NREL
Transforming ENERGY

ESIF 2020

Associate Director's Letter

This year has been monumental for the Energy Systems Integration Facility (ESIF) and the research and development that it supports. Thanks to an expansion in capabilities to support the Advanced Research on Integrated Energy Systems (ARIES) platform, the ESIF has entered a new era of research at the frontier of future energy systems. The ARIES initiative was officially announced in August, when the U.S. secretary of energy visited the National Renewable Energy Laboratory (NREL).

ARIES is a research platform designed to help the nation explore the possibilities of tomorrow's energy systems while addressing the realities of complexity and scale. Rather than evaluating new clean energy and energy-efficiency technologies in silos, ARIES expands the research view to take in the full picture, from consumers, to distribution, to transmission. This unprecedented perspective brings opportunities and risks to the surface in the spaces where sectors like transportation, communications, and the electric grid meet.

The ESIF is a key component of ARIES, bringing grid-edge research assets and high-performance computing (HPC) resources. A high-speed data link connects to city- and campus-scale research assets at NREL's Flatirons Campus, and an HPC-powered virtual emulation environment makes it possible to conduct research at the scale of a large metropolitan city or region.

ARIES capabilities allow the ESIF's users to access the true complexity and scale that define tomorrow's challenges in energy storage, power electronics, hybrid energy systems, future energy infrastructure, and cybersecurity.

Though it is early, the results rolling in from ARIES research hint at its promise. This year, the ESIF supported simulations for electrified mobility integration at an unprecedented scale: tens of millions of vehicles and their charging impacts on a grid the size of the San Francisco Bay Area. And at NREL's Flatirons Campus, ARIES graduated from a concept to a real-world application. Using on-site renewable generation and storage, NREL researchers and engineers demonstrated the ability to black-start the campus and run it as an islanded microgrid.

A key factor in NREL's ability to explore an ever-larger scale at great fidelity is our HPC center. Projects in energy systems integration and beyond—from immense simulations of distribution systems to evaluations of distributed optimization using reinforcement learning—rely on cutting-edge computational power at the ESIF. The Eagle supercomputer remains a beacon of energy efficiency, as computing occupies an ever-larger share of national energy consumption.

This year, as part of ARIES, the ESIF expanded its cybersecurity capability through commissioning a new Cyber-Energy Emulation Platform (CEEP). CEEP builds on NREL's internal research investment and makes it possible for users to interface physical energy and cyber devices with cross-domain simulations to visualize and evaluate security and resilience scenarios, such as outages, black-start recoveries, and response to cyberattacks. Users are now able to see the security impacts on their systems in real time, and they can better predict and defend against threats, whether cyberattacks or superstorms. On this platform, we are developing the latest research in energy security, such as artificial intelligence-based identification of grid anomalies and blockchain-secured energy transactions.

While we are advancing energy resilience in the labs, human resilience is also a vital part of the ESIF story this year. Because of COVID-19, running a safe lab has taken on new dimensions. Through the versatility and flexibility of our operations staff, researchers, and partners, we have been able to continue ESIF research by maintaining in-lab personnel where possible and by prioritizing safety and precaution above all. We are grateful for the resolve of the NREL community during this time.

The ESIF has also continued to support world-class research. The facility's research assets and expert staff contributed to two of the innovations honored in October 2020 by *R&D World* magazine this year. The Regional Energy Deployment System (ReEDS) received one of four R&D 100 Awards NREL won in 2020, and OptGrid garnered one of our two Special Recognition awards. In 2019, two NREL projects—PREconfiguring and Controlling Inverter SEt-points™ (PRECISE) and ResStock™—were also recognized by *R&D World* magazine as one of the nation's 100 most innovative technologies for that year.

The research featured in this report shows that our partners turn to NREL for reliable guidance to establish secure, resilient, and affordable energy systems. Industry, utilities, and grid operators are weighing many options to make the best decisions on grid modernization investments. At the ESIF, we can make those options clear by identifying the best path to reach ambitious goals. This year showed the promise of our new research strategy and capabilities—and the best is yet to come.

So I leave you with the same invitation that has driven us from the beginning: bring us your biggest energy systems integration challenges, and let's solve them together.

Sincerely,

Juan Torres

Associate Laboratory Director for Energy Systems Integration at NREL

Martha Symko-Davies

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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. To address this continuously changing landscape, DOE recently 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 Delivery and Energy Reliability (OE); the Office of Energy Efficiency and Renewable Energy (EERE); and the Office of Cybersecurity, Energy Security, and Emergency Response (CESER).
- 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. The National Renewable Energy Laboratory (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.

Learn more about the Grid Modernization Initiative at energy.gov/grid-modernization-initiative.

ARIES Overview

The ARIES Initiative

Energy Systems Integration Facility (ESIF) research has been enhanced by the Advanced Research on Integrated Energy Systems (ARIES) platform—a buildout in research and infrastructure and a corresponding vision for its application. ARIES will allow NREL researchers and the scientific community to address the fundamental challenges of integrated energy systems at scale.

ARIES represents a substantial scale-up in research experimentation from existing research platforms, allowing for research up to the 20-MW level and beyond. ARIES will make it possible to understand the impact and get the most value from the millions of new devices—such as electric vehicles (EVs), renewable generation, hydrogen, energy storage, and grid-interactive efficient buildings—that are being connected to the grid daily.

The scale of the platform will also make it possible to consider opportunities and risks with the increasing interdependencies between the power system and other infrastructure, such as natural gas, transportation, water, and telecommunications.

ARIES will leverage existing research capabilities at NREL's ESIF, new capabilities at NREL's Flatirons Campus, and a virtual emulation environment connecting hardware assets at these sites with up to millions of digitally emulated devices. A high-speed data link will interconnect ARIES with other national laboratories and research partners to enable access to a greater set of research capabilities.

Research areas

- **Energy Storage**
- **Power Electronics**
- **Hybrid Systems**
- **Future Energy Infrastructures**
- **Cybersecurity**

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High-Impact Projects Overview

Central to the mission of the ESIF is exploring 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) 2020, new high-impact projects began that are set to accelerate innovation and develop scalable technologies across industry.

Partners	Project
	2019
Anterix	Enabling Realistic Communications Evaluations for ADMS (ERCEA)
Salt River Project	Residential Battery Impacts on Home Owners and Grid
Centrica Business Solutions	Resilient and Cost-Effective Hybrid Li-ion Battery Energy Storage System for Sites With Solar Generation and EV Charging
Eaton	Modular Expeditionary Technology Evaluation Resource
	2020
Colorado State University	Development of Statistical Fault-Detection Algorithms for Modern Power Grid Networks
U.S. Department of Defense: Environmental Security Technology Certification Program	Large-Scale Energy Storage and Microgrids
Cummins	Advanced Microgrid Controller
Exelon/EWF	Zero-Export Feeder Through Transactive Markets

A highly flexible design allows the ESIF to provide unique, integrated research capabilities for major energy systems. From hydrogen and energy security to advanced mobility, the ESIF is committed to transforming science and research every day.

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

Key Performance Indicators

ESIF Laboratories

- 155 users
- Lab availability - 95%
- Lab utilization - 82%.

HPC Data Center

- 457 users
- Availability - 89%
- Utilization - 92%.

Devices & Integrated Systems

Project Spotlights

NREL Develops Innovative Models for Energy Storage with Arizona Utility Partner

Now in the third year of evaluating battery energy storage systems (BESS) with the Arizona utility Salt River Project (SRP), NREL has taken field data from the past 2 years to the lab. These extensive data will be used to develop high-fidelity models with the potential to transform the understanding of both residential and commercial battery systems.

The study, which centered on how BESS function in practice for SRP customers, has led to the development of two NREL software inventions for utilities to improve battery systems and rate design. During the past year, researchers validated the technologies in the ESIF and made each model commercial-ready and available for use.

The Thermo-Electric Model for Powering Energy Storage Technologies (TEMPEST) combines electrical and thermal modeling for residential-scale battery systems. Key inputs to the model include house load, temperature of the battery location, and solar generation. Built as a thermal electric model for residential battery performance, TEMPEST can be used to analyze the effect of battery temperature on the overall performance of a residential storage system. The model estimates how a battery system's thermal characteristics will impact the battery profile and its performance in meeting house load and generating solar output, thus helping to assess realistic value to customers.

A second model, Generation forecasting and parameter Estimation Tool for Solar (GET-Solar), was developed to estimate behind-the-meter solar generation from distributed data sets, providing value for applications where only partial solar generation data are available and on-site irradiance data are not available. Using sets of data from diverse solar-generating sites that are close in proximity, limited information can be used to generate accurate solar profiles. The tool calculates photovoltaic (PV) technical parameters, and it calculates energy output by modeling the impacts of shading and cloud cover that are added to clear-sky irradiance profiles. GET-Solar can also be used for applications where historical PV data are available to estimate local shading at various solar positions. Additionally, the tool is helping the NREL-SRP team model solar output for areas with limited data sets so energy storage data can be extracted from the utility's advanced metering infrastructure (AMI).

The development of these models represents a culmination of 2 years' worth of data collection, evaluation, and model refinement to help industry improve the performance of BESS and battery rate design. The real-world-informed models will allow SRP and other utilities to understand the varying constraints and benefits to solar-plus-storage systems, providing the decision tools that are needed for optimal BESS design as customer DER adoption continues to increase.

NREL and Centrica Develop Hybrid Storage System Optimal Design Tool

NREL is partnering with Centrica to design, build, and analyze a resilient and cost-effective hybrid BESS. In the ESIF, NREL has integrated a hybrid storage unit with Centrica's edge controller, an intelligent controller that leverages the strengths of three types of batteries—high power, high energy, and second life—to collectively optimize their dispatch and maximize their service life. Through optimal design analysis, the three battery stacks are sized with different energy capacities, power levels, costs, and life expectancies. Each stack provides a different trade-off where one outcome can benefit the whole system.

This project resulted in the development of HYBrid Robust Energy Storage Design (HYBRED), a hybrid storage system optimal design tool. Following multiple use cases conducted during this project, NREL researchers used HYBRED to determine that using high-power, high-energy, and second-life hybridization is more beneficial for participation in a dynamic regulatory market than using demand reduction and only one large high-energy stack, which has more energy (kWh) but lower power capability. The findings from this project uncovered that the success of the hybrid battery storage system optimal design depends on battery specifications, cost, and target use cases. Cheaper upfront costs, better use case performance, and higher lifetime cost benefits can be achieved if design and control are optimized for the target use cases.

Watch: "Centrica and NREL Pursue a Cost-Effective Hybrid Battery Storage System" to learn more about this partnership: (https://bit.ly/2Lk6JXp)

Sensing & Measurement

Project Spotlights

NREL and Industry Partner Anterix Use Private LTE Communications to Improve Performance of Modern Grid Systems

NREL has partnered with Anterix, the largest holder of licensed spectrum in the 900-MHz band, which has recently been reallocated for private utility use as a result of a Federal Communications Commission ruling. The two joined forces in 2018 to evaluate how private LTE wireless network performance could impact grid-related control and protection applications. During the past year, the team successfully demonstrated multiple utility wireless communications use cases and evaluated the performance of a real 900-MHz private LTE communications system performed under various grid conditions.

Leveraging NREL's advanced distribution management system (ADMS) test bed at the ESIF, researchers evaluated how the Anterix private LTE network impacted grid applications, such as fast DER disconnection, known as direct transfer trip, by reconfiguring the wireless network. Such functionality typically requires fiber-based communications, which is expensive to install and maintain, particularly for remote DERs. The team discovered that message prioritization has a large impact on communications timing; hence, control of message queuing is a key component for critical infrastructure applications. The team, in collaboration with an industry advisory board, also uncovered that private LTE technologies can help protect DERs and other distribution automation applications.

The results of this project will help derisk wireless communications implementations, particularly for utilities with high levels of DERs and other grid-edge devices.

Watch: "Enabling Realistic Communications Evaluations for ADMS, Insights and Opportunities" to learn more about this partnership: (https://bit.ly/3qkSgKr)

NREL and Eaton Slash Fuel Use for Microgrids with Broader Lessons for All Energy Systems

NREL and Eaton are showing that energy sensing and data analytics can be used to optimize multi-energy systems to reduce fuel use and smoothly operate DERs while protecting critical infrastructure. A remote microgrid is the first demonstration case, and the technology will be scalable to larger microgrids and building campuses.

The NREL-Eaton collaboration uses hardware and data resources across NREL, including grid simulators, representing a microgrid in the ESIF; a secondary remote microgrid setup at the Flatirons Campus; and real sensing, hardware, and communications infrastructure.

An important outcome of the NREL-Eaton collaboration is predictive analytics that simultaneously consider thermal and electric domains. This project also integrates data streams between hardware such as in-field devices and forecast modeling services in the cloud. Follow-on work will scale up this project to demonstrate federated data sharing among microgrids. With machine learning based on local energy sensing data and weather forecasting, the NREL-Eaton collaboration will allow proactive control across energy domains with significant performance improvement for microgrids, buildings, and other energy systems.

Project Highlights

NREL and Colorado State University Apply Advanced Mathematics to Find Faults on Modern Power Systems

In a new project funded by the National Science Foundation, Colorado State University and NREL are looking toward statistical algorithms to detect, classify, and localize faults. The project builds on efforts led by the DOE EERE Solar Energy Technologies Office (SETO) to characterize fault behavior caused by modern grid devices. NREL's partnership with Colorado State University will develop advanced fault-detection algorithms, which will open power systems research to a contemporary class of statistical mathematics that improve the accuracy and speed of fault-detection schemes. Specifically, the team will train algorithms to identify and classify faults based on real power flow data sets. Within the first year of the project, the team created the necessary data to explore statistical approaches to fault detection on systems with high numbers of DERs—a first for power systems engineering. Their results will be scalable for nationwide adoption, ensuring safer operation of modern power systems.

Go-Solar Project Leverages Advanced Machine-Learning Algorithms to Manage Millions of PV Devices

With co-funding from the SETO Enabling Extreme Real-Time Grid Integration of Solar Energy (ENERGISE) program and Hawaiian Electric Company (HECO), NREL researchers have designed an approach for managing distributed and centralized resources by optimizing limited data. Developed under a project called Go-Solar, this approach leverages advanced machine learning algorithms to estimate, predict, operate, and control a power system with up to tens of millions of solar energy arrays through only a small number of sensors and controllable devices.

Using the Hierarchical Engine for Large-Scale Infrastructure Co-Simulation (HELICS) and hardware-in-the-loop (HIL) validation, researchers are using HECO's data as well as transmission and development models to test and refine the Go-Solar algorithms. They will then conduct a full-scale simulation of the entire Oahu island to demonstrate the effectiveness of Go-Solar technologies in a real-world environment. With the goal of reaching 100% renewable energy by 2045, this is the next step toward making this a reality.

NREL Advances Grid Visibility through the Next Step in Advanced Metering Infrastructure Research

NREL, San Diego Gas & Electric Company (SDG&E), and OE are partnering to help improve utility planning models using AMI. With $5 billion invested in AMI across the United States, the networks of smart meters are predominantly used by the utility industry for energy metering and billing purposes. This AMI for operations research moves forward from the past ESIF project being implemented into the operations of SDG&E. This research leverages AMI's pervasive presence on the distribution grid to get an instant read of customers' power quality and to use this visibility to improve grid operations and situational awareness. Building on this past project, NREL will use the ESIF's ADMS test bed to recreate SDG&E's selected distribution feeders and realistically simulate high penetrations of PV to demonstrate an advanced AMI data-driven control for feeder voltage regulation. This use case will demonstrate the application of AMI data for real-time controls through a combination of software tools, real-time digital simulation platforms, and actual hardware equipment.

Watch: "NREL's ADMS Test Bed Connects Utilities to Modern Controls" to learn more: (https://bit.ly/39CxVue)

System Operations, Power Flow, & Control

Watch: "OptGrid: Optimizing Renewable Energy Technologies at the Grid Edge" to learn more about this tool: (https://bit.ly/2VqQQ2P)

Project Spotlights

An Architecture to Enable Distributed Resources with Modern Grid Management

On one end, the grid is centralized and coordinated by regional authorities that guarantee reliability; on the other end, it is increasingly distributed. Through the 2019 GMLC project 2.1.1, NREL is creating a middle ground, where aggregated DERs are economically dispatched to provide power and reliability services alongside other bulk power assets. This project leverages and brings together a group of collaborating institutions, including SDG&E and Oracle, for high impact.

The newly established project, named Federated Architecture for Secure and Transactive Distributed Energy Resource Management Solutions (FAST-DERMS), provides an architecture for aggregated DERs to participate in distribution and transmission markets. FAST-DERMS will use common communications standards and stochastic control methods that maximize the benefits of DERs and behind-the-meter technologies without disrupting centralized control systems.

In the project's first year, NREL contributed an initial draft of the system architecture and collaborated on a mathematical formulation of the tool's flexible resource scheduler. The scheduler is a stochastic, control-based solution that can be used for economic and reliable dispatch of DERs. The scheduler could be implemented on an ADMS or on a separate system that interfaces with an ADMS. An evaluation of the scheduler and other controls is planned for FY 2022 using DOE's ADMS test bed and GridAPPS-D.

NODES Leaves Legacy of ARPA-E Excellence, from Concept to Commercialization

NREL's work under the Advanced Research Project Agency-Energy (ARPA-E) Network-Optimized Distributed Energy Systems (NODES) projects finished in early FY 2020 with field deployments of NREL-developed control solutions in California and Colorado. The NODES algorithms also manifested in a commercial product for grid optimization, which has been licensed by industry partner Utilidata, Inc.

In FY 2020, NREL researchers achieved their largest simulation yet using NODES' algorithms: Hundreds of hardware DERs and tens of thousands of simulated DERs were optimally coordinated together to provide a first-of-its-kind demonstration of distribution feeder-scale fast frequency response. Following that effort, the ADMS test bed was connected with the 100+-device HIL test bed to further demonstrate how NODES algorithms can be integrated with commercial ADMS solutions.

Commercially, the NREL NODES project algorithms have entered the electrical industry as OptGrid (go.usa.gov/x7g3B), a software for distributed grid management that was recognized as a 2020 R&D 100 Awards finalist. OptGrid has been licensed by Utilidata, Inc. for advanced control and communications using smart meters. Meanwhile, industry partner Heila Technologies—which collaborated with NREL on the first field demonstrations of real-time optimal power flow—continues to support distributed grid optimization with its hardware implementation of NODES algorithms.

Project Highlights

Borrego Springs Microgrid Moves Toward 100% Renewable Energy

SDG&E's Borrego Springs microgrid is one of the largest in the United States, serving 2,500 residential and 300 commercial and industrial customers. To improve energy resilience in a remote community prone to extreme weather, NREL researchers are helping to deploy an advanced grid-forming battery. The battery inverter's fast frequency response will be used to stabilize the microgrid's voltage as it transitions to providing power from the microgrid's DERs. Funded by SETO, this project will leverage NREL researchers' prior microgrid controller work at the ESIF to evaluate the grid-forming battery inverter's ability to manage microgrid transitions. The addition of the battery will enable seamless transition to islanded power using 100% renewable energy when the microgrid disconnects from the grid to operate independently.

Researchers Develop a Self-Healing Distributed Grid for Optimized Resilience

With laboratory-directed funds, NREL researchers developed a self-healing grid model with an advanced machine learning algorithm. The model can change the topology of a grid system for optimal configuration if it is damaged and optimize DERs to support the disrupted grid's operation, minimizing load shedding and maximizing power supply for critical loads. As part of this project, NREL researchers also developed a resilience quantification method, which can identify how resilient a grid system is by analyzing its characteristics. Data obtained from the resilience quantification method can be used as feedback for the optimization model. For utilities and other industries that already have traditional distribution automation systems and DERs, the self-evolving model capability can leverage these two energy systems to work together and optimize total system resilience.

NREL Validates New Control Architecture to Improve System Performance

With the aim of helping utilities optimize systems with high penetrations of distributed PV generation, NREL partnered with Xcel Energy, Schneider Electric, the Electric Power Research Institute (EPRI), and Varentec on the Enhanced Control and Optimization of Integrated Distributed Energy Applications (ECO-IDEA) project. Funded by SETO through the ENERGISE program, ECO-IDEA enabled researchers to develop and evaluate an interoperable and cybersecure utility control architecture. Using a set of simulated Xcel Energy feeders, the architecture showed reliable and efficient system-wide operations at multiple spatiotemporal scales when facing volatile conditions. Demonstrations of the architecture showed that by coordinating the control of legacy assets and new grid-edge devices, which are edge-of-network grid optimizers, with control of PV inverters through NREL's real-time optimal power flow algorithms, utilities can improve voltage performance and situational awareness.

Deep Learning Overcomes Difficulty of Optimizing Buildings for Energy Efficiency and Grid Services

NREL and partner University of Colorado Boulder are creating a control architecture that blends building models and machine learning. With support from the DOE EERE Building Technologies Office (BTO), the project team developed the algorithmic foundations for controls that adapt to building energy preferences while optimizing energy efficiency. Next steps will involve programming the algorithms on controllers and a real building pilot in collaboration with project partners QCoefficient and Heila Technologies.

Zero Energy Homes Are Providing Smart Solutions for the Grid

In a 3-year project funded by SETO, NREL is partnering with Thrive Home Builders, Fort Collins Utilities, A.O. Smith Corporation, and Holy Cross Energy to design a smart community with state-of-the-art energy-efficiency technologies and high penetrations of energy storage and PV arrays. The challenge in constructing these high-efficiency homes is to improve their coordination with the grid. The team is using data from partners and artificial intelligence (AI)-driven methods to model personal behaviors of homeowners in a residential home research platform at the ESIF. A community-level aggregator coordinates individual and aggregate energy resources to adjust demand in response to real-time grid signals. In the final year of the study, NREL researchers will validate actual energy savings and homeowner benefits by demonstrating energy-efficiency models in more than 10 new-construction duplexes and townhomes in a new smart community in western Colorado.

Design & Planning Tools

Project Spotlight

HELICS Software Becomes Hub for Integrated Energy Modeling

HELICS is a glue-like software that links multiple off-the-shelf simulation tools to act as a single unified model. This year, the HELICS development team pursued significant usability upgrades and breakthrough case studies under GMLC project 1.3.2, HELICS+.

The HELICS+ developments helped to transform HELICS from a facilitator of integrated research into a hub with a wider user base and an enhanced code base. For NREL's part in the multi-laboratory effort, researchers made HELICS more accessible by expanding its documentation, designing an online graphical user interface, rewriting its command-line interface to support easier configuration, and creating a "Try HELICS Online" function.

Among performance-related improvements, NREL's team developed an easy-to-use Python interface, published multiple software updates, and performed a comprehensive code review to improve HELICS's overall structure. The team also launched multiple use cases to showcase HELICS in action.

In FY 2020, HELICS was also central to several large-scale simulations in multiple NREL projects. The OE-funded North American Energy Resilience Model (NAERM) project used HELICS extensively in simulating DER resilience use cases, and NAERM's real-time grid analysis framework has also been connected through HELICS. The Autonomous Energy Systems laboratory-directed research-and-development project made extensive use of HELICS for simulating advanced autonomous controls at unprecedented scales with hundreds of hardware devices. For mobility-grid integration, HELICS is being used in the DOE EERE Vehicle Technologies Office (VTO) Grid-Enhanced Mobility-Integrated Network Infrastructures—Extreme Fast Charging (GEMINI-XFC) project to understand the distribution system impact from EVs. And within the ADMS test bed, HELICS is now a core resource for integrating in-lab hardware with larger simulations. HELICS is also being used for large transmission-and-distribution cosimulation on the SETO-funded GO-Solar project and in the Los Angeles 100% Renewable Energy Study (LA100).

Ongoing development is planned for HELICS. In FY 2020, two new cost-share partnership agreements were established. The first is with long-term collaborator Eaton to explore enhanced convergence between commercial transmission and distribution tools. The second is with software company encoord and will expand HELICS' s natural gas grid modeling connections to support commercial tools and to validate cosimulation compared to single-tool simulations. Together, these use cases open possibilities for more integrated modeling across large-scale energy systems.

Project Highlights

High Returns for Reliability: NREL Develops Strategy for Battery Operation in Ancillary Markets

In FY 2020, NREL designed a high-revenue strategy for battery storage to operate in ancillary service markets. NREL's results show that battery system operators can enhance their net revenues by tailoring grid-supportive strategies in the ancillary market, creating new incentives for both operators and regulators to integrate battery storage.

NREL used data from partner Sumitomo Electric's 2-MW, 8-MWh redox-flow battery in California as well as historical data of settled ancillary market deals from the California Independent System Operator (CAISO). NREL also worked closely with CAISO to understand the market-settling engine and how batteries can optimally participate in ancillary service markets. Using these resources, NREL applied reinforcement learning to tailor a market participation strategy for the Sumitomo battery that increased revenue.

Real-Time Control Strategies Aid Utilities in Gearing Up for Surge in Electric Vehicles

To prepare for widescale EV deployment, utilities need to understand the potential impacts of charging to their grids and the specific equipment upgrades needed to support the load. In partnership with Xcel Energy, an NREL-led research team—including Sandia National Laboratories and Idaho National Laboratory—compared the impacts of different charge-control strategies on the distribution grid. The initial results of the VTO-funded study indicate that current mechanisms (such as time of use and advanced metering) are inadequate for handling larger EV penetrations. As such, the team plans to develop additional control strategies that account for real-time data pertaining to equipment capacity, voltage levels, and the status of DERs. This will enable utilities to perform cost-benefit analyses of smart-charge control strategies to maximize grid support and minimize implementation costs.

Blockchain-Based Distributed Market Software Developed to Meet Customer Supply and Demand

NREL is partnering with Exelon Utilities and Energy Web Foundation (EWF) to build out the technology to support energy blockchains that match community energy needs with local supply. The project will apply blockchain-based distributed market software adapted from EWF's open-source offerings to create a dynamic market. The market will serve a distribution feeder located in Washington, D.C., with 1,000 residential and 100 commercial buildings. Each building is registered with a secure digital identity and equipped with smart appliances and NREL's foresee™ home energy management system. This allows researchers to analyze the energy needs of each home, coordinate its communications with the distributed energy market, and integrate customers' supply and demand into grid operations based on the utility's distribution requirements. Using the ESIF's Eagle supercomputer, the project strives to reduce risks to distribution feeders by defining the technical architecture needed to fully implement a cost-effective transactive energy market with a decentralized digital platform. It is also expected to clarify the economic and operational benefits that such a market will offer to utility customers and to the utility itself, paving the way for future real-world pilots.

New Framework Is Helping a Hawaii Utility Achieve 100% Renewables and Helping Mainland Grids Schedule and Value Grid Services from Renewables

NREL has developed a new framework to support the transition to 100% renewables for states, cities, and regions pursuing that goal. The Multi-Timescale Integrated Dynamics and Scheduling (MIDAS) framework is a tool uniquely able to reveal interactions among the economics, reliability, and stability of grid operations. MIDAS simulates the impact of renewable variability on power systems operations—from day-ahead to subsecond intervals—integrating resource scheduling, economic dispatch, and dynamic simulation. It also uses machine learning to identify intervals for a more detailed stability assessment. The team is currently developing a use case for valuing renewables and grid services in the U.S. Western Interconnection. In partnership with HECO, NREL is also using MIDAS to help the island of Maui study critical scenarios for a future grid dominated by inverter-based resources.

Synthetic Data Sets Introduce High Standard of Realism and Scale for Grid Research

In FY 2020, the ARPA-E-initiated Synthetic Models for Advanced, Realistic Testing: Distribution Systems and Scenarios (SMART-DS) project made large strides in bringing replica power system data to researchers, replacing simplified toy models with highly accurate, large-scale, and configurable data sets. Among NREL research projects, SMART-DS data sets have become the standard for any-scale power systems research, enabling full-city, cross-domain simulations of energy systems and potential future technological scenarios. In this capacity, SMART-DS has been central to VTO's GEMINI-XFC project, the NREL-directed autonomous energy grids initiative, and others.

There are many synergies between SMART-DS and other NREL resources. ResStock™ and ComStock™ provide customer-level load time series, whereas the BTO-funded URBANopt™ tool is borrowing SMART-DS model generation methods to understand future connections between buildings and distribution systems. With follow-on funding from ARPA-E, a collaboration with the University of Texas at Austin is underway to extend SMART-DS to transmission system data and ultimately to create a replica model of the Electric Reliability Council of Texas grid.

Energy Security

Project Spotlight

Multi-Lab Project Advances Distributed Energy Security with Blockchain Solutions

Transactive energy markets that leverage blockchain—distributed ledgers that contain cryptographically signed, validated records of transactions—are gaining traction. Yet there has been little consistency in the security standards for how such transactions are executed, how devices are registered, and how devices are tracked.

One project, Blockchain for Optimized Security and Energy Management (BLOSEM), is a GMLC collaboration that aims to derisk and reduce cost through standardized metrics and testing while evaluating how domain expertise can inform blockchain technology solutions for the energy sector. The multi-laboratory team represents expertise from NREL, Ames Laboratory, the National Energy Technology Laboratory, Pacific Northwest National Laboratory, and SLAC National Accelerator Laboratory. Through a series of laboratory evaluation use cases, the team is exploring how blockchain can enable authentication of operating parameters for generation assets, secure communications for accessing and balancing demand response, secure market operations at the distribution level, and secure registration and authentication of DERs.

Since the project kicked off in FY 2020, the team assembled an industry advisory board and selected three high-priority cybersecurity use cases. Researchers are now developing detailed documentation of those three use cases and—in parallel—developing the software and hardware architecture that will be used to demonstrate these uses cases. The architecture will leverage NREL's cosimulation expertise, integrating with hardware throughout the ESIF and using the facility's high-performance computing (HPC) resources.

Increasing penetration levels of DERs are leading to millions of new connected devices across homes and neighborhoods, and transactive systems offer a market-based approach to engage these assets to meet future energy demand. At the same time, this growth in connectivity increases the potential for cyber vulnerabilities and necessitates methods that ensure transactions are secure. By getting ahead of cyber adversaries that see opportunity in exploiting new energy markets, blockchain can succeed in meeting such demands while introducing robust cybersecurity solutions for the future electric grid.

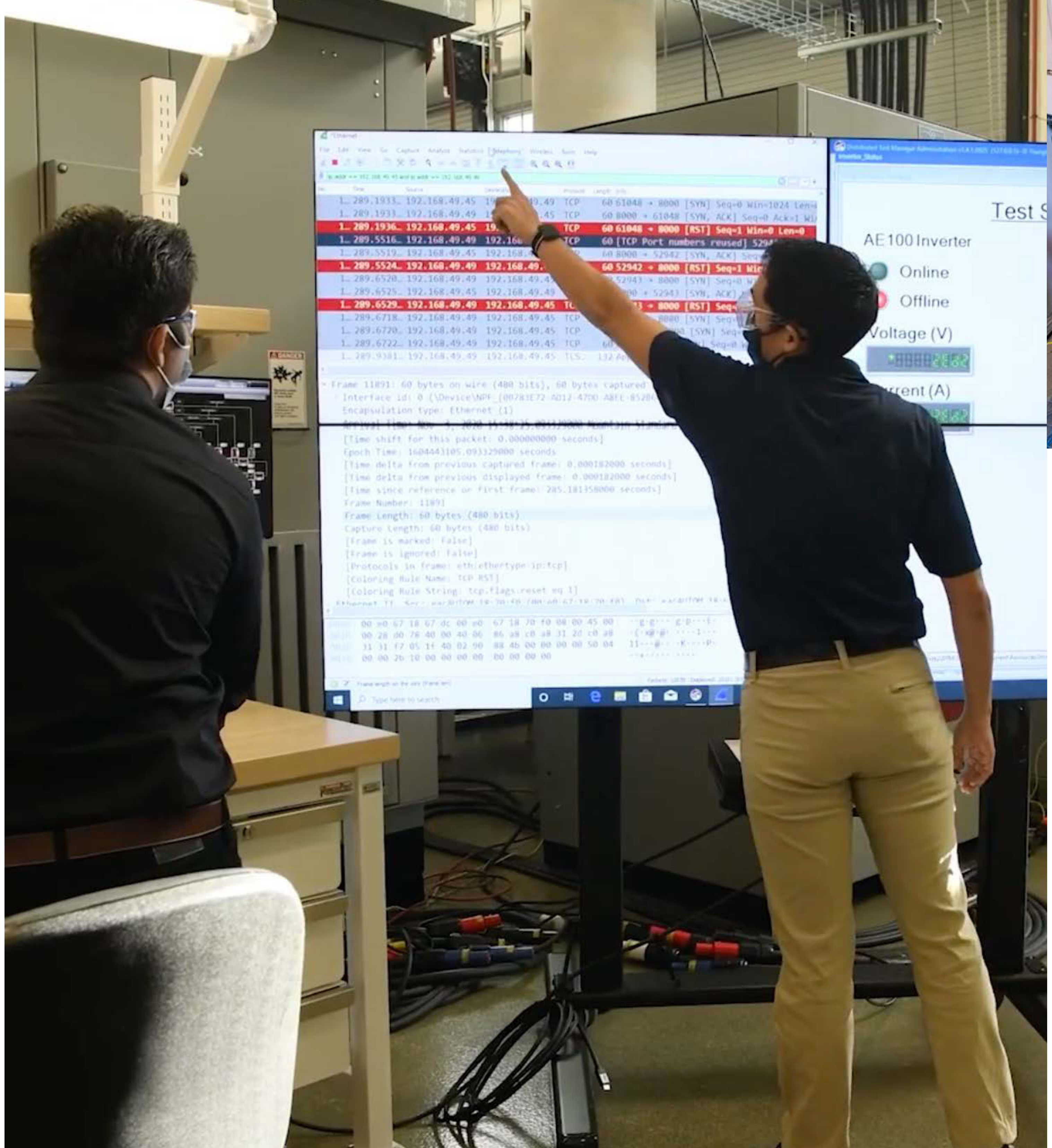
Project Highlights

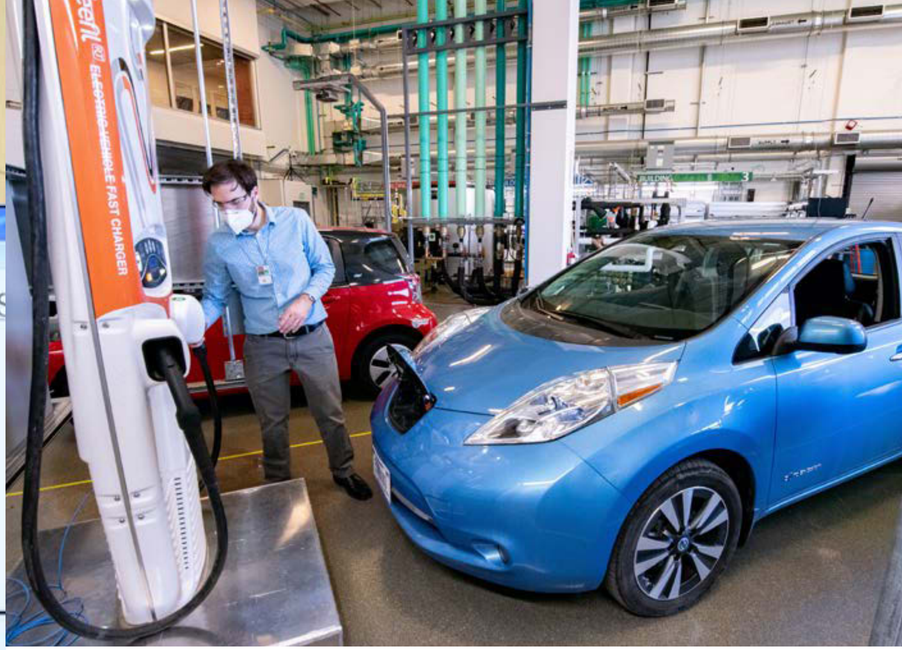
Creating Resources for Resilience, Situational Awareness with Cable Broadband Data

With support from CESER, NREL began working with CableLabs on advanced electric grid data analytics and visualization for situational awareness of grid activity. The project, Situational Awareness of Grid Anomalies (SAGA), leverages CableLabs' data and infrastructure with neighborhood-area-bounded models of the electric grid, and it enables integration with utility data for a high-speed monitoring and anticipatory tool. With cyber-physical anomaly detection through machine learning, early warning is possible for weather- or cyber-induced outages, safety violations, and economic disruption. In FY 2020, the team finalized SAGA's alpha version: connecting and streaming CableLabs's prototype application programming interface to data-driven power flow simulations. Researchers demonstrated transmission and distribution system models through cosimulation with a focus on Harris County, Texas, for grid and flood visualization.

Module-OT: A Low-Cost Tool That Provides Optimized Encryption for Distributed Energy Resources and Their Operational Networks

As urgency grows to secure modern electric grids with millions of new grid-edge devices, the NREL-developed technology Module-OT provides that security for energy resources, both new and old. In its final year of funding from CESER, NREL completed tasks to evaluate Module-OT for its ability to enhance the integrity of messages to and from DERs. This capability is especially important as new devices enter the market with limited consistency across security standards. Through a series of penetration tests, researchers demonstrated how Module-OT can withstand a variety of cyberattack scenarios. Taking this a step further, researchers connected Module-OT to the ESIF's Cyber-Energy Emulation Platform (CEEP) and validated its ability to secure DER devices against hypothetical and future attack scenarios. Now available for license, Module-OT can easily be customized and used with devices that support common industrial control system protocols.





Researchers Refine Mitigation Strategies and System-Level Awareness for Fast-Charger Cybersecurity Scenarios

With support from VTO, NREL continued work to identify high-consequence cyber events for EV fast chargers. In FY 2020, researchers leveraged the CEEP at the ESIF to connect a fast charger in the laboratory to an emulated distributed energy system. The platform allowed for the safe analysis of real and virtual network traffic on EV fast chargers in both normal and cyberattack scenarios—and the ability to develop threat detection and mitigation methods. This enhancement of cybersecurity research capabilities will impact the security of the 50,000+ fast-charger stations expected to be in operation by 2025. In the next fiscal year, researchers plan to add local energy storage as an optional fueling station component to simulations.

Energy Resilience

Project Spotlight

NREL Helps U.S. Department of Defense Power Military Bases with Large-Scale Energy Storage and Microgrids

Advanced microgrid technologies with large-scale energy storage are a key form of reliable energy for U.S. military installations to retain uninterrupted electricity despite grid outages, cybersecurity threats, or aging infrastructure. The U.S. Department of Defense (DOD) Environmental Security Technology Certification Program (ESTCP) provided funding for teams of industry partners to perform a phased high-impact research project to develop microgrids using large-scale energy storage solutions for U.S. military bases. Results from this effort are highly applicable to a wide range of nonmilitary applications as well, leveraging both the ESIF, at the 2-MW-scale, and the Flatirons Campus, at the 20-MW scale, for ultimate success.

The hardware-intensive 34-MW microgrid test system is based on Naval Air Station Patuxent River. In the first phase, companies designed and modeled microgrids with large-scale energy storage to supplement or replace aging, uninterruptable power supply battery systems. The old systems had formerly served downstream critical loads for 15 minutes of ride-through electricity. The new advanced batteries can power critical loads for several hours as well as export power upstream to run a microgrid for multiple value-stacked benefits when grid-tied or islanded. These advanced batteries are dispersed in the microgrid, and if one were to malfunction, its critical load could be served by the overall microgrid to provide extremely high reliability and resilience.

Three successful teams of strategic partners were selected to proceed to the next phase. The Ameresco team includes S&C Electric Company and Invinity Energy. The Arizona State University team includes 350Solutions, Ageto, and XENDEE. The Raytheon team includes Typhoon HIL and PXiSE. In addition, Cummins Power Systems joined as a fourth team because they were already testing their advanced microgrid systems with storage at the ESIF as part of a separate project.

In the last phase of the project, ESTCP provides funding for one or two successful teams to further demonstrate their advanced batteries and microgrid technologies at an even larger scale on actual military bases. As part of a deliberate outreach effort, the results of all phases of this high-impact project are fully releasable to inform DOD and the broader community of the economic and security benefits of large-scale, storage-enabled microgrids.

Project Highlights

Cummins Partnership Advances Resilient Microgrid Controllers for Industry

To evaluate the performance of an advanced energy storage microgrid controller, research engineers from Cummins Power Systems built a complex microgrid in the ESIF. The microgrid consisted of a grid-parallel natural gas generator, a grid-forming bidirectional BESS, and multiple solar PV inverters with independent solar irradiance profiles. Each DER had its own sophisticated local controller, and the entire system operation was orchestrated by the Cummins digital master controller with prototype programming. NREL researchers worked with Cummins to complete their controller programming and to validate the successful performance of the control algorithms. Aided by this collaboration, Cummins launched a new microgrid controller product for use across the United States and globally as the centerpiece for deploying advanced resilient microgrids.

North American Energy Resilience Model Project Advances Resilience in the Nation's Power Systems

Funded by OE, 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—to execute the project's national vision. In FY 2020, NREL supported the NAERM effort by performing real-time grid analysis simulation of electric sectors, threat modeling for electric and gas infrastructure (such as earthquakes and polar vortex modeling), and incorporating wind and solar forecasts. NREL researchers also developed a real-time operations platform for evaluating energy resilience in the United States, providing an engine for DOE and other national laboratories to synthesize their progress in bulk power system resilience.

Simplifying Fault Detection with Traveling Wave Signatures

In partnership with the University of Colorado Boulder, NREL researchers are developing methods to quickly detect faults and protect distribution systems with high penetrations of inverter-based PV. This project aims to use traveling wave signatures that exist in distribution systems—but are currently hard to extract—for fault detection. With funding from SETO, NREL researchers ran fault experiments in a medium-voltage test setup to simulate the traveling waves produced by these faults to immediately triangulate the fault location so utilities can respond to the problem quickly. Researchers are developing protection schemes and intelligent electronic devices that can detect traveling waves to ensure that the proposed method is scalable and can be used by multiple utilities across the country.

Institutional Support

Project Spotlight

NREL Develops Educational Resource Hub and Provides Technical Assistance for Stakeholder Adoption of IEEE Standard 1547-2018

The Institute of Electrical and Electronics Engineers (IEEE) Standard 1547-2018 lays the foundation for integrating DERs, including solar energy systems, with the electric distribution grid in the United States. With support from SETO, NREL researchers led the IEEE 1547 Revision Working Group, which brought the standard to its revised version in 2018.

With continued support from SETO in FY 2020, NREL researchers created a central educational hub with online resources (https://go.usa.gov/x7eMv) to help stakeholders adopt the revised standard, providing easy-to-scan summaries of technical reports, white papers, webinars, and presentations on the revised standard's requirements. The collection of materials showcases a wide range of material from industry groups as well as results from experimental studies performed at both the ESIF and at other national laboratories and research institutions.

In addition to the website, the NREL team provided technical assistance to support the adoption of the standard at the state and local levels, including the Michigan Public Service Commission (MPSC). During the past year, researchers provided technical expertise to help the commission update its interconnection rules for linking DERs to the electric grid. Enormous growth in interconnection requests from the state's two major utilities had increased to 3 GW in 2018, whereas in previous years the state's total operating solar generation had been slightly more than 100 MW. The team supported the MPSC efforts to revise Michigan's interconnection procedures to include the requirements of DERs based on IEEE Std 1547-2018.

With the launch of the educational website and technical assistance to utilities, the NREL team expects to fill knowledge gaps on how to achieve modern grid systems—ultimately to help accelerate the transition to a cleaner, more secure, resilient, and more efficient energy future.

Advanced Mobility

Project Spotlight

Electric Vehicle Research Infrastructure Evaluation Platform and Analysis Efforts Enable High-Power Charging Systems Research for Electrified Commercial Vehicles

A major challenge facing the electrification of commercial vehicle fleets centers around the need for a single fast-charging standard at rates exceeding 1 MW. An industry standard for megawatt chargers will streamline the introduction of commercial EVs by providing fleets with reliability and certainty when accessing high-power infrastructure. To help meet this challenge, NREL and the Charging Interface Initiative (CharIN), in partnership with the California Energy Commission, hosted a high-power charging connector event where industry participants conducted thermal, electrical, and ergonomic evaluations of their prototype charging connectors to ensure compatibility among devices from different manufacturers. The event employed the VTO-funded Electric Vehicle Research Infrastructure (EVRI) evaluation platform at the ESIF, including newly developed thermal evaluation benches for characterizing air- and liquid-cooled charging connectors for 350 to 3,000 A, along with a fit and ergonomics apparatus enabling the suspension of cables up to 11 feet in the air to simulate the dispenser-to-vehicle connection process.

Following the event, participants were provided with a full matrix of evaluation results mapping the temperature rise and current-carrying capability between each manufacturer's connector and inlet. The manufacturers will use the evaluation results to refine their designs. Ultimately, the results of this event will inform the design of interoperable connectors and inlets and support the development of a fast-charging standard for commercial vehicles—the Megawatt Charging System standard.

Such events also provide a forum for increased engagement on communications and control strategies to help reduce interconnection and site-equipment costs associated with new high-power charging stations for medium- and heavy-duty vehicles.

In related work, NREL also developed a modeling and analysis framework to investigate the potential effects of traffic volume and station constraints on multiport, multimegawatt charging station operation. Tapping into the Eagle HPC system at the ESIF, the framework integrated a DC, 1+-MW station model with vehicle arrival schedules (derived from Class 8 truck data from Fleet DNA) across different vehicle battery configurations. Researchers simulated the operation of 35,469 all-electric trucks across the United States to analyze charging requirements at key charging stations. Next, researchers will analyze station loads and examine grid and infrastructure requirements for selected scenarios to explore the impacts of controlled versus uncontrolled 1MW-level charging.

On the light-duty front, NREL has set the groundwork for a new project with EPRI, Eaton Corporation, Tritium, and Argonne National Laboratory to develop and validate a system of extreme fast-charging (XFC) equipment directly connected to the medium-voltage utility grid using a novel, modular, and interoperable approach. The project involves developing medium-voltage AC-to-DC conversion equipment—with active power management to reduce grid impacts—and a DC-to-DC head unit for fast charging light-duty vehicles or charging vehicles at 350 kW. This work will enable researchers to explore synergies applicable to commercial vehicle charging because depot or other long-duration charging of medium- and heavy-duty vehicles are expected to occur at these power rates and can leverage the flexibility of the DC-connected approach.

Project Highlight

Athena's High-Performance Computing-Enabled Planning Framework Provides Major Airport Insights to Understand and Mitigate Future Emissions and Congestion

Emerging mobility technologies along with increasing transportation demand make planning for the future more complex. The Athena project—a DOE-funded partnership with NREL, Oak Ridge National Laboratory, and the Dallas–Fort Worth (DFW) International Airport—has developed an HPC planning framework using the ESIF's newest supercomputer, Eagle, which provides insights and guidance around likely operational bottlenecks and potential solutions by exploring the impacts of emerging technologies and growth trends. Recently, using a data-driven approach for shuttle bus optimization, researchers at NREL have identified novel routes and schedules that result in a 20% reduction in energy use and emissions with minimal impact on passenger wait times. If passengers can tolerate more moderate ride and wait times, up to 50% savings can be achieved. Using NREL's framework, airports such as DFW can evaluate low-cost operational changes alongside infrastructure investments and consider long-term trade-offs to maintain efficient operations and maximize customer satisfaction while reducing emissions and delays.

Hydrogen & Renewable Fuel Systems

Project Spotlight

Materials Innovations Drive Improvements in Low-Temperature Electrolysis Cost, Performance

Through the HydroGEN Advanced Water Splitting Materials Consortium and other DOE EERE Hydrogen and Fuel Cell Technologies Office (HFTO) projects, NREL is developing materials characterization and fabrication techniques to accelerate the development of low-cost proton exchange membrane (PEM) electrolyzers.

In FY 2020, NREL researchers demonstrated that rotating disk electrode (RDE) characterization is a good catalyst screening method to predict electrolysis performance. RDE characterization is quicker and simpler than the alternative method of in situ membrane electrode assembly (MEA) testing. In an experiment with five commercial catalysts, catalyst activities measured via ex situ RDE were within +/- 20% of in situ MEA single-cell performance results.

Researchers also demonstrated scalable catalyst coating methods to produce MEAs for low-temperature PEM electrolysis. NREL fabricated iridium-oxide-based anodes using several coating methods and evaluated the MEA performance using in situ single-cell PEM electrolysis testing. The results showed no difference in cell performance between the cells fabricated with scalable coating methods and those fabricated using the laboratory-scale method. These findings suggest that MEA fabrication for PEM electrolysis can be scaled up by industry with minimal development effort to achieve laboratory-demonstrated performance and potentially lower hydrogen production costs.

Multiple industry and university partners are also using NREL's capabilities in materials characterization, device design and evaluation, and manufacturing and systems integration to advance their low-temperature electrolysis technologies.

Project Highlights

Hydrogen Filling Simulation Tool Drives Innovation for Fueling Stations

NREL researchers, in collaboration with Kyushu University in Japan, designed the Hydrogen Filling Simulation (H2FillS) tool to answer vital questions about the change in hydrogen temperature, pressure, and mass flow when filling a hydrogen fuel cell car. H2FillS (https://go.usa.gov/x7eMf) is the first free-to-use validated model of its kind and is intended to help industry develop novel methods for safe vehicle hydrogen fueling. H2FillS also offers insight into system design requirements and improvements that could help reduce operating costs. This project was supported by HFTO and eight industry partners, led by Frontier Energy, through DOE's H2@Scale initiative.

Electrolyzers Can Support Electric Vehicle Fast-Charging Demands on the Grid

Through system simulation, NREL demonstrated that a grid-integrated electrolyzer can stabilize the demand of an EV fast-charging station, presenting opportunities for fast-charging stations with colocated hydrogen fueling. The researchers, with support from HFTO, developed optimization models to estimate the station power for the integrated charging station with fluctuating intermittent EV fast-charging loads. Results showed that electrolyzers can maintain a constant power demand for an integrated station. The findings will be validated at the ESIF in early FY 2021 in a real-time power-hardware-in-the-loop setup using a 750-kW electrolyzer stack.

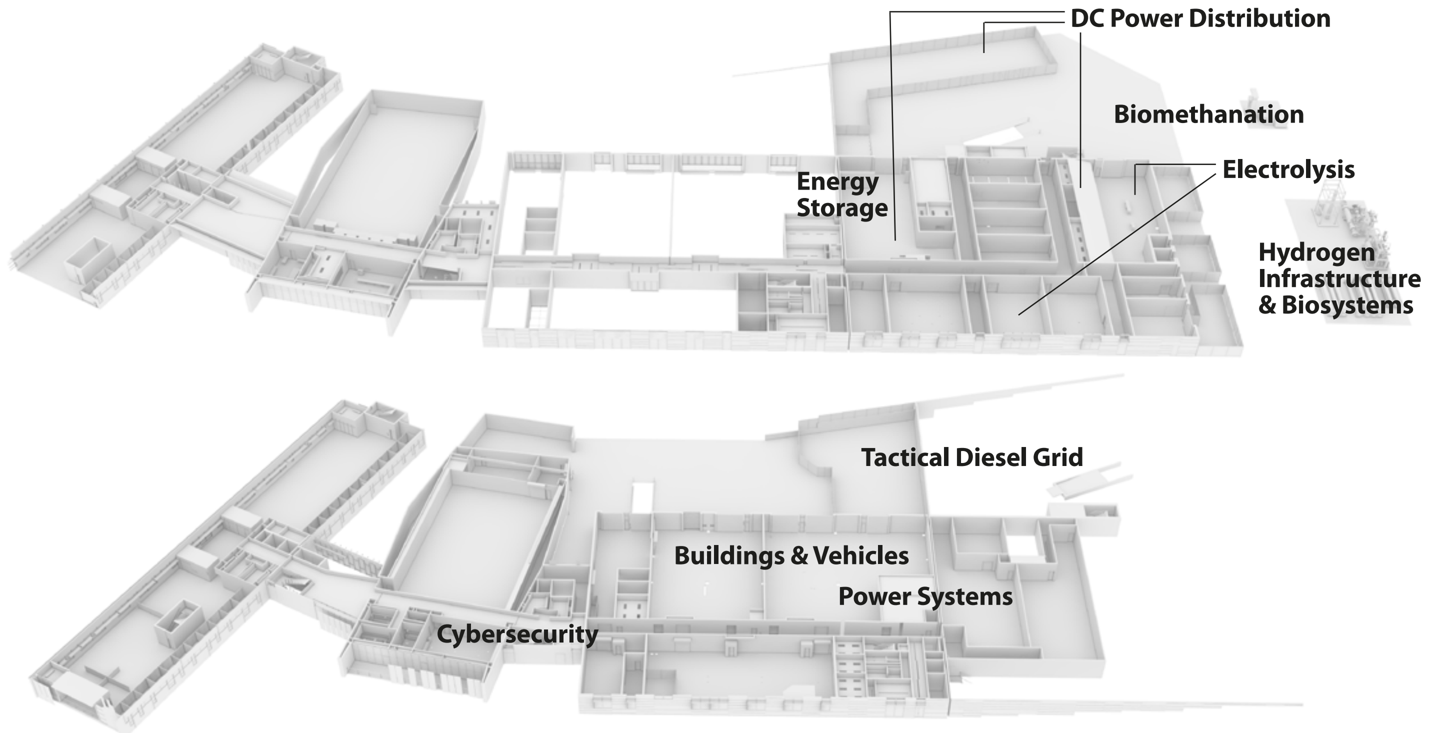
Scaling Up Electrochemical Conversion of Carbon Dioxide to Fuels and Chemicals

Researchers at NREL are improving electrochemical routes to convert carbon dioxide (CO2), which would otherwise be released into the atmosphere, into a range of value-added products. Previous limitations in energy efficiency, scalability, product selectivity, and production rate have prevented the widespread adoption of CO2 electrolyzers. Through research funded by HFTO and NREL's laboratory-directed research-and-development program, NREL scientists developed a scalable device design for electrochemical reduction of CO2 into formate, a chemical compound used as a hydrogen source for the synthesis of chemicals from biomass. NREL's device demonstrated a high rate of formate production and product selectivity using an industry-relevant cell size and is the first to achieve all three metrics simultaneously.

Validating Long-Duration Performance of Megawatt-Scale Electrolyzers

NREL is working with Nel Hydrogen to validate the long-duration performance of Nel's next-generation, megawatt-scale PEM electrolyzer stack. The 100-cell 750-kW stack requiring 3,500 amps was successfully installed and commissioned at NREL in August 2020. Working closely with Nel, NREL also upgraded nearly every aspect of the electrolyzer balance of plant. NREL will collect and analyze data on electrolyzer performance during 5,000 hours of 24/7 operations in fully unattended mode. The electrolyzer also produces 13 kg of hydrogen per hour for use in hydrogen and fuel systems research.

ESIF Lab Updates & Advanced Capabilities



Location and type of FY 2020 capability upgrades in the ESIF

Charging Research Focuses on the Integration of High-Power Electric Vehicle Charging with Buildings, the Grid, and Other Energy Systems

A robust set of hardware and software assets within the EVRI evaluation platform at the ESIF—which will include four 350-kW extreme fast chargers by the end of FY 2021—uniquely positions NREL in the national laboratory complex to examine the technical details for developing flexible, cost-effective control systems and strategies that balance the power demands of EVs with the realities of buildings and the grid.

By pairing a variety of EVs—including the notoriously difficult-to-electrify medium- and heavy-duty fleet—with a range of XFC equipment, simulators, and DERs, researchers can measure how varying loads and control systems affect the health of the broader system. This flexible infrastructure lets them predict how targeted interventions—such as behind-the-meter storage or on-site renewable energy generation—can help optimize on-the-ground EV charging together with the electrical loads of nearby buildings, a critical step for reducing the cost and time it takes to charge EV batteries. In another VTO-funded project, researchers are exploring integrated control approaches that would take advantage of flexibility in travel plans to help consumers decide where and when to charge for both their schedules and for the grid. In these ways, researchers are laying a foundation for the development of reliable, cost-effective infrastructure to support the shift to electrified transportation.

Following laboratory closures due to COVID-19, ESIF Operations implemented a three-phase approach to reopening laboratory activities, including verifying the functionality of all ESIF systems prior to reopening. Using this approach, the ESIF reached a laboratory productivity rate greater than 90% for the remainder of FY 2020.

Expansion of Cyber-Energy Emulation Platform Paves Way for High-Penetration Renewable and Distributed Energy Analysis

NREL completed a research network expansion and design of the CEEP, commissioning a new research space with immersive screens for enhanced observation, connecting with real hardware throughout the ESIF, and providing a more detailed view of a system's state. CEEP allows for the evaluation of complex, multilayer energy systems—and for the safe exploration of cyber- and physical attack scenarios. Enhancements to the platform enable the fast deployment of high-fidelity models, simplifying the process for spinning up complex system scenarios and providing an automation toolbox that hosts cosimulation frameworks. CEEP was used to evaluate a variety of cyber use cases in the ESIF, including the performance of the encryption technology Module-OT, the security of fast EV chargers, and the use of 5G communications for enhanced energy security. In the coming fiscal year, the platform will be used to study the cyber connections between research assets being evaluated under ARIES (see p. 6) and to develop emulated, digital twins of such devices.

Addition of Three High-Power Fast Chargers Boosts Extreme-Fast-Charging Experimentation

XFC is a critical technology for reducing the time required for EV charging. While enabling electrification, XFC requires intensive electric power use that could necessitate grid upgrades. With funding from VTO, NREL bolstered the capabilities of its EVRI evaluation platform with the addition of three high-power (350+-kW) XFCs (with a fourth charger expected soon), control and communications equipment for emulating EVs coupled with DC bidirectional sources, and real-time digital simulators. Such emulation and simulation equipment enables flexible, faster, and repeatable XFC experiments of current and future EVs. It also releases researchers from the bounds of specific vehicle charging profiles, allowing for experiments with future battery chemistries and charge profiles.

Expansion of Heavy-Duty Infrastructure

ESIF Operations staff prioritized expanding the physical footprint at the hydrogen systems research area through extending the high-load concrete pad and expanding the usable square footage adjacent to the existing hydrogen research pad, providing NREL researchers with space to add heavy-duty hydrogen fueling research equipment.

Implemented DC Circuit Breaker Technology for DC Power Distribution

ESIF engineering staff designed and implemented a DC circuit breaker for the research electrical distribution bus (REDB). This is a key upgrade from the original facility design, leveraging state-of-the art DC power system protection technology and making the ESIF a showcase for the advanced application of modern power system installations. Further, researchers implemented foundational design updates to the DC REDB system to implement the use of DC circuit breakers, which use fuses, contactors, and custom controllers, replacing the incumbent protection scheme. When the REDB was originally designed, DC circuit breakers were too large and did not offer the necessary ratings required by the ESIF. Now, the technology has advanced, and the ESIF is modernizing its DC distribution system to use this new technology.

Expanded Capabilities to Electrolysis Test Stands

In support of HydroGEN and H2NEW, NREL expanded electrolysis test station capabilities to include an additional two alkaline membrane water electrolysis single-cell test stations, four PEM water electrolysis single-cell test stations, and a PEM short-stack electrolysis test station capable of being expanded for multiple stack testing. Adding these capabilities to already existing capabilities at NREL will allow for increased support of hydrogen project needs.

Expanded Hydrogen Fueling Infrastructure Supports Heavy-Duty Fast-Fueling Research

To support existing and future heavy-duty hydrogen fueling research projects, NREL constructed additional experimental research space suitable for large-scale heavy equipment installations and installed a new isolated concrete pad suitable for use with large, vibration-causing research components, such as hydrogen compression systems. These facility upgrades support heavy-duty fast-fueling capabilities, including approximately 200 kg of additional high-pressure hydrogen storage, a heavy-duty hydrogen fueling dispenser and precooling system, and a vehicle storage simulation device developed by NREL through a project with Shell, Air Liquide, Toyota, and Honda. This device will be used to validate the ability to dispense hydrogen at 10 kg per minute, DOE's target fueling rate for long-haul trucks.

ADMS Test Bed Continues to Accelerate Grid Modernization Efforts for Utilities

Funded by the DOE OE Advanced Modeling Grid Research Program and located within the ESIF, the ADMS test bed (https://go.usa.gov/x7etZ) continues to support the utility integration of advanced grid management technologies and operations. With software simulations and hardware devices that recreate a utility power distribution system, the ADMS test bed can realistically simulate almost any modern grid scenario before these technologies are deployed. Work for two new projects began in FY 2020: One will gauge a data-driven paradigm for voltage regulation with high penetrations of DER systems using AMI with partner SDG&E; and the other will evaluate the performance of a fault location, isolation, and service restoration application in the presence of DERs with partners Central Georgia EMC and Survalent.

Securing Energy Networks with 5G Communications

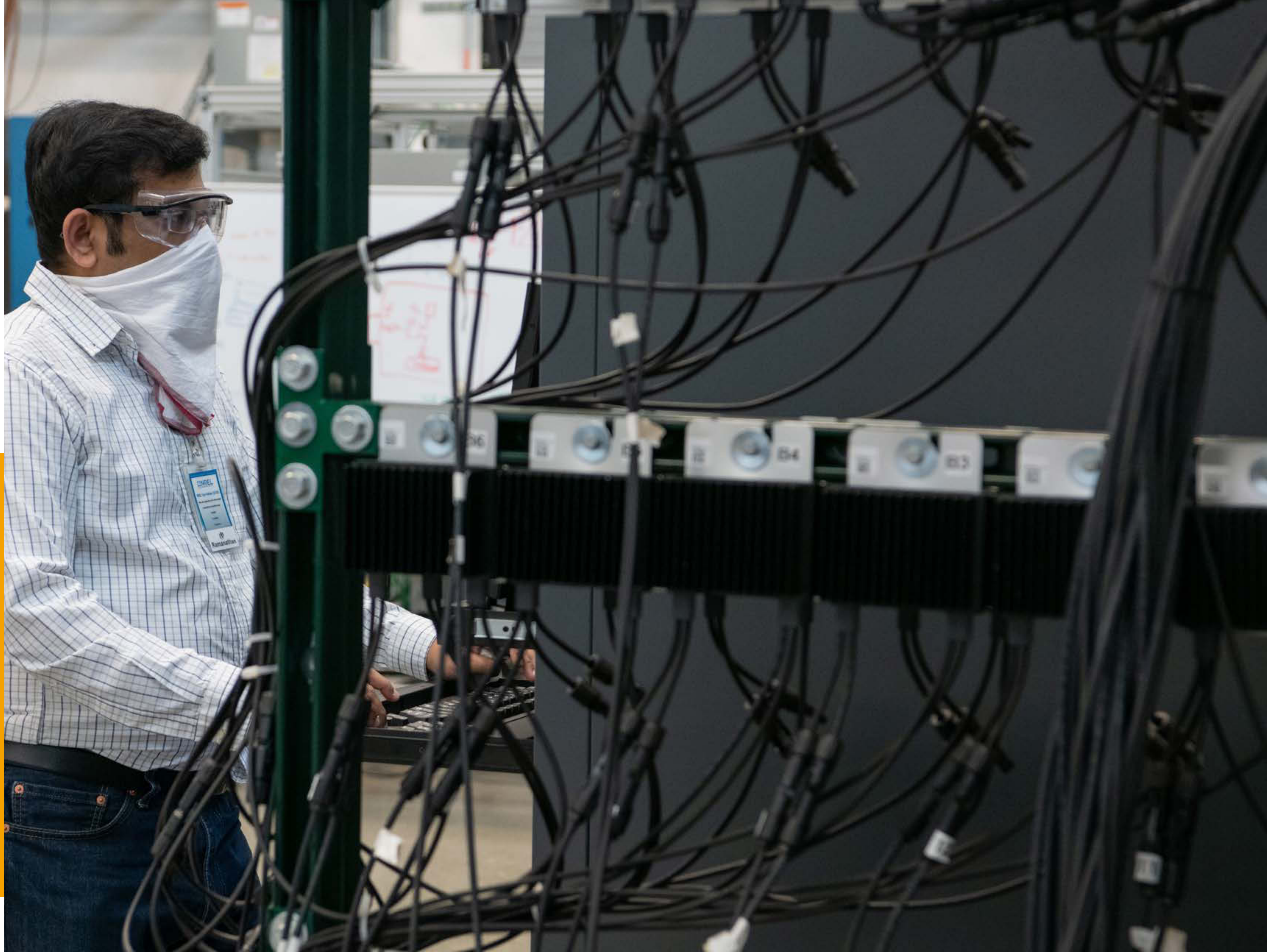
With the inherent cybersecurity risks of increased interconnections among new devices and the electric grid—and the supply chain risks of such devices—NREL researchers are evaluating the security benefits of 5G communications. Benefits such as network-slicing features can improve the performance, security, and reliability of grid devices and services, which are especially important as new technologies are introduced to increasingly distributed energy systems. With laboratory-directed funds, researchers began work in FY 2020 to evaluate use cases that employ 5G communications to mitigate the impact of cyber threats to distributed energy systems. Using the ESIF's CEEP, initial analyses included the evaluation of distributed control for DERs, distributed automation, DER monitoring and diagnosis, and DER application-based network reconfiguration.

Developing a Market-Ready Biomethanation System

NREL continues to leverage its partnership with Southern California Gas Company (SoCalGas), the largest provider of natural gas in North America, to develop a biomethanation system producing renewable natural gas from hydrogen and CO2. The project's other partner is Electrochaea, which holds patent rights to the microorganism and technology. In FY 2020, NREL and SoCalGas entered into a new licensing agreement to increase the productivity of biocatalysts, increase system efficiency, and decrease the capital cost of electrolyzer systems. Funding from SoCalGas and the BTO and HFTO is supporting research needed to accelerate market adoption of this technology.

Key Operations Updates at a Glance

- Finalized commissioning and procedural documentation and ran multiple research projects in the commercial buildings and advanced vehicles integration laboratory areas. Installed and commissioned new XFC vehicle chargers.
- Upgraded system capability of the advanced electrolysis stack test bed to accommodate up to a 1-MW electrolyzer stack, including thermal handling, deionized water, DC power, and hydrogen gas handling.
- Installed DC megawatt extensions to the ESIF's Medium-Voltage Outdoor Test Area.
- Installed a tactical diesel grid paralleling generator set in the ESIF's Low-Voltage Outdoor Test Area.
- Installed bidirectional DC power emulators with battery emulation.
- Installed multiple advanced inverters, ranging from 3 kW–150 kW.
- Commissioned a high-speed camera for hydrogen and biosystem process characterization.
- Commissioned and installed the Oblong Mezzanine virtual collaboration environment.
- Upgraded chiller capacity.



High-Performance Computing

Computational Science Center Director's Letter

Two hundred and fifty-three projects advanced the EERE mission in FY 2020 with the aid of NREL's advanced computing facilities. The impact of the facilities—anchored by the supercomputer Eagle and a team of computational scientists—is reflected in 290 technical outputs, including 95 peer-reviewed papers covering a wide range of topics, such as materials science and fluid mechanics, that foster improvements in energy affordability, storage, and the integration of DERs. Project highlights in the following pages show samples of these achievements.

A facility is rarely static, and the final increment to the Eagle system was installed midsummer, bringing the total size of Eagle to 10 E-cells. The two new E-cells were purchased by individual offices and will serve the needs of the DOE EERE Wind Energy Technologies Office (WETO) and the DOE EERE Advanced Manufacturing Office (AMO). These E-cells, numbers 9 and 10 for Eagle, will operate as part of Eagle through its service life. Already they have supported more than 32 projects for WETO and AMO and delivered 3.4 million AU's in the final quarter of FY 2020. Installation looked a bit different from a normal day in the data center—with personal protective equipment checks, social distancing, and an office empty except for essential personnel—but it was accomplished successfully, with less than one day of downtime impacting the system.

The HPC Data Center and Computational Science Center staff continue to push the boundaries of efficient data center operation. Now-proven waste heat recovery enabled the facility to end the year with an average power usage effectiveness rating of 1.028. Looking to the future, a new project in partnership with Hewlett Packard Enterprise (HPE) focuses on leveraging the "living lab" data streams from Eagle to develop AI algorithms for optimizing data center operation. This partnership—described in more detail on page 71—is one of many where Computational Science Center staff are developing the state of the art of AI in tandem with more traditional modeling and simulation capabilities to enable new data-centric workflows and lay the groundwork for new ways in which the advanced computing facility can contribute to transforming energy.

Looking to the future, the opportunities for advanced computing—including traditional HPC and emerging edge, fog, cloud, and data-centric workflows—are robust. As the year closed, requests for allocations of Eagle for FY 2021 were exceeding availability by twofold. The project to field Eagle's successor—now under the able leadership of the newly hired laboratory program manager for advanced computing, Kristin Munch—is in full swing. Responses to a request for information was considered in preparation for the project design review in October 2020.

Ray Grout

Director, NREL Computational Science Center

Kristin Munch

Laboratory Program Manager, Advanced Computing

Eagle Propels Innovation with Advanced Computing

NREL's HPC Data Center, Eagle supercomputing system, and visualization capabilities propel technology innovation by providing NREL researchers and industry partners the ability to tackle energy challenges that cannot be addressed through traditional experimentation alone.

NREL's HPC experts collaborate with scientists and engineers to take full advantage of advanced computing hardware and software resources, which provide the computing scale and speed necessary to advance renewable energy and energy-efficiency technologies. Advanced visualization technology helps researchers explore and interact with data in new ways that accelerate understanding and innovation.

EERE Office	# of FY 2020 Projects
Advanced Manufacturing Office (AMO)	3
Bioenergy Technologies Office (BETO)	23
Building Technologies Office (BTO)	20
Grid Modernization Initiative (GMI)	33
Geothermal Technologies Office (GTO)	2
Hydrogen and Fuel Cells Technologies Office (HFTO)	17
Solar Energy Technologies Office (SETO)	30
Strategic Priorities and Impact Analysis (SPIA)	10
Vehicle Technologies Office (VTO)	29
Wind Energy Technologies Office (WETO)	34
Water Power Technologies Office (WPTO)	4
Total	**205**

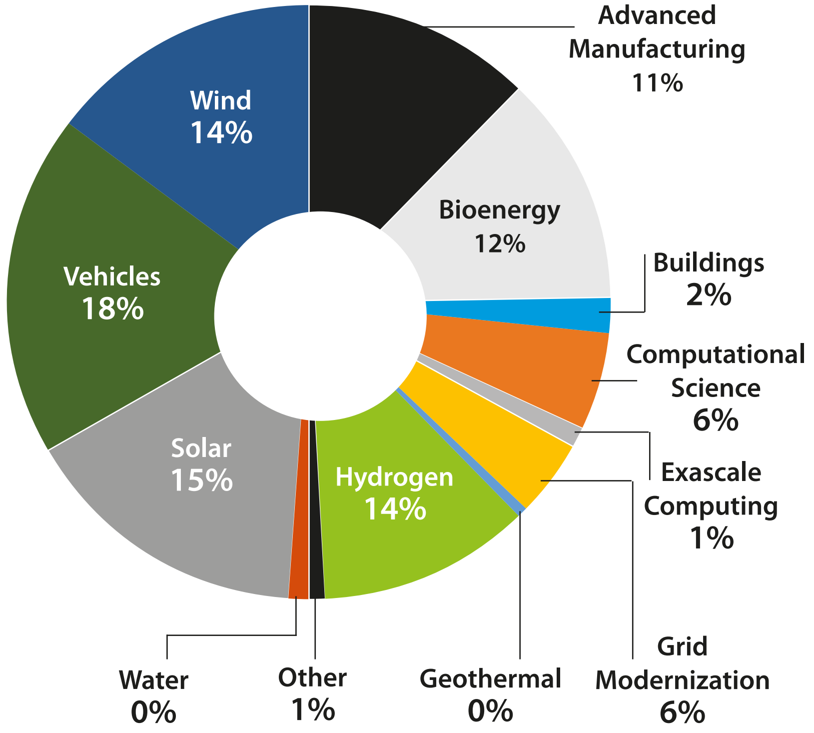
Key Performance Indicators

HPC Data Center

- 457 users
- Availability - 89%
- Utilization - 92%.

FY 2020 HPC Usage

NREL's HPC user facilities supported a total of 253 modeling and simulation projects, advancing the DOE mission across the spectrum of energy-efficiency and renewable energy technologies in FY 2020.



Materials Science

Project Spotlight

Biochemical Process Modeling and Simulation

NREL researchers are enlisting the power of supercomputers to address the plastics pollution problem and reduce the cost of biofuels and bio-derived materials and products. Funded by the DOE EERE Bioenergy Technologies Office (BETO), the Biochemical Process Modeling and Simulation project team focused their work on predictions of improved enzymes to deconstruct waste polyethylene terephthalate (PET) and other model plastics for subsequent upcycling as well as on catalysts for upgrading biomass-derived sugars and lignin to fuels, products, and materials precursors.

Leveraging Eagle, the research team completed bond dissociation enthalpy calculations to quantify the bond strength for every chemical bond in more than two dozen commodity plastics. Their results are pointing researchers toward which chemical bonds to target in developing strategies for depolymerization and plastics upcycling. In other plastics upcycling efforts, the team shed light on the catalytic mechanisms and synergy of enzymes that depolymerize PET, the world's most abundant polyester.

Another objective of the project is reducing the costs of biofuels and other bioproducts. As part of this work, the team is focusing on how to separate high-value coproducts, such as phenols and cresols, from crude pyrolysis oil. The team has also modeled the chemical reactions in a promising novel process to convert lactic acid, which can be efficiently produced from biomass into valuable platform chemicals, including methyl acrylate, acrylic acid, and acrylonitrile.

Finally, in collaboration with the DOE EERE Biological and Environmental Research-funded Deep Green program, this project has begun leveraging the AI capabilities of Eagle to develop learned representations of enzyme function directly from primary sequence. In an approach similar to how computers are achieving state-of-the-art performance in natural language processing and machine translation, researchers have trained large neural network models on vast libraries of unstructured protein sequence data to learn natural constraints present in evolved primary sequences. These models—when fine-tuned on downstream tasks, such as predicting gene ontology membership—demonstrate state-of-the-art performance over traditional approaches. These models are therefore enabling a better understanding of the proteome of energy-relevant organisms and might allow future enzyme discovery and engineering directly from primary sequence.

Project Highlights

Working Backward: Building Tomorrow's Bioeconomy through Custom-Made Polymers

The BETO-funded Inverse Polymer Design (IPD) project reverses the traditional polymer research workflow. Employing theoretical and predictive methods powered by HPC, IPD begins with the desired polymer properties—such as thermal stability, glass transition temperature, gas permeability, and combinations of properties—and then predicts which monomers, copolymers, or branching structure will produce them.

To date, the project has initiated or completed simulations of molecular dynamics to predict glass transition temperature, water contact angle, and barrier properties of performance-advantaged nylons; density functional theory calculations for density functional theory calculations for polymer reactivity; and the development and testing of PolyML, a machine learning tool for predicting polymer properties. The project also deployed PolyML to predict and screen polymers based on thermal, mechanical, and barrier properties.

Eagle was key to completing all three of the project's major types of calculations and simulations. High-throughput screening of these polymers can aid in the development of novel biosourceable materials, carrying significant implications for biofuel pricing and the development of a mature bioeconomy.

Identifying Next-Generation Materials for Tomorrow's Perovskites

Leveraging Eagle's immense processing capabilities, researchers completed calculations to identify improved materials for manufacturing perovskites. With funding from HFTO, the project team had the opportunity to investigate an exciting class of redox-active, mixed ionic-electronic conducting metal oxides. By characterizing key thermodynamic properties and the stability of these materials, the team hopes to offer strategies to boost solar-to-hydrogen thermal efficiency and provide a solid jumping-off point for the synthesis, validation, and testing of future promising solar thermochemical hydrogen materials.

The power of HPC allowed the team to complete the quantum mechanics calculations necessary to model oxygen vacancy formation in perovskites containing three or more different elements. The project also features a machine learning component, which comprises training and validating a model to predict oxygen vacancy formation energies in quaternary and quinary perovskites. This component of the project benefitted greatly from Eagle's data analysis and visualization nodes, which significantly accelerate model training.

Inverse Design of Future Transformative Energy Technologies

The development of tomorrow's breakthrough energy technologies begins with the synthesis of new materials. Through funding from SETO, the Energy Frontiers Research Centers' Center for Next Generation of Materials Design (CNGMD) is leveraging HPC to develop a thorough understanding of how key synthetic conditions can be predicted, measured, and controlled to create new functional materials. By providing the underpinning science and theory to guide their creation, the project aims to dramatically expand and accelerate the discovery of experimentally accessible materials for energy applications.

The project team completed complex simulations that required HPC, supporting breakthrough accomplishments, such as heterostructural alloys, crystal structure prediction, and the discovery of novel nitrides. In FY 2020, the HPC-enabled project predicted and synthesized antimony nitride for the first time. The discovery of such a new binary compound semiconductor is exceedingly rare, and the team went a step further—beyond predicting a new material. Molecular dynamics calculations allowed for the direct comparison with in situ synthesis experiments under nonequilibrium conditions, marking a significant advance in computational synthesis science. The metastability focus of the CNGMD was also highlighted in a recent high-impact publication where the team used first-principles calculations beyond density functional theory to predict the phase stability of novel ternary nitrides.

Beating the Lithium-Sulfur Battery Bottlenecks

Researchers are hard at work developing better electrolyte and cathode systems to clear the path to commercialization for lithium-sulfur (Li-S) batteries. As part of this work, with funding from VTO, the project team is developing new methods to study the discharge mechanism in Li-S batteries.

Specifically, the team employed NREL's Eagle HPC to:

- Explore Li-S cathode designs, theoretically testing a compact solid 3D design. They found that this concept solves several common Li-S cathode challenges, from lithium polysulfide dissolution to electrical insulating and structural instabilities.
- Theoretically design a new class polymer to enhance its ability to vulcanize with the element sulfur. The sulfur-vulcanized polymer was found to have better conductivity, higher specific capacity and gravimetric energy densities, better kinetic stability, and more.
- Apply a new fixed-potential method in the density functional theory (DFT) simulation to mimic the electrochemical processes in which the total number of the electrons in the system was floated to match the applied voltage.
- Develop a new time-evolution algorithm to significantly increase the time step for integration and to reduce computational costs for the simulation of large systems.

HPC-Powered Project Demystifies Important Catalyst, Enables Effective Catalyst Design

Researchers recently uncovered a missing piece of the puzzle in pinpointing catalytic origin. Employing ab initio molecular dynamics and a "slow-growth" sampling approach, the project team evaluated the reaction kinetic barriers, which had been neglected or oversimplified in previous DFT calculations.

Playing an essential role in identifying catalytic origin, this work, funded by HFTO, not only explains a long-standing unknown for an important catalyst but also highlights the crucial roles of charge capacity and hydrogen bonding. This information can shine a light on the mechanisms of other heterogeneous electrocatalysts in aqueous solutions, too, enabling more effective catalyst design.

Sustainably Powering Electric Vehicles in a Resource-Scarce World

Replacing traditional combustion engine vehicles with sustainable EVs is a major global challenge, particularly in the context of increasing resource scarcity. HPC-aided computations are helping to develop tomorrow's sustainable alternative to today's EV battery technology.

Only batteries based on lithium-ion (Li-ion) can have the practical energy density necessary for use in EVs. Because they feature very high energy density and facile lithium percolation, disordered rock salt Li-ion cathodes are of great interest for battery scientists. They are also competitive with existing materials and are based on cobalt-free sustainable elements; however, there is a limited understanding of how these materials function and how their specific chemistry controls the local environment of lithium and its extractability and transport. The project studies a particular class of partially disordered, spinel-like materials, which have been found to yield ultrahigh power and energy densities.

As part of this work, which is funded by VTO, the project team employed Eagle to complete the following calculations efficiently and quickly:

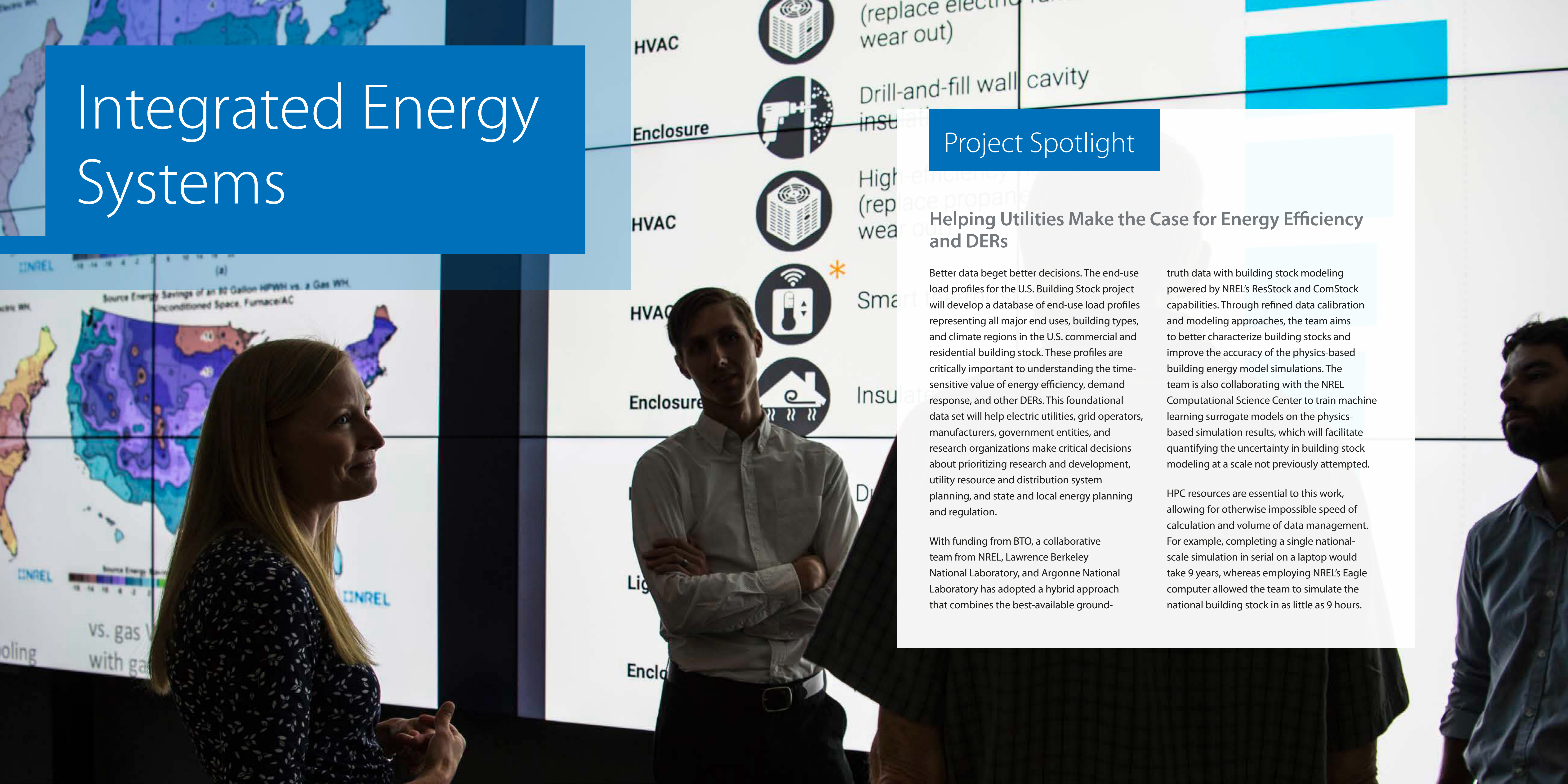
- Data set generation of structures to train energy models: VASP-SCAN calculations
- Monte Carlo sampling to search for additional data/structures
- Finer Monte Carlo sampling with fitted energy model, ongoing.

Paving the Way to the Lithium-Silicon Batteries of Tomorrow

The better batteries of tomorrow begin with today's research. Silicon anodes hold great promise for use in next-generation Li-ion batteries, offering a theoretical capacity nearly an order of magnitude greater than conventional graphite anodes; however, there are barriers blocking the development of these next-generation batteries. Solid electrolyte interphases (SEI) can impact various aspects of battery performance. Whereas Li-ion batteries developed with graphite anodes can form a stable—as well as ionically conducting—interface with common Li-ion organic electrolytes, the SEI in lithium-silicon (Li-Si) batteries do not passivate but rather grow continuously, impacting capacity retention.

To overcome this challenge, the research team is working to develop an understanding of both the silicon anode and the liquid electrolyte reactivity at the atomic level. With funding from VTO, the team was able to quickly and efficiently run calculations employing the precompiled and optimized codes, built-in development tools, and technical software libraries featured on the Eagle. Based on the results of this work, the team will recommend changes to the silicon anode electrolyte and additives to improve the performance of Li-Si rechargeable batteries.

Integrated Energy Systems



Project Spotlight

Helping Utilities Make the Case for Energy Efficiency and DERs

Better data beget better decisions. The end-use load profiles for the U.S. Building Stock project will develop a database of end-use load profiles representing all major end uses, building types, and climate regions in the U.S. commercial and residential building stock. These profiles are critically important to understanding the time-sensitive value of energy efficiency, demand response, and other DERs. This foundational data set will help electric utilities, grid operators, manufacturers, government entities, and research organizations make critical decisions about prioritizing research and development, utility resource and distribution system planning, and state and local energy planning and regulation.

With funding from BTO, a collaborative team from NREL, Lawrence Berkeley National Laboratory, and Argonne National Laboratory has adopted a hybrid approach that combines the best-available ground-truth data with building stock modeling powered by NREL's ResStock and ComStock capabilities. Through refined data calibration and modeling approaches, the team aims to better characterize building stocks and improve the accuracy of the physics-based building energy model simulations. The team is also collaborating with the NREL Computational Science Center to train machine learning surrogate models on the physics-based simulation results, which will facilitate quantifying the uncertainty in building stock modeling at a scale not previously attempted.

HPC resources are essential to this work, allowing for otherwise impossible speed of calculation and volume of data management. For example, completing a single national-scale simulation in serial on a laptop would take 9 years, whereas employing NREL's Eagle computer allowed the team to simulate the national building stock in as little as 9 hours.

Project Highlights

Applying Reinforcement Learning to the Real World

Reinforcement learning, the field of machine learning most associated with AI, has the potential to revolutionize everything from transportation to smart buildings and devices. With laboratory-directed funds, the RLLDRD: Assessment of Reinforcement Learning for Model NREL Problems project aims to apply reinforcement learning to real-world problems to reap systemic efficiency gains.

Reinforcement learning is a type of machine learning that allows for data-driven control of autonomous systems and other stochastic control processes via repeated interaction with the system, where the feedback is then used to improve a learned control policy. The promise of reinforcement learning lies in its ability to learn from—and adapt to—dynamic situations on the fly without the need to specify explicit models of the physics or control feedback. This project specifically looks at applications in smart device control, fleet rebalancing for mobility-on-demand systems, and distributed wind power plant control to assess the feasibility and efficacy of reinforcement learning compared with traditional approaches.

By employing HPC for scalable reinforcement learning, the team has completed the following studies to date:

- "An Edge-Cloud Integrated Solution for Buildings Demand Response Using Reinforcement Learning" (https://go.usa.gov/x7eex)
- "A Comparison of Model-Free and Model Predictive Control for Price Responsive Water Heaters."

These studies have scaled reinforcement learning training to more than 1,000 central processing unit cores across more than 30 Eagle nodes, thereby demonstrating the potential for HPC to accelerate the discovery of good control outcomes via distributed algorithms. In the second year of the project, the team is actively working to apply these lessons to the problems of fleet rebalancing for mobility-on-demand systems (transportation) and distributed wind power plant control.

Taking a Magnifying Glass to Hybrid Renewable Energy Plants

As the penetration of renewable energy increases, so, too, will the need for these technologies to serve as baseload generation and to participate in the ancillary services market; however, performing the analysis to ensure the bankability of utility-scale hybrid renewable energy plants, in terms of plant performance and costs, has been stymied by a host of technical challenges—until now.

The GMI-funded Hybrid Optimization and Performance Platform (HOPP) project aims to design, analyze, and optimize utility-scale hybrid power plants down to the component level. Pinpointing their value at the utility scale, HOPP identifies the conditions that make for a profitable hybrid plant.

The project explores the potential to colocate wind and solar technologies to take advantage of their often complementary generation profiles and shared infrastructure. The team employed NREL's Eagle to extract and analyze wind and solar data and to perform large-scale analysis. The analysis, which was conducted via a case study, also highlighted geographic regions in which hybrid plants are likely to offer the most value.

Detailed Power System Simulations Inform Insights to Los Angeles's Energy Future

NREL is providing rigorous, integrated engineering-economic analysis to the Los Angeles Department of Water and Power (LADWP) through the LA100. The objective of the multiyear study, which is funded by GMI, is to estimate the impacts of Los Angeles's transition to an all-renewable electricity service capability by 2045—presenting an analytical undertaking of unprecedented scale and complexity. Uniquely integrating diverse capabilities across the laboratory, this analysis demands sophisticated models that can accommodate changes in technology and trace all the ripple effects during the construction and operating phases of the new electricity generation mix.

In FY 2020, researchers used NREL's HPC capabilities at the ESIF to simulate LADWP's dispatch at hourly resolution, along with detailed modeling of the distribution network, to identify future challenges and needs for that system. HPC is critical to this work because the number of simulations needed to model the required level of detail would simply not be possible without it. Although the full impact of this research will not be realized until the study is complete in FY 2021, progress to date has had many important intermediate benefits—including better understanding of the implications and challenges of reaching 100% renewable futures and new and improved methods for electricity load modeling.

NREL Models Impact of COVID-19 Transmission Mitigation Strategies for Commercial Buildings

To inform building operation through the COVID-19 pandemic, NREL used DOE's ComStock tool and funding from BTO to analyze U.S. national commercial building stock implications on energy and comfort for several strategies recommended by the ASHRAE Epidemic Task Force. Examples of these strategies include upgrading to MERV-13 filters, increasing minimum outdoor ventilation air, and operating in heating, ventilating, and air-conditioning (HVAC) flushing mode before and after normal building operation hours. More than 110,000 building energy models representing the diversity of commercial buildings in the United States were simulated for each strategy and the baseline, resulting in more than 550,000 physics-based EnergyPlus® simulations. NREL's Eagle was a critical asset to completing the work with such a high computational load on the aggressive timeline necessitated by the pandemic. These results provide insight that could help building owners and operators make informed decisions regarding the safe operation of buildings through the COVID-19 pandemic.

Fluid Dynamics

Project Spotlight

A Coordinated Effort: High-Performance Computing-Powered Engineering Models Improve Wind Power Plant Output, Performance

Coordination might be the key to better wind power plant performance. Wind power plant control seeks to improve wind plant performance by coordinating the control systems of individual wind turbines. Long recognized as a worldwide leader in the research, design, and analysis of wind plant control, NREL's pioneering research has the potential to improve the performance of global wind power plants over what would be possible by controlling individual turbines alone.

Employing the vast power of NREL's Peregrine and Eagle HPC systems, researchers carried out high-fidelity modeling to develop and validate new wind control engineering models. From analyzing how to increase annual energy production through wake steering to using high-fidelity simulations to develop and validate low-fidelity models for optimization (e.g., FLOw Redirection and Induction in Steady State (FLORIS)), these models have the potential to substantially improve wind power plant performance.

With funding from WETO, in FY 2020 NREL researchers carried out a variety of research activities to:

- Analyze the potential for wake steering control of 60–80 wind power plants selected to be representative of all U.S. wind power plants
- Enable efficient yaw optimization
- Develop spatially heterogenous wake models
- Implement a new analytical wake model that captures near-wake phenomena
- Optimize wind power plant design to minimize fatigue
- Minimize the computational cost of steady-state wind power plant flow simulations involving wake steering physics.

HPC was the backbone of these efforts, enabling detailed studies analyzing the relationship between atmospheric conditions and wind plant control performance.

Project Highlights

Vehicle Technology Advancements Pick Up Partnership to Advance Combustion Engines

Fuel-efficient, clean, and cost-effective internal combustion engine technologies are picking up speed with the Partnership to Advance Combustion Engines (PACE), a research collaboration among the DOE national laboratories. With funding from VTO, the study aims to improve fuel efficiency by 25% in medium- and heavy-duty vehicles by creating smarter engine design tools. Simulation is critical to designing the ignition process. Using NREL's HPC system, NREL researchers trained a deep neural network (DNN) model to predict the interaction between turbulent mixing and chemical reactions that causes ignition. The DNN model has produced accurate predictions in test cases compared to traditional physics models.

Gas-Solid Flow Algorithm Simulates 1 Billion Particles in 24 Hours

It is now easier and faster for HPC systems to simulate industrial-scale particle flow using a hybrid of the computational fluid dynamics (CFD) discrete element method (DEM). DEM has long been considered the most accurate way to model gas-solid flows, but the computational complexity required to run the algorithm (MFIX) has prevented industrial-scale simulations. With funding from the DOE EERE Office of Science Exascale Computing Initiative, NREL researchers revised the algorithm to include error-controlled adaptive time-stepping and memory optimization using spatial reordering techniques. Large-scale test cases were run on NREL's Eagle supercomputer, resulting in two to three times faster computational speed, or 1 billion particles in 24 hours. This computational advancement relieves the bottleneck for industrial-scale simulations of systems such as biomass feedstock handling, pyrolysis, chemical-looping combustion, and catalytic upgrading.

Forecasting

Project Spotlight

NREL Completes Modeling and Analysis of North American Power System

In FY 2020, NREL used HPC resources at the ESIF to complete modeling and analysis for two major components of a study examining the interconnection of U.S., Canada, and Mexico power systems—the largest study of its kind from a geographic standpoint. A collaborative effort among Natural Resources Canada, SENER, and funded by the GMI, the North American Renewable Integration Study explores the potential to build a modern, reliable grid through increased use of wind, solar, hydropower, and other technologies across North America.

NREL researchers finished the modeling and analyses of Canadian and U.S. perspectives of the continental-scale power system—which would not have been possible without HPC capability. NREL also made available new open-source tools and data for stakeholders to use.

Project Highlights

Forecasting Sunny Skies for Solar Energy Applications

Publicly available, high-quality, probabilistic forecasting systems for the solar energy industry can directly contribute to the integration of PV generation on the grid, balancing electricity supply and demand and maintaining cost-effective grid stability.

The Weather Research and Forecasting (WRF)-Solar model, which is funded by SETO, is the first numerical weather prediction (NWP) model specifically designed to provide specialized products for solar power applications. The development of the model included the creation and implementation of a fast radiative transfer code (e.g., the Fast All-sky Radiation Model for Solar Applications (FARMS)) to provide surface irradiance forecasts every time step of the model (e.g., every few seconds) with minimal increase in the computational cost. The solar irradiance upgrades to the WRF model included (1) developments to diagnose internally relevant atmospheric parameters required by the solar energy industry, (2) improved representation of aerosol radiation feedback, (3) incorporation of cloud aerosol interactions, and (4) improved cloud radiation feedback.

The power of NREL's Eagle system will be leveraged to manipulate the voluminous data sets and to complete complex physics calculations as part of the NWP models. The goal of the project is to convert WRF-Solar into the first stand-alone framework to provide probabilistic solar irradiance forecasts specifically designed for solar energy applications.

Simulating High Electrification Futures for the U.S. Grid

Since 2017, NREL has led the Electrification Futures Study (EFS), a collaborative research effort funded by the DOE EERE Strategic Priorities and Impact Analysis, to examine the impacts of widespread electrification for the U.S. energy system. The series of reports published under the study have covered multiple facets of electrification, including advancement possibilities for a wide range of end-use electric technologies; demand-side scenarios with increasing adoption of such technologies in the buildings, transportation, and industrial sectors; supply-side scenarios of the evolution of the U.S. power system to serve new electrified demands; and new models and methods to represent the increased sectoral coupling from electrification.

In FY 2020, NREL researchers used the HPC capabilities at the ESIF to perform detailed grid simulations of power systems envisioned in the EFS scenarios for the year 2050. Hourly unit commitment and economic dispatch modeling was used to examine the operability of systems serving the electrified loads through increased renewable energy and increased flexibility from the demand side, e.g., from grid-integrated buildings or optimized charging of EVs. HPC is critical to this work, given the complexity of modeling storage and flexible loads at the level of detail performed in this study. This analysis will be published in 2021 and completes the ambitious EFS series.

Manufacturing

Project Spotlight

Boosting LED Light Efficiency via 2D and 3D Simulations

Researchers are envisioning the path toward a high-efficiency light-emitting diode (LED), thanks to HPC-powered simulations. With funding from AMO, Lawrence Livermore National Laboratory (LLNL) researchers are working with semiconductor chip manufacturer Applied Materials to improve a process for depositing thin-film materials on wafers used in high-efficiency LED lights and other products.

Reliably creating thin films with favorable electrical, optical, structural, and chemical properties is a critical manufacturing challenge. One possible technique for depositing thin films with controlled properties is high-powered impulse magnetron sputtering (HiPIMS). Though promising, HiPIMS has yet to be optimized because modeling magnetron plasma discharges at relevant densities is—as researchers have put it—a "grand challenge computing problem."

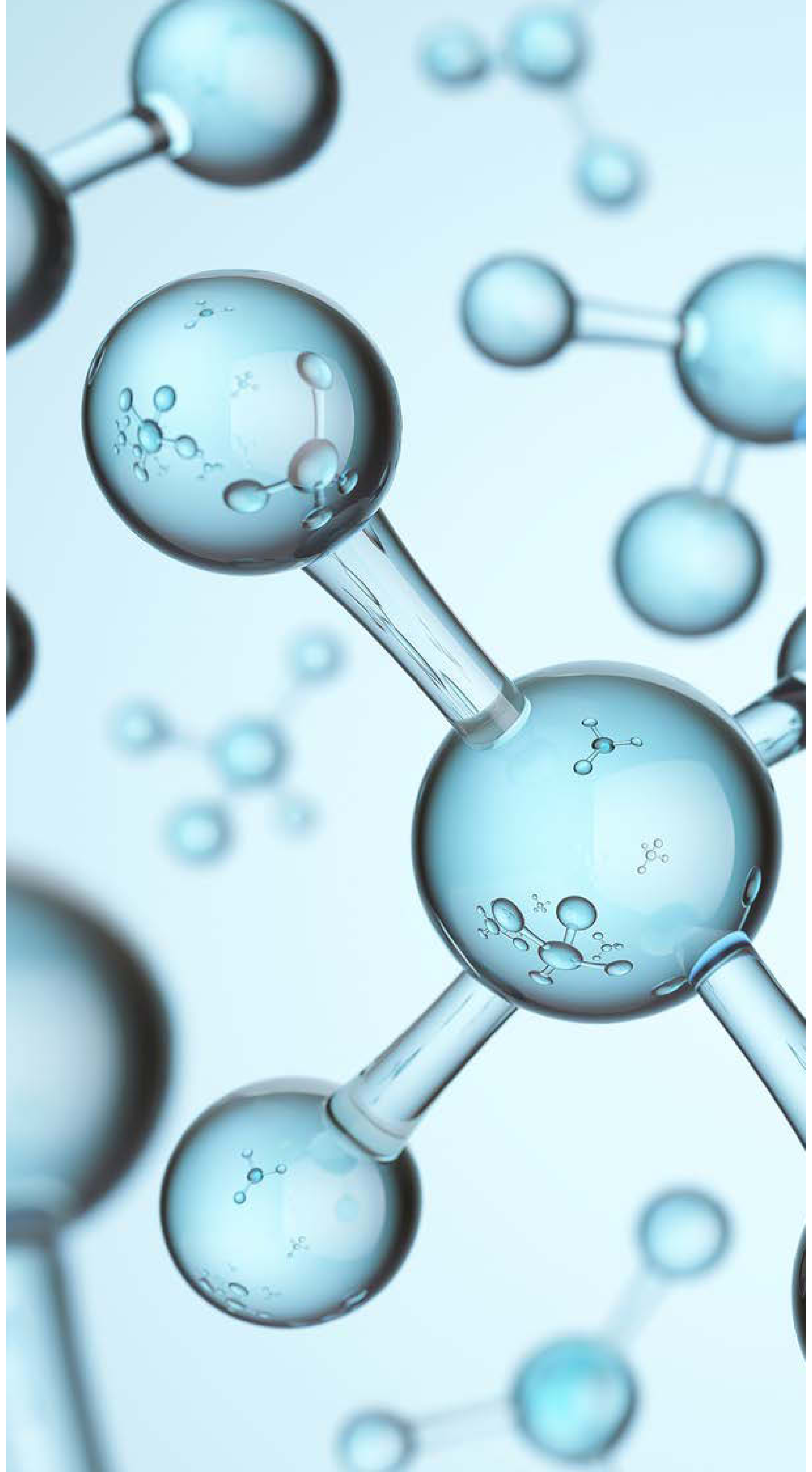
Using LLNL's HPC system, Quartz, and NREL's Eagle, researchers modeled how the plasma behaves during the HiPIMS process in three dimensions, bringing a predictive capability to the process and helping scientists determine how reactor geometry can be tailored to get the properties and uniformity that industry requires for optimal device performance.

Project Highlight

Eagle Enables First-Ever Simulations of More Energy-Efficient Method for Chemical Industry

Distillation in the chemical industry accounts for roughly 10% of energy use in the United States. Although methods such as porous mass separating agents (MSAs) could achieve the same process using much less energy, the manufacturing community needs to gain a better understanding of how MSAs work before this method can be applied to industrial applications.

A key step toward the design and application of MSA-based separations is to develop a fundamental understanding of the interplay between confined fluid behavior and the selectivity of molecular adsorption in MSA pores. Through funding from AMO, in FY 2020 researchers used the Eagle supercomputer to simulate the interactions between the MSA pores and the fluid, the strength of interaction, the molecular diameter, and the range of interaction. Using machine learning, researchers connected these models to realistic fluids used in industrial settings. The data set produced from these simulations will give researchers a new understanding of the behavior of molecular systems and will enable the first rational design of porous MSAs.



Capabilities & Facilities

EERE Offices Support Expanded Eagle Supercomputer Capability

During FY 2020, NREL installed additions to the Eagle supercomputer to support increasing computing needs because the demand for HPC cycles has increased in recent years from all quarters of DOE. To ensure program success and continuity of the projects, NREL purchased half an E-cell at the behest of the AMO and a full E-cell with WETO funding. An E-cell is the major building block of Eagle and contains up to 288 compute nodes. These additions—projects in their own right—support the procurement, operational, and eventual decommissioning costs associated with increasing off-specific computing capacity. These e-cells were coupled to Eagle during a planned outage in early June and started running jobs for the respective offices shortly thereafter.

The expansion of Eagle in this manner provides benefits to both the sponsoring program and the broader computing community. The sponsoring program receives an increase in total computing allocation commensurate with the investment, and their users experience priority access for jobs that fit within the dedicated hardware. With a larger pool of overall resources, utilization of the supercomputer tends to be higher, and all users benefit from the increased flexibility provided.

NREL and HPE Team Up to Apply Artificial Intelligence for Efficient Data Center Operations

AI is the latest buzzword in energy innovation—and when it comes to operating energy-intensive data centers, AI could be the key to improved efficiency. That is why NREL partnered with HPE in FY 2020 on a new research effort that will evaluate how applying AI in the ESIF's HPC Data Center could improve operations.

NREL and HPE are adding AI to NREL's existing real-time data collection/aggregation/streaming system and HPE's data monitoring/management system. The team will evaluate how this approach improves the operational efficiency of the ESIF's HPC Data Center through analytics on both historical and real-time data from information technology systems and facilities operations.

By learning historical trends and training models to operate on real-time data collected from the systems and facilities, AI and machine learning approaches could improve HPC Data Center operational efficiency as supercomputers approach exascale capability—which refers to HPC systems capable of performing at least 1 billion calculations per second.

From Streams to Rivers: NREL Upgrades Data Exchange for High-Use, Real-Time Applications

If research data at the ESIF were visible, visitors would be overwhelmed by a turbulence of crisscrossing data streams rushing in and out of laboratories, the Insight Center's visualization room, and the Eagle supercomputer. An FY 2020 upgrade brought some order to that data flow with a platform that makes data streaming and access much easier for ESIF researchers and partners.

For every project or partner at the ESIF, there is significant data exchange. Researchers generate data with laboratory devices (e.g., solar inverters, electrolyzers), they analyze data alongside simulated systems, they use data in visualizations, and they share those data with partners. The upgrade by NREL's team transforms this complicated connectivity into a standardized river of data, where users can simply tap in as consumers or send their data as publishers. This versatility can be attributed to Apache Kafka, an open-source streaming platform optimized for high-throughput, low-latency feeds. NREL installed Kafka on a 6-node cluster in the HPC Data Center, which interfaces with the ESIF's network, including Eagle, as well as private laboratory subnets and the entire Flatirons and South Table Mountain campuses of NREL.

An important outcome of this data streaming capability is its use in HIL experiments. In one example, an NREL project is leveraging the capability to connect building technologies across facilities. Some assets are in the ESIF—such as smart thermostats and energy storage equipment—and others are across the campus, where HVAC equipment is located. Data are now easily shared among the facilities, supporting NREL's Commercial Buildings Research Infrastructure by connecting the inputs and outputs from simulation and hardware at different facilities. Another example involves data from an ESIF laboratory where computer simulations communicate back and forth with diverse energy devices in real time. The Kafka upgrade benefits the data-centric, AI-driven projects within the laboratory.

Innovative Visualization Workflows and Critical Data Sets Enable Cross-Cutting Analyses

NREL's data management, data analysis, and scientific visualization capabilities help move the needle on high-impact projects dealing with complex, large-scale data. Capabilities include tools and expertise in scientific visualization; data analysis; data-focused predictive modeling using statistical, machine learning/deep learning algorithms; and advanced data management methods that support NREL researchers and the ESIF user facility community in the capture, mining, and investigation of data-driven research problems to address scientific and technical goals.

The Insight Center at the ESIF combines state-of-the-art visualization and collaboration tools to promote knowledge discovery in energy systems. Located adjacent to the HPC Data Center, the Insight Center uses advanced visualization technology to provide on-site and remote viewing of experimental data, high-resolution visual imagery, and large-scale simulation data.

NREL's latest data analysis and visualization capabilities include:

- New energy resource data sets available on Eagle: Critical energy resource data sets have been greatly expanded to allow fast and efficient access to data resources for users of NREL's flagship HPC system. New data sets include an expanded and reorganized Wind Integration National Dataset (WIND) Toolkit with mesoscale data for Hawaii and offshore as well as international locales (e.g., Canada, Bangladesh, Central Asia, India, Mexico, Vietnam, the Philippines, and others). The National Solar Radiation Database (NSRDB) has also been greatly expanded with version 3.0. Newly organized and released wave energy model data fill a meaningful gap and will enable new cross-cutting analyses. Work to develop and share these data resources, and the underlying data systems and software, will further enable massive future data sets—such as a fully revised WIND Toolkit model with 20 years of data—to be released in future years.
- New visualization workflows for Eagle's multiscale fluid dynamics simulations: NREL's visualization experts at the ESIF Insight Center developed new workflows to support a more advanced style of visualization called physically based rendering of large-scale, nonuniform grid data simulated on Eagle. This kind of rendering provides additional, more intuitive controls to researchers, allowing them to dial in on features of interest within their simulations. This new workflow helps reveal complex multiscale structures in large-scale CFD simulations, such as wind turbine wake modeling and combustion efficiency simulations, routinely run on Eagle.
- New linked collaboration tool: A new collaborative visualization capability links statistical interfaces and graphics on laptops and HPC systems with 3D visualizations on immersive displays (head-mounted displays and large-scale immersive environments). This capability enables collaborative scientific workflows and rapid exploration of large, high-dimensional data sets by teams of analysts. The data views can be different, tailored to each analyst, but the views are directly linked together. For example, one analyst might have an immersive view of a data set, whereas other analysts have more quantitative statistical views of that same data set. When one analyst introduces derived data or flags regions of interest, those actions are visible and available in all the views.

Partners

3M Company
ALD Nanosolutions
Anterix
Blue Frontiers
BREK Electronics
CARB Go-Biz
Centrica
Charging Interface Initiative
Colorado State University
ComEd Emerging Technology
Cornell University Energy Frontier Research Center
Cummins Power Systems
Drexel University
Dynapower Company, LLC
Eaton Corporation
Electric Power Research Institute
Element One
Ford Motor Company
Giner, Inc.
General Motors
Global Technical Regulation (GTR)
GVD Corporation
Hewlett Packard Enterprise
Holy Cross Energy
Honda Motor Company
Hydrogenics
HyET Hydrogen
Hyperlight Energy
Hyundai Motor Company
IVYS Energy Solutions
Mainstream Engineering
NanoSonic, Inc.
Navitas Systems, LLC
NEL Hydrogen
OverDrive Fuel Cell Engineering, Inc.
Pennsylvania State University
Peroxygen Systems
pH Matter
Plug Power
Salt River Project
San Diego Gas & Electric Company
Shell
Solar Dynamics, LLC
SolarReserve
Southern California Gas Company
Sunvapor
TCPoly, Inc.
Tetramer
Toyota
Turboexpander
University of Alaska Fairbanks
University of Colorado Boulder
University of Illinois at Urbana-Champaign
University of Minnesota
University of Tennessee
U.S. Department of Defense

DOE Program Research

Advanced Research Projects Agency-Energy

Network Optimized Distributed Energy Systems (NODES)

- RONIN
- ROBUST

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

- Synthetic Models for Advanced & Realistic Testing of 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

Prime PERFORM SDS

Buildings

3.2.6.80 NREL - Multiobjective Deep Reinforcement Learning for Grid-interactive Energy-Efficient Buildings

3.4.6.53 NREL - Machine-Learning-Driven and Site-Specific Weather Inference for Building Energy Forecasting

GMLC Category 1 Projects:

1.4.04 Advanced Sensor Development

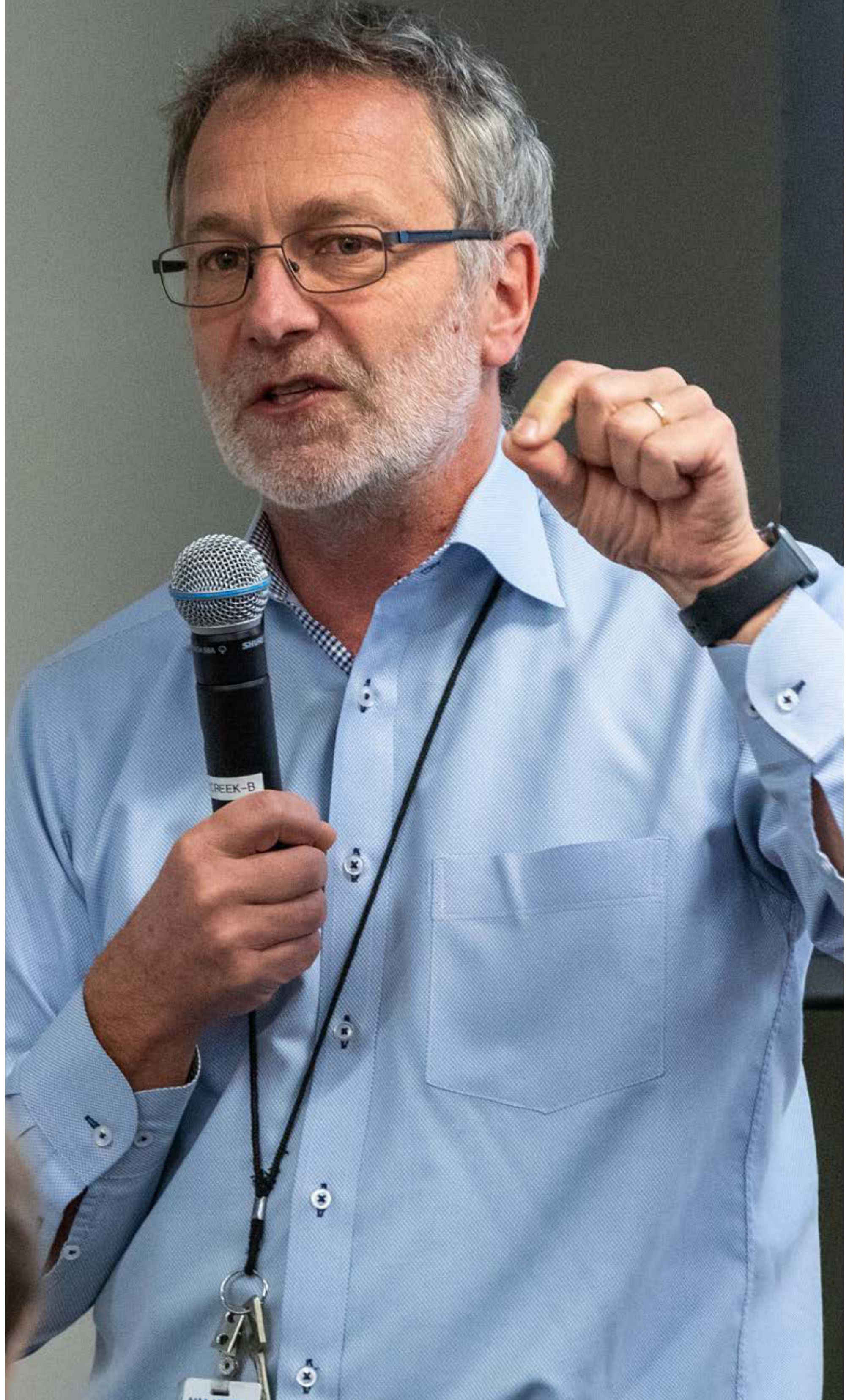
1.2.2 Interoperability

1.2.4 Grid Services and Technologies Valuation Framework

1.3.21 Alaska Microgrid Partnership

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

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



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

2.4.2 Multiport Modular Medium-Voltage (M3) Transactive Power Electronics Energy Hub

2.5.2 Grid Services, Energy Services Interfaces & Grid Connected Devices

4.2.5 Technical Assistance: Grid-interactive Efficient Buildings

4.2.4 Integrated Distribution System Planning Training: Education, Training and Assistance

Fuel Cell Technologies Office

EHIL Grid Val

GMLC Category 1 Projects:

1.3.05 DER Siting and Optimization Tool for California

1.1 Foundational Analysis for GMLC Establishment

6.1.2 Design and Optimization Infrastructure for Tightly Coupled Hybrid Systems (DISPATCHES)

Grid Modernization

GMLC Category 1 Projects:

1.1 Foundational Analysis for GMLC Establishment

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

1.3.05 DER Siting and Optimization Tool for California

1.3.10 Vermont Regional Partnership Enabling the Use of DER

1.3.2 HELICS+: From a Facilitator to a Hub

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

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

2.5.2 Grid Services, Energy Services Interfaces & Grid Connected Devices

4.2.1 Foundational Assistance to ISO/RTOs under Electricity Market Transformation

4.2.2 Technical Assistance to PUCs

4.2.3 Future Electric Utility Regulation

4.2.4 Integrated Distribution System Planning: Education, Training and Assistance

4.2.5 Technical Assistance: Grid-interactive Efficient Buildings

5.2.3 Blockchain for Optimized Security and Energy Management (BLOSEM)

6.1.2 Design and Optimization Infrastructure for Tightly Coupled Hybrid Systems (DISPATCHES)

GMLC Category 2 Projects:

GM0063 Development of an Open-Source Platform for Advanced Distribution Management Systems (Grid Apps-D)

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

GM0187 Community Control of Distributed Resources for Wide Area Reserve Provision

GM0237 Advanced Distribution Management System Testbed Development

WGRID-38 North American Renewable Integration Study (NARIS)

GMLC Resilient Distribution Systems Projects:

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

1.5.7 Laboratory Value Analysis Team

Office of Electricity Delivery and Energy Reliability

SuperFACTS; Federated Sensor Network to Identify Dynamic Interactions Among Critical Infrastructure and Inverter Based Energy Resources

Office of Electricity Microgrids Research and Development Offshore Regional Cost Analyzer

Distribution Transformation Tool (DiTTo)

Power Distribution Sensing and Communications (TCF-20-20213)

Technology Agnostic Loss and Life Informed Dispatch of battEry Assets (TALLIDEA)

Maximizing Sensor Measurement Data through Adaptive Real Time Control

Office of Electricity Resilient Operation of Networked Microgrids (RONM)

Autonomous Energy Systems

Future of the Grid

GMLC Category 1 Projects:

1.1 Foundational Analysis for GMLC Establishment

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

1.3.05 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 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

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

5.2.3 Blockchain for Optimized Security and Energy Management (BLOSEM)

6.1.2 Design and Optimization Infrastructure for Tightly Coupled Hybrid Systems (DISPATCHES)

GMLC Category 2 Projects:

GM0063 Development of an Open-Source Platform for Advanced Distribution Management Systems (GridAPPS-D)

GM0187 Community Control of Distributed Resources for Wide Area Reserve Provision

GM0237 Advanced Distribution Management System Testbed Development

GMLC Resilient Distribution Systems Projects:

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

1.5.7 Laboratory Value Analysis Team

Solar Energy Technologies Office

GMLC Category 1 Projects:

1.1 Foundational Analysis for GMLC Establishment

1.2.1 Grid Architecture

1.3.2 HELICS+: From a Facilitator to a Hub

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

North American Energy Resilience Model (NAERM)

4.2.2 Technical Assistance to PUCs

4.2.3 Future Electric Utility Regulation

GMLC Resilient Distribution Systems Projects:

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

1.5.7 Laboratory Value Analysis Team

Other Direct Projects

32402 North American Renewables Integration Study (NARIS)

32887 PV Plant and Battery Energy Storage Integration

Systems Integration Testbed

2064 Adaptive Protections

2064 Risk Informed

2064 Advanced GFM

2064 Multi Level Cyber

2064 Improving Solar

TCF: Interface for PV

FY 2019 Solar Energy Technologies Office Lab Call Projects

3.4.0.70 Solar Radiation Research Laboratory (SRRL)

3.3.0.5 The National Solar Radiation Database (NSRDB)

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

3.4.0.86 Multi-Timescale Integrated Dynamic and Scheduling for Solar (MIDAS-Solar)

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

3.4.0.80 Innovative Protection Systems for High-Pen PV Grids

3.4.0.82 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:

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

Advanced Systems Integration for Solar Technologies (ASSIST)

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:

1.2.3 Grid Modernization Laboratory Consortium Testing Network

1.4.02 Definitions Standards and Test Procedures for Grid Services

1.4.10 Control Theory

Wind Power 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

4.2.1 Foundational Assistance to ISO/RTOs under Electricity Market Transformation

Wind Grid Projects – FY 2019 Start:

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

Integrated Hydropower

Predictive Microgrid

Hydropower Cyber

Controller HIL Eval

GMLC Category 1 Projects:

4.2.1 Foundational Assistance to ISO/RTOs under Electricity Market Transformation

Nuclear Energy

GMLC Category 1 Projects:

4.2.1 Foundational Assistance to ISO/RTOs under Electricity Market Transformation

Advanced Manufacturing Office

Grid Application Development, Testbed, and Analysis for MV SiC (GADTAMS)

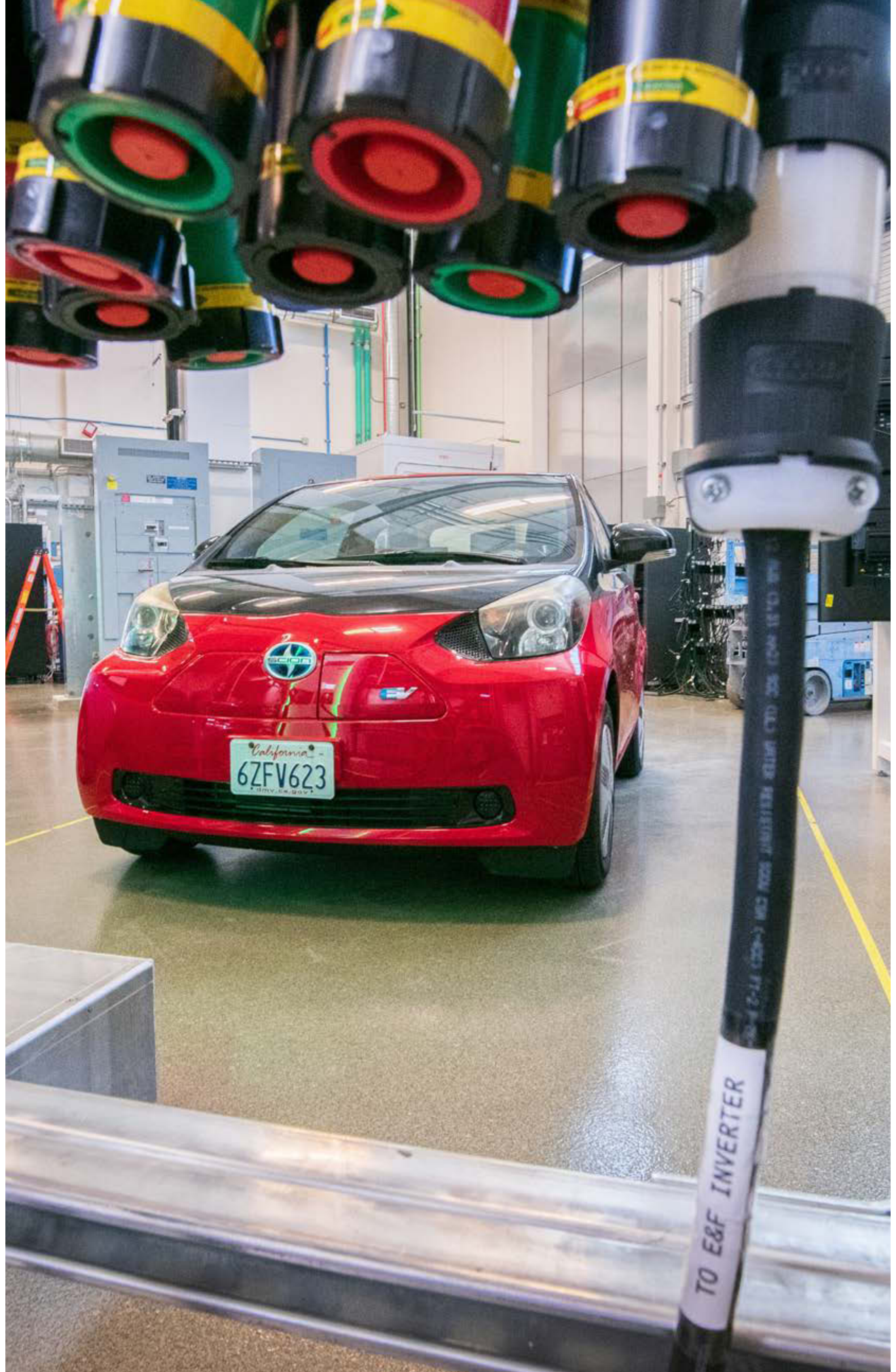
Knowledge Sharing

Despite some unique challenges related to COVID-19, the laboratory's education and outreach initiatives adapted and thrived this year.

NREL offered more than 52 internships at the ESIF (many of them virtual because of the pandemic) to graduate and undergraduate students. Internships at the ESIF offer students exposure to myriad topics in energy systems integration, guiding and forming the future research community. The internships also provide the opportunity for students to build long-term professional relationships with our experts throughout the facility.

Supporting its strong commitment to education, NREL also hosted six university teams participating in this year's DOE CyberForce Competition. This was the first year NREL participated in the competition, which included 106 teams hosted by 10 national laboratories across the United States. CyberForce participants had the opportunity to see NREL's advanced cybersecurity capabilities at the ESIF, including the CEEP. This competition aims to inspire and develop the next generation of energy sector cybersecurity professionals.

Although tours in the ESIF were suspended halfway through the year because of the pandemic, prior to March, NREL hosted 113 tours and more than 1,567 visitors at the ESIF, providing the opportunity for power systems engineers, visitors from industry, elected officials, and the local community to experience the state-of-the-art facility.



Workshops, Conferences, & Events

The following table includes a snapshot of the workshops, conferences, and events held in the ESIF in FY 2019 and FY 2020.

Title	Date
North American Energy Resilience Model (NAERM) Technical Meeting	November 12–13, 2019
ADMS Test Bed Workshop	November 13, 2019
ECO-IDEA Workshop	November 14, 2019
DOE CyberForce Competition	November 15–16, 2019
Workshop and Demo on Real-Time Optimization and Control of Next-Generation Distribution Infrastructure	January 16, 2020
DOE Microgrids Peer Review	June 9–11, 2020 (virtual)
Workshop on Autonomous Energy Systems	August 19–20, 2020 (virtual)
ARIES Industry Workshop	September 2, 2020 (virtual)
Charging Interface Initiative (CharIN) High-Power Charger for Commercial Vehicles (HPCCV) Event	September 22–24, 2020 (virtual)

Innovations

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

Title	Primary NREL Center	NREL Number
Network Visualization, Intrusion Detection, and Network Healing	5R00 - Energy Security & Resilience	SWR-17-41
S-PLN (Scientific Perceptual Loss Network)	2C00 - Computational Science	ROI-19-04
PhIRE (Physics-Informed Resolution-Enhancing Generative Adversarial Network)	2C00 - Computational Science	SWR-18-09
MIiAA (multi-input adaptive Antoulas--Anderson)	5D00 - Power Systems Engineering	ROI-19-10
Dynamic Power Network State Estimation with Asynchronous Measurements	5D00 - Power Systems Engineering	SWR-19-05
Distributed Energy Resources Cybersecurity Framework DERCF	5R00 - Energy Security & Resilience	SWR-19-08
Distribution Feeder Modelling and Analysis Tool DFMAT	5D00 - Power Systems Engineering	SWR-19-10
DERMS-RT (Distributed Energy Resource Management Solution using Real-Time	5D00 - Power Systems Engineering	ROI-19-20
Modelica Builder ModBuild	5D00 - Power Systems Engineering	ROI-19-23
Grid Edge Flexibility Quantification and Optimization	5D00 - Power Systems Engineering	SWR-19-17
Image-Based Solar Estimates	5D00 - Power Systems Engineering	SWR-19-18
powerscenarios	2C00 - Computational Science	SWR-19-27
Model-Free State Estimation	5D00 - Power Systems Engineering	ROI-19-68
Open Energy Data Initiative - Open Data Access Tools OEDI-ODAT	5D00 - Power Systems Engineering	SWR-19-34
Cyber Resilience for High Availability Orchestration in Energy Systems	5R00 - Energy Security & Resilience	SWR-19-35; ROI-16-96

Title	Primary NREL Center	NREL Number
pypsse	5D00 - Power Systems Engineering	ROI-17-37
Distribution Feeder-Scale Fast Frequency Response via Optimal Coordination of Net-load Resources	5D00 - Power Systems Engineering	ROI-17-67
EVOLVE	5D00 - Power Systems Engineering	ROI-17-28
AMR-Wind	2C00 - Computational Science	SWR-17-35
Phase Identification Using Statistical Analysis	5D00 - Power Systems Engineering	SWR-17-36
Hierarchical Distributed Voltage Regulation	5D00 - Power Systems Engineering	SWR-17-06
Non-PLL Grid-Forming Inverter	5D00 - Power Systems Engineering	SWR-17-26
Hydrogen Mass/Ration Control and Passive Membrane Water Management	5B00 - Energy Systems Integration Facility	ROI-17-43
Coordinated Net-Load Management	5D00 - Power Systems Engineering	ROI-17-38
Emerging Technologies Analytical Assessment Framework	5D00 - Power Systems Engineering	SWR-17-18
DW TAP Computational Framework	2C00 - Computational Science	ROI-17-77

Patent Filings

Title	Primary NREL Center	NREL Number
Network-Cognizant Voltage Droop Control	5D00 - Power Systems Engineering	17-28
Game Changer IPA with Span.IO - Smart DEMS Management at the Fuse Box Level	5D00 - Power Systems Engineering	IPA-20-00366
GCxN IPA with Intertie - Battery Compliment-ed Islanded Fast Charging Stations	5D00 - Power Systems Engineering	IPA-20-00368
GCxN IPA with Hygge Power - Outlet Level Energy Storage and Management	5D00 - Power Systems Engineering	IPA-20-00369
Government Use Acknowledgment to ORNL for SWR-20-09	2C00 - Computational Science	LIC-20-00365
Real Time Feedback-Based Optimization of Distributed Energy Resource EAL TIME Feedback-Based Optimization of Distributed Energy Resources	5D00 - Power Systems Engineering	16-124
Virtual Oscillator Control	5D00 - Power Systems Engineering	16-74
IN-LICENSE from CU Boulder for SWR-20-21	5D00 - Power Systems Engineering	LIC-20-00375
Option with Utilidata, Inc. for 16-124 and SWR-18-27	5500 - Building Technologies & Science	LIC-20-00373
Utilidata, Inc.; Option with Utilidata, Inc. for 16-124 and SWR-18-27	5D00 - Power Systems Engineering	IPA-20-00382
Jolt Energy Storage: GCxN IPA with Jolt Energy (no NREL BIP	5D00 - Power Systems Engineering	IPA-20-0388
Coordinate Net-Load Management	5D00 - Power Systems Engineering	18-59
Exclusive license with SoCalGas for NREL 18-48	5B00 - Energy Systems Integration Facility	LIC-19-00352
IN-LICENSE: Data Use Agreement with Univ. of Arizona for their Solar Forecast Arbiter (SFA) platform	5D00 - Power Systems Engineering	LIC-20-00387
IN-LICENSE for LANL QUIC software	2C00 - Computational Science	LIC-20-00388
License with Univ of Alaska Fairbanks for CUBE control software	5D00 - Power Systems Engineering	LIC-20-00381

Publications

10 Most Downloaded Publications

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

1. *ESIF 2019 Annual Report*
2. *Inertia and the Power Grid: A Guide Without the Spin*
3. *Opportunities for Research and Development of Hybrid Power Plants*
4. "Integrated Synchronization Control of Grid-Forming Inverters for Smooth Microgrid Transition"
5. *Model of Operation-and-Maintenance Costs for Photovoltaic Systems*
6. *Simulating Distributed Energy Resource Responses to Transmission System-Level Faults Considering "IEEE" 1547 Performance Categories on Three Major WECC Transmission Paths*
7. *Guide to the Distributed Energy Resources Cybersecurity Framework*
8. *Photovoltaic Inverter Reliability Assessment*
9. *Blackstart of Power Grids with Inverter-Based Resources*
10. *Carbon-Free Resource Integration Study*

Conference Papers (Preprints)

Bernstein, A., C. Yue, M. Colombino, E. Dall'Anese, P. Mehta, and S. Meyn. 2019. "Quasi-Stochastic Approximation and Off-Policy Reinforcement Learning: Preprint" (NREL/CP-5D00-73518). Presented at the 2019 IEEE 58th Conference on Decision and Control (IEEE CDC), Nice, France, December 11–13, 2019.

Brunhart-Lupo, N., B. Bush, K. Gruchalla, K. Potter, and S. Smith. 2020. "Collaborative Exploration of Scientific Datasets Using Immersive and Statistical Visualization: Preprint." Prepared for the SEA's Improving Scientific Software Conference 2020.

Cavraro, G., A. Bernstein, R. Carli, and S. Zampieri. 2020. "Distributed Minimization of the Power Generation Cost in Prosumer-Based Distribution Networks: Preprint" (NREL/CP-5D00-76367). Presented at the 2020 American Control Conference (ACC), Denver, Colorado, July 1–3, 2020.

Cavraro, G., E. Dall'Anese, and A. Bernstein. 2019. "Dynamic Power State Estimation with Asynchronous Measurements: Preprint" (NREL/CP-5D00-75064). Presented at the 2019 IEEE Global Conference on Signal and Information Processing (GlobalSIP), Ottawa, Canada, November 11–14, 2019.

Chang, C. H., I. L. Carpenter, and W. B. Jones. 2020. "The ESIF-HPC-2 Benchmark Suite: Preprint." Presented at the Principles and Practice of Parallel Programming (PPoPP) 2020, San Diego, California, February 22–26, 2020.

Chen, Y., A. Bernstein, A. Devraj, and S. Meyn. 2020. "Model-Free Primal-Dual Methods for Network Optimization with Application to Real-Time Optimal Power Flow: Preprint" (NREL/CP-5D00-76338). Presented at the 2020 American Control Conference (ACC), Denver, Colorado, July 1–3, 2020.

Chen, Y., and A. Bernstein. 2020. "Data-Driven Linear Parameter-Varying Modeling and Control of Flexible Loads for Grid Services: Preprint" (NREL/CP-5D00-76334). Presented at the 2020 American Control Conference, Denver, Colorado, July 1–3, 2020.

Comden, J., M. Colombino, A. Bernstein, and Z. Liu. 2019. "Sample Complexity of Power System State Estimation Using Matrix Completion: Preprint" (NREL/CP-5D00-74580). Presented at the 2019 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm), Beijing, China, October 21–24, 2019.

Furlani Bastos, A., S. Santoso, V. Krishnan, and Y. Zhang. 2020. "Machine Learning-Based Prediction of Distribution Network Voltage and Sensors Allocation: Preprint" (NREL/CP-5D00-75247). Presented at the 2020 IEEE Power and Energy Society General Meeting (IEEE PES GM), Montreal, Canada, August 3–6, 2020.

Giraldez, J., M. Emmanuel, A. Hoke, and S. Suryanarayanan. 2019. "Impacts of Voltage-Based Grid Support Functions on Energy Production of PV Customers: Preprint" (NREL/CP-5D00-72701). Presented at the 2019 IEEE Power and Energy Society General Meeting (IEEE PES GM), Atlanta, Georgia, August 4–8, 2019.

Gomes, G., J. Ugirumurera, and X. S. Li. 2020. "Distributed Macroscopic Traffic Simulation with Open Traffic Models: Preprint." Presented at the 23rd IEEE International Conference on Intelligent Transportation Systems (IEEE ITSC), Rhodes, Greece, September 20–23, 2020.

Habte, A., M. Sengupta, and C. A. Gueymard. 2020. "Consensus International Solar Resource Standards and Best Practices Development: Preprint" (NREL/CP-5D00-75879). Presented at the 47th IEEE Photovoltaics Specialists Conference (IEEE PVSC 47), June 15–August 21, 2020.

Habte, A., M. Sengupta, P. Gotseff, and C. A. Gueymard. 2020. "Annual Solar Irradiance Anomaly Features Over the USA During 1998–2017 Using NSRDB V3: Preprint" (NREL/CP-5D00-76858). Presented at the 47th IEEE Photovoltaics Specialists Conference (IEEE PVSC 47), June 15–August 21, 2020.

Hadi, A. A., G. Bere, T. Kim, J. J. Ochoa, J. Zeng, and G-S. Seo. 2020. "Secure and Cost-Effective Micro Phasor Measurement Unit (PMU)-Like Metering for Behind-the-Meter (BTM) Solar Systems Using Blockchain-Assisted Smart Inverters: Preprint" (NREL/CP-5D00-75447). Presented at the 2020 IEEE Applied Power Electronics Conference and Exposition (IEEE APEC), New Orleans, Louisiana, March 15–19, 2020.

Hupp, W., A. Hasandka, R. Siqueira de Carvalho, and D. Saleem. 2020. "Module-OT: A Hardware Security Module for Operational Technology: Preprint" (NREL/CP-5R00-74697). Presented at the 2020 IEEE Texas Power and Energy Conference (IEEE TPEC), College Station, Texas, February 6–7, 2020.

Jain, A. K., A. Nagarajan, I. Chernyakhovskiy, T. Bowen, B. Mather, and J. Cochran. 2019. "Overview of Evolving Distributed Energy Resource Grid Interconnection Standards: Preprint" (NREL/CP-5D00-72714). Presented at the 2019 North American Power Symposium (NAPS), Wichita, Kansas, October 13–15, 2019.

Jain, A. K., R. Bryce, S. Ghosh, A. Latif, M. Emmanuel, A. Nagarajan, D. Palchak, and J. Cochran. 2019. "Distribution Systems Planning and Analysis Framework for Indian Feeders: Preprint" (NREL/CP-5D00-73589). Presented at the 2nd International Conference on Large-Scale Grid Integration of Renewable Energy in India, New Delhi, India, September 4–6, 2019.

Jain, H., G-S. Seo, E. Lockhart, V. Gevorgian, and B. Kroposki. 2020. "Blackstart of Power Grids with Inverter-Based Resources: Preprint" (NREL/CP-5D00-75327). Presented at the 2020 IEEE Power and Energy Society General Meeting (IEEE PES GM), Montreal, Canada, August 3–6, 2020.

Jain, H., M. Sengupta, A. Habte, and J. Tan. 2020. "Quantifying Solar PV Variability at Multiple Timescales for Power Systems Studies: Preprint" (NREL/CP-5D00-75869). Presented at the 47th IEEE Photovoltaics Specialists Conference (IEEE PVSC 47), June 15–August 21, 2020.

Kenyon, R. W., A. Hoke, J. Tan, and B-M. Hodge. 2020. "Grid-Following Inverters and Synchronous Condensers: A Grid-Forming Pair?: Preprint" (NREL/CP-5D00-75848). Presented at the 2020 Clemson University Power Systems Conference (PSC), Clemson, South Carolina, March 10–13, 2020.

Kim, J-H., P. A. Jimenez, J. Dudhia, J. Yang, M. Sengupta, and Y. Xie. 2020. "Probabilistic Forecast of All-Sky Solar Radiation Using Enhanced WRF-Solar: Preprint" (NREL/CP-5D00-77693). Presented at the 37th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2020), September 7–11, 2020.

Latif, A., R. Bryce, and A. Nagarajan. 2020. "Novel Technique for Developing Linearized Convex System Models from Experimentally Derived Data: Preprint" (NREL/CP-5D00-72754). Presented at the IEEE Power and Energy Society General Meeting (IEEE PES GM), Atlanta, Georgia, August 4–8, 2019.

Liu, B., H. Wu., Y. Zhang, R. Yang, and A. Bernstein. 2019. "Robust Matrix Completion State Estimation in Distribution Systems: Preprint" (NREL/CP-5D00-74530). Presented at the IEEE Power and Energy Society General Meeting (IEEE PES GM), Atlanta, Georgia, August 4–8, 2019.

Liu, W., F. Ding, and C. Zhao. 2020. "Dynamic Restoration Strategy for Distribution System Resilience Enhancement: Preprint" (NREL/CP-5D00-74735). Presented at the 2020 IEEE Innovative Smart Grid Technologies North America Conference, Washington, D.C., February 17–21, 2020.

Liu, W., F. Ding, U. Kumar, and S. Paul. 2020. "Post-Disturbance Dynamic Distribution System Restoration with DGs and Mobile Resources: Preprint" (NREL/CP-5D00-75372). (NREL/CP-5D00-75247). Presented at the 2020 IEEE Power and Energy Society General Meeting (IEEE PES GM), Montreal, Canada, August 3–6, 2020.

Lundstrom, B., G. Saraswat, and M. V. Salapaka. 2020. "High-Frequency, Multiclass Nonintrusive Load-Monitoring for Grid-Interactive Residential Buildings: Preprint" (NREL/CP-5D00-74701). Presented at the 2020 IEEE Innovative Smart Grid Technologies North America Conference, Washington, D.C., February 17–21, 2020.

Mahmud, R., A. Hoke, and D. Narang. 2020. "Fault Response of Distributed Energy Resources Considering the Requirements of IEEE 1547-2018: Preprint" (NREL/CP-5D00-75046). Presented at the 2020 IEEE Power and Energy Society General Meeting (IEEE PES GM), Montreal, Canada, August 3–6, 2020.

Mahmud, R., A. Hoke, and J. White. 2020. "Impact of Aggregated PV on Subsynchronous Torsional Interaction: Preprint" (NREL/CP-5D00-74790). Presented at the 47th IEEE Photovoltaics Specialists Conference (IEEE PVSC 47), June 15–August 21, 2020.

Majmunovic, B., S. Mukherjee, R. Mallik, S. Dutta, G-S. Seo, B. Johnson, and D. Maskimovic. 2020. "Soft Switching Over the Entire Line Cycle for a Quadruple Active Bridge DCX in a DC to Three-Phase AC Module: Preprint" (NREL/CP-5D00-74449). Presented at the 2020 IEEE Applied Power Electronics Conference and Exposition (IEEE APEC), New Orleans, Louisiana, March 15–19, 2020.

Monzon, L., W. Johns, S. Iyengar, M. Reynolds, J. Maack, and K. Prabakar. 2020. "A Multi-Function AAA Algorithm Applied to Frequency-Dependent Line Modeling: Preprint" (NREL/CP-5D00-75381). Presented at the 2020 IEEE Power and Energy Society General Meeting (IEEE PES GM), Montreal, Canada, August 3–6, 2020.

Netto, M., V. Krishnan, L. Mili, P. Sharma, and V. Ajjarapu. 2020. "Real-Time Modal Analysis of Electric Power Grids: The Need for Dynamic State Estimation: Preprint" (NREL/CP-5D00-76124). Presented at the 2020 IEEE International Conference on Probabilistic Methods Applied to Power Systems (IEEE PMAPS), Liege, Belgium, August 18–21, 2020.

Pandey, S., A. K. Srivastava, S. Srivastava, M. U. Mohanpurkar, G. Kandaperumal, and R. Hovsapian. 2020. "Optimal Operation for Resilient and Economic Modes in an Islanded Alaskan Grid: Preprint" (NREL/CP-5D00-75375). Presented at the 2020 IEEE Power and Energy Society General Meeting (IEEE PES GM), Montreal, Canada, August 3–6, 2020.

Patel, S., V. Khatana, G. Saraswat, and M. V. Salapaka. 2020. "Distributed Detection of Malicious Attacks on Consensus Algorithms with Applications in Power Networks: Preprint" (NREL/CP-5D00-76848). Presented at the 2020 IEEE International Conference on Control, Decision and Information Technologies (CoDIT), June 29–July 2, 2020.

Paudyal, P., F. Ding, S. Ghosh, M. Baggu, M. Symko-Davies, C. Bilby, and B. Hannegan. 2020. "The Impact of Behind-the-Meter Heterogeneous Distributed Energy Resources on Distribution Grids: Preprint" (NREL/CP-5D00-74736). Presented at the 47th IEEE Photovoltaics Specialists Conference (IEEE PVSC 47), June 15–August 21, 2020.

Paul, S., and F. Ding. 2020. "Identification of Worst Impact Zones for Power Grids During Extreme Weather Events Using Q-Learning: Preprint" (NREL/CP-5D00-74737). Presented at the 2020 IEEE Innovative Smart Grid Technologies North America Conference, Washington, D.C., February 17–21, 2020.

Prabakar, K., A. Pratt, J. Fossum, J. Wang, B. Miller, M. Symko-Davies, M. U. Usman, and T. Bialek. 2019. "Site-Specific Evaluation of Microgrid Controller Using Controller and Power-Hardware-in-the-Loop: Preprint" (NREL/CP-5D00-72770). Presented at the 45th Annual Conference of the IEEE Industrial Electronics Society (IECON), Lisbon, Portugal, October 14–17, 2019.

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Habte, A., M. Sengupta, and C. A. Gueymard. 2020. "Consensus International Solar Resource Standards and Best Practices Development" (NREL/PO-5D00-76954). Presented at the 47th IEEE Photovoltaics Specialists Conference (IEEE PVSC 47), June 15–August 21, 2020.

Habte, A., M. Sengupta, and P. Gotseff. 2020. "Annual Solar Irradiance Anomaly Feature Over the USA During 1998-2017 Using NSRDB V3" (NREL/PO-5D00-76967). Presented at the 47th IEEE Photovoltaics Specialists Conference (IEEE PVSC 47), June 15–August 21, 2020.

Kumler, A., M. Sengupta, A. Habte, and Y. Xie. 2020. "Sensitivity Analysis of Validation Strategies for the National Solar Radiation Database" (NREL/PO-5D00-75577). Presented at the American Geophysical Union Fall Meeting, San Francisco, California, December 9–13, 2019.

Kumler, A., Y. Xie, M. Sengupta, Y. Liu, W. Zhang, A. Florita, and B. Mather. 2020. "High-Frequency Forecasting of Solar Radiation Using a Hybrid Numerical Weather Prediction and Stochastic Downscaling Model" (NREL/PO-5D00-75587). Presented at the American Geophysical Union Fall Meeting, San Francisco, California, December 9–13, 2019.

Liu, W., F. Ding, and C. Zhao. 2020. "Dynamic Restoration Strategy for Distribution System Resilience Enhancement" (NREL/PO-5D00-76078). Presented at the 2020 IEEE Innovative Smart Grid Technologies North America Conference, Washington, D.C., February 17–21, 2020.

Lundstrom, B., G. Saraswat, and M. V. Salapaka. 2020. "High-Frequency, Multiclass Nonintrusive Load Monitoring for Grid-Interactive Residential Buildings" (NREL/PO-5D00-76068). Presented at the 2020 IEEE Innovative Smart Grid Technologies North America Conference, Washington, D.C., February 17–21, 2020.

Maack, J., D. Sigler, I. Satkauskas, M. Reynolds, W. Jones, S. Abhyankar, S. Peles, and C. Oehmen. 2020. "Scalable Stochastic Transmission Expansion: A Use Case for ExaSGD (NREL/PO-2C00-75840)." Presented at the Exascale Computing Project Annual Meeting, Royal Sonesta Houston Galleria, Houston, Texas, February 3–7, 2020.

Mahmud, R., A. Hoke, and J. White. 2020. "Impact of Aggregated PV on Subsynchronous Torsional Interaction" (NREL/PO-5D00-76904). Presented at the 47th IEEE Photovoltaics Specialists Conference (IEEE PVSC 47), June 15–August 21, 2020.

Mahmud, R., and A. Nejadpak. 2019. "Distributed Cooperative Control of Hybrid AC/DC Microgrid" (NREL/PO-5D00-74190). Presented at the 46th IEEE Photovoltaics Specialists Conference (IEEE PVSC 46), Chicago, Illinois, June 16–21, 2019.

Paul, S., Z. Ni, and F. Ding. 2020. "An Analysis of Post-Attack Impacts and Effects of Learning Parameters of Vulnerability Assessment of Power Grid" (NREL/PO-5D00-76118). Presented at the 2020 IEEE Innovative Smart Grid Technologies North America Conference, Washington, D.C., February 17–21, 2020.

Prabakar, K., A. Pratt, D. Krishnamurthy, and A. Maitra. 2020. "Hardware-in-the-Loop Test Bed and Test Methodology for Microgrid Controller Evaluation" (NREL/PO-5D00-71338). Presented at the 2018 IEEE Power and Energy Society Transmission and Distribution Conference and Exposition (IEEE PES T&D), Denver, Colorado, April 16–19, 2018.

Prabakar, K., A. Pratt, J. Fossum, J. Wang, B. Miller, M. Symko-Davies, and M. Usman. 2019. "Site-Specific Evaluation of Microgrid Controller Using Controller- and Power-Hardware-in-the-Loop" (NREL/PO-5D00-75025). Presented at the 45th Annual Conference of the IEEE Industrial Electronics Society (IECON), Lisbon, Portugal, October 14–17, 2019.

Shaffery, P., R. Yang, and Y. Zhang. 2020. "Bayesian Structural Time Series for Behind-the-Meter Photovoltaic Disaggregation" (NREL/PO-5D00-76108). Presented at the 2020 IEEE Innovative Smart Grid Technologies North America Conference, Washington, D.C., February 17–21, 2020.

Ugirumurera, J., J. Severino, Q. Wang, S. Ravulaparthy, A. Berres, P. Nugent, H. Sorenson, A. Moore, A. Todd, A. Nag, S. Tennille, S. Peterson, K. Potter, H. Xu, W. Jones, and J. Sanyal. 2020. "High Performance Computing Traffic Simulations for Real-Time Traffic Control of Mobility in Chattanooga Region (NREL/PO-2C00-75009)." Presented at the 2019 Tennessee Sustainable Transportation Forum & Expo, Knoxville, Tennessee, October 1–2, 2019.

Utkarsh, K., F. Ding, C. Zhao, H. Padullaparti, and X. Jin. 2020. "A Model-Predictive Hierarchical-Control Framework for Aggregating Residential DERs to Provide Grid Regulation Services" (NREL/PO-5D00-76093). Presented at the 2020 IEEE Innovative Smart Grid Technologies North America Conference, Washington, D.C., February 17–21, 2020.

Wang, J., B. Lundstrom, I. Mendoza, and A. Pratt. 2019. "Systematic Characterization of Power Hardware-in-the-Loop Evaluation Platform Stability" (NREL/PO-5D00-74970). Presented at the 2019 IEEE 11th Annual Energy Conversion Congress and Exposition (IEEE ECCE), Baltimore, Maryland, September 29–October 3, 2019.

Yuan, H., Y. Zhang, S. Murthy, S. You, H. Li, Y. Su, and Y. Liu. 2020. "Machine Learning-Based PV Reserve Determination Strategy for Frequency Control on the WECC System" (NREL/PO-5D00-76048). Presented at the 2020 IEEE Innovative Smart Grid Technologies North America Conference, Washington, D.C., February 17–21, 2020.

Zhang, X., D. Biagioni, P. Graf, and J. King. 2020. "Cooperative Load Scheduling for Multiple Aggregators Using Hierarchical ADMM" (NREL/PO-2C00-76083). Presented at the Innovative Smart Grid Technologies (ISGT 2020) North America, Washington, D.C., February 17–20, 2020.

Presentations

Ayala Pelaez, S., C. Deline, B. Marion, B. Sekulic, B. McDanold, J. Parker, M. Monarch, and J. S. Stein. 2020. "Ultimate Bifacial Showdown: 75kW Field Results (NREL/PR-5K00-77486)." Presented July 29, 2020.

Baggu, M., and A. Pratt. 2020. "NREL's Advanced Distribution Management System (ADMS) Test Bed" (NREL/PR-5D00-75936). Presented at the ADMS Overview Webinar, February 13, 2020.

Bastos, A. F., S. Santoso, V. Krishnan, and Y. C. Zhang. 2020. "Machine Learning-Based Prediction of Distribution Network Voltage and Sensor Allocation" (NREL/PR-5D00-77371). Presented at the IEEE Power and Energy Society General Meeting, August 3–6, 2020.

Ding, F. 2019. "Data-Enhanced Hierarchical Control to Improve Distribution Voltage with Extremely High PV Penetration" (NREL/PR-5D00-74505). Presented at the 2019 IEEE PES General Meeting, Atlanta, Georgia, August 4–8, 2019.

Ding, F. 2019. "Grid Modernization via Breakthrough System Monitoring, Control, and Optimization Using Distributed Energy Resources" (NREL/PR-5D00-74514). Presented at the Workshop on Advanced Distribution Management System (ADMS) Test Bed, Golden, Colorado, November 13, 2019.

Gevorgian, V. 2019. "Energy Transition and Reliability Challenges in Modern Power Grids" (NREL/PR-5D00-75143). Presented at the XVI International Electrical Equipment Conference: JIEEC2019, Bilbao, Spain, October 2, 2019.

Gevorgian, V., H. Villegas, P. Koralewicz, E. Mendiola, S. Shah, and R. Wallen. 2019. "Ultrafast Frequency Response of Converter-Dominant Grids Using PMUs" (NREL/PR-5D00-75259). Presented at the 18th Wind Integration Workshop, Dublin, Ireland, October 17, 2019.

Gevorgian, V., S. Shah, and P. Koralewicz. 2019. "Validation and Testing of Advanced Grid Services by Inverter-Coupled Resources" (NREL/PR-5D00-75479). Presented at eGrid-2019, Xiamen, China, November 12, 2019.

Gevorgian, V., S. Shah, P. Koralewicz, and R. Wallen. 2019. "Impedance Measurement of Inverter-Coupled Generation Using a Multimegawatt Grid Simulator" (NREL/PR-5D00-75258). Presented at the 18th Wind Integration Workshop, Dublin, Ireland, October 18, 2019.

Ghosh, S. 2019. "ADMS Performance: VVO Application on Xcel Energy Feeders" (NREL/PR-5D00-75413). Presented at the Workshop on Advanced Distribution Management System (ADMS) Test Bed, November 13, 2019.

Ghosh, S., and S. Veda. 2020. "EV Grid Integration: Pass Cars and Commercial Fleets" (NREL/PR-5D00-76121). Presented at the 2020 IEEE ISGT North America Conference, Washington, D.C., February 17–20, 2020.

Guerra, O. J., M. N. Koleva, J. Eichman, B.-M. Hodge, and J. Kurtz. 2019. "Economic Analysis of Integrated Solar Power, Hydrogen Production, and Electricity Markets" (NREL/PR-5D00-75443). Presented at the 2019 AIChE Annual Meeting, Orlando, Florida, November 11, 2019.

Ingram, M. 2020. "Updating Interconnection Procedures and Incorporating IEEE-1547" (NREL/PR-5D00-75969). Presented at the 2020 Winter Policy Summit of the National Association of Regulatory Utility Commissioners, Washington, D.C., February 9, 2020.

Jain, H., G.-S. Seo, E. Lockhart, V. Gevorgian, and B. Kroposki. 2020. "Blackstart of Power Grids with Inverter-Based Resources" (NREL/PR-5D00-77286). Presented at the IEEE Power and Energy Society General Meeting, August 3–6, 2020.

Jain, H., M. Sengupta, A. Habte, and J. Tan. 2020. "Quantifying Solar PV Variability at Multiple Timescales for Power Systems Studies" (NREL/PR-5D00-76966). Presented at the 47th IEEE Photovoltaic Specialists Conference, June 15–August 21, 2020.

Koebrich, S., B. Sigrin, R. Spencer, P. Schwabe, S. Haase, S. Choi, and J. Kramer. 2021. "Distributed Solar Adoption in Orlando: A Household-Level Model for Distribution Resource Planning (NREL/PR-6A20-77308)." Presented January 2021.

Krishnan, V., B. Bugbee, T. Elgindy, B. Palmintier, C. Mateo, F. Postigo, T. Gomez San Roman, P. Duenas, and J.-L. Lacroix. 2019. "Realistic Synthetic Distribution Grids: Summary of Validation Results" (NREL/PR-5D00-75723). Presented at the Power Systems Engineering Research Center (PSERC) Industry Advisory Board (IAB) Systems Stem Meeting, Dominion Energy, Richmond, Virginia, December 4, 2019.

Kumler, A., Y. Xie, Y. C. Zhang, R. Yang, X. Jin, M. Sengupta, and Y. Liu. 2020. "Integration of Total-Sky Imager Data with a Physics-Based Smart Persistence Model for Intra-Hour Forecasting of Solar Radiation" (NREL/PR-5D00-75755). Presented at the 2020 AMS Meeting, January 15, 2020.

Lin, C. A., Y. Zhang, G. Heath, D. K. Henze, and M. Sengupta. 2020. "Improvement of Aerosol Optical Depth Data for Localized Solar Forecasting" (NREL/PR-5D00-75816). Presented at the 100th AMS Annual Meeting, Boston, Massachusetts, January 12–16, 2020.

Lunacek, M., and C. Phillips. 2020. "Advanced Transportation Hub Efficiency Using Novel Analysis (ATHENA) (NREL/PR-2C00-76679)." Presented at the DOE Vehicle Technologies Program 2020 Annual Merit Review and Peer Evaluation Meeting, June 2, 2020.

Mahmud, R., A. Hoke, and D. Narang. 2020. "Fault Response of Distributed Energy Resources Considering the Requirements of IEEE 1547-2018" (NREL/PR-5D00-77208). Presented at the IEEE Power and Energy Society General Meeting, August 3–6, 2020.

Martin, M. 2020. "NREL HPC FY21 Allocation Webinar (NREL/PR-2C00-77068)." Presented June 11, 2020.

Mather, B. 2019. "Advanced Distribution Management System (ADMS) Evaluations with Private LTE Communication Networks" (NREL/PR-5D00-75101). Presented at the UTC Region 10 Meeting, Las Vegas, Nevada, October 10–11, 2019.

Mather, B. 2020. "Advanced Inverter Functions and Their Impact on Hosting Capacity" (NREL/PR-5D00-77392). Presented at the IEEE Power and Energy Society General Meeting, August 3–6, 2020.

Narang, D. 2019. "Highlights of IEEE Standard 1547-2018" (NREL/PR-5D00-75436). Presented to the Arkansas DER Interconnection Stakeholders, October 28, 2019 (revised November 21, 2019).

Narang, D., and M. Ingram. 2019. "Highlights of IEEE Standard 1547-2018" (NREL/PR-5D00-75105). Presented at the PJM Technical Workshop on DER Integration with IEEE 1547/1547.1 Standards, Audubon, Pennsylvania, July 30–31, 2019.

Padullaparti, H. 2019. "AMI for Operations" (NREL/PR-5D00-75415). Presented at the Workshop on Advanced Distribution Management System (ADMS) Test Bed, November 13, 2019**.**

Padullaparti, H. 2019. "ECO-IDEA Simulations" (NREL/PR-5D00-75415). Presented at the Workshop on Enhanced Controls and Optimization of Integrated Distributed Energy Applications (ECO-IDEA) ENERGISE Project, November 14, 2019.

Palmintier, B. 2020. "How Use Cases Drove the Design of the HELICS Co-Simulation Framework" (NREL/PR-5D00-71160). Presented at the HELICS Mini-Tutorial, March 16, 2018.

Palmintier, B., and B.-M. Hodge. 2020. "Smart-DS: Synthetic Models for Advanced, Realistic Testing: Distribution Systems and Scenarios" (NREL/PR-5D00-71099). Presented at the Emerging Technologies for Stable and Secure Grid Management ARPA-E Energy Innovation Summit, National Harbor, Maryland, March 14, 2018.

Palmintier, B., and T. Elgindy. 2019. "Large-Scale Grid Models: Synthetic Data and Co-Simulation" (NREL/PR-5D00-75655). Presented at the INFORMS Annual Meeting, Seattle, Washington, October 21, 2019.

Prabakar, K., A. Valibeygi, S. A. R. Konakalla, B. Miller, R. A. de Callafon, A. Pratt, M. Symko-Davies, and T. Bialek. 2020. "Remote Hardware-in-the-Loop Approach for Microgrid Controller Evaluation" (NREL/PR-5D00-76279). Presented at the Clemson University Power Systems Conference Clemson, South Carolina, March 10–13, 2020.

Prabakar, K., N. Wunder, N. Brunhart-Lupo, C. Pailing, K. Potter, M. Eash, and K. Munch. 2020. "Open-Source Framework for Data Storage and Visualization of Real-Time Experiments" (NREL/PR-5D00-76519). Presented at the 2020 IEEE Kansas Power and Energy Conference (KPEC 2020), July 14–15, 2020.

Pratt, A. 2019. "ADMS Test Bed Capabilities" (NREL/PR-5D00-75418). Presented on November 13, 2019.

Pratt, A. 2019. "ADMS Test Bed: Use Case 1" (NREL/PR-5D00-75417). Presented on November 13, 2019.

Pratt, A. 2019. "ADMS Test Bed: Use Case 2" (NREL/PR-5D00-75412). Presented on November 13, 2019.

Pratt, A. 2019. "Site-Specific Evaluation of Microgrid Controller Using Controller- and Power-Hardware-in-the-Loop" (NREL/PR-5D00-75024). Presented at the 45th IECON, Lisbon, Portugal, October 14–17, 2019.

Roy, J., A. K. Jain, and B. Mather. 2020. "Impacts of Experimentally Obtained Harmonic Spectrums of Residential Appliances on Distribution Feeder" (NREL/PR-5D00-76024). Presented at the Texas Power and Energy Conference, College Station, Texas, February 7, 2020.

Sengupta, M., A. Habte, G. Buster, M. Rossol, Y. Xie, M. J. Foster, and C. Gueymard. 2020. "A Status Update on the National Solar Radiation Database (NSRDB)" (NREL/PR-5D00-77121). Presented at the PVPMC Webinar on Solar Resource Assessment for PV Performance Modeling, June 24, 2020.

Sengupta, M., A. Habte, Y. Xie, and B. Grant. 2020. "Improving the Accuracy of the National Solar Radiation Database (NSRDB) Using High-Resolution Data" (NREL/PR-5D00-75814). Presented at the 100th AMS Annual Meeting, Boston, Massachusetts, January 12–16, 2020.

Sengupta, M., and A. Habte. 2019. "Measurement, Modeling, and Database of Solar Irradiance" (NREL/PR-5D00-75573). Presented at the 2019 NIST/UL Workshop on Photovoltaic Materials Durability, Gaithersburg, Maryland, December 12–13, 2019.

Shah, S. 2020. "Impedance of Three-Phase Systems in DQ, Sequence, and Phasor Domains" (NREL/PR-5D00-77669). Presented at the IEEE Power and Energy Society (PES) Webinar, August 18, 2020.

Shah, S., P. Koralewicz, V. Gevorgian, and R. Wallen. 2020. "Measuring Commercial Wind Turbine Impedances for Stability Analysis" (NREL/PR-5D00-77668). Presented at the IEEE Power and Energy Society General Meeting, August 3–6, 2020.

Shah, S., V. Gevorgian, P. Koralewicz, and R. Wallen. 2020. "Control System Stability for Converter-Dominated Grids" (NREL/PR-5D00-76862). Presented at the ESIG Spring Technical Workshop, April 28, 2020.

Shah, S., V. Gevorgian, P. Koralewicz, R. Wallen, and W. Yan. 2019. "Impedance Methods for Analyzing Stability Impacts of Inverter-Based Resources" (NREL/PR-5D00-75345). Presented at the NSF Workshop on Power Electronics-Enabled Operation of Power Systems, Chicago, Illinois, October 31–November 1, 2019.

Sitaraman, H., M. Rahimi, J. Lischeske, and J. Stickel. 2020. "Multiphase Reacting Flow Simulations and Optimization of Commercial-Scale Aerobic Bioreactors (NREL/PR-2C00-75490)." Presented at the 2019 AIChE Annual Meeting, Orlando, Florida, November 11, 2019.

Spyrou, E., J. King, A. Kumler, C. Bay, Y. C. Zhang, V. Gevorgian, and D. Corbus. 2020. "An Integrated Platform for Wind Plant Operations: From Atmosphere to Electrons to the Grid" (NREL/PR-5D00-77097). Presented at the FERC Technical Conference regarding Increasing Market and Planning Efficiency and Enhancing Resilience through Improved Software, June 25, 2020.

Spyrou, E., V. Krishnan, Q. Xu, and B. F. Hobbs. 2020. "What Is the Value of Alternative Methods for Estimating Ramping Needs?" (NREL/PR-5D00-76624). Presented at the 12th IEEE Green Technologies Conference, Oklahoma City, Oklahoma, 2020.

Tan, J. 2019. "Frequency Control and Modeling of Inverter-Based Renewables for Grid Study: An Industry Perspective" (NREL/PR-5D00-74577). Presented at the 2019 IEEE Power and Energy Society General Meeting, Atlanta, Georgia, August 7, 2019.

Veda, S. 2019. "ADMS Testbed: Use Cases (NREL/PR-5D00-72739)." Presented at the ADMS Test Bed Workshop, September 25–26, 2018.

Veda, S., and H. Padullaparti. 2020 "ADMS-Centric Operation for High-PV Distribution Grids" (NREL/PR-5D00-76152). Presented at the Electric Distribution Engineering (EDE) Conference, Aurora, Colorado, February 27, 2020.

Velaga, Y. N., K. Prabakar, A. Singh, and P. K. Sen. 2020. "High-Frequency Signature-Based Fault Detection for Future MV Distribution Grids" (NREL/PR-5D00-77133). Presented at the 2020 Industrial and Commercial Power Systems Technical Conference, June 29–July 28, 2020.

Walker, A., J. Desai, and B. McDonald. 2020. "Solar Photovoltaic Systems Time-Series Simulation: Subinterval Distribution vs. Steady-State Assumption" (NREL/PR-5C00-76859). Presented at the 2020 ASME 14th International Conference on Energy Sustainability (ES2020), June 17–18, 2020.

Wang, J. 2019. "ECO-IDEA Hardware-in-the-Loop Test" (NREL/PR-5D00-75411). Presented at the Workshop on Enhanced Controls and Optimization of Integrated Distributed Energy Applications (ECO-IDEA) ENERGISE Project, November 14, 2019.

Wang, J., B. Lundstrom, and A. Bernstein, Andrey. 2020. "Design of a Non-PLL Grid-Forming Inverter for Smooth Microgrid Transition Operation" (NREL/PR-77338). Presented at the IEEE Power and Energy Society General Meeting, August 3–6, 2020.

Wang, J., H. Padullaparti, S. Veda, I. Mendoza, S. Tiwari, and M. Baggu. 2020. "Performance Evaluation of Data-Enhanced Hierarchical Control for Grid Operations" (NREL/PR-5D00-77301). Presented at the IEEE Power and Energy Society General Meeting, August 3–6, 2020.

Xie, Y.-K., M. Sengupta, Y. Liu, H. Long, Q. Min, and W. Liu. 2020. "Finite-Surface Integration Algorithm for Improving the Forecast of Cloudy-Sky DNI" (NREL/PR-5D00-75800). Presented at the 100th AMS Annual Meeting, Boston, Massachusetts, January 15, 2020.

Yang, J., M. Sengupta, Y. Xie, P. A. Jimenez, and J.-H. Kim. 2020. "Sensitivity Study for Forecasting Variables of WRF-Solar Using a Tangent Linear Approach" (NREL/PR-5D00-75802). Presented at the 2020 AMS Conference, Boston, Massachusetts, January 12–16.

Yang, R., Y. C. Zhang, P. Shaffery, N. Yu, and F. Kabir. 2020. "Predictive Analytics for Behind-the-Meter Resources" (NREL/PR-5D00-76095). Presented at the 11th Conference on Innovative Smart Grid Technologies, Washington, D.C., February 20, 2020.

Yuan, H. 2020. "Multi-Timescale Integrated Dynamic and Scheduling Model (MIDAS-Solar)" (NREL/PR-5D00-76086). Presented at the Innovative Smart Grid Technologies (ISGT 2020) North America, Washington, D.C., February 18, 2020.

Technical Reports

Brancucci, C., M. McCall, O. Zinaman, H. N. Villegas Pico, and V. Gevorgian, Vahan. 2020. *Iquitos Solar Energy Integration Study* (NREL/TP-5D00-73675). Golden, CO: National Renewable Energy Laboratory.

Cox, J., S. Bragg-Sitton, J. Gorman, G. Burton, M. Moore, A. Siddiqui, T. Nagasawa, H. Kamide, T. Shibata, S. Arai, K. Araj, E. Chesire, T. Stone, P. Rogers, G. Peel, M. Berthelemy, H. Paillere, P. Fraser, B. Wanner, C. Pavarini, S. Bilbao-Y-Leon, A. Rising, S. Feutry, A. Herzog, D. Throne, M. Korsnick, K. Frick, C. Forsberg, C. Hughes, M. Brown, and A. Omoto. 2020. *Flexible Nuclear Energy for Clean Energy Systems* (NREL/TP-6A50-77088). Golden, CO: National Renewable Energy Laboratory.

Diaz, P., R. King, D. Sigler, W. Cole, and W. Jones. 2020. *Uncertainty Quantification for Capacity Expansion Planning* (NREL/TP-2C00-76708). Golden, CO: National Renewable Energy Laboratory.

Doubleday, K., A. Parker, F. Hafiz, B. Irwin, S. Hancock, S. Pless, and B.-M. Hodge. 2020. *Pena Station NEXT Energy District Master Plan: Cooperative Research and Development Final Report, CRADA Number CRD-17-681* (NREL/TP-5D00-76242). Golden, CO: National Renewable Energy Laboratory.

Fang, X., K. Sedzro, B.-M. Hodge, J. Zhang, B. Li, Binghui, and M. Cui. 2020. *Providing Ramping Service with Wind to Enhance Power System Operational Flexibility* (NREL/TP-5D00-73643). Golden, CO: National Renewable Energy Laboratory.

Habte, Aron. 2020. *Low-Cost Sensor for Solar Resource Assessment and Microclimate Monitoring: Cooperative Research and Development Final Report, CRADA Number CRD-17-686* (NREL/TP-5D00-76509). Golden, CO: National Renewable Energy Laboratory.

Hasandka, A., J. Rivera, and J. Van Natta. 2020. *NREL's Cyber-Energy Emulation Platform for Research and System Visualization* (NREL/TP-5R00-74142). Golden, CO: National Renewable Energy Laboratory.

Johnston, H., A. Kolker, G. Rhodes, and N. Taverna. 2020. *Sedimentary Geothermal Resources in Nevada, Utah, Colorado, and Texas* (NREL/TP-5500-76513). Golden, CO: National Renewable Energy Laboratory.

Kenyon, R. W., and B. Mather. 2020. *Simulating Distributed Energy Resource Responses to Transmission System-Level Faults Considering IEEE 1547 Performance Categories on Three Major WECC Transmission Paths* (NREL/TP-5D00-73071). Golden, CO: National Renewable Energy Laboratory.

Kroposki, Benjamin. 2020. *NREL CITIES Support: Cooperative Research and Development Final Report, CRADA Number CRD-14-00558* (NREL/TP-5D00-77641). Golden, CO: National Renewable Energy Laboratory.

Marqusee, J., S. Ericson, and D. Jenket. 2020. *Emergency Diesel Generator Reliability and Installation Energy Security* (NREL/TP-5C00-76553). Golden, CO: National Renewable Energy Laboratory.

Martin, M., J. Foster, S. Lawson, and S. Cox. 2020. *Cybersecurity and Distributed Energy Resources* (Russian Translation) (NREL/TP-5R00-76988). Golden, CO: National Renewable Energy Laboratory.

Matsuda-Dunn, R., M. Emmanuel, E. Chartan, B.-M. Hodge, and G. Brinkman. 2020. *Carbon-Free Resource Integration Study* (NREL/TP-5D00-74337). Golden, CO: National Renewable Energy Laboratory.

Nagarajan, A., R. Thiagarajan, I. Repins, and P. Hacke. 2019. *Photovoltaic Inverter Reliability Assessment* (NREL/TP-5D00-74462). Golden, CO: National Renewable Energy Laboratory.

Nagarajan, A., S. Ghosh, A. K. Jain, S. Akar, R. Bryce, M. Emmanuel, T. Remo, A. Latif, D. Palchak, J. Cochran, A. Ranjan, and N. Nagpal. 2020. *Preparing Distribution Utilities for Utility-Scale Storage and Electric Vehicles: A Novel Analytical Framework* (NREL/TP-5D00-75973). Golden, CO: National Renewable Energy Laboratory.

Narang, D., A. Hoke, S. Gonzalez, R. Mahmud, J. Johnson, and S. Meor-Danial. 2019. *Accelerating Systems Integration Standards (ACCEL)* (NREL/TP-5D00-73020). Golden, CO: National Renewable Energy Laboratory.

Narang, D., M. Ingram, A. Hoke, A. Bhat, and S. M. Danial. 2020. *Clause-by-Clause Summary of Requirements in IEEE Standard 1547-2018* (NREL/TP-5D00-75184). Golden, CO: National Renewable Energy Laboratory.

Perr-Sauer, J., A. Duran, and C. Phillips. 2020. *Clustering Analysis of Commercial Vehicles Using Automatically Extracted Features from Time Series Data* (NREL/TP-2C00-74212). Golden, CO: National Renewable Energy Laboratory.

Powell, C., K. Hauck, A. Sanghvi, A. Hasandka, J. Van Natta, and T. Reynolds. 2019. *Guide to the Distributed Energy Resources Cybersecurity Framework* (NREL/TP-5R00-75044). Golden, CO: National Renewable Energy Laboratory.

Powell, C., K. Hauck, A. Sanghvi, and T. Reynolds. 2020. *Distributed Energy Resource Cybersecurity Framework Best Practices* (NREL/TP-5R00-75921). Golden, CO: National Renewable Energy Laboratory.

Sengupta, M., A. Habte, and M. Dooraghi. 2019. *PV Variability at the DeSoto Next Generation Solar Energy Center: Cooperative Research and Development Final Report, CRADA Number CRD-11-425* (NREL/TP-5D00-75427). Golden, CO: National Renewable Energy Laboratory.

Sengupta, M., and C. Turchi, Craig. 2020. *Australian Solar Energy Forecasting System (ASEFS): Cooperative Research and Development Final Report, CRADA Number CRD-14-541* (NREL/TP-5D00-77091). Golden, CO: National Renewable Energy Laboratory.

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NREL/BR-5B00-79354 • February 2021