Chairman. And I want to thank the witnesses for your valuable testimony here today and want to particularly welcome Dr. Sanders, who's the Department Head at our flagship university, the University of Illinois, and for what you do at the electrical and computer engineering program there. Great to have all of you here today.

Dr. Sanders, in your testimony, you mentioned your work at the U of I, the University of Illinois with the cyber infrastructure for the power grid center and also the Cyber Resilient Energy Delivery Consortium. Two questions on that, could you talk a bit more about how these two centers are helping to make the U.S. power grid more resilient, and then secondly, is this the type of work that's happening at other universities?

Dr. SANDERS. Thank you, Mr. LaHood. I'll—at the risk of being self-promoting, I'll try to be a bit brief on this. The University of Illinois started work on cyber infrastructure making trustworthy and making resilient and cyber secure the infrastructure for the grid back in 2005. I can say that this is a real need that we realized by the turn of the century, but it took time to get the attention of the funders and really have people understand this was an important thing to work on.

The first of those efforts, TCIP we call it, or Trustworthy Cyber Infrastructure for Power was funded by the National Science Foundation in a grant, and in the wisdom of the National Science Foundation, even though financial contribution was not large at the time, they brought in Department of Energy and Department of Homeland Security to work closely with us.

It was very different than your typical academic research project. From the very beginning, we brought in people from industry and the National Labs. People from Mr. Imhoff's group were with us at 2005, and we were defining the research agenda. People from about 35 companies came together at that first meeting, and they worked closely with us from that point out.

A follow-on effort was funded by the Department of Energy, which is called TCIPG, and TCIPG expanded the scope to say don't just do the good academic research but find ways to transition that and get that in the hands of people that need it.

Several startup companies have come out of that effort. Technology has been specifically transitioned to large power system equipment manufacturing, and you can see really that kind of input going on.

Most recently, in 2015 there was once again an open competition from the Department of Energy, and the University of Illinois then received something called CREDC. That's Cyber Resilient Energy Delivery Consortium. And at that point in time—and I should say in the original centers that I talked about, there were four universities that partnered together. Now, 10 universities and two National Labs, including PNNL, banded together to look at resiliency issues in the grid.

So that, once again, is a project that takes basic research but takes basic research and then industry-government partnership in a way that we can have impact. In fact my colleague David Nicol, who is the principal investigator of the CREDC effort, is in Texas today talking with people from the oil and gas industry about how we can transition our technologies to them. We flew out together last night from Champaign, him to Texas, me to here, and this is the kind of effort we place going on. So thank you for that question.

Mr. LAHOOD. Thank you. Those are all my questions. I yield back. Thank you, Mr. Chairman.

Chairman SMITH. Thank you, Mr. LaHood. A good Texas-Illinois connection there I didn't know about.

The gentleman from Florida, Mr. Crist, is recognized for his questions.

Mr. CRIST. Thank you very much, Mr. Chairman. And let me add, thank you for holding this hearing on this important issue. As a Floridian, I certainly appreciate it. I want to thank the panelists for being here, too. I appreciate your presence and taking of your time to help educate us even more about our grid and its resiliency.

I recently saw a comparison that the Energy Information Administration did on grid resiliency during Hurricane Irma and Hurricane Wilma, which hit Florida in 2005. The assessment states, quote, "Although the percentage of Florida customers without power during Irma was significantly higher than during Wilma, the rate of electric service restoration has been more rapid." Five days after Irma's landfall, the share of customers without power had fallen from a peak of 64 percent down to 18 percent, a recovery rate of about nine percent of the customers per day. Power outages during Wilma back in 2005 went from 36 percent of customers to 16 percent by the fifth day after landfall, an average recovery rate of about four percent of customers per day.

Dr. Dillingham, I'm curious. You know, with this in mind and—can you speak generally about improvements that have been made to make our grid more resilient and specifically maybe focus on discussion of the utilization of underground lines as a means of increasing resiliency? We see a lot of our barrier islands and beach communities in Florida moving to this not only because it's aesthetically appealing, but we get hit by hurricanes a lot.

Dr. DILLINGHAM. Yes, absolutely. Thank you for that question. Yes, there have been significant improvements, particularly in the resilience of the transmission distribution infrastructure. We are seeing quicker response times. There's a lot better coordinated deployment, as Mr. Baum talked about within the ERCOT region. The systems are just becoming more robust to deal with this.

When you talk about burying lines versus aerial lines, the significant issues with that is it may solve some problems in some areas where there is high wind events but where there's a lot of flooding, that could actually put it at considerable risk if they're not properly designed. And so you need to—as I kind of mentioned earlier, developing——

Mr. CRIST. I think I'm assuming proper designing.

Dr. DILLINGHAM. Proper designing, right.

Mr. CRIST. Wouldn't we?

Dr. DILLINGHAM. We would assume proper design there, but what we typically find is that if we start—you know, like within Houston we have lines that are aboveground and belowground. The concern there is that in more flooding environments, you just have a higher risk of those lines being disrupted versus if they're aboveground, and so it's just—you have to make that tradeoff. If you're going to pay the additional dollars to bury them, are they properly developed and properly can mitigate against that, that flooding risk there.

But to your point, they're—we have seen significant improvements in the way in which our systems have been designed. They're more flexible. They're allowing for better rerouting of power. And so yes, they have improved considerably, but we need to keep in mind also that, you know, the focus right now of course we've had three significant hurricane events, and so we are talking about that quite a bit right now, but there's a lot of other issues that are being dealt with across the country if it's wildfire, if it's ice storms, if it's drought that can also have significant impacts, and if we're preparing just for hurricanes and preparing for floods, we may be missing the point as far as preparing for some of these other disasters. And so we need to continue to figure out what's the best way to develop a diverse resiliency grid that can deal with as many problems as possible.

Mr. CRIST. Maybe we should talk about those then. If we're talking about fire, isn't it probably better to have your transmission lines underground than aboveground also?

Dr. DILLINGHAM. I would assume so, yes, because you're taking away that risk.

Mr. CRIST. And if you're talking about ice, wouldn't the same hold?

Dr. DILLINGHAM. For ice it could, but then you're—you're looking at just a significant increase in the cost when you bury lines versus having them aboveground, and so it becomes how much are we willing to pay to have that additional resilience in there, and where is that funding going to come from them, and how much are we going to pass on to ratepayers in that regard? And that's just the tradeoff there. In many cases, particularly—except for pretty much flooding, you can have a more resilient system underground. It's just a—it's protected from those events. But are we willing to pay that additional cost to have that resilience in there?

Mr. CRIST. Maybe we should look at it this way. If you're talking about additional cost and you don't underground them but you keep replacing them aboveground, you've got that replacement cost every time or the repair cost every time versus maybe you come close to eliminating it.

Dr. DILLINGHAM. Absolutely right, but the way in which economics are typically valued into these projects is first costs and what is the first cost and that initial cost for me versus long-term lifecycle analysis, which needs to be considered further.

Mr. CRIST. Wouldn't it be more enlightened to consider the reality of, you know, having to replace over and over and over again versus the likelihood of maybe not?

Dr. DILLINGHAM. Absolutely, it's just that's not how decisions are made at this point. It's very much kind of a short-term viewpoint versus a long-term viewpoint and so——

Mr. CRIST. We're in this for the long haul.

Dr. DILLINGHAM. Oh, absolutely—you're absolutely right.

Mr. CRIST. Right.

Dr. DILLINGHAM. I agree with you on that. Yes.

Mr. CRIST. I yield my time. Thank you very much, sir.

Chairman SMITH. Thank you, Mr. Crist.

The gentleman from South Carolina, Mr. Norman, is recognized.

Mr. NORMAN. Thank you, Mr. Chairman. I just want to thank each of you for your testimony. It's been very interesting on a very important subject.

Let me switch gears with you. Smart meters, Mr. Imhoff, what kind of information is gathered and how is it used?

Mr. IMHOFF. The smart meters typically monitor consumption in the home. The utilities then use that to support their billing function, and then in addition, the utilities use them in support of their outage management systems to help detect in real time when outages occur. Today, the majority of utilities still wait for a phone call from a customer to inform them that the power is out in a distribution feeder area. But in areas that are served by a combination of smart meters and then distribution automation devices in the substation have delivered substantial improvements.

Vista in Washington State, an investor-owned utility there, as they moved to distribution and smart metering, they reduced the frequency of outages by 21 percent for the customers and they reduced the duration of outages by ten percent and in a very cost-effective fashion. So typically, that's how that information is used, to support the billing and the outage management systems. I'm not aware of any other key value streams.

Mr. NORMAN. Let me ask you this. What is your opinion? Are privacy and security concerns on the information that is gathered something that we ought to—that the customer ought to be concerned with? And is it encrypted in your—from what you know?

Dr. SANDERS. So, thank you very much for that question. I'll jump in. So with regard to the—well, to answer your question simply, there are many different brands of smart meters, there are many different schemes that are being used, but in general, yes, the information is encrypted, and steps are taken for privacy.

With regard to cybersecurity issues and the meters, there's probably less concern about privacy but a potential concern that again is being thought about carefully so the sky is not falling but potential concerns with regard to someone who may try to gain control of their—those smart meters from the outside. So smart meters do have the ability to control power flow to the house, and so one must design architectures—and those who are designing smart meters are well aware of this—that ensures that the control of those meters cannot be placed in the hands of an adversary.

Mr. NORMAN. And we would depend on experts like each of you to tell us which meters, as technology improves, can avoid some of this because, as Congressman Banks said, the—when you mentioned cybersecurity hacks, particularly with the Chinese with the military, their face gets very serious and it's a huge problem.

And, Dr. Dillingham, again, back on the underground versus overhead, I'm a—we're a developer. I've seen the number of lines that are cut inadvertently and the problems that it has, additional to the heavy cost that it takes to put them underground and the rights-of-way that come with that, so I appreciate your—mentioning the cost because it's a huge factor.

Mr. Chairman, I yield back.

Chairman SMITH. Thank you, Mr. Norman.

The gentleman from Virginia, Mr. Beyer, is recognized.

Mr. BEYER. Thank you, Mr. Chairman, very much, and thank all of you for being with us today.

You know, it's very important that we're having this hearing, especially because our President is visiting Puerto Rico today. And it's in a time when we talk about electrical grid utility—resiliency, Puerto Rico has virtually no electrical grid to speak of. As FEMA Director Long said yesterday, "Rebuilding Puerto Rico after Hurricane Maria will be a Herculean effort."

The Army Corps of Engineers is doing temporary power right now, 74 generators in place, 400 to come, but I think, as of this morning, only a little more than five percent of Puerto Ricans have had their power restored. According to the Army Corps of Engineers, for some areas of Puerto Rico, it might take upwards of 10 months before their power is restored. And it's not just the electrical grid system that's in crisis. As of 3:00 p.m. yesterday, fewer than half of all Puerto Ricans had access to clean drinking water, limited to no cell phone service, 90,000 applications for FEMA assistance, we know of 16 known fatalities, and that doesn't count those who may have died in their homes yet to be discovered. It's two weeks after Maria, but now we do finally have an aid package for Puerto Rico and the U.S. Virgin Islands.

So, Mr. Chairman, may I suggest perhaps a follow-up meeting—follow-up hearing on the resiliency of the electrical grid in Puerto Rico.

And, Dr. Dillingham, if today was a hearing about how we should respond to Puerto Rico, based on your expertise, what solutions would you suggest to make the grid more resilient? What are the near-term solutions to bring power back faster to those, including renewables?

Dr. DILLINGHAM. Thank you for that question. This is very—absolutely a very important topic at this point. The significant problem within Puerto Rico was the lack of—the loss of the transmission distribution infrastructure. The power plants fared just fine there, and they have a fairly diverse set of power plants there from—they have natural gas plants, solar, wind, variety of plants. There was a transmission distribution infrastructure that went down and is going to take a while to get back up.

When you look at the power prices within Puerto Rico and look at what are the different microgrid options that are out there, it makes—it's starting to make some pretty good economic sense to start seeing more solar battery deployments out there. We've already seen the—potentially the wall packs being donated by Tesla to some degree, but a wider distribution of these types of microgrid systems that are not dependent on fuel resources necessarily or not dependent on LNG terminals being on or transmission distribution terminals working or making sure that different types of fuel shipments make it there.

And if you're in a hurricane-prone area such as Puerto Rico, the ability to have smaller resilient microgrid systems is probably the best effort. And the quickness in which you can deploy a microgrid system, especially solar battery system, is far—happens far more quickly than you can deploy any other type of infrastructure out there at this point.

And when you look at models of what's happening in Hawaii, who has similar power costs, and you start seeing their distribution or their development and deployment of microgrids out there, it just—it's a good example to start looking at. The economics are there, the technology is there, and it's really just a matter of starting to introduce it.

Mr. BEYER. Great. Great. Thank you very much. You know, this hurricane season, which isn't even over yet, it's generated more destructive storms than we've seen in a long time. Four of this year's storms became category 4 or 5 storms. Three of those made landfall in the United States. The University of Wisconsin called Harvey a 1,000-year flood, once every thousand years. Quote, "Nothing in the historical record rivals this." Maria was the 10th-most intense hurricane ever. José and Irma, only time in recorded history that two active hurricanes simultaneously had wind speeds in excess of 150 miles an hour.

So while we talk about electrical grid, we cannot afford to avoid the larger-scale issue that these storms are becoming more intense as the climate warms as it changes. So, Mr. Baum, are utilities, especially those in Texas, taking climate change, the increasing severity of storms into account in their planning? What are you doing to upgrade the grid system to recognize that, you know, we're living in a world where the climate is changing?

Mr. BAUM. I think there's no question that we are taking into consideration the new normal after events like this. And as I stated earlier, we had a substation in Houston that flooded that had not flooded in 50 years. That substation is now being rebuilt to prepare for, you know, what is now the flood of record. And I think all of the design that utilities do, it basically says, all right, what's the worst-case scenario that we've seen and now how do we build our system to prepare and be ready to face the next type of storm? So I definitely think practical planning is something that utilities are doing and will continue to do going forward.

Mr. BEYER. Well, thank you for your vision and your answer. Mr. Chairman, I yield back.

Chairman SMITH. Thank you, Mr. Beyer.

The gentleman from Florida, Mr. Webster, is recognized.

Mr. WEBSTER. Thank you, Mr. Chairman. Thank you all for coming.

I thought about, as Mr. Foster was talking about A.C. and D.C., maybe Edison will get a car named after him instead of the Tesla. And it's amazing all the things he's doing, including the battery packs that the company is sending are all D.C., and yet he was the greatest promoter of A.C. It's a kind of interesting switch of events.

Mr. Baum, in Texas in the last hurricane, which just passed, was there a lot or minimal or in between those two damage to the high tension wires from the generator to, let's say, the substation, or were most of the outages caused by the lower voltages?

Mr. BAUM. A combination of both, but I would say most of the customer outages were caused by—on—were more on the distribution system that were caused by flooding and substations being out, which then knocks out the distribution system. But we did have some large—we had six of our largest 345 kilovolt transmission lines were downed or damaged for a while during the storm, and a large number of smaller transmission lines were also affected. So it was both in this storm, transmission and distribution, which goes it—which again, the lights in the whole State never flickered, and a lot of that is because of the redundancy in both the transmission and the distribution network.

Mr. WEBSTER. So from just a hardening standpoint, is there any change that needs to be done to the high tension lines in order to make them more resilient?

Mr. BAUM. I think you're always looking at ways to develop——

Mr. WEBSTER. Let me ask you—my knowledge is from a long time ago, so are they still aluminum with steel cable running with them or is it—is there a new type of transmission wiring?

Mr. BAUM. Most of the transmission wiring is still as you described.

Mr. WEBSTER. Okay.

Mr. BAUM. I think if there are advancements being made, a lot of it is in the structures that hold up the transmission lines and finding ways to design those better to withstand storms.

Mr. WEBSTER. So what was the cause of a structure? Was it external flying debris or was it water or what was it that would——

Mr. BAUM. With our transmission lines that were affected, it was high winds that were twisting the structures that hold up the lines or—and you didn't really have a lot of lines breaking. It was more high winds twisting the structures that holds them up that brought down power lines.

Mr. WEBSTER. So was there—is—would there be an effort now to come up with a better way to build those structures or to harden them in any way?

Mr. BAUM. I think definitely. We have a new Chair of our Public Utility Commission. DeAnn Walker was just named after the storm, and the—at a meeting last week, she basically said let's get the utilities and other providers together to see what ways we can improve for the next storm, and I'm sure that's one of the things that we'll be looking at.

Mr. WEBSTER. I mean, I would think that we'd be—building something like that would be a long-term—is there—was there a way—you were talking about rerouting, doing some other things. Were those all able to be rerouted around those structures that fell or were twisted?

Mr. BAUM. We—they were able—through a combination of rerouting and having some power plants that our grid operator contracts with to ramp-up to provide voltage support to some of those areas that were affected by the lines that went down, and so there were ways to make it to where this did not—the loss of the transmission system didn't cause a cascading effect.

Mr. WEBSTER. Okay. I yield back.

Chairman SMITH. Thank you, Mr. Webster.

That concludes our questions for the day. Thank you all for your wonderful testimony. It was very enlightening to us, and we have lots to do on our part as well.

So I appreciate everybody being here, and we stand adjourned.

[Whereupon, at 12:06 p.m., the Committee was adjourned.]

# Appendix I

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

*Responses by Mr. Carl Imhof*

**U.S HOUSE OF REPRESENTATIVES**
**COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY**
**Full Committee**

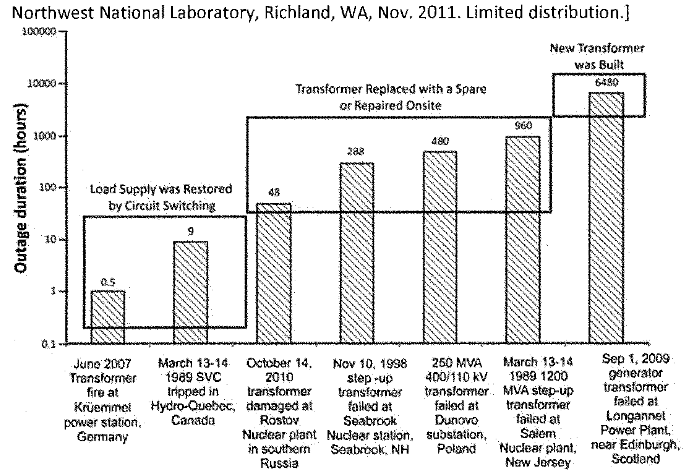
**Hearing Questions for the Record**
**The Honorable Bill Foster**

***Resiliency: The Electric Grid's Only Hope***
**Questions for Mr. Carl Imhoff**

**1. How long and costly would it be for the US to remanufacture high power transformers and related components after a nuclear EMP pulse or large solar event, as compared to the amount of time it would take to rebuild a system based on DC-to-DC converters?**

**Answer:** Large transformers typically take 12-18 months to manufacture if using custom designs that are predominant in the U.S. infrastructure today. DOE has developed a plan and proposed program to conduct stockpiling of flexible standardized transformers to improve the speed of recovery in the face of major geomagnetic disturbance (GMD) or electromagnetic EMP (or other risks) but the program is in its infancy.

Regarding the relative benefits of DC versus AC, PNNL believes that AC devices are currently less expensive than DC. We also believe that the DC converters have more vulnerabilities to EMP than the AC devices. The figure and reference below give some sense of historic replacement times required to recover from transformer failures. [H. Kirkham, J. E. Dagle, M. A. Elizondo, Y. V. Makarov, J. G. DeSteese, and R. Diao, Geomagnetic Storms and Long-term Impacts on Power Systems, Project Report PNNL-21033, Prepared for the Department of Homeland Security, Pacific Northwest National Laboratory, Richland, WA, Nov. 2011. Limited distribution.]



**2. If it was decided to add sufficient spare capacity and protection for recovery from an EMP event, would this be the most economically achieved with an AC or DC electric grid?**

**Answer:** We do not have access to a full economic comparison of a U.S. system rebuild. Generally, DC transmission lines become more economic above distances of 600 kilometers. For shorter hauls and the distribution system, our intuition is that a DC rebuild would be more expensive but we do not have definitive supporting information.

It may be that planners could identify subsets of new transmission and distribution expansion planning that would merit DC to better serve large DC loads such as server farms and critical industrial loads.

Both AC and DC systems have opportunities to harden them to EMP or GMD effects but the nation lacks a common wave form analytic basis for design and evaluation, and there are not have common protection standards and guidance for industry. Some recent publications in system protection literature express the view that current industry standards provide some EMP resilience value; we do not believe that there is consensus on this topic.

*Responses by Dr. Gavin Dillingham*

**U.S. HOUSE OF REPRESENTATIVES**
**COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY**
**Full Committee**

**Hearing Questions for the Record**
**The Honorable Elizabeth Esty**

## *Resiliency: The Electric Grid's Only Hope*

**Questions for Dr. Dillingham**

1. In your testimony, you explain that current policies and regulations do not favor integrating more renewable energy into the U.S. power grid. How would bringing more renewable energy into the grid improve its resilience and reliability?

The diversity of power supply is important, particularly distributed energy systems that are locally based. This would include solar, battery storage, combined heat and power and geo-thermal energy sources. These systems reduce costs and risk associated with more centralized generation systems that require long range transmission and distribution systems. We saw during the recent hurricanes, the impact that major storm events can have on the transmission infrastructure. More diverse, distributed energy systems are not as susceptible to this risk. Unfortunately, the grid benefits these systems provide, particularly ancillary benefits are not properly valued or accounted for in the market, thus creating a significant disadvantage in comparison to traditional generation resources. The benefits include reliability benefits such as grid regulation and frequency, as well as the resiliency benefits of being able to withstand storm events that the centralized system are vulnerable to.

2. In Connecticut, green bonds and loans issued by the Connecticut Green Bank are key funding mechanisms used to:
    - accelerate funding of microgrid projects
    - and increase the deployment of renewable energy.
    - Costs related to building out and powering a microgrid are also eligible for Commercial and Industrial Property Assessed Clean Energy (C-PACE) financing.

    Can you explain how the use of green bonds and C-PACE financing would be beneficial to other states currently in the process of building a more reliable and more resilient grid?

One of the limiting factors of the deployment of distributed energy systems that are capable of improving the resilience and reliability of the grid is lack of funding options. Unlike the fossil fuel industry which can use master limited partnerships to fund projects, renewable energy resources and distributed energy resources do not have this access. C-PACE and green bonds can provide low-interest funding that otherwise is not available for many clean energy projects. Further, the structure of these funding tools can allow for the bundling of energy efficiency projects and renewable energy projects within the same project. This allows for a reduction in energy demand and an increase in clean energy supply. In Texas, much of the PACE projects that have been developed have combined solar with energy efficiency and water conservation projects. The development of projects that can improve energy efficiency and increase diversity of the power supply results in a more resilient and reliable grid.

*Responses by Mr. Walt Baum*

**U.S. HOUSE OF REPRESENTATIVES**
**COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY**
**Full Committee**

**Hearing Questions for the Record**
**The Honorable Bill Foster**

***Resiliency: The Electric Grid's Only Hope***
**Questions for Dr. William Sanders**

1. What studies have been done on the potential resiliency advantage of high voltage DC grids, which are intrinsically immune to destructive phase imbalances and frequency mismatches, and are more easily protected via passive means like diode clamping against overvoltage and reverse voltage conditions?

2. What are the resiliency and characteristics of DC vs AC systems contemplated for home and micro-grid systems that may include local photovoltaic arrays and battery storage?

3. How long and costly would it be for the US to remanufacture high power transformers and related components after a nuclear EMP pulse or large solar event, as compared to the amount of time it would take to rebuild a system based on DC-to-DC converters?

4. If it was decided to add sufficient spare capacity and protection for recovery from an EMP event, would this be most economically achieved with an AC or DC electric grid?

*The questions submitted above did not receive a response before the stated deadline.*

# Appendix II

## Additional Material for the Record

STATEMENT SUBMITTED BY COMMITTEE RANKING MEMBER EDDIE BERNICE JOHNSON

OPENING STATEMENT
**Ranking Member Eddie Bernice Johnson (D-TX)**

House Committee on Science, Space, and Technology
*Resiliency: The Electric Grid's Only Hope*
October, 3, 2016

Good morning. Let me begin by saying my heart is with all those affected by Hurricanes Harvey, Irma, and Maria, including the families of those who lost their loved ones as a result of these devastating hurricanes. As the floodwaters recede and the rebuilding process begins, we should take note of just how important conversations like the one we are having today really are. Emergency response planning, investments in research, and basic building and infrastructure standards make all the difference in moments like these. Efforts to create resilient communities save lives.

I am pleased to welcome two resilient Texans on the panel today – Dr. Dillingham and Mr. Baum. Dr. Dillingham is with the Houston Advanced Research Center and saw the damage of Hurricane Harvey for himself. I am glad to hear that you and your family are doing okay and that your community is recovering. I look forward to hearing your initial assessment of Hurricane Harvey's impact on the Texas electricity infrastructure and what should be done to make it more resilient going forward.

The hurricanes we just experienced were indeed devastating, but we need to prepare for much worse. Hurricanes are projected to become more intense in the coming decades. Climate change is happening, and scientists indicate that one of the long-term consequences of it is more intense hurricanes and tropical storms. A National Academies report released just last year, which included some of the foremost experts on this topic, concluded that there is considerable confidence that tropical cyclones will become more intense as the climate warms.

So, what does this mean for our communities? It means that our existing flood maps, can no longer reliably project the scale of hurricane-related flooding. For our electricity infrastructure in particular, it means that there will be more flooded substations in our coastal regions and more power outages as a result. Today in West Houston, thousands of CenterPoint customers are still relying on a temporary mobile substation because their substation was under four feet of water after Hurricane Harvey, and it will take months to repair.

While natural disasters have certainly dominated our attention over the past several weeks, they are not the only threats to the electric grid. Solar flares, cyber-attacks, physical attacks, operator mistakes, and aging infrastructure also pose unique risks to the electric grid and each must be addressed if we want to improve the resiliency of our electricity infrastructure. So, how can we do it? Fortunately, the National Academies addressed this very question in a report released in July. I look forward to hearing from Dr. Sanders, one of the authors of that report, about the conclusions he and his colleagues reached.

In particular, I would like to draw attention to one key overarching recommendation that I strongly believe this Committee should act on. The report recommends that Congress and DOE sustain and expand R&D activities in grid modernization, cybersecurity, and systems integration.

It specifically highlights the critical work of DOE's Office of Electricity Delivery and Energy Reliability and the Office of Energy Efficiency and Renewable Energy. Unfortunately, the President has proposed to slash programs in these offices. I hope my colleagues will join me in offering our strong support for these activities in the face of these ill-advised proposed funding cuts.

Before I conclude, I would also like to note for the record that it is now October and we have still not had a representative from the Department of Energy come before the Committee. That is unacceptable. In order for this Committee to be able to fulfill its oversight responsibilities, I urge the Chairman to schedule a hearing with Secretary Perry as soon as possible, and to invite Administration witnesses to relevant hearings as we examine key issues under their purview.

Thank you. I yield back the balance of my time.

DOCUMENT SUBMITTED BY REPRESENTATIVE
MARC A. VEASEY

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# Silverstein: If I'd written the DOE grid study recommendations

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The following is a guest post from energy consultant Alison Silverstein, who organized the drafting of the Department of Energy "Staff Report on Electricity Markets and Reliability." It was written before the agency issued its Notice of Proposed Rulemaking to provide cost recovery for coal and nuclear generators on Sept. 29.

The Department of Energy's "Staff Report on Electricity Markets and Reliability," released on Aug. 23, 2017, addressed Secretary Perry's specific questions about the causes for recent power plant retirements and their implications for grid reliability. That study's summary and recommendations didn't take the longer view many stakeholders had hoped for, but it did answer the secretary's immediate questions.

Between late May and early July 2017, I organized the research and drafted the bulk of the technical portions of the DOE "Staff Report." DOE staff and management modified the technical study draft and prepared the summary of findings (Section 2) and recommendations (Sections 7 and 8). But that summary and recommendations missed some important points about reliability and resilience that are worth keeping in mind as stakeholders and policy-makers consider next steps.

### Key DOE study findings

DOE's staff summary of the technical study was narrowly focused to answer the Secretary's specific questions. That summary got many things right:

- Baseload generation is an operational mode, not a type of power plant.
- Low natural gas costs and low electric demand growth were principal causes of conventional power plant retirements.
- Many of the power plants that retired between 2002 and 2016 were used for baseload generation in the past, but they had moved to lower capacity factors and no longer served a baseload function by the time they retired.
- Wholesale markets are good at optimizing and delivering basic grid reliability at low cost, but they must evolve to address further reliability and resilience services as well as extra-market interventions and societally valued benefits such as air quality and jobs.
- The characteristics, metrics, benefits and compensation for essential resilience and reliability services are not yet fully understood.

But the DOE summary didn't recognize a broader set of conclusions about why those power plants retired, and it offered too few constructive recommendations about how to address reliability and resilience going forward.

**Rethinking the conclusions about power plant retirements**

A broader look at the technical sections of the Staff Report offers some inescapable conclusions about why so many coal, nuclear and natural gas power plants retired between 2002 and 2016. It is necessary to understand these retirement causes in order to design effective policy, market and operational solutions for the future.

Many of the retirement stories differ by region, but here are some over-arching observations:

- While coal and nuclear generation were once the preferred choice for low-cost, round-the-clock generation, the drastic fall in natural gas prices has irrevocably changed the competitive economic balance between fuel types, with gas driving coal and nuclear farther out the supply curve.
- Continuing improvements in natural gas plant flexibility and fuel efficiency have exacerbated gas plants' competitive advantage over coal and nuclear resources, particularly given the faster pace of grid operations driven by variable generation on both sides of the meter.
- Flat or falling electricity demand has removed the expected rising revenue and demand cushion that once helped high-cost plants.
- As a root cause of retirements, wholesale competition worked as intended, driving inefficient, high-cost generation out of the market. This is evident in the pattern of retirements, which occurred earlier in the highly competitive, easy entry and exit markets of ERCOT, California, and the Northeast, and much more slowly in the vertically integrated Midwest, West and Southeast.
- As another root cause, most of the plants that have retired were old, smaller, inefficient, and high-cost. These plants did not have the flexibility and cost profiles to compete in a fast-moving grid and were old enough to merit retirement.
- Renewable generation was an exacerbating factor, but in most cases not a causal factor behind power plant retirements. Many of these retirements occurred before significant quantities of renewable generation were added to the grid, or in regions with little or no renewable production. Negative prices occurred – often bid by nuclear plants behind transmission constraints — before the advent of deep renewables penetration.
- In many cases, the plants that retired were already less economically competitive and were being dispatched less before the time (2011-2016) when they would have to make new regulatory compliance investments. Therefore, regulations forced many plant retirement decisions and set their retirement dates, exacerbating but not causing many retirements.

## Policy recommendations

Many more coal and nuclear plants face borderline economic viability and are at risk of retirement over the next few years. Before all of those plants retire, we need to understand –

based on valid reliability analyses, not just the desire to protect existing assets and jobs – whether those plants play a valid reliability role.

If I had written DOE's policy recommendations, they would include the following:

**Wholesale markets** – Today's wholesale electric markets were designed to manage reliability and low costs, not to manage carbon, jobs or preferred resources. But as we patch and re-patch the current market system, what have we learned from the past 20 years of experience with competitive wholesale markets? FERC and stakeholders might explore the question, if we were to design wholesale electric markets fresh today, to address the conflicting cost, reliability and societal needs and goals in a consistent and integrated fashion, what would those markets look like?

**Essential reliability and resilience services** – NERC has given us a starting set of essential reliability services, but many of those services are not yet compensated adequately. We don't yet have a comparable understanding of the key elements of resilience (including fuel security), nor how to measure, productize and compensate them. We do know that a wide variety of supply- and demand-side resources can provide many of these services – and the better we define and productize these services and specify their need and value, the more resources can step up to deliver them.

We must figure out what all these essential services are and how to compensate providers appropriately for each, even if compensation is not determined based on market solutions. Such compensation may help meet some generators' missing revenues problem.

**Frequency response provision** – Not all inertia is created equal. While rotating mass-based generation was the only source of frequency response decades back in the days of a slow grid, such sources are no longer the only way to get frequency response. DOE, NERC and others should conduct immediate research to determine the capabilities and limits of rotating mass-based inertia, inverter-based synthetic inertia, and a variety of storage and automated demand response sources to provide primary and secondary frequency response.

If there is unique value to rotating mass-based inertia, we need to know the value of that resource relative to other frequency response sources, and how much and where (topologically) such rotating mass-based resources must be located for maximum effectiveness. Early studies suggest that inverter-based resources can be used to great advantage to manage frequency control and response and voltage, if we first identify the necessary performance expectations on a technology-neutral basis and build those into grid participation requirements.

**Building portfolios to mitigate risk** – We have a complex society and a complex grid with conflicting sets of goals and requirements. Our electronically-based, electricity-dependent society needs a mix of fast, flexible, clean, resources that collectively deliver a low-cost, high-reliability, highly resilient energy system. Diverse supply- and demand-side resources should be assembled in portfolios that have a solid probability of meeting societal and operational goals effectively under a wide variety of possible future paths, under a reasonable range of costs. Market operators are trying to incorporate societal needs and state preferences into reliability and market rules, but they need help (as do state and federal regulators) to design cost-effective, risk-moderating portfolios of supply- and demand-side resources that will deliver lasting value under diverse, uncertain future paths. DOE and NERC should work with stakeholders to conduct research and offer guidance on better portfolio design.

**Subsidies** – Every type of energy resource today receives some type of support or subsidy. Oil and gas get depletion allowances, renewables get production tax credits, investment tax credits and R&D, nuclear generation gets insurance, R&D and construction work in progress, natural gas gets depletion allowances and R&D, and so on. But new subsidies for coal and nuclear plants won't level the playing field relative to renewables nor undo the impact of old subsidies – they'll just make the playing field even bumpier.

Any new subsidies – including direct state payments, out-of-market uplift payments, or potential cost-of-service payments for non-competitive resources -- should have a specific purpose and a limited duration. As renewable PTCs end, Congress and regulators should consider also ending old subsidies of traditional resources insofar as they are based on outdated assumptions about the unique role and value of these resources.

**Better information and modeling** – Effective power system planning and operation requires a solid set of models and forecasts of supply resources and loads whose behavior is interdependent and hard to predict. EIA, FERC, NERC and the reliability coordinators should be directed to collect more information to improve models and forecasts of the individual and compound interactions of rapidly changing loads, behind-the-meter resources, demand response and energy efficiency, and all supply-side resources.

**Decision processes** – Regulatory and administrative law processes can be painfully slow. So are NERC and reliability coordinator stakeholder processes, which can produce decisions and outcomes that don't always favor reliability and resilience over entrenched interests and precedent. This is not news, but the grid and reliability challenges are moving faster than ever and formal decision processes aren't keeping up. It is worth taking another look at whether there are good reasons and effective methods to make critical time-sensitive, reliability-affecting decisions more quickly.

## In closing

Secretary Perry's April memo raised important and timely questions about power system reliability and resilience. We designed the Staff Report's technical analyses to explain why and how changes in the bulk power system economics, technology and markets caused coal, nuclear and natural gas plant retirement. There is much more work to be done to determine the evolving nature of reliability and resilience requirements, and to identify the additional changes in technology, economics and markets associated with a modern grid. This broad set of challenges will require far more than 60 days to study, understand and implement effective, forward-looking solutions.