NREL
Transforming ENERGY

ESIF 2019

Associate Director's Letter

Across the globe, we are witnessing the greatest transformation of our energy systems in history. Since the Energy Systems Integration Facility's (ESIF's) creation just over six years ago, the research and resources dedicated to developing, evaluating, and reimagining these systems have grown exponentially in importance. While the facility continues to be a meeting ground for countless partners to explore these concepts, we are looking intently at the future of how these partners will count on the ESIF: for resilience and security, integrated modeling and simulation, and studies at an even greater scale.

That growth in scale has been front and center this past year. Early in the year, the National Renewable Energy Laboratory (NREL) welcomed one of its newest and most powerful research assets, the Eagle supercomputer. Eagle is a big leap in computational ability and allows users to simulate technical challenges across the spectrum—from materials to architectures of large-scale autonomous energy systems with millions of devices. Not only does Eagle support innovation, it also demonstrates it: in Fiscal Year 2019, the data center connected to Eagle won the prestigious *DatacenterDynamics* (DCD) Data Center Eco-Sustainability Award, bolstering NREL's status as a world leader in data center efficiency and sustainability.

Eagle will also serve as a critical component of the Advanced Research for Integrated Energy Systems (ARIES) initiative—a visionary step toward expanding capabilities at both the ESIF and NREL's Flatirons Campus. Research at the ESIF can go up to 2 MW and 13.2 kV. NREL is developing its Flatirons Campus to allow for research at the 20-MW scale with a 115-kV link to the utility. The ARIES initiative will employ a 100-Gbps fiber-optic link that NREL is implementing between the ESIF and the Flatirons Campus to create an unprecedented research environment at the +20-MW scale, representing the interface between the distribution and bulk grid power levels. Researchers and partners will be able to leverage capabilities at both sites, including high-performance computing, to explore breakthrough solutions for optimizing the integration of renewables, buildings, energy storage, and transportation.

Resilience and security have a renewed importance across our entire body of grid research. In fact, resilience is the cornerstone of autonomous energy grids (AEGs), an NREL research agenda that has spread from its abstract beginnings in Advanced Research Projects Agency-Energy (ARPA-E) to a practical grid solution that is as effective at controlling wind systems as it is buildings. AEG algorithms optimize distributed energy resources autonomously and in real time. AEGs debuted in the real world in 2019 on a rural Colorado grid, following validation at the ESIF. We are also excited to showcase our new cybersecurity visualization capability, which will add a new dimension to our grid integration and AEG research.

A close connection to industry has always driven research at the ESIF. Nowhere is that more evident than with the high-impact projects that NREL and the U.S. Department of Energy (DOE) select each year. Reflecting on last year's projects, the topics are as relevant as ever and are already showing their scalability. Algorithms from NREL's collaboration with Holy Cross Energy are being reapplied to other energy systems, and our stakeholder involvement with Eaton Corporation studying fleet electrification keeps us aligned with concerns of industry. Likewise, the high-impact projects that began in 2019 reflect growing challenges: understanding how to store energy from the residential to utility scale, identifying communications solutions for enhanced grid control, and improving microgrid technologies that reliably serve forward operating bases.

In FY 2019, NREL signed some of the biggest agreements with industry in our history. Energy industry leader ExxonMobil is investing in NREL's ability to broadly innovate in renewable energy technologies. Alongside another industry giant, Hewlett Packard Enterprise, we are developing a vision to apply edge and data-centric computing to solve complex energy system challenges. And we are equally committed to working with smaller partners on their big ideas. The Shell GameChanger Accelerator™ Powered by NREL (GCxN), is one of our newest venues to help startups accelerate their path from concept to market.

What remains constant throughout these exciting changes is what got us here in the first place: NREL's unwavering commitment to world-class science and research. This year, two of our innovations were recognized among the 100 most important inventions of 2019 by *R&D Magazine*: PREconfiguring and Controlling Inverter SEt-Points (PRECISE™) and ResStock™. Both relied on the ESIF's capabilities for their development, will help grid modernization keep its momentum, and were recognized because they show where costs can be saved in our transition to renewable energy.

There is no shortage of work ahead, and NREL is uniting sectors and industries to help define our national direction. DOE's Grid Modernization Initiative (GMI) is the nation's most important resource for fulfilling the changes our grid needs, and the 2019 GMI lab call again places great responsibility on NREL and the ESIF to drive innovation across domains. With expanding capabilities and visionary partners, we look forward to seeing how the ESIF will continue to carry the nation toward a modern power system.

Sincerely,

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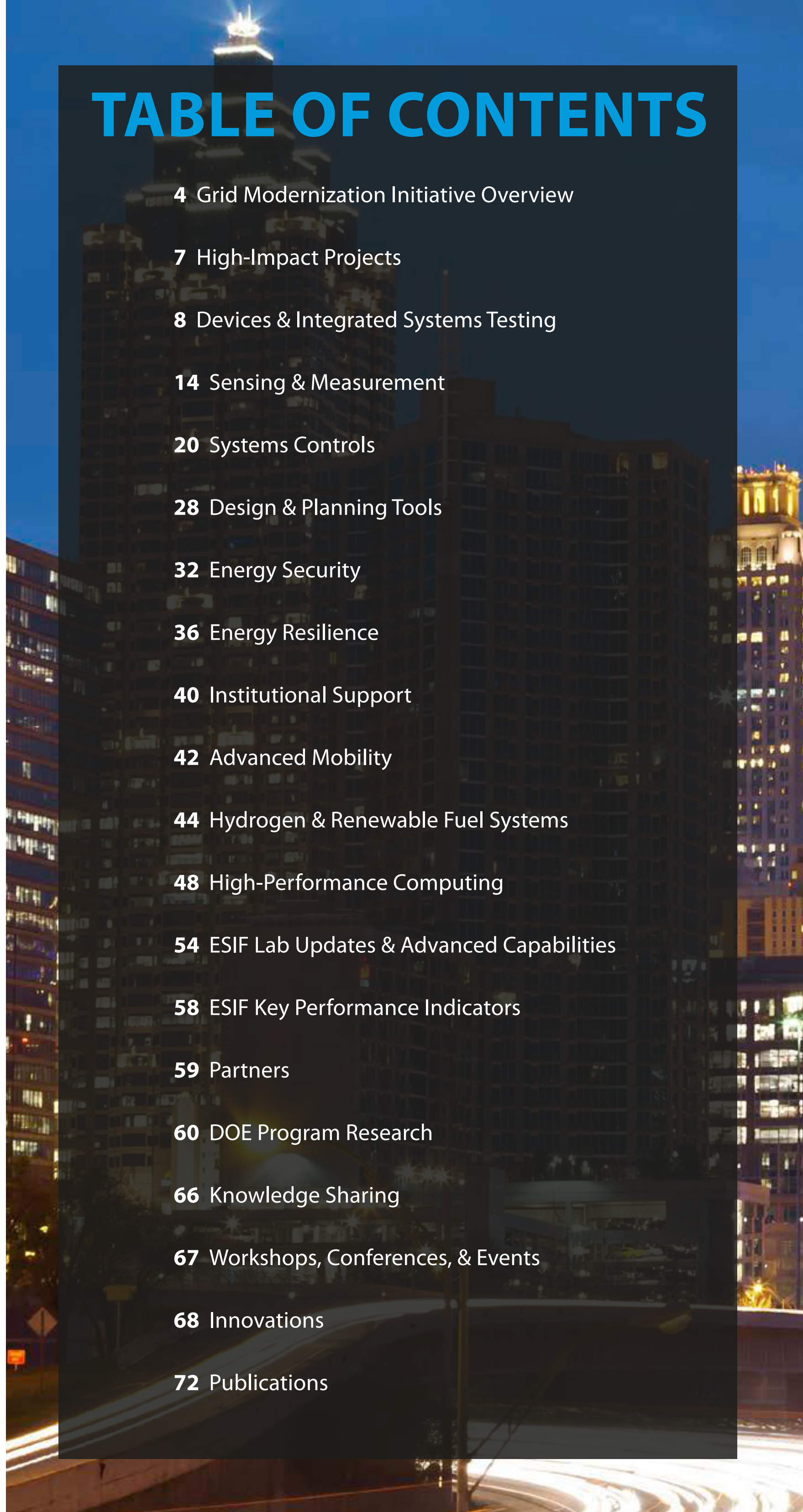


TABLE OF CONTENTS

Grid Modernization Initiative Overview

The U.S. Department of Energy (DOE) established the Grid Modernization Initiative (GMI) to develop a coordinated approach to grid modernization research across the national laboratories. GMI is a crosscutting effort that focuses public and private partnerships to develop a portfolio of new tools and technologies that measure, analyze, predict, protect, and control the grid of the future.

The development and application of new energy technologies will introduce both risks and opportunities across the U.S. economy. The U.S. electric power system must prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. In addition, we must understand how distributed energy resources (DERs) can support both the distribution and bulk power systems now and in the future. As a result, the GMI focused on security challenges of the electric power system in the 2019 lab call and selected portfolio of projects.

To address this continuously changing landscape, DOE expanded the vision of the GMI to:

- Include more participation across the department: The GMI reflects a collaborative partnership of five DOE offices, including the Office of Fossil Energy; the Office of Nuclear Energy; the Office of Electricity; the Office of Energy Efficiency and Renewable Energy; and the Office of Cybersecurity, Energy Security, and Emergency Response.
- Address a fully integrated energy system: The GMI focuses on a fully integrated vision of energy systems—from fuel to generation to load, including interdependent infrastructures.
- Strengthen reliability and resilience: The complexity of the electric grid and its interconnection with other critical systems can accentuate the risk of cascading failures, so it is paramount that the grid is reliable and resilient against all malicious threats, natural disasters, and other systemic risks.

The GMI is implementing this vision by investing approximately $80 million through its latest lab call. NREL supports the GMI through the Grid Modernization Laboratory Consortium (GMLC), a strategic partnership between DOE and the national laboratories that brings together leading experts, technologies, and resources to modernize the nation's electric grid.

Get the full list of projects awarded through the 2019 grid modernization lab call at: https://www.energy.gov/2019-grid-modernization-lab-call-awards

The Next Step in Grid Modernization

In 2019, the GMI announced the 2019 lab call awards, which are distributed among 23 projects that extend the initiative's vision to include more participation across DOE, a focus on fully integrated energy systems, and increased security and resilience. Of those 23 projects, NREL will contribute to 11 and lead three, displaying leadership in DER management, institutional assistance, and resources to integrate energy domains. The ESIF, as well as the Flatirons Campus, will be front and center for these projects, lending essential grid technologies and expertise to each collaboration.

Federated Architecture for Secure and Transactive Distributed Energy Resource Management Solutions (FAST-DERMS)

An architecture that can aggregate and manage a broad range of DERs—photovoltaics (PV), storage, electric vehicles (EVs), flexible loads, combined heat and power, and other distributed generators—across the grid for bulk system services.

Clusters of Flexible PV-Wind-Storage Hybrid Generation (FlexPower)
Demonstration of how utility-scale wind and PV generation can be leveraged as more than simple variable-energy resources to technologies that provide a full range of reliability services to the bulk power system.

Water Risk for the Bulk Power System: Asset to Grid Impacts
An analysis platform that advises utilities on short-term operational and long-term investment decisions related to the impacts and risks of water resources.

Development and Calculation of Performance-Based Resilience Metrics for Defense Critical Infrastructure
Models and metrics for calculating the time-varying performance of defense critical infrastructure during long-duration bulk power system outages.

HELICS+: From a Facilitator to a Hub
An improvement to the GMLC-created Hierarchical Engine for Large-Scale Infrastructure Co-Simulation (HELICS) that will address gaps in scalable integration with diverse infrastructures and usability for cosimulation complexity.

Multi-Port Modular Medium-Voltage (M3) Transactive Power Electronics Energy Hub
Development of smart power electronics hardware and software interfaces for grid applications, including a multiport, medium-voltage energy hub.

Grid Services, Energy Services Interfaces and Grid Connected Devices
Defining common frameworks that represent grid services and standardize energy systems integration specifications to simplify DER integration.

Foundational Assistance to ISO/RTOs under Electricity Market Transformation
Robust analytic support to address challenges faced by independent system operators and regional transmission operators in maintaining reliability, resilience, and affordability.

State Technical Assistance to Public Utility Commissions
Technical assistance to state public utility commissions on topics that can support their grid modernization or energy infrastructure initiatives.

Future Electric Utility Regulation
Access to high-quality and impartial analyses, case studies, and support tools for decision makers to enlist utilities and customers as partners in considering alternative regulatory approaches.

Integrated Distribution System Planning: Education, Training, and Assistance
Education, training, and technical assistance to decision makers on best practices in integrated distribution system planning.

Technical Assistance: Grid-interactive Efficient Buildings
Technical assistance to state energy offices and public utility commissions to advance buildings that can provide grid services through demand flexibility using DERs.

Firmware Command and Control
A response capability using baseline firmware and bidirectional sharing of threats to upstream energy security operations.

Blockchain for Optimized Security and Energy Management (BLOSEM)
Cross-sector guidance, standardized metrics, and testing environments for advancing blockchain-based concepts for device security, secure communications, and grid resilience.

High-Impact Projects Overview

Central to the mission of the ESIF is exploration of new areas of research that push the boundaries of conventional thinking. Each year, NREL issues a Call for High-Impact Projects, seeking partners that demonstrate the use of multiple technologies (such as storage, wind, solar, hydrogen, and buildings), address the challenges outlined in the Grid Modernization Multiyear Program Plan, and provide lessons that could be implemented across the United States.

As previous work concluded in Fiscal Year (FY) 2019, new high-impact projects began that are set to accelerate innovation and develop scalable technologies across industry.

Partners	Project
2018	
San Diego Gas & Electric Company	Enhanced visibility of the grid edge with an analytics platform that visualizes and interprets distribution-level activity for utilities
Holy Cross Energy	Proving real-time, self-optimizing power systems with highly reliable and efficient control infrastructure on a rural utility grid
Eaton	Co-optimization of electric vehicle fleets with the grid—charging dynamics, grid services, and fleet sizing
2019	
Salt River Project	Data characterization of customer battery systems—their economics, performance, and impact on customer power use
Centrica	Hybrid battery energy storage systems that minimize system costs, maximize use of various battery technologies, and serve the grid with a mix of dispatch profiles
Anterix	Dedicated private long-term evolution (LTE) networks for low-latency, highly reliable device communications

Look for the high-impact project icon throughout the report.

Devices & Integrated Systems Testing

Project Spotlight

NREL Evaluates Commercial Batteries in High-Fidelity Energy Storage Study with Arizona Utility

The potential for energy storage systems to save energy costs is exciting to consumers, yet until now surprisingly little information had been gathered from the field about the economics and energy use of deployed battery energy storage systems (BESS). NREL has embarked on a three-year study with support from Arizona utility Salt River Project (SRP) to collect and characterize data around customer BESS, which will provide a reservoir of knowledge for other utilities and BESS vendors about how battery technologies impact ways that customers use power.

This study centers on how BESS function in practice for SRP customers and how efficiently these batteries coperform with other DER technologies. SRP provided price-reduced batteries to volunteer participants in this study, which amounted to several hundred customers within SRP's solar energy-rich jurisdiction in central Arizona. BESS performance in a warm climate is specifically relevant to SRP, so NREL researchers are evaluating how the technologies will perform in Arizona on days that exceed temperatures of 100°F.

The batteries offered were among those validated at the ESIF's residential battery test bed, where researchers tested factors related to BESS use. SRP then collected demographic and geographic information on the volunteer participants to supplement data around storage system adoption. In the past fiscal year, NREL began collecting use data with SRP's support. In addition to the collection of BESS data directly from the devices, inverter data and advanced metering data across SRP's distribution system provide a more complete picture of customer energy use. The data collected will also reveal opportunities for renewable energy incentive programs, such as the one SRP offers its customers.

Data collected throughout the program are being used to refine models at NREL on customer DER use. High-performance computing (HPC) resources at the ESIF will be used to study relationships among the data and perform large-scale modeling. Ultimately, these real-world-informed models will allow SRP to understand DER growth scenarios on its electric grid and provide utilities across the United States with a clear, high-fidelity vista of customer DER adoption.

Project Spotlights

Centrica and NREL Pursue a Resilient and Cost-Effective Hybrid Battery Energy Storage System

NREL and Centrica are partnering on a high-impact project to explore a hybrid BESS design that will provide more economic solutions without compromising grid services. By combining multiple battery technologies into a single hybrid storage unit, researchers intend to maximize the use of each battery and meet various use cases while minimizing overall system costs.

Centrica is providing NREL researchers a hybrid battery storage system based on sizing guidelines from a system design optimization task led by NREL under this project. In the ESIF, NREL will integrate the hybrid storage unit and Centrica's edge controller, an intelligent controller that leverages the strengths of each battery to mix their dispatch in various ways to meet each use case and maximize the service life of all the batteries. With Centrica's input, NREL developed and filed a software record for an optimal hybrid battery design tool that can come up with the most economic battery stack designs and dispatch based on site load, EV charge profile, and PV capacity and generation.

New design guidelines for hybrid energy storage systems can foster a decrease in the price of energy storage for value stacking while increasing their penetration. A lower cost BESS immediately unlocks a larger addressable market, spurring investment and job creation across the entire value chain.

NREL-Led Working Group Signs Off on Distributed Energy Resource Standard, Sets the Path for Market Adoption

FY 2019 marked a major milestone for NREL's leadership in the Institute of Electrical and Electronics Engineers (IEEE) revised 1547 standard, the market-forming standard that will guide consumer inverters interfacing with nearly all DERs integrated into the grid. This year, IEEE P1547.1, the draft test standard for DERs, obtained 97% working group approval, sending the standard to a public ballot. The working group, led by an NREL team, is now resolving comments to further improve industry consensus.

Inverter testing related to IEEE 1547 has been ongoing in the ESIF since the ESIF's inception and has been informed by partnerships that span private industry, utilities, and DOE. The future set of inverter functions as prescribed by IEEE 1547 is a result of hardware testing and simulated systems of many inverters. In the ESIF, researchers have refined the necessary functions of inverters—from fault responses to control features—leading to dozens of project insights and progress toward national consensus.

IEEE 1547.1 is expected to be published in 2020, and inverters compliant with the standard will become available soon after. The nationwide rollout of smart inverters will enable much higher levels of renewable energy integration while preserving grid stability and reliability.

Hardware-in-the-Loop Simulation Shapes New Fort Collins Smart Community Design

NREL Hardware-in-the-loop (HIL) simulation and HPC are shaping the design of a unique smart community in Fort Collins, Colorado. Centralized coordination of behind-the-meter DERs and flexible loads will provide energy savings, ensure homeowner comfort, and minimize grid impacts.

Developed in partnership with Fort Collins Utilities, Thrive Home Builders, A.O. Smith, and technology and hardware providers, the community will feature best-in-class home energy-efficiency technologies, high-penetration battery storage, and PV arrays. Within the community's 498 homes, NREL's **foresee**™ software will automate and coordinate smart devices according to homeowner preferences. A community-level aggregator will coordinate individual and aggregate energy resources to adjust demand in response to real-time grid signals.

ESIF-based simulations and testing will inform decisions related to the sizing of community solar arrays and battery storage as well as the adoption of additional smart home technologies. After the project breaks ground in the next year, NREL will validate actual energy savings and homeowner benefits.

Project Spotlights

Electrolyzers on Double Duty, Providing Both Grid Stability and Hydrogen

Since the project's inception in 2014, Southern California Gas Company (SoCalGas) and NREL researchers, with support from DOE's Office of Energy Efficiency and Renewable Energy (EERE), are studying how to reduce voltage and frequency disturbances on the electric grid using dispersed electrolyzers that provide both grid services and usable hydrogen. In FY 2019, the research team found that controlling the dispatch of dispersed electrolyzers helped reduce voltage disturbances on the distribution grid and frequency disturbances on the transmission grid. The results showed that electrolyzers integrated on a grid with high penetrations of renewable generation and baseload nuclear generation can reduce voltage disturbances up to 35% and reduce frequency disturbances by more than 30%. These improvements were validated using a commercially available 225-kW electrolyzer integrated in the ESIF along with a 1-MW grid simulator.

In the open arena of new vendor technologies, grid-stabilizing support will be a critical asset. This work elevates the role that electrolyzers could play in future systems. The NREL team is looking into follow-on work that considers trade-offs among transmission, distribution, and hydrogen production requirements for economics, fueling demand profiles, and fuel cell electric vehicle (FCEV) applications.

Expansion of ESIF Capabilities for Building- and Vehicle-to-Grid Integration

NREL is partnering with midwestern company Commonwealth Edison (ComEd) to help the utility reach their goal of nearly doubling savings for customers and reducing electricity use in Illinois by 21% in 2030. To meet this goal, NREL used its network of industry partners, incubators, and conferences to create a list of the most viable energy-efficient technologies applicable to buildings and provide annualized energy savings for ComEd's specific territory. This allowed the company to determine the value of each identified and prioritized technology, several of which are now being validated in the ESIF. In FY 2019, NREL expanded the ESIF's capabilities to enable HIL testing for grid-interactive efficient buildings, allowing the NREL-ComEd team to begin evaluating energy savings for the company and determining how the selected technologies could offer additional value by providing grid services. The crosscutting, renovated space brings together commercial building infrastructure, energy storage equipment, and an EV test bed to evaluate how loads can provide flexibility to the grid and reduce overall consumption while providing comfort to building occupants.

Watch: Grid-scale electrolyzers could play a significant role in the integration of hydrogen into the electric grid. Watch this video to learn more about NREL's grid-scale electrolyzer work: (https://bit.ly/35HnSOB).

Project Highlights

Controlling Inverters to Lead—Rather Than Follow—Grid Conditions

As inverter-based resources such as solar increase on the grid, they become more responsible for maintaining the grid's stability. DOE's Solar Energy Technologies Office is supporting NREL and Oak Ridge National Laboratory through the SunShot National Laboratory Multiyear Partnership (SuNLaMP) program to stabilize power systems using well-coordinated, digitally controlled inverters. Most critically, this project is discovering how inverters can replace traditional inertial (mechanical) means of regulating frequency. The solution will accommodate both newer and existing inverters, ensuring that devices can be seamlessly integrated into electric power systems with service functions enabled.

In FY 2019, the interlaboratory team developed a programmable smart frequency control that uses machine learning-based predictions of frequency conditions. Evaluating the inverter controls, the team found that their technique could save 50% on PV headroom—the power reserved to provide frequency control. In future work, researchers will consider a model for grids with extremely high PV penetration and perform hardware validations and field tests to evaluate the range of operating conditions.

NREL Creates Transmission-Level Control with Ternary Pumped Storage Hydropower

One option for the United States to expand its sizable hydropower capacity is through a technique called ternary pumped storage hydropower (T-PSH), which can provide grid services while pumping water as storage for later use. NREL was awarded funding by DOE's Water Power Technologies Office to develop detailed dynamic and economic models of T-PSH plants with the goal of analyzing their technical feasibility and quantifying their ability to provide frequency-related ancillary services to the grid.

The NREL team evaluated advanced pumped storage on the Western Interconnection under different penetration levels of renewable energy and assessed the value of these services under different market structures. For example, a vendor-neutral dynamic model of T-PSH was created at the ESIF to simulate the seamless transition among three operation modes: generation mode, pumping mode, and hydraulic short-circuit mode. Comparing conventional pumped storage hydropower (PSH) and T-PSH, researchers found that T-PSH can provide frequency support to the grid while pumping water.

The range of operation provided by T-PSH could offer increased flexibility in managing diverse energy resources integrated into the U.S. electric grid. This work puts essential techno-economic results into the hands of PSH stakeholders, informing industry and government of possibilities for developments in this sector.

Sensing & Measurement

Project Spotlight

NREL Extends Grid Visibility for Utilities with Down-to-the-Home Data

In FY 2019, NREL and SDG&E brought the grid edge into utility control rooms through a data analytics, management, and visualization platform.

Utilities across the country have invested more than $5 billion in deploying advanced metering infrastructure (AMI), or an integrated system of smart meters. While most utilities use AMI for billing or metering the NREL-SDG&E partnership has transformed such data into a tool for grid monitoring and control. With the ESIF's capacity for large-scale data analytics, management, and visualization capabilities, NREL created an analytics platform for AMI data that reveals and interprets behind-the-meter activity for utilities. This transformation is essential for utilities to manage the integration of behind-the-meter assets, such as PV and EVs.

AMI picks up where traditional grid monitoring ends: at the secondary/behind-the-meter level, which focuses on phase and power information from homes at the grid edge. Using SDG&E's feeder model and billions of data points, researchers first generated synthetic measurements that resemble the AMI deployed on SDG&E's system. The researchers then used HPC resources at the ESIF to transform large data sets into actionable, salient features that are useful for verifying grid planning models. The team's result included 2-D and 3-D visualization tools for real-time secondary system awareness and a derivation of customer phase information based on AMI data. This tool includes insights into predicting locations on the feeder that might witness voltage exceedances, especially in the presence of high penetrations of PV.

This work will empower utilities across the nation that require more informed grid operations and controls as increasing numbers of DERs come online. The AMI analytics and tools developed between SDG&E and NREL can assist in directing policy, contingency planning, and general real-time awareness at the grid edge, and they can greatly improve the process for planning model remediation. This technology has the potential to significantly reduce the costs for supporting high levels of DERs while enhancing the flexibility, affordability, reliability, and robustness of grid operations.

Looking ahead, NREL is searching for opportunities that operationalize the phase information and distribution system data, possibly through real-time DER control. SDG&E plans to deploy tools from this project to validate results against planning models.

Project Spotlights

NREL Targets Efficient Buildings with Site-Specific Weather Forecasts

Buildings are large energy consumers, and their energy use depends acutely on the conditions outdoors. With expertise in weather forecasting, multisystem simulations, and automated control, NREL has begun a three-year study on developing site-specific weather forecasts for individual buildings and advanced building control techniques based on local weather conditions and using information learned from the ESIF's building assets. The project is funded by DOE's Building Technologies Office and extends the work of two NREL-led GMLC projects in the domains of sensor development and multiscale control systems.

In its first year, the NREL team showed that building site-specific weather conditions could be reliably derived from distributed weather data and sensors. Advanced machine learning methods were developed to learn the spatiotemporal correlations between weather conditions at the nearby weather stations and the individual building site. Conditions such as temperature, solar irradiance, relative humidity, and wind speed variously impact building loads. The NREL team then performed sensitivity analyses to evaluate the impact of local weather conditions on building energy consumption under different climate zones and for different prototype buildings.

Future work is planned for improving forecasts, unifying building controls with energy-use predictions, and characterizing the impact of such controls. The team's effort is taking advantage of historical meteorology and building energy consumption data collected by sensors at the ESIF to validate the developed technologies in this project. The final product will include a platform to make buildings responsive to their local environment, which is the most significant variable affecting their energy use.

NREL Improves High-Solar-Power Systems with New Method for Finding Faults

With funding from DOE's Solar Energy Technologies Office, NREL is studying a method to detect and characterize faults associated with systems containing significant penetrations of PV.

Inverter-based systems, such as those with PV, could interfere with the grid's traditional electrical protection system to identify and remediate faults. The potential dangers span both high-penetration solar and microgrid systems, possibly hindering their future growth. NREL's exploration of traveling wave-based fault protection could unlock the techniques needed to secure future power systems.

This past year, NREL researchers launched an initial study analyzing how traveling wave-based schemes could operate on a distribution grid. For system simulations, researchers identified power line models and considered inaccuracies that needed to be corrected. On the hardware side, researchers leveraged the ESIF's Medium-Voltage Outdoor Test Area, which supports systems up to 13.2 kV and can simulate two utility distribution feeders. Researchers performed preliminary analyses of traveling wave techniques on this system and determined how to process resulting data for the novel protection scheme.

Looking ahead, NREL is connecting with partners to scale up this research. With a suitable outdoor test facility, NREL can improve the fidelity of traveling wave-based protection experiments and reliably evaluate how this protection technique could perform on real systems.

Project Spotlight

LTE Communications Shown to Support Grid Through Critical Events

NREL and Anterix, the largest holder of licensed spectrum in the 900-MHz band, successfully piloted private LTE networks in utility control applications. Anterix, alongside an advisory board largely comprising utility representatives, sought to understand how advanced distribution management systems (ADMS), with their increasing communications dependence, would perform using private LTE networks. With a low-latency, high-capacity, and highly reliable communications platform, utilities can overcome control issues associated with poor signal strength and avoid the congestion of thousands of grid-edge devices, which could otherwise become a showstopper if not prioritized.

NREL tested a critical protection function that demands low latency over private LTE communications. Leveraging ESIF assets and portions of the ADMS test bed, NREL showed that the wireless network successfully communicated critical protection-related signals, even under congested and weak-signal scenarios. Future work will consider other ADMS use cases that apply private LTE as the communications backbone to grid-edge equipment.

System Controls

Project Spotlight

Breakthroughs in Control and Optimization Lead to Vision of Autonomous Energy Grids

NREL's work with autonomous energy grids (AEGs) draws on all assets and connects all facets of the modern energy transformation. It is a vision made for grid management at every scale, inclusive of every technology, and as economically compelling as it is operationally. AEGs are a pivot away from traditional systems to decentralized rather than centralized control, and they are resilient rather than vulnerable to system-wide blackouts. The vision for AEGs is that we can wield widespread data collection, machine learning methods, and a suite of new power flow algorithms to optimally match supply and demand across energy systems.

FY 2019 was a landmark for the broad portfolio of work included in AEGs. NREL was granted new funding from DOE's Office of Electricity Advanced Modeling Grid Research Program, Building Technologies Office, Wind Energy Technologies Office, as well as an ARPA-E program that helped develop the core control functions behind AEGs for program-specific applications. NREL used laboratory-directed research and development (LDRD) funds to explore the foundational science behind AEGs at the intersection of energy systems. NREL also hosted several conferences that connected industry and research circles that formalized AEG initiatives and released dozens of AEG-related publications and presentations. NREL continues to construct the theoretical underpinnings of AEGs, which include groundbreaking work at the intersection of control theory and optimization.

The AEG body of work is ramping up and creating new opportunities for energy innovation. In the laboratory, AEGs have been successful in simulations that cross energy domains. On the grid, AEG applications are currently operational on two real-world systems for NREL industry partners. Meanwhile, the AEG research team participated in a DOE technology acceleration program that positioned AEGs for broader market adoption.

As automated control guides the moment-to-moment dynamics of the grid, researchers are asking how energy markets can participate in transactive control and how communications can be secured from cyber threats.

Building off NREL's foundational work in AEGs, researchers are now evaluating how to expand the functionality of autonomous algorithms into less predictable events, such as cascading failures. A new LDRD project, named Autonomous Grids—Identification, Learning, and Estimation, kicked off in FY 2019 and seeks to overcome current issues in autonomous grid control, including barriers to computational scalability and oversimplified system dynamics, to accurately assess stability and decisions for device control.

Project Spotlights

From Theory to Lab to Live: NODES Algorithms Transform Grid Control for Modern Energy Systems

During the past three years, NREL's work under the ARPA-E Network Optimized Distributed Energy Systems (NODES) program achieved the ideal outcome for DOE's ARPA-E research portfolio: bold, creative, transformational solutions.

NODES began with the unique concept to leverage existing grid flexibility to fundamentally change the way parts of the grid are operated and increase reliability. In FY 2019, the final year of ARPA-E funding for the NREL NODES team, researchers demonstrated how the work evolved from theory and simulation, to laboratory demonstration at the ESIF, and finally to real-world field deployment—providing a proven foundation for new avenues in grid control.

The NREL-developed NODES algorithms coordinate autonomous decisions across thousands of connected distributed resources and loads to improve local operating conditions while providing coordinated control of these resources as a single virtual power plant that can provide strength to the grid. Having achieved an in-laboratory hardware simulation of real-time DER optimization with a record number of interconnected power devices and control hardware by leveraging devices at the ESIF, the NODES architects are now proving their project on small-scale grids, including a microgrid at a vineyard in California and a net-zero energy district in Basalt, Colorado.

For the NODES team, ARPA-E support provided the opportunity to take a leap of faith, landing with the algorithms that are now at the center of NREL's growing research portfolio in AEGs. This project inspired momentum in many others that employ real-time grid control, and it will serve as a foundation for NREL researchers to continue to bridge early-stage research with industry innovation.

Watch: Learn more about the NREL-Holy Cross Energy partnership that's taking NREL algorithms for AEGs to a net-zero energy development in Basalt, Colorado: (https://bit.ly/3amdPCo).

Think Big, Start Small: A Colorado Utility Tests NREL Innovations in Grid Modernization

Through a collaborative research-and-development (R&D) agreement between DOE and NREL, Holy Cross Energy has modernized its system operations in pursuit of fast-tracked renewable energy goals. The Colorado cooperative, which oversees power in such diverse districts as Aspen Snowmass and rural ranching communities, is leveraging NREL's accomplishments in AEGs and ADMS to demonstrate intelligent control on its distribution grid. Such capabilities allow the utility to achieve advanced visibility into their power system as more DERs are engaged.

ADMS research at NREL has allowed Holy Cross to simulate its grid in a realistic management environment under various renewable scenarios using a common protocol for device communications, MultiSpeak, from the National Rural Electric Cooperative Association (NRECA) and a Survalent ADMS controller. Beyond planning for increasing renewable penetrations, NREL's ADMS test bed at the ESIF also helped Holy Cross achieve more tangible outcomes. In FY 2019, Holy Cross applied NREL's breakthrough control algorithms—developed under the ARPA-E NODES program—to a zero energy neighborhood, collecting first-ever data around energy devices and their complex control and optimization. The algorithms, which serve as the foundations for AEGs, were piloted on a four-home—soon to be 27-home—neighborhood managed by Holy Cross. The algorithms were programmed onto controllers manufactured by partner Heila Technologies that are now located within the homes.

This demonstration is allowing Holy Cross to transition toward renewables with resilience in mind. Grid resilience is especially important to Holy Cross because its service territory includes some of the nation's most wildfire- and avalanche-prone terrain.

The results of NREL and Holy Cross Energy's grid modernization partnership will be watched by other rural utilities and cooperatives around the United States and is being sponsored by NRECA. The partnership also marks the real system debut of NODES and a novel application of ADMS. It is an opportunity for these technologies to start small and scale up to systems around the United States.

Advanced Distribution Management System Evaluation Targets Partner Needs with Case Studies

The ADMS test bed at the ESIF is central to one partner's labeling of the facility as a "distribution system in a box." The focus of the test bed is on helping utilities modernize operations and safely test options for managing an upsurge in customer-sited energy devices.

NREL asked its partners how to best use the test bed's capabilities. The results were two case studies addressing one of the industry's most urgent needs facing an ADMS rollout and one of its most keen interests for future applications.

The first case study considers the impact that model quality will have on ADMS performance. Researchers used a feeder from Colorado's Xcel Energy utility and simulated how an ADMS application responded at different levels of model quality.

The second case study simulated a feeder from rural utility partner Holy Cross Energy to study a future high-DER scenario and enhanced ADMS data collection that extends observability and controllability behind the meter. The study revealed that by using NREL's real-time control algorithms (see NODES and AEGs) and model-predictive control framework to control DERs, overvoltage events are completely prevented, and the flexibility of DERs to provide active and reactive power support is well leveraged to optimize distribution grid operation.

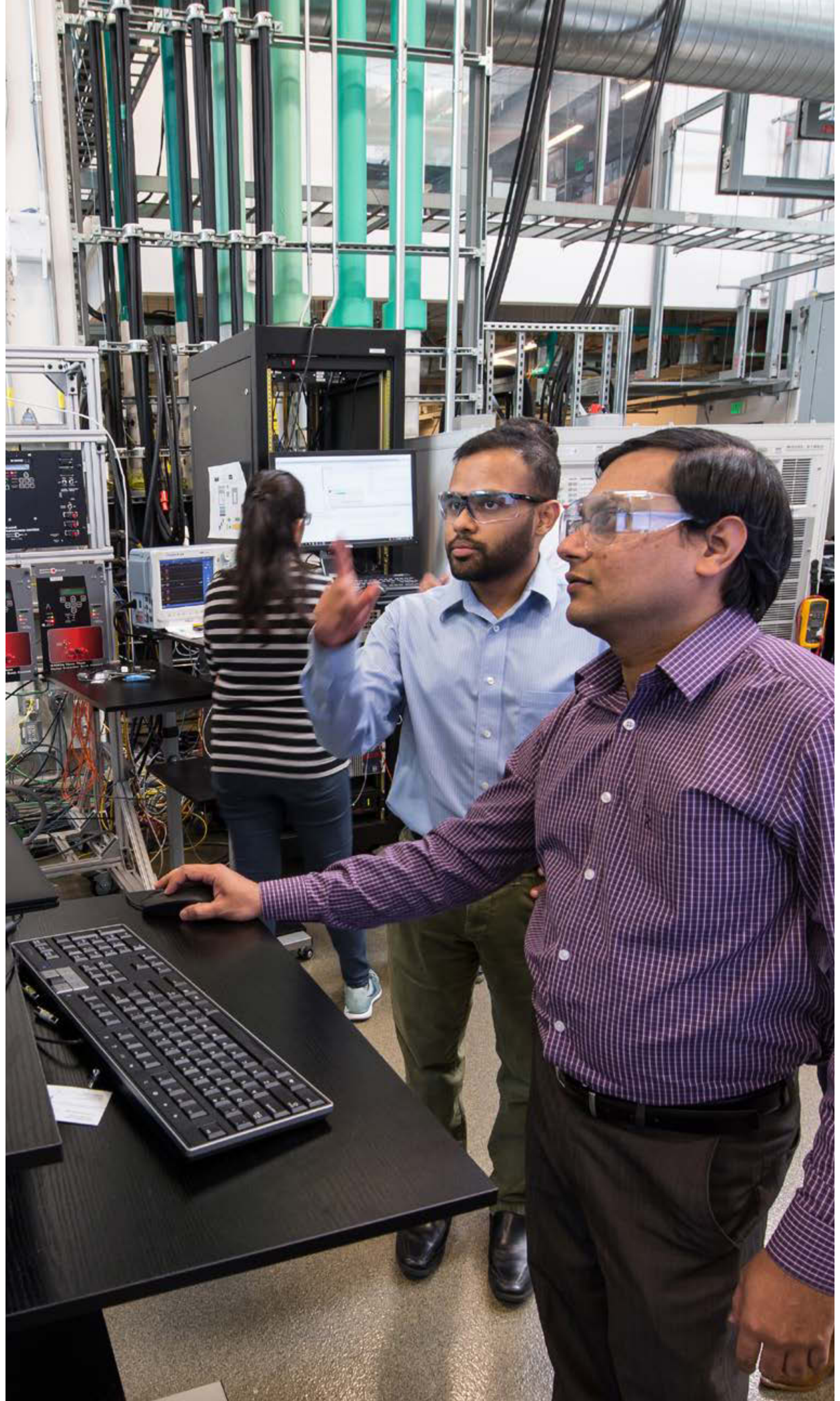
With support from DOE's Office of Electricity, the ADMS test bed continues to be built around partner needs, and with the recent integration of the ESIF's most advanced capabilities—from cosimulation to communications—the ADMS test bed is a national resource that can be leveraged to modernize our grid.

Making the Most of Data for Grid Optimization

Two NREL projects are part of the Enabling Extreme Real-Time Grid Integration of Solar Energy (ENERGISE) program, an initiative from DOE's Solar Energy Technologies Office to innovate fast-acting grid control that pulls out all the stops, including widespread data collection, machine-learned forecasting, and controllable energy devices. NREL's projects are cornerstones of this task: researchers are building frameworks around efficient grid forecasting and centralized control for a decentralized grid.

One project, Grid Optimization with Solar (GO-Solar), is learning how to use the fewest measurements and the fewest control points to optimize the grid. With diverse sensor data, the GO-Solar platform will estimate and forecast the state of the grid and then efficiently direct its behavior. The entire island of Oahu, Hawaii, will be simulated and used to validate GO-Solar and test cyberattacks on the platform using the GMLC-funded cosimulation software HELICS. Large-scale HIL demonstration will also be performed in the ESIF.

The other project, Enhanced Control and Optimization of Integrated Distributed Energy Applications (ECO-IDEA), is creating an architecture to control the grid hierarchically from the perspective of a utility. This project is using an ADMS for real-time operation of DERs. This past fiscal year, researchers modeled the control architecture on NREL's ADMS test bed and initiated a field validation of the controls on Xcel's grid in Colorado.



NREL and Eaton Mobilize Industry to Unite, Plan for EV Fleet Growth

The electrification of vehicle fleets presents unique challenges for utility companies and fleet owners. At the same time, it presents a synergistic opportunity for stakeholders to consider fleet electrification within the bigger context of DER integration. During the last two years, NREL and on-site partner Eaton have continuously engaged stakeholders from across industry to develop a co-optimization platform and techno-economic analyses for how DER technologies can operate in concert with EV fleets.

EV fleet use is an important constraint in determining battery sizing, availability, and charging rates—these considerations can make or break the decision to electrify a fleet and could make a difference in many millions of dollars annually for corporations and utilities. Additional concerns, such as impact on battery life and charging infrastructure needs, make the optimization of EVs with DERs very complex, especially at the scale of deployment expected in the coming years. The NREL-Eaton team has developed a framework to co-optimize these technologies.

The ESIF—with its capacity for high-performance testing on real and simulated DERs as well as its suite of techno-economic analysis resources—offers a unique destination for this project. In FY 2019, the ESIF's HPC and power hardware-in-the-loop (PHIL) capabilities were used to elevate the fidelity of testing. NREL's in-house tools—including Renewable Energy Integration and Optimization (REopt™), Electric Vehicle Infrastructure Projection (EVI-Pro), and Battery Life Assessment and Simulation (BLAST)—have been central to optimizing the economics of EV fleets. Additionally, NREL leveraged Eaton's Power Xpert controller to understand the coordinated control of diverse energy devices. This NREL-Eaton partnership represents a significant collaboration with regular on-site work; an industry advisory board; and highly visible, consensus-driven research.

The growth in EV fleets has the potential for impact that will be felt across the grid, and this project evaluates how systems can be co-optimized with other technologies and with consideration of location. Questions that have been asked and that will influence the future of electrification include: How can we co-optimize other grid resources when electrifying fleets to make the most economic sense? How can we optimally size EV fleets? And how can these assets be coordinated to provide the required grid flexibility to enable an electrified future?

Watch: See how NREL and Eaton are drawing on industry input to understand the economics and energy dynamics of fleets: (https://bit.ly/304tcuo).

Award-Winning Software Safely Puts New Solar on the Grid, Cuts Cost on Infrastructure

As hardware costs drop, ratepayers are rushing toward solar; however, some utilities are overwhelmed by their responsibility to safely program each new solar inverter. An NREL-developed software, PREconfiguring and Controlling Inverter SEt-Points (PRECISE™), offers a solution to speed up inverter registrations while optimizing inverters' reliability and energy savings. In FY 2019, PRECISE was deployed on a real grid, recognized as one of the year's most important inventions by receiving an R&D 100 award, and prepared for application worldwide.

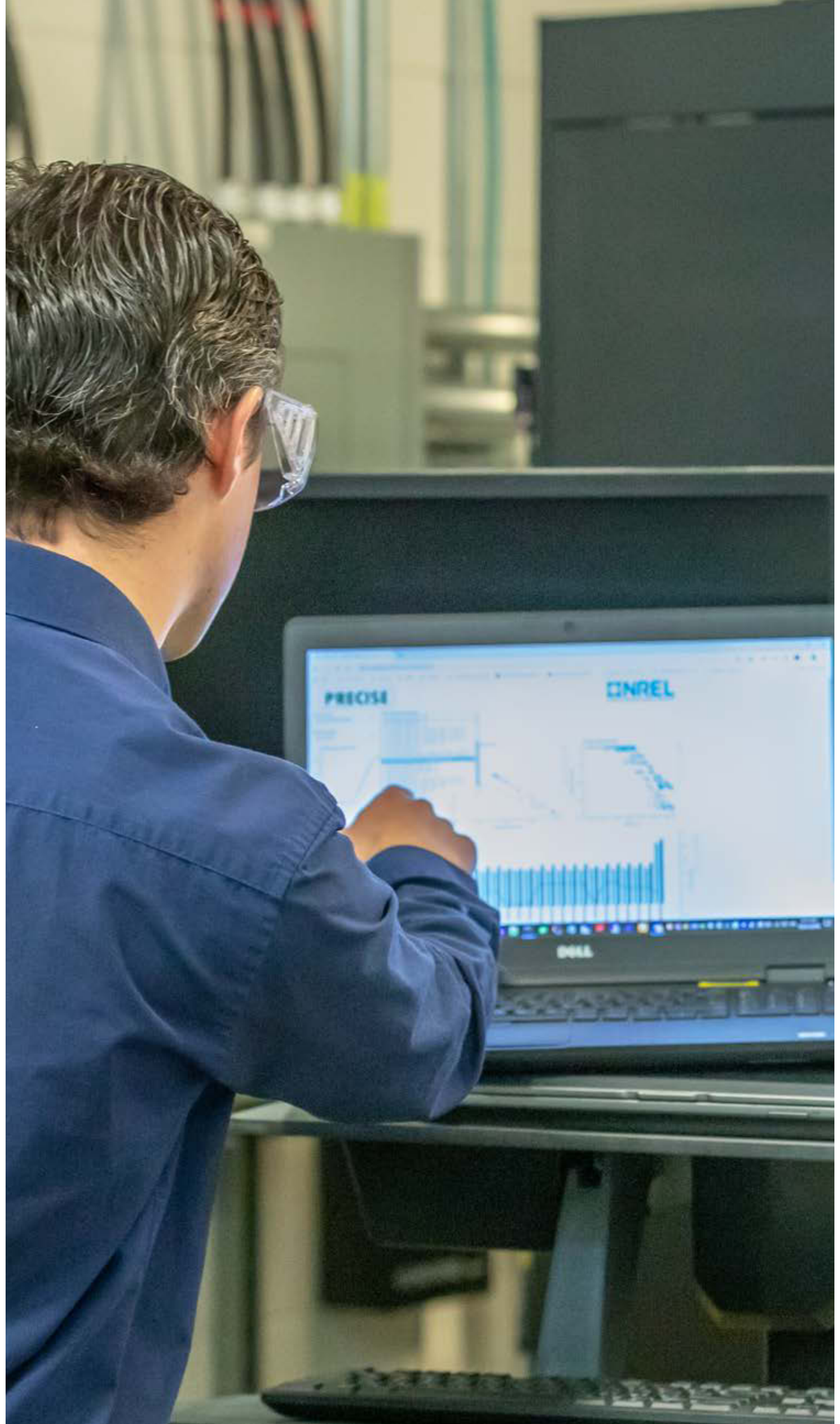
NREL's partner in the development of PRECISE, the Sacramento Municipal Utility District (SMUD), helped motivate this software. SMUD's distribution system contains some of the fastest growth in residential solar, but customer solar applications were being delayed by the critical and time-consuming process of reviewing inverter settings. SMUD and NREL collaborated to automate the process, resulting in SMUD's adoption of the new technology. An inverter application used to take more than a week to review, but now PRECISE optimizes inverter settings in a matter of seconds.

PRECISE was developed at the ESIF by combining newly built grid optimization techniques with the latest standards for inverter settings. PRECISE's ability to optimize inverter settings across a multitude of variables was accomplished through large-scale system simulation using NREL's PHIL.

The success of PRECISE could soon save solar-rich grids from hefty investments. An outcome of the software is that grids will no longer need multimillion-dollar command and control infrastructure updates to optimize inverter performance in real time; instead, PRECISE places operational windows on each inverter that will last throughout the device's lifetime. It is an efficient optimization scheme for millions of new devices that requires minimal investment from utilities.

For the next steps, NREL is seeking to support grids that are undergoing a shift to high-penetration solar by adapting PRECISE to their grids. PRECISE will optimize power systems with any type of technical requirements, whether they contain legacy or advanced inverters or have inverter control infrastructure.

Watch: PRECISE helps utilities identify optimal inverter modes and settings for distributed PV, cutting costs and delays for rooftop PV. Learn more by watching this video: (https://bit.ly/306jnfn).



Algorithms for Building Controls Balance Comfort and Efficiency

A building's energy use can be forecasted, and a new project is showing that smart controls can benefit from those forecasts. The project is funded by DOE's Building Technologies Office and connects NREL and the University of Colorado Boulder with companies that are also pushing the frontier in buildings science.

In collaboration with QCoefficient, a company that integrates heating, ventilating, and air-conditioning operations with the grid, and Heila Technologies, which creates hardware solutions for microgrid control, NREL is learning the optimal control of buildings that will balance grid services, resilience, and occupant comfort. The approach could provide enormous energy savings by integrating two sectors that have historically operated independently.

This partnership is applying ESIF assets to learn building behavior and how buildings will respond to NREL's control algorithms. HPC will be used to first learn—through reinforcement-learning techniques—how building energy behavior correlates with building occupancy, and later how that behavior responds to NREL's algorithms. The ESIF's simulation capabilities will allow researchers to validate numerous approaches to building control.

The team's embrace of model-free learning will be a unique outcome of this project—an approach that will reduce the expense and labor of producing building-specific models and extend the results of this project to generic buildings with minimal customization. This project will also allow buildings to participate in resilience services by automatically supplying critical assets in disaster or severe weather events.

Finding Common Ground Between Control Systems

Mirroring changes to the grid, energy management is about to become much more complex. In the cross-laboratory GMLC project "Multi-Scale Integration of Control Systems," NREL and partners are synthesizing control for energy management systems (EMS), distribution management systems (DMS), and building management systems (BMS) into an open framework.

The past year has recorded important steps toward integrating the control frameworks. NREL and Pacific Northwest National Laboratory have virtually linked their DMS and EMS, respectively, through the Energy Sciences Network, an intersite data link. NREL researchers have also successfully defined and demonstrated a use case that uses distribution system assets to support voltages in transmission systems.

Coordination among the control systems will smooth management for system operators in an increasingly connected grid. While each management system evolves, NREL and partner laboratories are helping to find common ground related to data integration, decision support, and risk-based operations.

Improving Grid Resilience with Distributed Device Controls

The spread of grid devices means, metaphorically, a lot more eyes on the grid and a new level of grid intelligence. These two attributes are being channeled in the collaborative GMLC project "Increasing Distribution Resiliency Using Flexible DER and Microgrid Assets Enabled by OpenFMB" to protect distribution systems from faults and service outages and step up system resilience with fast communications and controls.

The approach to resilience involves an algorithm created by partner General Electric, which NREL tailored for testing on a real-world feeder, as identified by another partner, Duke Energy. This past year, NREL worked with project partners to install the ADMS and complete remote connection testing between NREL, Oak Ridge National Laboratory, and the University of North Carolina-Charlotte with digital and analog simulation capability.

This project is representative of the GMLC Resilient Distribution Systems portfolio as a technology that can overcome a cyber incident in an early stage, specifically by focusing on fault location, isolation, and system recovery. Also in line with the portfolio, this year marked a field validation on a distribution system. Next steps will use the secure cross-laboratory link as well as a decentralized form of the algorithms created at the Pacific Northwest National Laboratory to further understand how distribution system management and grid intelligence can come together for system resilience. The team's developments will be scalable, fast, and widely relevant to power system operators within the open-source messaging protocol OpenFMB.

Design & Planning Tools

Project Spotlight

Simulation Engine HELICS Continues to Drive Large-Scale Studies at the ESIF

At the heart of the ESIF's large-scale power simulations environment is HELICS. By providing interfaces between modeling tools, HELICS enables highly scalable cosimulation links among multiple interconnected energy systems, including the power system, communications and controls systems, and more. The platform enables unprecedented integrated physical-market-controller simulations that include hundreds to tens of thousands of individual software models running across multiple HPC nodes through NREL's super computer Eagle.

In FY 2019, HELICS served as the foundation for some of the ESIF's most impactful research, including city-scale simulations to support NREL's work in AEGs. Researchers used HELICS to develop grid control simulations for a new high-penetration solar control scheme and to help manage millions of devices on Hawaii's grid. HIL simulations relied on HELICS to coordinate interactions among slower timescale models and faster real-time transient simulations that directly interact with hardware on NREL's ADMS test bed. Additionally, researchers began using HELICS for resilient energy systems analysis—from developing cybersecurity assessment plans for novel control schemes to supporting the multi-lab continental-scale North American Energy Resilience Model (NAERM).

HELICS has been developed as part of a GMLC initiative and in collaboration with Lawrence Livermore National Laboratory, Pacific Northwest National Laboratory, and Argonne National Laboratory. In FY 2019, HELICS was recognized as a finalist for an R&D 100 award.

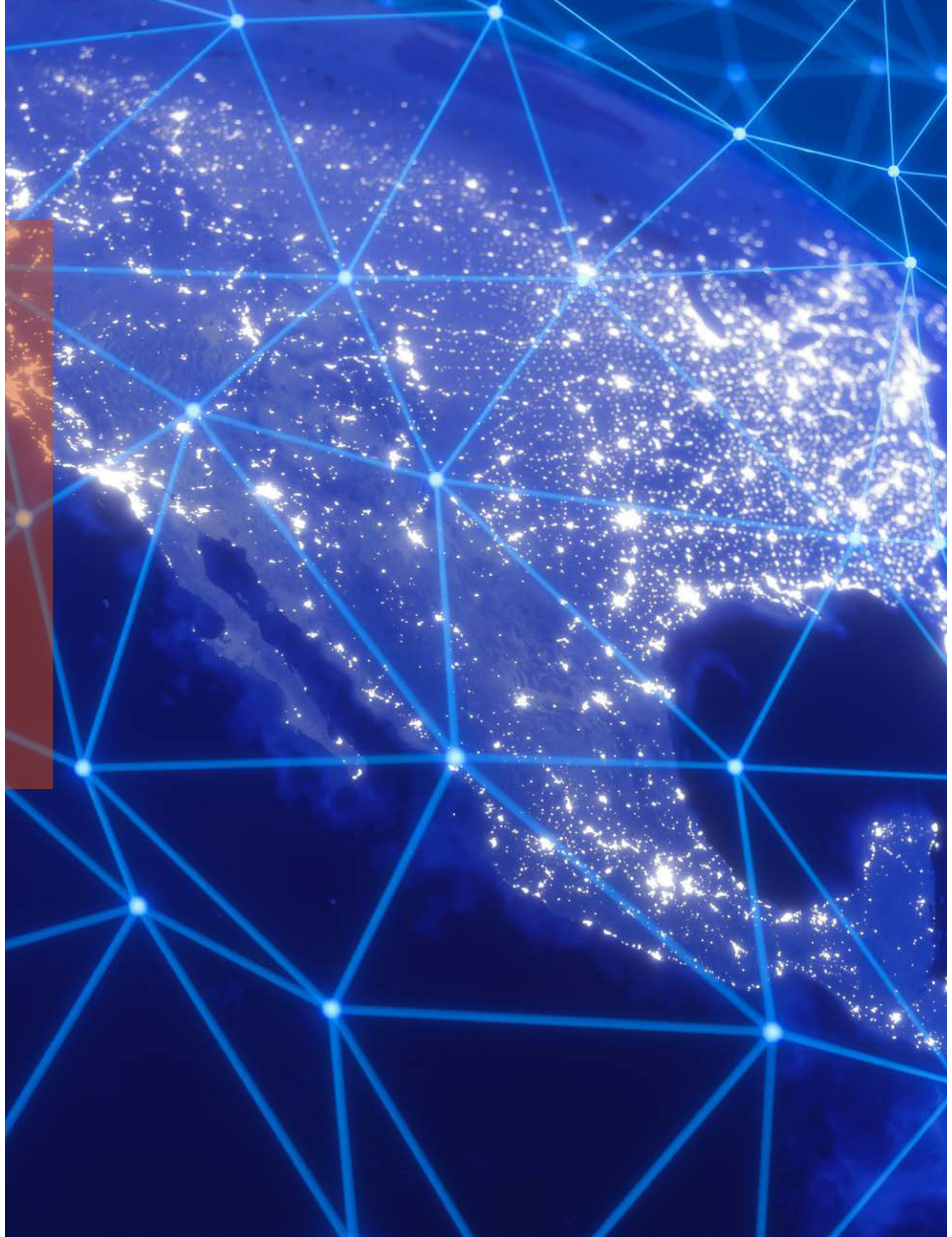
Project Highlights

Cooperation Across Countries Informs Transcontinental Power System Modeling

Renewable energy is transforming power systems in each North American country, leading researchers to ask how the continent's grid could look if its transmission systems were coordinated. The North American Renewable Integration Study (NARIS) pulls together NREL modeling resources and supercomputer simulation capacity to assess the challenges and opportunities of coordinating power system planning and operations across Canada, Mexico, and the United States through the year 2050.

NARIS will inform grid planners, operators, and regulators around the possibilities of interregional and international cooperation while delivering scenarios, methods, and data sets to enable future studies. NREL tools for modeling resource planning, production costs, power flow, and reliability have been expanded through NARIS using the ESIF's HPC and NREL's continent-wide wind data sets.

Using NREL's open-source tools and upcoming results from NARIS simulations, stakeholders will be able to perform deeper analyses into topics such as power system stability and resilience in the transition to a modern electric power system.



Realistic-But-Not-Real Data Sets Offer Work-Around for Grid Research

With a final year of funding from ARPA-E, researchers further developed the Synthetic Models for Advanced Realistic Testing of Distribution systems and Scenarios (SMART-DS) repository of synthetic power system data sets. SMART-DS creates power system models with consideration of real geography, line characteristics, and typical utility practices. The models are compared against thousands of utility feeders to ensure that the structure and operation of the SMART-DS data sets are representative of realistic electrical networks. The development of synthetic power system data sets is a boon for researchers who in the past were limited to trialing their grid advancements on small feeder models. Not only are all SMART-DS models freely available online, but the models also contain numerous customizable scenarios, including EV penetrations, solar and battery deployments, outage scenarios, and demand response, to name a few. SMART-DS was developed in collaboration with the Comillas Institute for Research in Technology, Massachusetts Institute of Technology, CYME International, and Electrical Distribution Design.

Solar Planning Tool Links Economics and Operation

NREL partnered with the Electric Power Research Institute (EPRI); University of Tennessee, Knoxville; and Southern Methodist University to create a resource for understanding the interplay of economic scheduling and power system response. The project is named the Multi-timescale Integrated Dynamics and Scheduling for Solar (MIDAS-Solar). MIDAS-Solar will provide an essential planning tool for system operators. The modeling tool will accurately assess system reliability, including all forms of reliability services currently provided by modern PV power plants. It will also simulate grid scenarios between day-ahead (economic scheduling) and subsecond (system response analysis) timescales.

In its first year, this project, which was funded by DOE's Solar Energy Technologies Office, was applied to California's goal for extremely high renewable energy deployment. The team successfully modeled an integrated power system within its multitimescale operation framework, showing how deployments of many renewable energy systems can be represented in the MIDAS-Solar modeling scheme.

Upcoming work will consider reserve scheduling under critical contingency conditions and will study interactions of reliability services at all timescales.

Energy Security

Project Spotlight

Exploring Dynamic Cyber Solutions on a Virtual Utility Grid

Evaluating cybersecurity for an evolving electric grid requires a special kind of validation space—one that goes beyond our physical world.

With continued LDRD support to increase the security and resilience of the electric grid, NREL researchers have built an emulation environment for the safe evaluation of vulnerabilities within complex cyber-energy systems. This novel emulation platform allows NREL to clone thousands of virtual grid devices working with physical grid devices—solar inverters, wind turbine control systems, batteries, and EV chargers—throughout NREL's ESIF and Flatirons Campus.

The platform leverages Sandia National Laboratories' Sandia Computational Engine for Particle Transport for Radiation Effects (SCEPTRE), a tool that provides the ability to emulate multiple infrastructures (electric, water, gas, and transportation) and communications networks. Looking ahead, the team plans to integrate the multilaboratory HELICS cosimulation framework into the platform, enabling even more dynamic emulation and visualization for advanced threat analysis.

With the increase in DERs and growing potential of cyber threats, the attack surface across the distribution grid is expanding. New cyber vulnerabilities accompany distributed grid devices, calling for advanced cyber solutions that can protect such assets. By emulating a virtualized utility grid, NREL can safely evaluate the impact of these trends, implement intrinsic security in the system design phase, and position the distributed grid as a much more challenging target for malicious attacks.

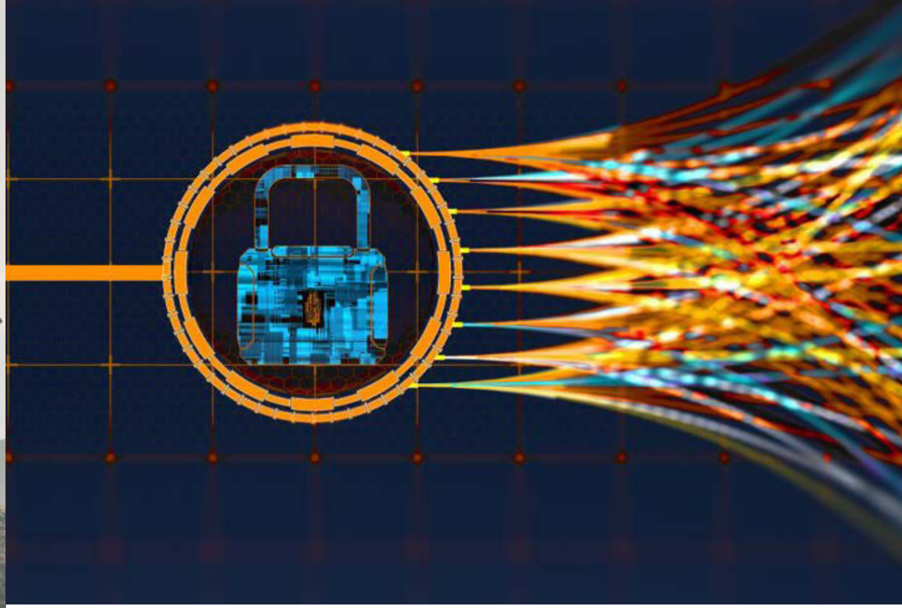
Project Highlights

Advancing Encryption for Distributed Energy Resources with Module-OT

During the past two years, NREL has worked with Sandia National Laboratories, the Public Service Company of New Mexico, and Yaskawa-Solectria Solar to develop Module-OT, a low-cost, modular device that provides optimized encryption for DERs and their operational networks. The device software is compatible with a variety of operating systems and is compliant with the three major communications protocols used in DER systems: Modbus, Distributed Network Protocol 3, and Smart Energy Profile 2.0.

In FY 2019, advancements to the technology focused on improving data privacy for user applications through encryption, authentication, authorization, certificate management, and user access control. Researchers evaluated and verified the performance of the module with emulated distribution system devices and data. The device was then physically validated both in the laboratory at the ESIF and in the field at a 500-kW solar-plus-storage site in New Mexico that is owned and operated by the Public Service Company of New Mexico.

This technology will help protect command-and-control messages over communications channels, allowing distributed systems to operate smoothly without disruption from malicious adversaries.



The Distributed Energy Resources Cybersecurity Framework

With support from DOE's Federal Energy Management Program, NREL researchers developed the Distributed Energy Resources Cybersecurity Framework (DERCF) to help federal agencies across the country mitigate gaps in cybersecurity for distributed energy. This framework expands on DOE's Cybersecurity Capability Maturity Model (C2M2), the nation's current framework for cybersecurity evaluation, placing increased focus on DERs as well as physical security and technical management. NREL developed a written version of the DERCF, detailing best practices and security controls for DERs, in addition to a web application for cybersecurity assessments. The web application guides account owners through a series of questions about the controls and practices that pertain to their DER use and application, including PV generation, wind turbine generation, EVs and charging stations, and electrical battery storage.

Watch: Learn more about what NREL is doing to mitigate threats to today's energy infrastructure and provide a pathway to a more secure and resilient energy future: (https://bit.ly/2FyN7Z9).

Energy Resilience

Project Spotlight

From Sea to Sea, DOE Eyes National Resilience Solution with NREL Insight

Resilience has become a key focus area across modern grid studies, and one DOE project is taking the largest look yet at how to improve the resilience of the North American power system. NAERM is a broadly useful platform for planning, situational awareness, and recovery from emerging challenges to the grid. The NAERM effort has counted on NREL leadership—as well as seven other national laboratories—throughout FY 2019, which included several accomplishments toward the project's national vision.

In mid-2019, DOE released the NAERM congressional report, which NREL helped author. The report includes NREL input into strategic planning, industry engagement, and technical development. It also details modeling efforts performed at NREL on the Eagle supercomputer and leveraging past DOE-funded projects at NREL, including the National Solar Radiation Database, the Wind Integration National Dataset (WIND) Toolkit, and the North American Renewable Integration Study.

With HPC at the ESIF, NREL modeled disasters and unexpected outages on the North American grid system. In one use case, NREL simulated multiday, long-duration events, such as a polar vortex. NREL modeled the combined impact on the electric gas infrastructure from an unexpected outage; dual-fuel-firing generator limitations; and wind turbine cold temperature and icing cutoffs that affected all bulk system loads, transmission, and renewable resources. In another study that NREL leads, researchers are characterizing the impact of DERs in resilience scenarios. Their studies this past year simulated DER response in the event of delayed voltage recovery from a fault. Results from such studies help utilities develop best practices for resilience planning across all grid scales.

NREL's support of NAERM also extended to stakeholder engagement. NREL created visualizations that enable modeling analysts and executive management to understand grid operations and impacts. Also, the NREL-developed Resilient Operations Model will empower stakeholders to support nationwide resilience. With the continued development of NAERM, NREL will lend its expertise in exploring critical "what if" questions regarding our energy infrastructure and the challenges it will face.

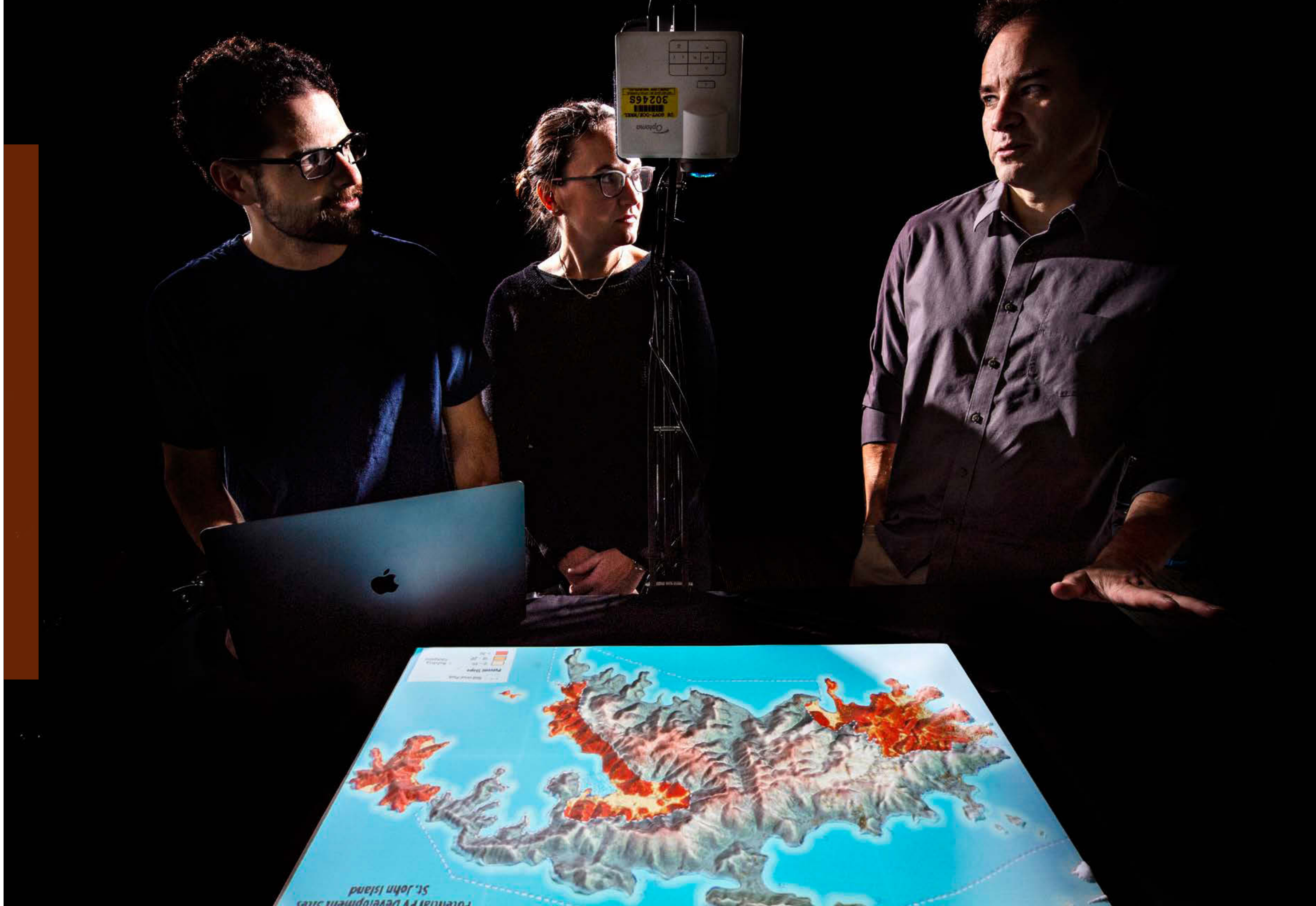
Project Highlight

NREL and the National Park Service Visualize Improved Resilience at Coastal Parks

Researchers at NREL partnered with the National Park Service (NPS) to examine the risk of coastal park infrastructure to natural hazards with the intent to improve operational resilience. Through prior work, the NPS determined that rising sea levels coupled with storm events endanger natural and cultural resources and park-built assets. A new visualization platform is helping researchers develop a planning guide for improved resilience for the NPS as well as other land management agencies and entities facing similar threats.

An initial site assessment entailed a resilience analysis of infrastructure related to energy, transportation assets, fuel delivery, communications, cybersecurity, and water systems. Using the ESIF's unique 3-D visualization capabilities, researchers developed a spatial augmented reality platform that combines site data with a physical 3-D model of the study area. This platform allows researchers to physically demonstrate the impact of various natural hazards on infrastructure and assets.

The new spatial augmented reality framework is a first-of-its-kind tool that combines measured and modeled data with a physical 3-D model, providing the unique capability to demonstrate the impact of climate hazards on infrastructure and assets. This tool provides an economic and transportable method to communicate complicated data sets in a visually compelling and straightforward manner.



Institutional Support

Project Spotlight

Renewable Energy Tools Increase Resilience for Storm-Struck Puerto Rico and Virgin Islands

In the wake of several high-intensity Caribbean storms, NREL expanded resilience tools to U.S. territories Puerto Rico and the Virgin Islands. Collaboration between NREL and the islands will prepare both territories to make renewable energy investments and decisions that strengthen their infrastructure against future events.

NREL first extended its National Solar Radiation Database to the islands. These data, as well as Puerto Rico grid models developed in the ESIF, helped NREL produce an extension of the System Advisor Model (SAM) that is specific to Puerto Rico, enabling stakeholders to perform production cost modeling and cost-benefit analysis of renewable energy systems. NREL then trained decision makers in Puerto Rico on how to use the tools as well as on best practices around emerging energy resources.

During two workshops in March 2019, stakeholders shared their energy planning needs and learned about tools from NREL and other national laboratories to support energy planning in Puerto Rico. NREL also organized a webinar series for participating laboratories to provide stakeholders access to tools, resources, and modeling results.

The NREL planning tools are now nationally inclusive and contain models for Puerto Rico's exceptionally vulnerable grid. Comprehensive resilience planning is a national priority, and this project provides support to the DOE-led NAERM initiative.

Advanced Mobility

Project Highlight

Improving Grid Resilience with Vehicle-to-Grid Characterization

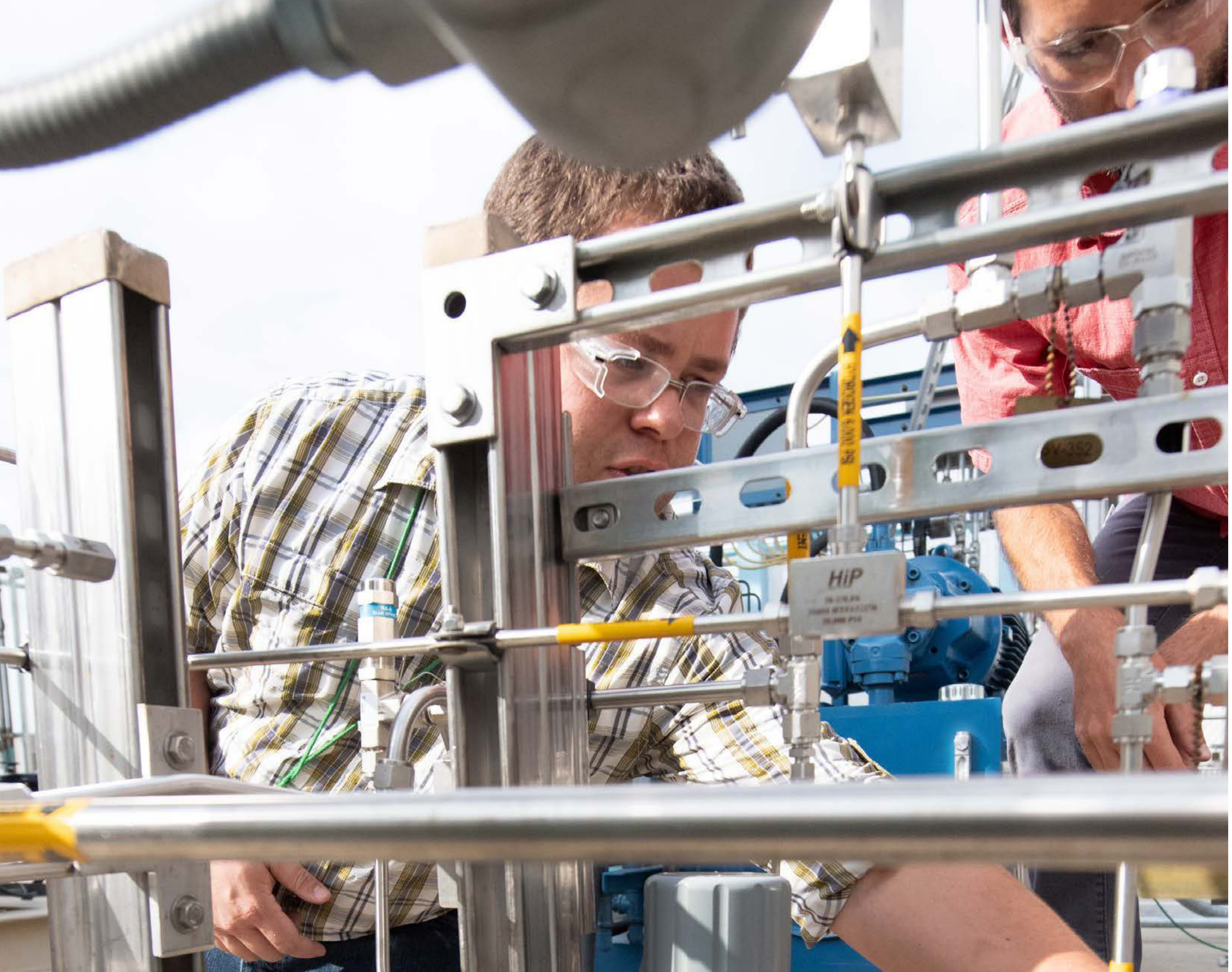
NREL researchers are comparing the degradation of two Chrysler Pacifica plug-in hybrid electric vehicle (PHEV) battery packs for DOE and EPRI. In the ESIF, researchers are evaluating one pack that would undergo a normal PHEV profile, modeling a scenario where a car drives to work and charges at home. In comparison, researchers are evaluating a second pack subjected to a PHEV profile where, after arriving home, the car battery would contribute to powering grid activities. In the coming year, researchers will cycle these batteries through the equivalent of two years' worth of vehicle use while evaluating capacity degradation and power loss as the battery packs age. Results of this study are anticipated to shed light on whether PHEV batteries can supplement the energy demands of a home and provide increased grid resilience.

Hydrogen & Renewable Fuel Systems

Project Highlight

H2@Scale Brings New Partners to Advance Station Design and Operating Strategies

Through DOE's H2@Scale initiative, NREL continues to work with industry partners to advance the large-scale production, transport, storage, and use of hydrogen across multiple sectors of the economy. Power generators, technology developers, and automakers are leveraging NREL expertise and ESIF capabilities through cooperative H2@Scale research projects to address early-stage R&D challenges in hydrogen infrastructure, low-temperature electrolysis, energy storage, and renewables-to-grid integration. In FY 2019, NREL kicked off a new project with Shell, Air Liquide, Toyota, and Honda to research innovative hydrogen station designs and operating strategies. The team will address challenges related to component reliability at high-throughput fueling stations and develop high-flow-rate systems for new applications such as medium- and heavy-duty truck fueling.



Project Highlights

Improving Alkaline Membrane Fuel Cell Performance

Alkaline membranes are a promising technology at a low level of technology readiness with significant potential for decreasing costs and precious metal use in energy conversion devices. NREL is developing high-performance alkaline fuel cell membranes and electrodes to improve the commercial viability of this technology. In FY 2019, NREL, with partners Georgia Institute of Technology and the University of South Carolina, demonstrated for the first time alkaline membrane fuel cell power density at more than 3 W/cm^2 using advanced membranes, electrodes, and cell testing. This level of performance is more than double the highest reported performance in 2017 and is near parity with the proton-conducting systems that are available today.

Converting Waste Carbon Dioxide and Hydrogen to Fuels and Chemicals

NREL is leading a multilaboratory collaboration to develop an industrially scalable electrochemical process for reducing waste carbon dioxide (CO_2) to useful chemicals and fuels. This "electrons-to-molecules" approach uses a waste product as the backbone to store inexpensive renewable electricity as hydrogen and carbon bonds in the form of high-density liquid fuels and valuable chemicals. NREL leveraged its experience in hydrogen fuel cell and electrolyzer test stand construction and operation to develop test stands for CO_2 electrolysis. These new capabilities provide critical electrochemical diagnostics information about CO_2 electrolyzers and establish NREL as a facility for benchmarking CO_2 reduction devices and electrocatalyst performance.

Bioreactor Begins Producing Renewable Natural Gas from Renewable Hydrogen and Carbon Dioxide

NREL, SoCalGas, and Electrochaea are developing a flexible biomethanation process to upgrade biogas waste streams to produce pipeline quality renewable natural gas using a pressurized 700-L bioreactor designed and built by SoCalGas. The biomethanation process converts CO_2 and hydrogen gases using the biocatalyst *Methanothermobacter thermautotrophicus* (methanogen) to produce methane, water, and heat. This process is a way to store low-cost renewable electricity in the expansive natural gas grid and to recycle CO_2 using renewable hydrogen. In FY 2019, NREL commissioned the bioreactor and began operations with the methanogen, which was celebrated with a ribbon-cutting ceremony at NREL's Partner Forum in August. The first methane production from the bioreactor was confirmed with the onboard gas chromatograph within six hours of starting gas flows. As the microorganism population grew, the reactor pressure was increased gradually, and methane production reached 90% after about 40 hours. Moving forward, the hydrogen and CO_2 flow rates as well as the bioreactor pressure will be increased to achieve the operating target of 18-bar pressure and gas composition of greater than 97% renewable methane.

Enabling High-Volume Manufacturing of Fuel Cell Membranes

NREL completed a multiyear project with W.L. Gore & Associates to develop methods for characterizing the full-production-roll quality of fuel cell membranes as they are being manufactured. Using ESIF roll-to-roll processing equipment and laboratory-developed optical inspection techniques and apparatus, the team provided full-width, full-length, high-resolution imaging of 14 production and experimental rolls of GORE-SELECT Membrane, totaling more than 1.6 km of membrane mapped. Researchers also used NREL-developed automated algorithms to detect and classify membrane defects in each roll.

High-Performance Computing

Project Spotlight

High-Performance Computing Powers Detailed Study of Future Energy Pathways for Los Angeles

The City of Los Angeles could take many routes to reach its goal of 100% renewable energy by 2045. In a study of unprecedented detail for the Los Angeles Department of Water and Power, NREL is performing hundreds of thousands of simulations to understand the options and trade-offs among the various investments Los Angeles could make.

NREL's supercomputer Eagle has been programmed to simulate factors in Los Angeles's energy transition, including EV adoption, building electrification, and energy-efficiency improvements. The simulations depend on an integrated suite of sophisticated NREL energy modeling tools, and results will reveal possible net macroeconomic impacts in addition to an analysis of all capacity needs and bulk power operations.

As more cities adopt near-term renewable energy goals, this project could empower stakeholders with an example of objective, high-fidelity power systems analysis for informed planning and decision making.

Watch: See how NREL's new supercomputer Eagle is helping NREL researchers find the answers to smart, bold questions about transforming our energy system: (https://bit.ly/2T3VKTo).

Project Highlights

Eagle: NREL's Newest Supercomputer Dedicated to Energy Efficiency and Renewable Energy Research

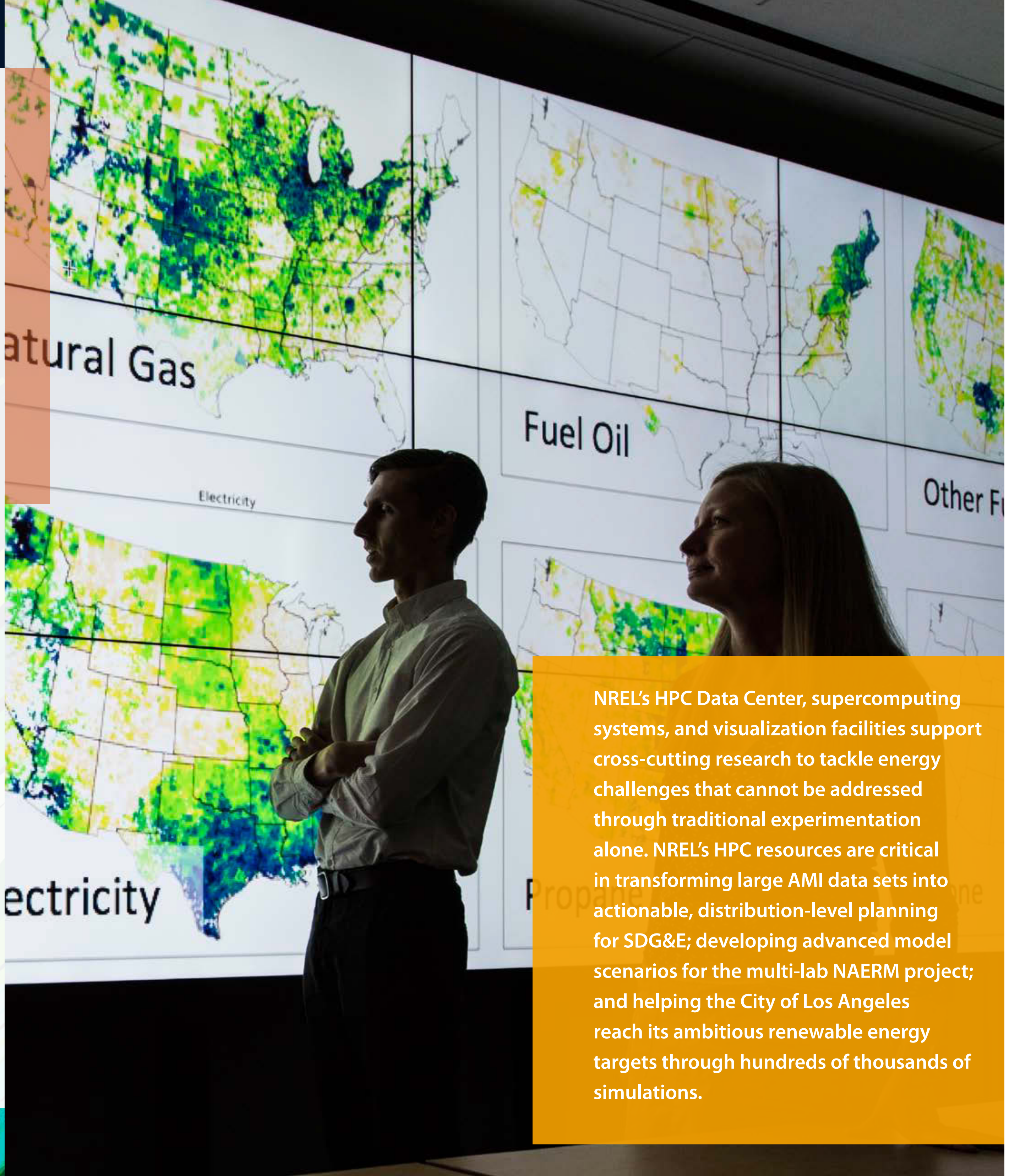
As a replacement for NREL's prior supercomputer, Peregrine, Eagle was put into production use in January 2019. Like Peregrine, Eagle was designed and built by Hewlett Packard Enterprise and has an innovative warm-water liquid-cooling system that allows waste heat to be captured for reuse. The system is a Linux cluster that uses a fast InfiniBand network. It comprises 2,114 interconnected compute nodes with 4,228 Intel Skylake processors and 76,104 total cores—along with 14 petabytes of high-speed data storage. The peak performance of Eagle is approximately 8 petaflops, or 8 million billion floating point (mathematical) operations per second.

NREL Garners Top Sustainability Honor at Data Center Dynamics Awards

In December 2018, NREL won the prestigious Data Center Dynamics (DCD) Data Center Eco-Sustainability Award, bolstering the laboratory's status as a world leader in data center efficiency and sustainability. Referred to as the Oscars of the data center industry, the annual DCD Global Awards recognize the industry's top data center projects and people. An independent panel of data center experts selected finalists from hundreds of entries from organizations around the world. This award recognizes innovative and pioneering approaches to sustainability through the design or major retrofit of a data center facility. The win solidifies NREL's claim to the most energy-efficient data center in the world, which NREL designed in partnership with SmithGroup LLC and Johnson Controls Inc.

ResStock™ Building Analysis Tool Improves Energy Efficiency for States, Municipalities, Utilities, and Manufacturers

NREL received a 2019 R&D 100 Award in the Software Services category for ResStock™, a highly granular energy simulation tool that leverages the ESIF's HPC for a new approach to large-scale residential energy analysis. Using the Eagle supercomputer, ResStock combines large data sources, statistical sampling, and detailed subhourly building simulations to model hundreds of thousands of buildings and identify cost-effective efficiency upgrades. Drawing from real-world characteristics and physics-based models, it has identified potential upgrades worth $49 billion in annual savings across the United States. In FY 2019, the ResStock team released a resource for communities planning their own building stock analysis, and the technology was a key component of a first-of-its-kind 100% renewable energy study for the City of Los Angeles.



NREL's HPC Data Center, supercomputing systems, and visualization facilities support cross-cutting research to tackle energy challenges that cannot be addressed through traditional experimentation alone. NREL's HPC resources are critical in transforming large AMI data sets into actionable, distribution-level planning for SDG&E; developing advanced model scenarios for the multi-lab NAERM project; and helping the City of Los Angeles reach its ambitious renewable energy targets through hundreds of thousands of simulations.

Improving Load Predictions to Better Understand Offshore Wind Systems Physics

NREL is working on an international research project focused on validating the modeling tools used to design offshore wind systems with HPC. The goal is to improve load predictions from engineering-level models through comparison to measurement data and higher fidelity simulations using computational fluid dynamics (CFD). In FY 2019, NREL performed simulations with the system in a fixed condition for multiple regular wave scenarios. The system was also forced to oscillate in the surge direction for different frequencies and amplitudes. This simpler structure was used as a starting point to understand the methodology and needs when performing CFD simulations of offshore wind structures.

Developing a Next-Generation Capability for Simulating Modern Wind Turbines

NREL is developing Nalu-Wind, a next-generation wind power plant fluid flow solver, with funding from both DOE's Water Power Technologies Office and the Office of Science's Exascale Computing Project. In FY 2019, NREL and partners created a new blade-resolved model of a large modern wind turbine, enabling scientists and engineers to begin understanding the complex flow physics in multiturbine wind power plants that will take advantage of future exascale modeling and simulation capability. When validated by targeted experiments, these and other predictive physics-based high-fidelity computational models—and the new knowledge derived from their solutions—provide an effective path to optimizing wind power plants. With a code that can run at exascale, researchers will be able to simulate wind power plant cases at unprecedented resolutions and domain extents, allowing for new scientific discoveries about wind power plant physics. Likewise, future smaller HPC systems will borrow technology from these systems.

Evaluating the Impact of Water Availability on Grid Configurations

The U.S. electric power sector relies heavily on cooling water and hydroelectric power for reliable and consistent operation. The impacts of water scarcity on power sector operations can be quantified using a variety of metrics, including total system production costs, regional energy generation, and regional energy prices, among others. Using a power systems model and HPC to evaluate the impact of water availability and grid configurations, NREL is considering region-wide impacts as well as subregional responses to capture regional capacity differences and realistic grid connectivity dynamics. In FY 2019, NREL researchers used Eagle to capture multiple climate-forced water availability scenarios across a range of historical and future years. Researchers believe this work represents the largest set of power system simulations under climate-forced water constraints to date. With traditional computing, run time for this type of simulation could take two months. HPC is critical for this project, allowing each of the 700 individual-year simulations to require only about two days.

Analyzing Costs, Benefits of Distributed Photovoltaic Generators to Help Evaluate Solutions for Distributed Photovoltaic Systems

To help utilities, solar developers, and DER aggregators evaluate different solutions to integrate distributed photovoltaics (DPV) onto the grid, NREL is evaluating the costs and benefits of DPV generators to distribution systems as a function of penetration level. Researchers use a bottom-up methodology that combines power flow modeling and hosting capacity analysis with techno-economic analysis. In FY 2019, NREL incorporated innovative quasi-static time-series simulations to capture time-dependent impacts of PV as well as consider a broader set of advanced technology options for grid integration, including distributed energy management systems and flexible interconnection approaches. With access to Eagle, researchers can conduct this analysis for a much larger number of DPV penetration levels to elucidate the key drivers of costs. Additionally, the HPC allows for rapid prototype development of new algorithms and tools for distribution grid integration.

Demonstrating Power, Utility of High-Fidelity Computation Methods to Model Meaningful Catalytic Systems

Affordable energy storage is of paramount importance if renewables are to become a dominant contribution to the U.S. energy supply. One approach is to store the energy in the form of a liquid fuel, using either a photo-electrochemical cell or an electrolyzer hooked into an electrical source. In FY 2019, NREL used a promising catalyst as a model to demonstrate how the implementation of high-fidelity computational methods can scale to large system sizes, extend this framework to systems involving solvent screening, and incorporate additional energetic terms. Results demonstrated the power and utility of techniques to model physically meaningful catalytic systems at realistic operating conditions using high-fidelity computational methods.

Assessing the Relationship Between Energy Efficiency and Demand Response in Future Power Systems

NREL is using HPC to provide a realistic and detailed understanding of the relative value of and interaction between the energy-efficiency and demand characteristics of building technologies in terms of power systems' time-varying costs and emissions. In FY 2019, researchers launched the first phase of this project, which was built on past work to tackle grid reliability challenges; researched occupant requirements and preferences; and analyzed the value of energy efficiency and demand response in at least three regions, leveraging several NREL models. The outcome will be an analysis platform that can assess trade-offs and cobenefits between energy efficiency and demand response in a variety of power system futures. Having access to HPC resources allows NREL to work unconstrained in terms of geospatial extent and resolution of the analysis.

ESIF Lab Updates & Advanced Capabilities

Top Operations Updates

- Commissioned an outdoor bioreactor system designed to operate in hazardous locations (Class 1, Division 2). Currently operating to biologically convert hydrogen and CO_2 to pure methane (natural gas)
- Upgraded overhead medium-voltage research distribution line in the Medium-Voltage Outdoor Test Area to triple its length, add platforms for equipment mounting, and include connection points for advanced data acquisitions and easy equipment hookup
- Built out ADMS test bed functionality by deploying commercial ADMS platforms with advanced applications and prototype control systems, integrating HELICS, and including input from industry advisory partners
- Built and commissioned a 30-kWe, 60-kW thermal natural gas combined heat and power system in the Power Systems Integration Laboratory
- Expanded electrolyzer fuel cell test capabilities in the Energy Sciences Laboratories
- Reconfigured 25% of office space, doubling occupancy in that area
- Reconfigured common spaces, adding meeting spaces and huddle rooms for additional staff
- Reconfigured Eaton laboratory space in the Energy Storage Laboratory as well as office space per proprietary user agreement
- Completed audit. The International Organization for Standardization (ISO) commended the ESIF, finding no opportunities for improvement and no items of noncompliance. The ESIF was further recognized for four system strengths: one in quality and three in health and safety.

Optimization and Control Laboratory Converted to Include New Capabilities

ESIF Operations converted more than 5,000 ft^2 of high-bay laboratory space into integrated capabilities for commercial buildings infrastructure and completed research electric distribution bus and thermal capability extensions in this space. The new commercial building infrastructure capabilities combine building automation technology with both thermal and electric power optimization. Researchers in the space can also leverage new capabilities in advanced behind-the-meter energy storage integration, such as ice storage, refrigeration, and combined heat and power.

ESIF Operations Expanded Power Hardware-in-the-Loop Capabilities

The ESIF's PHIL capabilities were completed to offer the set of all pertinent HIL platforms. The ESIF specified and acquired the Typhoon HIL platforms and added the NovaCore RTDS Simulator and Opal-RT systems. The RTDS and Opal-RT systems were also expanded to meet future project needs. ESIF Operations plans to blend these capabilities by linking them across remote sites (the Flatirons Campus to the ESIF) and increasing functionality in thermal systems-in-the-loop and network-in-the-loop capabilities.

New Facility-Wide Data Acquisition Network

ESIF Operations built a versatile, cost-effective data platform serving multiple protocol translation and streaming data for real-time monitoring. Included is a web-based visualization tool that allows quick and easy visualization of data setups and project views for demonstration, offering a huge set of viewable data tags from across the facility. The end points of the OPC Unified Architecture-based data stream are low cost and quickly configurable for high-speed data on voltage, current, and temperature. It also includes local processing for power and energy calculations.

The ESIF was verified through internationally recognized ISO and Occupational Health and Safety Assessment Series certifications, including ISO 9001 standard for quality management, ISO 14001 standard for environmental health and safety, and OHSAS 18001 standard for proper and effective management of health and safety in the workplace.

The verifications validate the ESIF's best-in-class facility mission, demonstrating its commitment to implementing continuous improvement.

Improved Safety Evaluation for Next-Generation Lithium-Ion Batteries

Researchers have devised a new strategy for testing the limits of next-generation lithium-ion batteries, including evaluating and ensuring that the batteries meet the highest safety standards before sending them to market. The new capability fills a crucial gap between the laboratory's world-class computational models and thermal evaluation of advanced battery chemistries. The ESIF provides a space to integrate comprehensive, real-time, multiscale, multidomain models with modern experimental characterization capabilities that stretch batteries under abuse conditions. This capability combines NREL's HPC capabilities with sophisticated characterization tools to facilitate studies of multiple simultaneous failure modes.

Benchmarking Study Showed Excellent Electrolyzer Performance and Durability

NREL developed anion exchange membrane and proton exchange membrane electrolysis test stations to perform state-of-the-art performance and durability experiments with high reproducibility and repeatability. This research supports the HydroGEN Advanced Water Splitting Materials consortium and other DOE Fuel Cell Technologies Office projects. In a published benchmarking study, NREL's experimental data showed excellent agreement with those of highly acknowledged international institutions. These results establish NREL as a leading institution for validating the performance and durability of electrolyzer technologies. NREL currently operates seven proton exchange membrane test stations and is expanding its anion exchange membrane test station capacity to three test stations.

Improved Reliability of Hydrogen Dispenser Nozzles for Hydrogen Fueling

To allow for fast fueling, hydrogen is cooled to subzero temperatures (-40°C) before it is dispensed into FCEVs. These cold temperatures can cause moisture in the air to condense and frost over on nozzle and receptacle components and in some cases to freeze-lock the nozzle onto the vehicle for up to several minutes. NREL designed and built a climate-controlled test stand to evaluate hydrogen nozzle freeze-lock and the ideal conditions under which freeze-lock occurs. Results will be used to help nozzle manufacturers and station providers supply more robust and reliable nozzles in various climate conditions.

ESIF Key Performance Indicators

ESIF Laboratories

- 155 users
- 95% lab availability
- 83% lab utilization.

HPC Data Center

- 361 users
- 90% lab availability
- 80% utilization.

PARTNERS

Air Liquide

Anterix

BREK Electronics

California GO-Biz

Centrica

The Chemours Company

Commonwealth Edison Company

Daimler AG

Eaton Corporation

Electric Power Research Institute

Element One

Emerson Electric

Energy Web Foundation

Exelon Corporation

Ford

Frontier Energy

Garmor Tech

General Motors

Giner Inc.

GVD Corporation

Hawaiian Electric Companies

Hewlett Packard Enterprise

Holy Cross Energy

Honda

HyET Hydrogen

Hyperlight Energy

Hyundai

KWJ Engineering

Leviton Manufacturing

Lynntech Inc.

Mainstream Engineering

Michigan Economic Development Corporation

NanoSonic

National Park Service

Nel Hydrogen

Ocean Renewable Power Company

OverDrive

Pacific Gas & Electric Company

Peroxygen Systems

pH Matter

Port of Long Beach

Powerfield Energy

Power Innovations

Proton OnSite

Public Service Company of New Mexico

RIX Industries

Salt River Project

San Diego Gas & Electric Company

Shell

SolarReserve

Southern California Gas Company

Southern Company

Sunvapor

Tatsuno Corporation

Toyota

University of California at Irvine

University of Colorado at Boulder

Walmart

Xcel Energy

Yasakawa Solectria Solar

Partnerships are key to NREL's success and mission. In 2019, two NREL projects were recognized by *R&D World* magazine as one of the nation's 100 most innovative technologies in the past year, both of which leveraged the ESIF's unique capabilities and were built with industry partners in mind.

The NREL-developed software PRECISE was built with partner Sacramento Municipal Utility District as a response to challenges in the solar industry. PRECISE, validated at the ESIF, offers a solution to speed up inverter registrations while optimizing inverter reliability and energy savings.

Also recognized, the building analysis tool ResStock allows states, municipalities, utilities, and manufacturers to identify which home improvements save the most energy and money. With access to NREL's Eagle supercomputer, ResStock has run more than 20 million simulations using a statistical model of housing stock characteristics. With these data, researchers have uncovered $49 billion in potential annual utility bill savings through cost-effective energy efficiency improvements.

DOE PROGRAM RESEARCH

ARPA-E

Network Optimized Distributed Energy Systems (NODES)

- Real-Time Optimization and Control of Next-Generation Distribution Infrastructure (RONIN)
- A Robust Distributed Framework for Flexible Power Grids: Enabling the Grid of the Future (ROBUST)

Generating Realistic Information for the Development of Distribution and Transmission Algorithms (GRID DATA)

- Synthetic Models for Advanced, Realistic Testing: Distribution Systems and Scenarios (SMART-DS)

Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors (CIRCUITS)

- A High-Voltage, High-Reliability Scalable Architecture for Electric Vehicle Power Electronics

Saving Energy Nationwide in Structures with Occupancy Recognition (SENSOR)

- Battery-Free RFID Sensor Network with Spatiotemporal Pattern Network Based Data Fusion System for Human Presence Sensing

Buildings

GMLC Category 1 Projects:

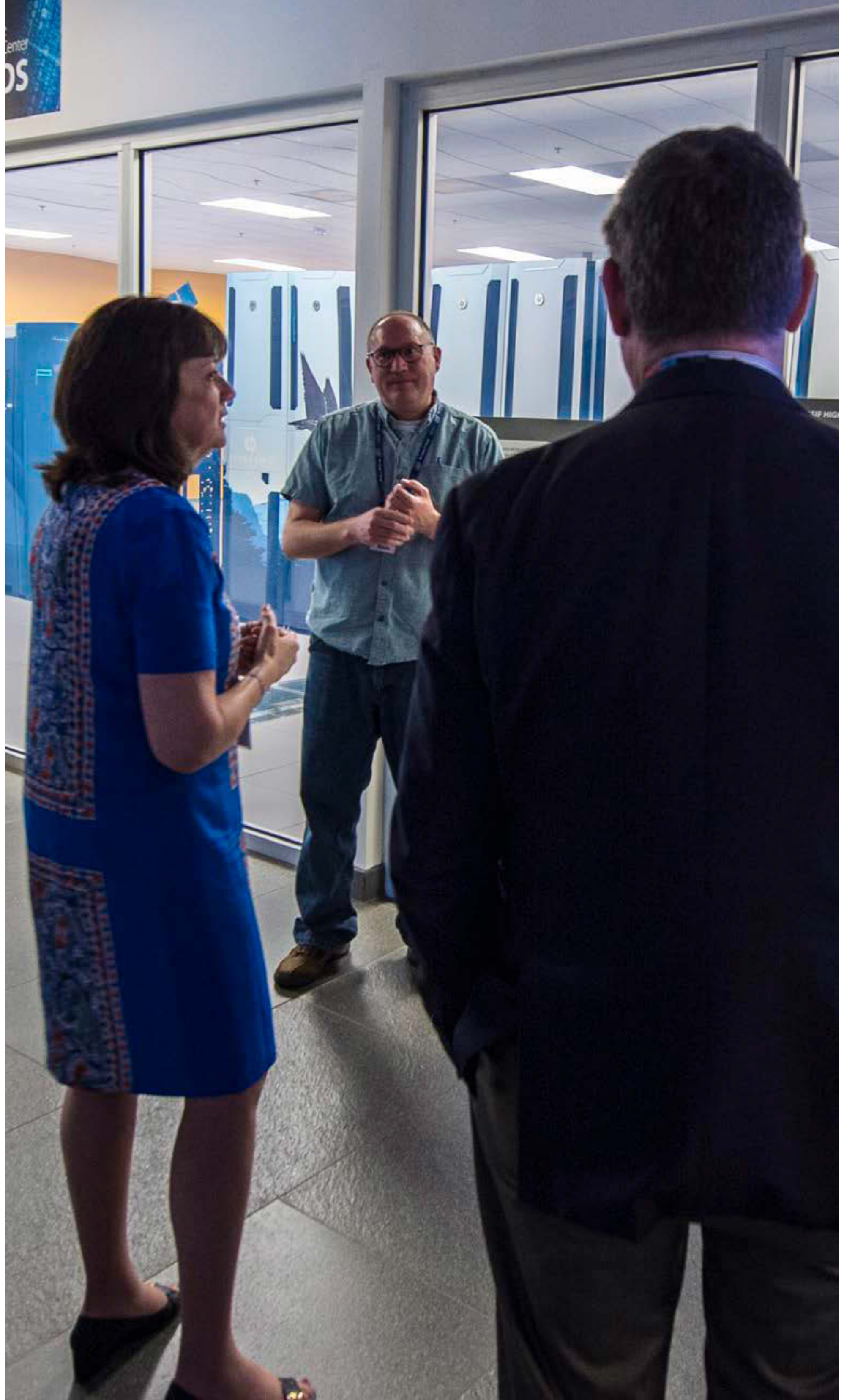
Advanced Sensor Development

Grid Sensing and Measurement Strategy

Interoperability

Integrated Multi-Scale Data Analytics and Machine Learning for the Grid

Distribution System Decision Support Tools



Fuel Cell Technologies Office

GMLC Category 1 Projects:

DER Siting and Optimization Tool for California

Grid Modernization

GMLC Category 1 Projects:

1.1 Foundational Metrics Analysis

1.2.1 Grid Architecture

1.2.2 Interoperability

1.2.3 Grid Modernization Laboratory Consortium Testing Network

1.2.4 Grid Services and Technologies Valuation Framework

1.2.5 Grid Sensing and Measurement Strategy

1.3.05 DER Siting and Optimization Tool for California

1.3.10 Vermont Regional Partnership Enabling the Use of DER

1.3.21 Alaska Microgrid Partnership

1.3.29 Grid Frequency Support from Distributed Inverter-Based Resources in Hawaii

1.3.33 Midwest Interconnection Seams Study

1.4.01 Standards and Test Procedures for Interconnection and Interoperability

1.4.02 Definitions, Standards and Test Procedures for Grid Services

1.4.04 Advanced Sensor Development

1.4.09 Integrated Multi Scale Data Analytics and Machine Learning for the Grid

1.4.10 Control Theory

1.4.11 Multi-Scale Integration of Control Systems (EMS/DMS/BMS)

1.4.15 Development of Integrated Transmission, Distribution, and Communication Models

1.4.17 Extreme Event Modeling

1.4.18 Computational Science for Grid Management

1.4.25 Distribution System Decision Support Tools

1.4.26 Development and Deployment of Multi-Scale Production Cost Models

1.4.29 Future Electricity Utility Regulation

GMLC Category 2 Projects:

GM0061 Virtual Battery-Based Characterization and Control of Flexible Building Loads Using VOLTTRON

GM0062 Vehicle to Building Integration Pathway

GM0063 Development of an Open-Source Platform for Advanced Distribution Management Systems

GM0085 Systems Research Supporting Standards and Interoperability

GM0086 Modeling and Control Software Tools to Support V2G Integration

GM0094 Measurement-Based Hierarchical Framework for Time-Varying Stochastic Load Modeling

GM0163 Diagnostic Security Modules for Electric Vehicle to Building Integration

GM0172 VOLTTRON Message Bus Protocol Adapter

GM0187 Community Control of Distributed Resources for Wide Area Reserve Provision

GM0229 Integrated Systems Modeling of the Interactions between Stationary Hydrogen, Vehicle and Grid Resources

GM0237 Advanced Distribution Management System Testbed Development

GM0252 Optimal Stationary Fuel Cell Integration and Control (DG-BEAT)

SI-1545 Rapid QSTS Simulations for High-Resolution Comprehensive Assessment of Distributed PV Impacts

SI-1583 Stabilizing the Power System in 2035 and Beyond: Evolving from Grid-Following to Grid-Forming Distributed Inverter Controllers

SI-1586 Opportunistic Hybrid Communications Systems for Distributed PV Coordination

SI-1631 Assessing the Value of Concentrating Solar Power in a SunShot Future

SI-1639 System Advisor Model

SI-1689 Additively Manufactured PV Inverter

SI-1695 Accelerating Systems Integration Codes and Standards

SI-1728 Solar Resource Calibration, Measurement and Dissemination

WGRID-04 Providing Ramping Service with Wind to Enhance Power System Operational Flexibility

WGRID-05 Power System Reliable Integration Support to Achieve Large Amounts of Wind Power (PRISALA)

WGRID-35 Market and Reliability Opportunities for Wind on the Bulk Power System

WGRID-38 North American Renewable Integration Study (NARIS)

WGRID-49 Understanding the Role of Short-term Energy Storage and Large Motor Loads for Active Power Controls by Wind Power

WGRID-59 WindView: An Open Platform for Wind Energy Forecast Visualization

GMLC Resilient Distribution Systems Projects:

Increasing Distribution Resiliency using Flexible DER and Microgrid Assets Enabled by OpenFMB (Decentralized FLISR)

Laboratory Value Analysis Team

Office of Electricity Delivery and Energy Reliability

GMLC Category 1 Projects:

1.1 Foundational Metrics Analysis

1.2.1 Grid Architecture

1.2.2 Interoperability

1.2.3 Grid Modernization Laboratory Consortium Testing Network

1.2.4 Grid Services and Technologies Valuation Framework

1.2.5 Grid Sensing and Measurement Strategy

1.3.05 DER Siting and Optimization Tool for California

1.3.10 Vermont Regional Partnership Enabling the Use of DER

1.3.21 Alaska Microgrid Partnership

1.3.29 Grid Frequency Support from Distributed Inverter-Based Resources in Hawaii

1.3.33 Midwest Interconnection Seams Study

1.4.02 Definitions, Standards and Test Procedures for Grid Services

1.4.04 Advanced Sensor Development

1.4.10 Control Theory

1.4.11 Multi-Scale Integration of Control Systems (EMS/DMS/BMS)

1.4.15 Development of Integrated Transmission, Distribution and Communication (TDC) Models

1.4.17 Extreme Event Modeling

1.4.18 Computational Science for Grid Management

1.4.25 Distribution System Decision Support Tools

1.4.26 Development and Deployment of Multi-Scale Production Cost Models

1.4.29 Future Electricity Utility Regulation

GMLC Category 2 Projects:

GM0061 Virtual Battery-based Characterization and Control of Flexible Building Loads Using VOLTTRON

GM0062 Vehicle to Building Integration Pathway

GM0063 Development of an Open-Source Platform for Advanced Distribution Management Systems

GM0085 Systems Research Supporting Standards and Interoperability

GM0086 Modeling and Control Software Tools to Support V2G Integration

GM0094 Measurement-Based Hierarchical Framework for Time-Varying Stochastic Load Modeling

GM0163 Diagnostic Security Modules for Electric Vehicle to Building Integration

GM0172 VOLTTRON Message Bus Protocol Adapter

GM0187 Community Control of Distributed Resources for Wide Area Reserve Provision

GM0229 Integrated Systems Modeling of the Interactions between Stationary Hydrogen, Vehicle and Grid Resources

GM0237 Advanced Distribution Management System Testbed Development

GM0252 Optimal Stationary Fuel Cell Integration and Control (DG-BEAT)

GMLC Resilient Distribution Systems Projects:

Increasing Distribution Resiliency using Flexible DER and Microgrid Assets Enabled by OpenFMB (Decentralized FLISR)

Laboratory Value Analysis Team

Solar Energy Technologies Office

SuNLaMP Prime Projects (GMLC Category 2)

Additively Manufactured PV Inverter

Solar Resource Calibration, Measurement and Dissemination

System Advisor Model

Assessing the Value and Impact of Dispatchable Concentrated Solar Power

Opportunistic Hybrid Communications Systems for Distributed PV Coordination

Accelerating Systems Integration Standards (ACCEL)

Stabilizing the Power System in 2035 and Beyond: Evolving from Grid-Following to Grid-Forming Distributed Inverter Controllers

SuNLaMP Subrecipient Projects (NREL as subrecipient)

Oak Ridge National Laboratory Prime: Frequency Response of Three Major U.S. Power Grids

Sandia National Laboratories Prime: Distribution System Modeling

Argonne National Laboratory Prime: An Integrated Tool for Improving Grid Reliability

GMLC Category 1 Projects:

1.1 Foundational Metrics Analysis

1.2.1 Grid Architecture

1.3.21 Alaska Microgrid Partnership

1.4.01 Standards and Test Procedures for Interconnection and Interoperability

1.4.15 Development of Integrated Transmission, Distribution and Communication Models

1.4.25 Distribution System Decision Support Tools

1.4.29 Future Electricity Utility Regulation

1.3.29 Grid Frequency Support from Distributed Inverter-Based Resources in Hawaii

1.4.04 Advanced Sensor Development

Other Direct Projects

U.S. Representation for the International Energy Agency Photovoltaic Power Systems (IEA PVPS) Task 14

Demonstration of Ancillary Services by Large PV Plant in California

North American Renewables Integration Study (NARIS)

PV Plant and Battery Energy Storage Integration

Solar Technology Cost Modeling and Competitive Analysis

Eclipse Peak

North American Energy Resiliency Model (NAERM)

FY 2019 Solar Energy Technologies Office Lab Call Projects

Solar Radiation Research Laboratory (SRRL)

The National Solar Radiation Data Base (NSRDB)

Interconnection & Interoperability Standards Accelerating Systems Integration Standards (ACCEL II)

Multi-timescale Integrated Dynamic and Scheduling for Solar (MIDAS-Solar)

Artificial-Intelligence-Driven Smart Community Control for Accelerating PV Adoption and Enhancing Grid Resilience

Innovative Protection Systems for High-Pen PV Grids

FY21-End-Lab Call sub, DER Cyber Security Standards Development (Sandia National Laboratories Prime)

Multi-Lab Grid Modeling Support for Puerto Rico Phase II

INTEGRATE Projects (Collaborative)

Southern California Gas Company

ENERGISE Projects

NREL Primes:

Grid Optimization with Solar (GO-Solar)

Enhanced Control, Optimization, and Integration of Distributed Energy Applications (Eco-Idea)

NREL Subs:

Scalable/Secure Cooperative Algorithms and Framework for Extremely-high Penetration Solar Integration (SolarExPert)

Electric Access System Enhancement (EASE)

Solar Forecasting II Projects

NREL Primes:

Probabilistic Cloud Optimized Day-Ahead Forecasting System Based on Weather Research and Forecasting Solar System

Solar Uncertainty Management and Mitigation for Exceptional Reliability in Grid Operations (SUMMER-GO)

NREL Subs:

Coordinated Ramping Product and Regulation Reserve Procurements in California Independent System Operator and Midcontinent Independent System Operator Using Multi-Scale Probabilistic Solar Power Forecasts

Advancing the Weather Research and Forecasting Solar Model to Improve Solar Irradiance Forecast in Cloudy Environments

Advanced Systems Integration for Solar Technologies

NREL Subs:

Enhancing Grid Reliability and Resilience through Novel Distributed Energy Resource Control, Total Situational Awareness, and Integrated Distribution-Transmission Representation (Lead: Arizona State University)

Enabling Cybersecurity, Situational Awareness and Resilience in Distribution Grids with High Penetration of Photovoltaics (Lead: Kansas State University)

Modeling and Control of Solar Photovoltaics for Large Grid Disturbances and Weak Grids (Lead: University of South Florida)

Protection and Restoration Solutions to Reliable and Resilient Integration of Grid-Connected Photovoltaic Installations and Distributed Energy Resources: Design, Testbed, Proof of Work, and Impact Studies (Lead: University of Oklahoma)

Solar Critical Infrastructure Energization System (Lead: Electric Power Research Institute)

Autonomous and Resilient Operation of Energy Systems with Renewables (Lead: Siemens Corp.)

Vehicle Technologies Office

GMLC Category 1 Projects:

1.3.33 Midwest Interconnection Seams Study

1.4.11 Multi-Scale Integration of Control Systems (EMS/DMS/BMS)

1.4.26 Development and Deployment of Multi-Scale Production Cost Models

GMLC Category 2 Projects:

WGRID-04 Providing Ramping Service with Wind to Enhance Power System Operational Flexibility

WGRID-05 Power System Reliable Integration Support to Achieve Large Amounts of Wind Power (PRISALA)

WGRID-35 Market and Reliability Opportunities for Wind on the Bulk Power System

WGRID-38 North American Renewable Integration Study (NARIS)

WGRID-49 Understanding the Role of Short-term Energy Storage and Large Motor Loads for Active Power Controls by Wind Power

WGRID-59 WindView: An Open Platform for Wind Energy Forecast Visualization

Wind Power Technologies Office

Wind Grid Projects – FY 2019 Start:

Continental-Scale Transmission Modeling Methods for Grid Integration Analysis

Atmosphere to Electrons to Grid (A2e2g)

Wind Grid Integration Stakeholder Engagement

Wind Power as Virtual Synchronous Generation (WindVSG)

Advanced Modeling, Dynamic Stability Analysis, and Mitigation of Control Interactions in Wind Power Plants

Water Power Technologies Office

North American Grid Integration Study (NARIS)

Pumped Storage and Hydropower Value Consortium (HVC)

Ternary PSH Design and Evaluation

Obermeyer PSH Valuation

FY2017 Small Business Voucher – Natel

Dehlsen

Integrated Hydropower

Ocean Renewable Power Company

KNOWLEDGE SHARING

Expanding Awareness of Tomorrow's Grid through Outreach, Tours, and Mentorship

Educational outreach is vital to the advancement of R&D at the ESIF. NREL embraces its role in educating the next generation of power systems engineers, visitors from industry and Washington, D.C., and our neighbors here in Golden, Colorado. In honoring this commitment, the ESIF hosted more than 330 tours and more than 4,500 visitors in FY 2019, providing the opportunity for many to witness the state-of-the-art research being conducted at the facility.

NREL is also fostering the future of energy systems integration research through its continued support of internship opportunities. In FY 2019, the ESIF offered more than 50 internships to graduate and undergraduate students. Internships at the ESIF offer students exposure to a multitude of topics in energy systems integration, from hydrogen fuel cell development to the evaluation of cyber anomalies in a virtual grid environment. These opportunities propel the future research community in energy systems integration to build long-term relationships with our experts throughout the facility. Several types of internships are available to students who have a variety of backgrounds in science and technology.

WORKSHOPS, CONFERENCES, & EVENTS

The following table includes a snapshot of the workshops, conferences, and events held in the ESIF in FY 2019.

Title	Date
Networked Microgrids	October 17–18, 2018
Artificial Intelligence at NREL Technical Meeting	January 11, 2019
Survalent ADMS Training	January 14–18, 2019
NREL Mobility Industry Advisory Board Workshop	March 13, 2019
Innovative Optimization and Control Methods for Highly Distributed Autonomous Systems	April 11–12, 2019
Exascale Computing Project's Stochastic Grid Dynamics Project, ExaSGD, Technical Meeting	July 8–9, 2019
NREL Data-Driven Forecasting and Prediction for Energy Systems Workshop	July 10–11, 2019

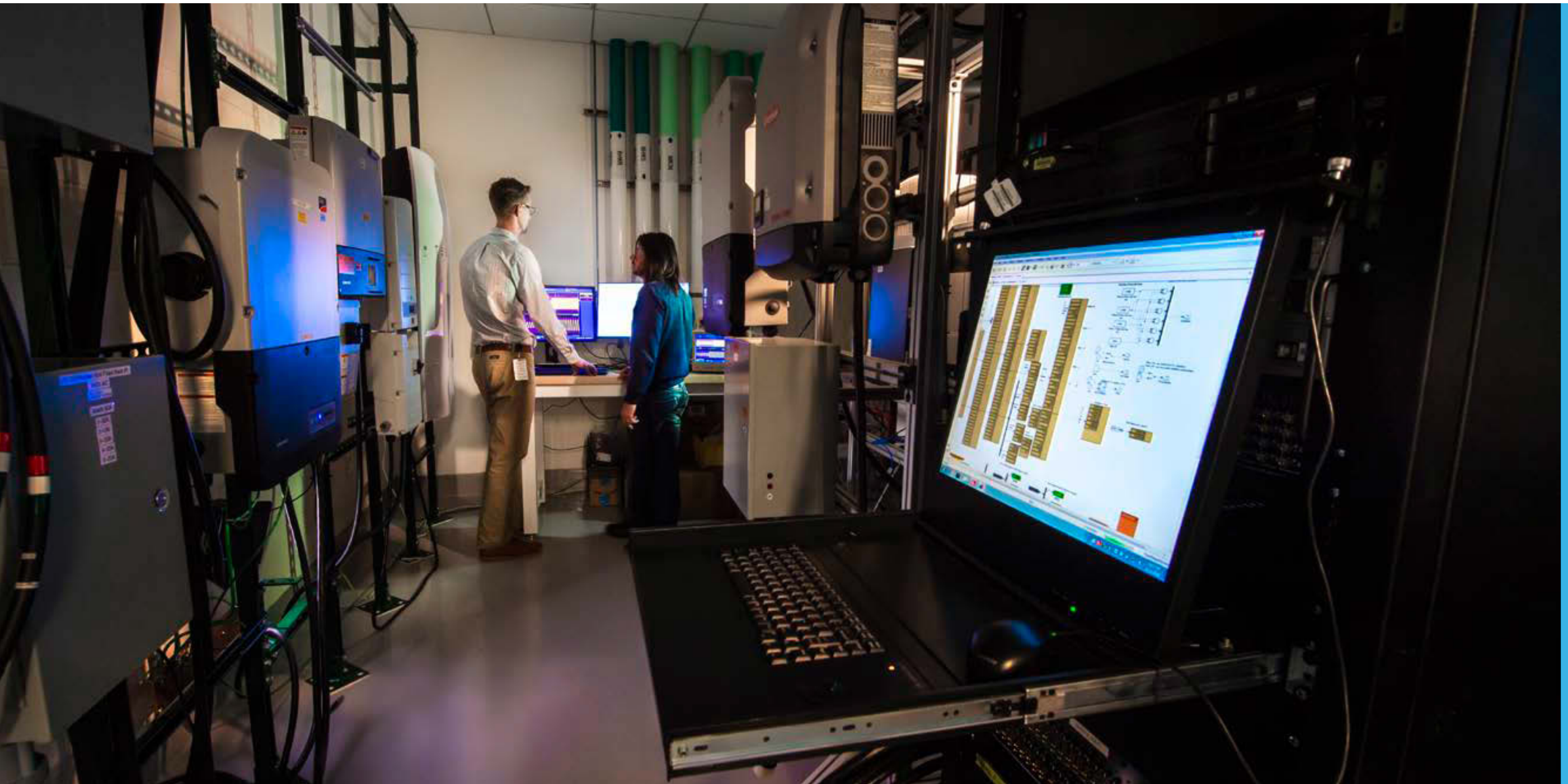
INNOVATIONS

The ESIF delivered **352 technical outputs**, including journal articles, records of invention, software, and conference papers.

Title	Primary NREL Center	NREL Number
Hydrogen Fueling Analyzer	5B00 - Energy Systems Integration Facility	SWR-17-41
Gray-box Model Identification of Inverter Non-linear Control Dynamics	5D00 - Power Systems Engineering	ROI-19-04
Configuration of Advanced Inverter Functions using IEC 61850 AMPVI_ICD	5B00 - Energy Systems Integration Facility	SWR-18-09
Advanced control strategy to generate fault initiated current signatures for distribution-pole mounted PV micro-inverters	5D00 - Power Systems Engineering	ROI-19-10
ACES-CoSim (Advanced Computational Energy Systems - Co-Simulation)	2C00 - Computational Sciences	SWR-19-05
Bokeh-streaming	5D00 - Power Systems Engineering	SWR-19-08
CKAN Data Tools for EMN Data Hubs	2C00 - Computational Sciences	SWR-19-10
System and Method for using AMI measurements for Phase identification	5D00 - Power Systems Engineering	ROI-19-20
Hierarchical Distributed Voltage Regulation in Networked Autonomous Grids	5D00 - Power Systems Engineering	ROI-19-23
Bewley Lattice Visualization (BL-Vis)	5D00 - Power Systems Engineering	SWR-19-17
TC4E (Transactive Control for Energy)	7A40 - Integrated Applications	SWR-19-18
OpenSMEMS (Open source Sequential Multi-timescales Electricity Market Simulation Tool)	5D00 - Power Systems Engineering	SWR-19-27
Joint Optimization of Electricity Generation and Use	5D00 - Power Systems Engineering	ROI-19-68
Fidelity-Weighted Neural Network Training (FWNNT)	2C00 - Computational Sciences	SWR-19-34
GPU Implementation of Thickness Mapping and Quality Control For Films Moving Through A Web-Line System	2C00 - Computational Sciences	SWR-19-35; ROI-16-96

Title	Primary NREL Center	NREL Number
Scientific Perceptual Loss Networks	2C00 - Computational Sciences	ROI-19-75
Distributed Reinforcement Learning for Control of Large-Scale Energy Systems	2C00 - Computational Sciences	ROI-19-77
Carbon Free Data Center Control and Assessment	2C00 - Computational Sciences	ROI-20-03
SOLARUN (Solar Resource Uncertainty Application)	5D00 - Power Systems Engineering	SWR-19-41
ProgressiveHedging.jl	2C00 - Computational Sciences	SWR-19-42
IGMS-HELICS (or IGMS v3) Integrated Grid Modeling System	5D00 - Power Systems Engineering	SWR-19-43
Module OT - Software	5R00 - Energy Security and Resilience	SWR-19-44
MAFRIT (Multi-Area Frequency Response Integration Tool)	5D00 - Power Systems Engineering	SWR-19-48
Hybrid Intrusion Detector for Energy System	5R00 - Energy Security and Resilience	ROI-19-128
HERMES: A Cyber-Physical Visualization and Research Platform	5R00 - Energy Security and Resilience	ROI-19-131
HERMES: A Cyber-Physical Visualization and Research Platform HERMES	5R00 - Energy Security and Resilience	SWR-19-53
Hydrogen Mass/Ratio Control and Passive Membrane Water Management	5B00 - Energy Systems Integration Facility	ROI-19-140
SHARP-Net: Platform for Self-Healing and Attack Resilient PMU Networks	5R00 - Energy Security and Resilience	ROI-19-144
Electric Power and Gas System Co-Simulation Platform	5D00 - Power Systems Engineering	SWR-19-62; SWR 19-61
Python Electromagnetic Transients PyEMT	2C00 - Computational Sciences	SWR-19-63
Platform for Self-Healing and Attack Resilient PMU Networks SHARP-Net	5R00 - Energy Security and Resilience	SWR-19-64

Title	Primary NREL Center	NREL Number
HIDES (Hybrid Intrusion Detection for Energy Systems)	5R00 - Energy Security and Resilience	SWR-19-65; ROI-19-128
Loss Informed Dispatcher for Battery Systems (LIDBS)	5D00 - Power Systems Engineering	SWR-19-68
Battery Ensemble ANN Modeler (BEAM)	5D00 - Power Systems Engineering	SWR-19-69
Grid-Edge Resource Controller to Enhance Distribution Grid Resilience	5D00 - Power Systems Engineering	SWR-19-70
Network Load Forecasting (NLF)	5D00 - Power Systems Engineering	SWR-19-72
Station Data Analyzer	2C00 - Computational Sciences	SWR-20-04
Heavy-duty Hydrogen Vehicle Simulator	5B00 - Energy Systems Integration Facility	SWR-20-05
Dynamic Electrolyzer Control	5B00 - Energy Systems Integration Facility	SWR-20-06



Patent Filings

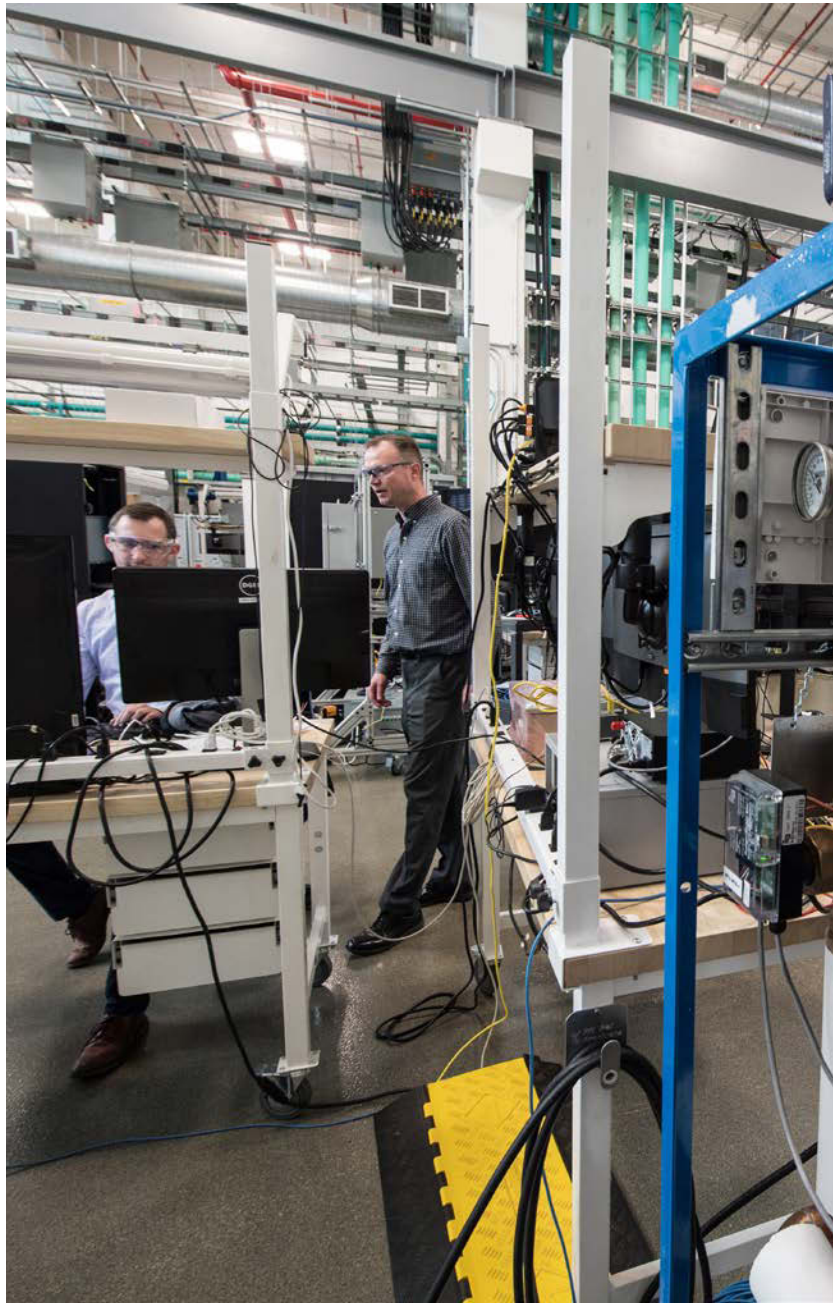
Title	Primary NREL Center	NREL Number
Heterogenous Network Topology Management and Control	5D00 - Power Systems Engineering	17-95
Low-Observability Matrix Completion	5D00 - Power Systems Engineering	18-26
Low-Observability Matrix Completion	5D00 - Power Systems Engineering	PCT/18-26
Image-Based Solar Estimates	5D00 - Power Systems Engineering	PROV/18-56A
Modular Scalable Power Conversion	5D00 - Power Systems Engineering	PROV/17-74B
Coordinated Net-Load Management	5D00 - Power Systems Engineering	18-59
Modular Scalable Power Conversion	5D00 - Power Systems Engineering	17-74
Integrated Synchronization Control of Grid-Forming Inverters	5D00 - Power Systems Engineering	PROV/18-134
Distribution Network Phase Identification	5D00 - Power Systems Engineering	PROV/19-20
Hierarchical Distributed Voltage Regulation	5D00 - Power Systems Engineering	PROV/19-23
Renewable Power to Renewable Natural Gas Using Biological Methane Production	5B00 - Energy Systems Integration Facility	PCT/18-48
Real Time Voltage Regulation Through Gather and Broadcast Techniques	5D00 - Power Systems Engineering	16-35
Decentralized Oscillator-Based Converter Control	5D00 - Power Systems Engineering	17-64

PUBLICATIONS

Most Downloaded Publications

The following were the most downloaded FY 2019 ESIF publications on NREL.gov:

1. *Phase I Microgrid Cost Study: Data Collection and Analysis of Microgrid Costs in the United States*
2. "ESIF 2018 Annual Report"
3. "Cost-Competitive Electrolysis-Based Hydrogen Under Current U.S. Electric Utility Rates"
4. *Advanced Inverter Voltage Controls: Simulation and Field Pilot Findings*
5. *A New Approach for Short-Term Solar Radiation Forecasting Using the Estimation of Cloud Fraction and Cloud Albedo*
6. "Capacity Market Model Considering Flexible Resource Requirements: Preprint"
7. *Certification Procedures for Data and Communications Security of Distributed Energy Resources*
8. "Cost-Effectiveness of Grid Energy Storage Technologies in Current and Future U.S. Power Systems"
9. *Baja California Sur Renewable Integration Study*
10. "NREL + Holy Cross Energy"



Conference Papers (Preprints)

Abraham, S.A., K. McKenna, and A. Nagarajan. 2019. "Development and Clustering of Rate-Oriented Load Metrics for Customer Price-Plan Analysis: Preprint" (NREL/CP-5D00-72655). Presented at the IEEE Power and Energy Society General Meeting (IEEE PES GM), Atlanta, Georgia, August 4–8, 2019.

Aworo, O.J., and B. Mather. 2019. "Experimental Determination of PV Inverter Response to Grid Phase Shift Events: Preprint (NREL/CP-5D00-70496)." Presented at the 2018 IEEE Power and Energy Society General Meeting (IEEE PES GM), Portland, Oregon, August 5–9, 2018.

Bernstein, A., and E. Dall'Anese. 2019. "Asynchronous and Distributed Tracking of Time-Varying Fixed Points: Preprint (NREL/CP-5D00-73422)." Presented at the 2018 IEEE Conference on Decision and Control (IEEE CDC), Miami Beach, Florida, December 17–19, 2018.

Biswas, R.S., J. Tan, H. Jain, V. Gevorgian, and Y.C. Zhang. 2019. "Equivalent Test Bed in PSCAD and PSLF for Studying Advanced Power Systems Controller Performance: Preprint" (NREL/CP-5D00-73106). Presented at the 2019 IEEE Conference on Innovative Smart Grid Technologies (IEEE ISGT), Washington, D.C., February 17–20, 2019.

Chartan, E., and H. Obermeyer. 2019. "Grid Integration and Market Analysis of Adjustable-Speed Pumped Storage Hydropower: Preprint" (NREL/CP-5D00-74282). Presented at HydroVision International 2019, Portland, Oregon, July 23–25, 2019.

Chartan, E., J. Wright, and G. Landwehr. 2019. "Comparing the Value of Improved Variable Renewable Energy Forecasting Accuracy in South African and United States Power Systems: Preprint" (NREL/CP-5D00-72593). Presented at WindAc 2018, Cape Town, South Africa, November 5–6, 2018.

Chen, Y., and Y. Lin. 2019. "Hierarchical Management of Distributed Energy Resources Using Chance-Constrained OPF and Extremum Seeking Control: Preprint" (NREL/CP-5D00-73404). Presented at the American Control Conference, Philadelphia, Pennsylvania, July 10–12, 2019.

Ding, F., H.V. Padullaparti, M. Baggu, S. Veda, and S. Meor Danial. 2019. "Data Enhanced Hierarchical Control to Improve Distribution Voltage with Extremely High PV Penetration: Preprint" (NREL/CP-5D00-72755). Presented at the 2019 IEEE Power & Energy Society General Meeting (IEEE PES GM), Atlanta, Georgia, August 4–8, 2019.

Ding, F., K. Horowitz, B. Mather, and B. Palmintier. 2019. "Sequential Mitigation Solutions to Enable Distributed PV Grid Integration: Preprint" (NREL/CP-5D00-70411). Presented at the 2018 IEEE Power and Energy Society General Meeting (IEEE PES GM), Portland, Oregon, August 5–10, 2018.

Dutta, S., R. Mallik, B. Majmunovic, S. Mukherjee, G.-S. Seo, D. Maksimovic, and B. Johnson. 2019. "Decentralized Carrier Interleaving in Cascaded Multilevel DC-AC Converters: Preprint" (NREL/CP-5D00-74846). Presented at the 2019 IEEE Workshop on Control and Modeling for Power Electronics (IEEE COMPEL), Toronto, Canada, June 17–20, 2019.

Fang, X., B.-M. Hodge, and F. Li. 2018. "Capacity Market Model Considering Flexible Resource Requirements: Preprint (NREL/CP-5D00-70162)" 2019. Presented at the IEEE Power and Energy Society General Meeting (IEEE PES GM), Portland, Oregon, August 5–10, 2018.

Fang, X., B.-M. Hodge, V. Krishnan, and F. Li. 2018. "Potential of Wind Power to Provide Flexible Ramping Products and Operating Reserve: Preprint (NREL/CP-5D00-70161)." Presented at the IEEE Power and Energy Society General Meeting (IEEE PES GM), Portland, Oregon August 5–10, 2018.

Fang, X., M.T. Craig, and B.-M. Hodge. 2019. "Linear Approximation Line Pack Model for Integrated Electricity and Natural Gas Systems OPF: Preprint" (NREL/CP-5D00-73763). Presented at the IEEE Power and Energy Society General Meeting (IEEE PES GM), Atlanta, Georgia, August 4–8, 2019.

Faqiry, M., L. Wang, H. Wu, D. Krishnamurthy, and B. Palmintier. 2019. "ADP-Based Home Energy Management System: A Case Study Using Dynamo: Preprint" (NREL/CP-5D00-70422). Presented at the Power and Energy Society General Meeting (IEEE PES GM), Portland, Oregon, August 5–10, 2018.

Gevorgian, V. 2019. "Highly Accurate Method for Real-Time Active Power Reserve Estimation for Utility-Scale PV Power Plants: Preprint" (NREL/CP-5D00-72419). Presented at the Solar Integration Workshop, Stockholm, Sweden, October 16-17, 2018.

Gevorgian, V., M. Baggu, and D. Ton. 2019. "Interconnection Requirements for Renewable Generation and Energy Storage in Island Systems: Puerto Rico Example: Preprint" (NREL/CP-5D00-73848). Presented at the 4th International Hybrid Power Systems Workshop, Crete, Greece, May 22–23, 2019.

Guo, L., C. Zhao, and S.H. Low. 2019. "Graph Laplacian Spectrum and Primary Frequency Regulation: Preprint" (NREL/CP-5D00-71124). Presented at the IEEE Conference on Decision and Control Miami, Florida, December 17–19, 2018.

Jain, A.K., K. Horowitz, F. Ding, N. Gensollen, B. Mather, and B. Palmintier. 2019. "Quasi-Static Times Series PV Hosting Capacity Methodology and Metrics: Preprint" (NREL/CP-5D00-72284). Presented at the 2019 IEEE Conference on Innovative Smart Grid Technologies (IEEE ISGT), Washington, D.C., February 17–20, 2019.

Jain, H., B. Palmintier, D. Krishnamurthy, I. Krad, and E. Hale. 2019. "Evaluating the Impact of Price-Responsive Load on Power Systems Using Integrated T&D Simulation: Preprint" (NREL/CP-5D00-70197). Presented at the 2019 IEEE Conference on Innovative Smart Grid Technologies (IEEE ISGT), Washington, D.C., February 17–20, 2019.

Janine F., G.T. Klise, A. Walker, and O. Lavrova. 2018. "Evaluating Energy Impacts and Costs from PV Component Failures: Preprint" (NREL/CP-6A20-72212. Presented at the World Conference on Photovoltaic Energy Conversion (WCPEC-7), Waikoloa, Hawaii, June 10–15, 2018.

Jhala, K., V. Krishnan, B. Natarajan, and Y.C. Zhang. 2019. "Data-Driven Preemptive Voltage Monitoring and Control Using Probabilistic Voltage Sensitivities: Preprint" (NREL/CP-5D00-72661). Presented at the 2019 IEEE Power and Energy Society General Meeting (IEEE PES GM), Atlanta, Georgia, August 4–8, 2019.

Lin, Y., D. McLarty, A. Pratt, B. Ball, G. Henze, and G. Saur. 2018. "Optimal Dispatch Controller for Fuel Cell-Integrated Building: Preprint" (NREL/CP-5D00-71423). Presented at the High Performance Buildings Conference, West Lafayette, Indiana, July 9–12, 2018.

Liu, Z., Z. Zhang, and Y. Lin. 2019. "Impact of Inverter-Interfaced Renewable Generation on Transient Stability at Varying Levels of Penetration: Preprint" (NREL/CP-5D00-70489). Presented at the IEEE Annual Conference of the IEEE Industrial Electronics Society (IEEE IECON), Washington, D.C., October 21–23, 2018.

Lu, M., G.-S. Seo, M. Sinha, F. Rodriguez, S. Dhople, and B. Johnson. 2019. "Adaptation of Commercial Current-Controlled Inverters for Operation with Virtual Oscillator Control: Preprint" (NREL/CP-5D00-72318). Presented at the 2019 IEEE Applied Power Electronics Conferences (IEEE PELS), Anaheim, California, March 17–21, 2019.

Mahmud, R., and A. Nejadpak. 2019. "Distributed Cooperative Control of Hybrid AC/DC Microgrid: Preprint" (NREL/CP-5D00-73879). Presented at the 46th IEEE Photovoltaic Specialists Conference (IEEE PVSC 46), Chicago, Illinois, June 16–21, 2019.

Mallik, R., B. Majmunovic, S. Mukherjee, S. Dutta, G.-S. Seo, D. Maksimovic, and B. Johnson. 2019. "Equivalent Circuit Models of Voltage-Controlled Dual Active Bridge Converters: Preprint" (NREL/CP-5D00-74061). Presented at the 2019 IEEE Workshop on Control and Modeling for Power Electronics (IEEE COMPEL), Toronto, Canada, June 17–20, 2019.

Mukherjee, S., Y. Gao, R. Ramos, V. Sankaranarayanan, B. Majmunovic, R. Mallik, S. Dutta, G.-S. Seo, B. Johnson, and D. Maksimovic. 2019. "AC Resistance Reduction Using Orthogonal Air Gaps in High-Frequency Inductors: Preprint" (NREL/CP-5D00-74060). Presented at the 2019 IEEE Workshop on Control and Modeling for Power Electronics (IEEE COMPEL), Toronto, Canada, June 17–20, 2019.

Nazir, M.S., I.A. Hiskens, A. Bernstein, and E. Dall'Anese. 2019. "Inner Approximation of Minkowski Sums: A Union-Based Approach and Applications to Aggregated Energy Resources: Preprint" (NREL/CP-5D00-73423). Presented at the 2018 IEEE Conference on Decision and Control (IEEE CDC), Miami Beach, Florida, December 17–19, 2018.

Netto, M., V. Krishnan, L. Mili, Y. Susuki, and Y.C. Zhang. 2019. "A Hybrid Framework Combining Model-Based and Data-Driven Methods for Hierarchical Decentralized Robust Dynamic State Estimation: Preprint" (NREL/CP-5D00-72685). Presented at the 2019 IEEE Power and Energy Society General Meeting (IEEE PES GM), Atlanta, Georgia, August 4–8, 2019.

Padullaparti, H., S. Veda, S. Dhulipala, M. Baggu, T. Bialek, and M. Symko-Davies. 2019. "Considerations for AMI-Based Operations for Distribution Feeders: Preprint" (NREL/CP-5D00-72773). Presented at the 2019 IEEE Power & Energy Society General Meeting (IEEE PES GM), Atlanta, Georgia, August 4–8, 2019.

Paret, P., G. Moreno, B. Kekelia, R. Kotecha, X. Feng, K. Bennion, B. Mather, A. Zakutayev, S. Narumanchi, S. Kim, and S. Graham. 2019. "Thermal and Thermomechanical Modeling to Design a Gallium Oxide Power Electronics Package: Preprint" (NREL/CP-5400-72291). Presented at the 6th IEEE Workshop on Wide Bandgap Power Devices and Applications (WiPDA 2018), Atlanta, Georgia, October 31–November 2, 2018.

Pierre, B.J., H.N. Villegas Pico, R.T. Elliott, J. Flicker, Y. Lin, B.B. Johnson, J.H. Eto, R.H. Lasseter, and A. Ellis. 2019. "Bulk Power System Dynamics with Varying Levels of Synchronous Generators and Grid-Forming Power Inverters: Preprint" (NREL/CP-5D00-74107). Presented at the 46th IEEE Photovoltaic Specialists Conference (IEEE PVSC 46), Chicago, Illinois, June 16–21, 2019.

Pratt, K. A., D. Krishnamurthy, and A. Maitra. 2019. "Hardware-in-the-Loop Test Bed and Test Methodology for Microgrid Controller Evaluation: Preprint" (NREL/CP-5D00-73627). Presented at the 2018 IEEE PES Transmission and Distribution Conference and Exposition (T&D), Denver, Colorado, April 16–19, 2018.

Prabakar, K., A. Singh, and C. Tombari. 2019. "IEEE 1547-2018 Based Interoperable PV Inverter with Advanced Grid-Support Functions: Preprint" (NREL/CP-5D00-73131). Presented at the 46th IEEE Photovoltaic Specialists Conference (IEEE PVSC 46), Chicago, Illinois, June 16–21, 2019.

Prabakar, K., M. Shirazi, A. Singh, and S. Chakraborty. "Advanced Photovoltaic Inverter Control Development and Validation in a Controller-Hardware-in-the-Loop Test Bed: Preprint (NREL/CP-5D00-68511)" Presented at the IEEE Energy Conversion Congress and Exposition (IEEE ECCE), Cincinnati, Ohio, October 1–5, 2017.

Pratt, A., M. Baggu, F. Ding, S. Veda, I. Mendoza, and E. Lightner. 2019. "A Test Bed to Evaluate Advanced Distribution Management Systems for Modern Power Systems: Preprint" (NREL/CP-5D00-73705). Presented at the 2019 IEEE EUROCON, Novi Sad, Serbia, July 1–4, 2019.

Ren, H., V. Krishnan, Y. C. Zhang, and N. N. Schulz. 2019. "Online Static Load Model Estimation in Distribution Systems: Preprint" (NREL/CP-5D00-73228). Presented at the 2019 IEEE 28th International Symposium on Industrial Electronics (IEEE ISIE), Vancouver, Canada, June 12–14, 2019.

Roy, J., G.-S. Seo, and A. Singh. 2019. "Highly Reliable Multi-Port Smart Inverter Modules for PV-Based Energy Systems: Preprint" (NREL/CP-5D00-73857). Presented at the 46th IEEE Photovoltaic Specialists Conference (IEEE PVSC 46), Chicago, Illinois, June 16–21, 2019.

Sengupta, M., A. Habte, and J. M. Freeman. 2019. "The Case for Custom TMYs: Examples Using the NSRDB: Preprint" (NREL/CP-5D00-74063). Presented at the 46th IEEE Photovoltaic Specialists Conference (IEEE PVSC 46), Chicago, Illinois, June 16–21, 2019.

Sengupta, M., A. Habte, Y. Xie, A. Lopez, and C. A. Gueymard. 2019. "The National Solar Radiation Database (NSRDB) for CSP Applications: Preprint" (NREL/CP-5D00-72310). Presented at the 2018 Solar Power and Chemical Energy Systems Conference (SolarPACES), Casablanca, Morocco, October 2–5, 2018.

Sengupta, M., A. Lopez, A. Habte, and Y. Xie. 2019. "Improving the Accuracy of the National Solar Radiation Database (1998-2016): Preprint" (NREL/CP-5D00-72410). Presented at the 2018 European PV Solar Energy Conference and Exhibition (EU PVSEC), Brussels, Belgium, September 24–28, 2018.

Seo, G.-S., M. Colombino, I. Subotic, B. Johnson, D. Gross, and F. Dorfler. 2019. "Dispatchable Virtual Oscillator Control for Decentralized Inverter-Dominated Power Systems: Analysis and Experiments: Preprint" (NREL/CP-5D00-72774). Presented at the 2019 IEEE Applied Power Electronics Conferences (IEEE PELS), Anaheim, California, March 17–21, 2019.

Shah, S., P. Koralwicz, R. Wallen, and V. Gevorgian. 2019. "Impedance Characterization of Utility-Scale Renewable Energy and Storage Systems: Preprint" (NREL/CP-5D00-73173). Presented at the 2019 Energy Conversion Congress and Exposition (IEEE ECCE), Baltimore, Maryland, September 29–October 3, 2019.

Shah, S., V. Gevorgian, and H. Liu. 2019. "Impedance-Based Prediction of SSR-Generated Harmonics in Doubly-Fed Induction Generators: Preprint (NREL/CP-5D00-72559)." Presented at the 2019 IEEE Power and Energy Society General Meeting (IEEE PES GM), Atlanta, Georgia, August 4–8, 2019.

Singh, A., and K. Prabakar. 2019. "Controller-Hardware-in-the-Loop Test Bed for Fast-Switching SiC-Based 50-kW PV Inverter: Preprint" (NREL/CP-5D00-71544). Presented at the 44th Annual Conference of the IEEE Industrial Electronics Society (IEEE IECON), Washington, D.C., October 21–23, 2018.

Singh, A., M. Chinthavali, S. Sudhoff, K. Bennion, K. Prabakar, X. Feng, Z. Wang, and S. Campbell. 2018. "Development and Validation of a SiC Based 50 kW Grid-Connected PV Inverter: Preprint" (NREL/CP-5D00-70872). Presented at the 2018 IEEE Energy Conversion Congress and Exposition (IEEE ECCE), Portland, Oregon, September 23–27, 2018.

Singh, A., S. Reese, and S. Akar. 2019. "Performance and Techno-Economic Evaluation of a Three-Phase, 50-kW SiC-Based PV Inverter: Preprint" (NREL/CP-5D00-73124). Presented at the 46th IEEE Photovoltaic Specialists Conference (IEEE PVSC 46), Chicago, Illinois, June 16–21, 2019.

Tan, S. Y., H. Saha, A. Florita, G.P. Henze, and S. Sarkar. 2019. "A Flexible Framework for Building Occupancy Detection Using Spatiotemporal Pattern Networks: Preprint" (NREL/CP-5D00-73359). Presented at the IEEE American Control Conference, Philadelphia, Pennsylvania, July 10–12, 2019.

Thiagarajan, R., A. Nagarajan, P. Hacke, and I. Repins. 2019. "Effect of Reactive Power on Photovoltaic Inverter Reliability and Lifetime: Preprint" (NREL/CP-5D00-73648). Presented at the 46th IEEE Photovoltaic Specialists Conference (IEEE PVSC 46), Chicago, Illinois, June 16–21, 2019.

Thiagarajan, R., P. Gotseff, A. Hoke, and E. Ifuku. 2019. "Inverter Testing for Verification of Hawaiian Electric Rule 14H: Preprint (NREL/CP-5D00-73647)." Presented at the 46th IEEE Photovoltaic Specialists Conference (IEEE PVSC 46), Chicago, Illinois, June 16–21, 2019.

Veda, S., M. Baggu, and A. Pratt. 2019. "ADMS Test Bed: Defining a Use Case for Data Improvement for ADMS Deployment: Preprint" (NREL/CP-5D00-72404). Presented at the 2019 IEEE Innovative Smart Grid Technologies Conference (IEEE ISGT), Washington, D.C., February 18–21, 2019.

Vignola, F., J. Peterson, F. Mavromatakis, S. Wilbert, A. Forstinger, M. Dooraghi, and M. Sengupta. 2019. "Removing Biases from Rotating Shadowband Radiometers: Preprint" (NREL/CP-5D00-72278). Presented at the 2018 Solar Power and Chemical Energy Systems Conference (SolarPACES), Casablanca, Morocco, October 2–5, 2018.

Vignola, F., J. Peterson, R. Kessler, V. Sandhu, M. Sengupta, and A. Habte. 2019. "Improved Field Evaluation of Reference Cell Using Spectral Measurements: Preprint" (NREL/CP-5D00-74037). Presented at the 46th IEEE Photovoltaic Specialists Conference (IEEE PVSC 46), Chicago, Illinois, June 16–21, 2019.

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Conference Papers (Published Proceedings)

Aworo, O.J., and B. Mather. 2018. "Experimental Determination of PV Inverter Response to Grid Phase Shift Events" (NREL/CP-5D00-74635). In *Proceedings of the 2018 IEEE Power & Energy Society General Meeting* (IEEE PES GM). Piscataway, NJ: Institute of Electrical and Electronics Engineers.

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Habte, A., M. Sengupta, A. Andreas, R. Narasappa, T. Thomas, A. Wolf, and C.A. Gueymard. "Characterization of a Low-Cost Multi-Parameter Sensor for Solar Resource Applications" (NREL/CP-5D00-73701). In *Proceedings of the 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC)*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

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