NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Modernizing Our Grid and Energy System

ESIF 2016

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Three years ago, we had a simple vision: let's create **clean, affordable, and reliable energy systems at a pace and scale that matters** to society and to our economy. Rapid advances in higher efficiencies, better performance, lower costs, stronger materials, and new chemistries were helping to create the components of a stronger energy future, but we were lacking the place to put them all together, make them work as a system, and show their additive value.

Now in our third year of operations, the U.S. Department of Energy's (DOE's) Energy Systems Integration Facility (ESIF) is the nation's premier facility for the research, development, and demonstration of the components and strategies needed to achieve this vision. The ESIF provides a unique, contained, and controlled integrated energy systems platform on which our academic, industry, or laboratory partners can identify and resolve the technical, operational, and financial risks of integrating emerging energy technologies into today's environment.

At the ESIF, we ask and answer complex questions about how our energy systems can be designed and operated to provide a more affordable, sustainable, and secure energy future.

This 2016 ESIF annual report highlights our work in finding new ways to control and protect electric grids, showing how they can accommodate more renewables, demonstrating that utility-scale solar photovoltaic (PV) installations can provide grid services, challenging inventors to create a smaller inverter, determining the best way to dispatch battery energy storage systems (BESS), using big data to improve solar forecasting, and developing new test devices for hydrogen refueling. At the ESIF, we have also completed a series of groundbreaking projects under the Integrated Network Testbed for Energy Grid Research and Technology Experimentation (INTEGRATE) initiative, funded by the U.S. Department of Energy (DOE), that have demonstrated new approaches to operating and managing electric distribution grids with very high levels of distributed energy resources in an interoperable and scalable manner.

During 2016, we also expanded the world's leading energy efficient, high-performance computing (HPC) data center—Peregrine—and used it to blaze new frontiers in energy systems integration (ESI). Nearly 80 projects conducted on Peregrine focused on accelerating the design of new materials, studying the performance of vehicle and building components, and optimizing the interaction of wind turbines for improved wind power plant performance. Notably, we used the expanded Peregrine to successfully model the operations of the electric grid in the eastern United States at an unprecedented 5-minute resolution, providing insights to operators and asset owners on the future opportunities presented by a modernized grid. All of this work was conducted while maintaining a world's best power usage effectiveness of 1.04 and while installing new dry cooling technology that will cut our future water consumption in half.

All of our capabilities and resources at the ESIF are available to you at little or no cost by virtue of our designation as a DOE user facility. During 2016, 80 academic and industry partners used the ESIF's unique megawatt-scale distribution buses for electricity, heat, and fuel; its specialized laboratories and equipment; and its HPC and visualization spaces to design, operate, and validate our future energy systems. In 2017, we will provide new funding opportunities for high-impact projects, start new programs for academic faculty and graduate students, and expand our engineering team to support work in thermal energy, fuels, and water.

Now is the time to bring your complex energy systems questions to the ESIF so that we can answer them together and accelerate the arrival of **clean, affordable, and reliable energy systems at a pace and scale that matters**.

Bryan Hannegan
Associate Laboratory Director for Energy Systems Integration at NREL

The ESIF was established in 2013 by DOE's Office of Energy Efficiency and Renewable Energy (EERE) on the campus of its National Renewable Energy Laboratory (NREL) and is a designated DOE user facility.

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GRID MODERNIZATION

The future grid will solve the challenges of **seamlessly integrating** conventional and renewable sources, storage, and central and distributed generation. It will provide a critical platform for U.S. prosperity, competitiveness, and innovation in a global clean energy economy.

—*Grid Modernization Multi-Year Program Plan*

DEVICES & INTEGRATED SYSTEMS

Google Little Box Challenge

Can you build a kilowatt-scale solar inverter that is smaller than a tablet (instead of the size of a picnic cooler)?

Yes, and you don't have to compromise on power.

Project Spotlight

Google Little Box Challenge

Currently, residential solar inverters are approximately the size of a picnic cooler; however, there are many potential benefits to reducing that size. Shrinking inverters by 10 times or more and making them cheaper to produce and install would enable more solar-powered homes, more efficient distribution grids, and help bring electricity to remote areas.

So Google, with the help of the IEEE Power Electronics Society and NREL, laid out a challenge to the world: design a smaller, more efficient, residential-scale solar power inverter. The team that best meets all the requirements for the competition would take home a $1 million prize.

NREL researchers assisted in the competition by designing the specifications and evaluation methodology for the prototype inverters. NREL researchers then evaluated the performance and efficiency of each inverter at the ESIF, using the same set of typical operating conditions. The inverters needed to meet most of the same specifications required of inverters already available commercially.

More than 100 teams from across the world submitted designs, and 18 teams made it to the final round for evaluation at NREL. In the end, CE+T Power's Red Electrical Devils team from Belgium put forward the winning design and took home the $1 million prize.

A key factor in the Red Electrical Devils' and the other contending teams' designs was the use of wide-bandgap semiconductors. Wide-bandgap technology makes it possible for power electronics to operate at higher voltages and temperatures and transmit more energy through a smaller volume.

The technical approach documents for the 18 finalists are publicly available and can be downloaded here: https://www.littleboxchallenge.com/.

Watch: Researcher Blake Lundstrom talks about how NREL helped evaluate inverters for the Google Little Box Challenge: ***https://www.youtube.com/watch?v=CupGG7P33vk*****.**

Project Spotlight

NREL Demonstrates That Photovoltaic Systems Large and Small Can Provide Grid Services

NREL has confirmed that utility-scale PV technologies can provide grid-support functions when needed. NREL teamed up with AES, Puerto Rico Electric Power Authority, First Solar, and the Electric Reliability Council of Texas to try providing grid ancillary services using two actual multimegawatt PV power plants. The PV power plants were able to provide variability smoothing through automatic generation control, frequency regulation for fast response and droop response, and power quality control.

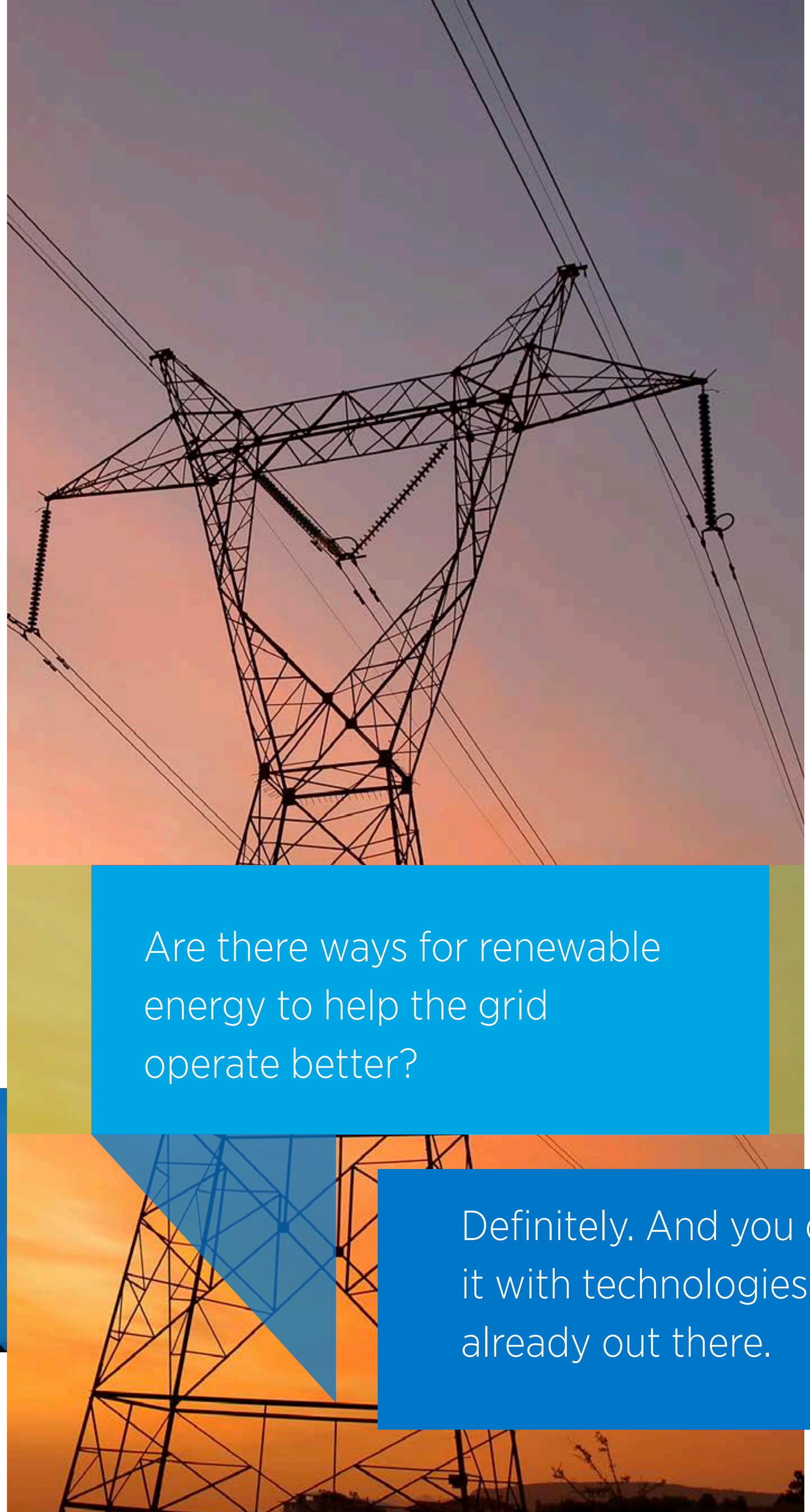
Of course, a single, centrally located PV plant affects the grid much differently than a number of small, distributed PV systems, which can cause control problems by driving up daytime voltages, possibly exceeding voltage limits on the distribution feeder. However, newer "smart" inverters can sense grid conditions and respond to them to help maintain grid stability.

San Diego Gas & Electric Company (SDG&E) and SolarCity contracted with NREL to examine how smart PV inverters can provide voltage support on the utility's distribution feeder lines. NREL modeled one SDG&E feeder and used that model to simulate and analyze the impact of smart PV inverters on distribution feeder voltages by studying three different autonomous Volt/VAR controls and six different power factor settings under a variety of feeder loads and PV production levels. The research indicates that smart PV inverters installed in sufficient quantity at the right location can either shift voltage levels through the use of constant power factor settings or reduce voltage variability and improve the voltage profile through autonomous Volt/VAR control.

Smart PV inverters can also ride through some short-term grid disturbances, helping to maintain grid voltage and frequency while the grid tries to recover. But this must be balanced with the inverters' anti-islanding feature, which prevents a PV system from keeping power lines energized during a grid failure. To ensure that smart inverters are achieving this balance, SolarCity teamed up with NREL to examine whether grid support functions or the presence of multiple inverters would impact the anti-islanding feature. The testing included interconnecting three smart inverters to a real-time simulation of an electric distribution system. Under these test scenarios, any impacts were within acceptable limits.

NREL Researchers Honored for Research on Grid Support from Solar PV

With partners from Puerto Rico Power Authority, First Solar, and AES, NREL's Vahan Gevorgian and Barbara O'Neill were recognized by the Utility Variable Generation Group for leadership and contributions to the field trials of ancillary services from PV power plants.



Are there ways for renewable energy to help the grid operate better?

Definitely. And you can do it with technologies that are already out there.

Project Highlights

NREL Evaluates Smart Inverter Functions for Florida Power and Light

NREL collaborated with Florida Power & Light (FPL) to evaluate various features for a range of smart inverters located at the 1.3-MW solar PV project at the Daytona International Speedway in Daytona Beach, Florida. NREL provided test data for such advanced inverter functions as fixed power factor operation, voltage and frequency ride-through, volt/VAR control, and frequency-watt control. NREL also measured the inverters' efficiencies across a wide range of operating conditions and evaluated their reliability under abnormal conditions such as islanding, faults, and load-rejection scenarios.

UL Updates Smart Inverter Standard with the Help of NREL Researchers

UL, a global independent safety science company, released the latest standard for advanced inverters (UL 1741SA) in early September 2016. This highly anticipated standard provides a certification method to determine if advanced inverters can safely stay connected and help stabilize the grid during disturbances by adapting their behavior and output. NREL researchers supported this extensive revision by providing a series of draft test procedures, attending many online meetings, and providing comments and suggestions for the final draft. NREL researchers also provided key test data and performed critical early tests at the ESIF using the UL 1741SA test procedures to help validate the standard and effectively "tested the tests" to verify their repeatability and effectiveness.

Project Spotlight

Getting the Most Value from Utility-Scale Energy Storage

Utilities are increasingly pursuing grid-connected energy storage systems to help control the grid while also making greater use of renewable energy resources. In Fiscal Year 2016, NREL ESI researchers modeled two feeders on the SDG&E grid, each of which was modeled with an interconnection to at least one commercial-scale solar PV system, as well as capacitor banks. Using historical load and PV production data for 1 year, the researchers modeled the performance of a 1-MW lithium-ion BESS with 3 MWh of energy storage. The round-trip efficiency of the BESS was set to 92%, and the state of charge was maintained between 10% and 90% to prolong the battery life, although a battery degradation feature was included.

The model prioritized the use of the BESS for grid-support functions, including smoothing the output from the PV systems. Using the model to determine how much battery capacity was needed for grid support, the remaining capacity could be used to participate in wholesale markets. NREL ESI researchers demonstrated that a BESS could provide multiple grid services at the same time, a concept known as "multiservice dispatch." For instance, the system could smooth PV power production while also shaving peak power demands on the feeder. In addition, volt/watt control of the feeder can be stacked with peak shaving.

Based on this detailed analysis, NREL was then able to create two simplified algorithms that SDG&E can employ in its operations: a day-ahead algorithm for unit commitment and dispatch and a real-time algorithm to take advantage of dispatch opportunities throughout the day. All three models predict a BESS market participation potential income of approximately $30–$80 per day, after accounting for battery degradation and replacement costs. The BESS multiservice dispatch algorithms developed by NREL ESI researchers can help other utilities maximize the potential income from energy storage systems.

For utilities adding battery energy storage systems to their grid, what is the best way to dispatch these systems?

Detailed studies by NREL indicated some general rules regarding when and how the system should be dispatched, and NREL has incorporated these rules into algorithms that could be adapted for other utilities.

Project Highlights

NREL Demonstrates Coordinated Battery and Photovoltaic Controls with SunPower

BESS can now be combined with solar PV systems and interconnected to the grid with a PV-battery inverter, allowing the system to be used as a dispatchable resource and to support the grid's operation by providing ancillary services. Through a project with SunPower Corporation, ESI researchers examined the system-wide impacts of controlling hundreds of distributed PV-battery inverters in four key operational modes—PV smoothing, dispatched operation, scheduled operation, and self-consumption—using power hardware-in-the-loop (PHIL) techniques. The project demonstrated that coordinated control of many distributed PV-battery inverter units provided valuable grid services, including voltage smoothing, reduced wear and tear on utility voltage regulators, and reduced peak power requirements for the distribution system.

Project Spotlight

NREL Advances Hydrogen Refueling through New Test Devices, Real-World Data Gathering

Current hydrogen refueling stations are facing a commissioning challenge: the stations are required to meet the fueling protocols established by the SAE J2601 - 2014 standard, but there is currently no entity that formally certifies a station as being compliant with this standard. Instead, each auto manufacturer has individually conducted its own testing and verification process at each refueling station using its own vehicles—a slow and clearly unsustainable approach as the number of fueling stations and manufacturers of fuel-cell vehicles grows.

To address this problem, NREL and Sandia National Laboratories contracted with Powertech Labs to develop and build the Hydrogen Station Equipment Performance (HyStEP) device, which is meant to replace the testing performed by each auto manufacturer without the need for a fuel-cell vehicle. Part of the DOE's H2FIRST project, HyStEP is equipped with modular tanks and all the instrumentation and communications needed to perform fueling and validation tests.

HyStEP is being used in California in parallel with the auto manufacturers' tests, allowing comparisons between the two approaches. The intent is to work toward acceptance of HyStEP as a certification device, but in the meantime HyStEP has helped California commission 16 new refueling stations. In recognition of the significance of this achievement, HyStEP won a regional Federal Laboratory Consortium award for outstanding partnership in 2016. To encourage others to use the same approach, HyStEP is not patent-protected.

NREL has also developed a vehicle simulator device that can test a hydrogen station's ability to perform limitless back-to-back fills without requiring actual fuel-cell vehicles, enabling research on system controls for improved reliability and performance. In addition, a hydrogen flow meter validation device will allow manufacturers of hydrogen flow meters to assess and improve flow meter accuracy.

NREL's work with hydrogen refueling infrastructure is far from academic: NREL has a small fleet of fuel-cell vehicles on loan from manufacturers and is gathering vital real-world data on fueling and usage to understand how to optimize the vehicle-station interface while maximizing vehicle and station performance.

In FY 2016, NREL's Hydrogen Infrastructure Testing and Research Facility produced more than 1,000 kg of hydrogen, including more than 200 kg for 70 refuels of fuel-cell vehicles. The system experienced less than 5% system downtime.

NREL's refueling statistics should increase next year, as a new electrolyzer test bed has been installed in the ESIF with the capability to produce approximately 50 kg of hydrogen per day, enough to fuel more than 10 fuel-cell vehicles.

How can state, local, and private entities successfully build new hydrogen refueling infrastructure at a pace to meet their clean energy goals?

Through a variety of projects, NREL is providing the technical knowledge and the equipment needed to best establish new hydrogen refueling stations. And by creating new certification tools, such as the HyStEP device, it will be possible to meet ambitious infrastructure implementation goals.

Project Highlights

Grid Evaluation Network Includes Nine Stations with Remote Load-Control Capabilities

An electric vehicle (EV) distribution grid evaluation network at the ESIF is being used to characterize EV integration with distribution systems, home energy loads, and solar PV systems. The system allows for full modulation and shaping of the EV load to smooth out variations in the PV output. Up to nine interconnected vehicles can be used to raise or lower distribution system voltage and maximize the use of renewable energy resources. These early demonstration units have led to broader deployment in the NREL parking garage. The NREL EV charging stations will be managed with respect to both solar production and driver demands.

ESIF Research Aims to Avoid High-Pressure Hydrogen Leaks

Hydrogen is dispensed as a high-pressure gas, so leaks are always a concern. NREL has been performing thousands of simulated refueling events using a robotic arm to accelerate and evaluate the wear and tear on a high-pressure hydrogen fueling hose under real-world conditions. Results from these high-cycle rates are revealing insights into leak patterns and characteristics of all 700-bar fueling equipment, which can help equipment manufacturers improve reliability. With the aid of a DOE Small Business Voucher, NREL also helped develop and test a novel hydrogen leak-detection tape that changes color when exposed to hydrogen.

NREL Study of Hydrogen Venting Plumes May Lead to Shorter Setback Distances

Liquid hydrogen storage facilities require routine hydrogen venting, typically released 20 to 30 feet aboveground, and setback distances are required to keep people and equipment safe from potential ignition of the vented hydrogen cloud. NREL has built a test apparatus for field deployment directly within these hydrogen plumes that measures hydrogen concentrations and temperatures with 10 gas-sampling points. The project supports the validation of a dispersion model used to calculate concentrations of hydrogen from releases, the results of which will support more flexible code requirements for siting hydrogen storage systems, thereby aiding the deployment of hydrogen refueling infrastructure.

Watch: Toyota and NREL are finding ways to sustainably produce large amounts of hydrogen. See more at *https://youtu.be/3OiSOeUQ4hg*.

SENSING & MEASUREMENT

How can you take advantage of big data to improve solar forecasting?

Using a machine-learning technology from IBM to mix different forecasting models and learn from past prediction accuracy has shown impressive results: 30% improvement compared to the best individual model and 10% improvement compared to conventional machine-learning model blending. And that's just the beginning.

Project Spotlight

IBM and NREL Build a Better Solar Forecasting Tool Using Big Data

A big hurdle to unlocking the full potential of solar energy is knowing ahead of time when it will be available. Because of the complexity of solar forecasting, even the best models have weaknesses, and that uncertainty brings costs for utilities, from not getting the full value out of solar technologies to keeping costly spinning reserves waiting in the wings.

To help solve this problem, IBM, ESIF researchers, and a team of partners set out to build a better solar forecasting model using deep-machine-learning technology. Since individual models each have limitations, this approach would blend multiple models and forecast data together to identify what mix works best to predict solar resources under specific weather conditions. This "multimodel" (aptly named Watt-sun) would learn from the accuracy of past predictions to continuously improve its mix of models and data.

One of the technical challenges that needed to be addressed to build this complex and data-intense multimodel was to effectively quantify forecast accuracy. With so many factors at play (location, cloud cover, time of day, etc.), no consistent and robust set of metrics existed to measure the accuracy of a solar forecast. As part of this project, NREL led the development of a standard set of metrics for assessing solar forecast accuracy as well as forecasting baseline and target values.

Validation of Watt-sun at multiple sites across the United States demonstrated a more than 30% improvement compared to forecasts based on the best individual model and a more than 10% improvement compared to conventional machine-learning forecasts. One of the positive aspects of the technology is that it serves as an accuracy multiplier to other forecasting technologies. As new and better models are developed, Watt-sun's machine-learning methods will produce increasingly precise forecasts, leading to better integration of solar energy in electric grids.

This project was developed through DOE's SunShot Initiative. The solar forecasting framework uses only nonproprietary weather and solar radiation models, allowing the technology to be scaled and to be adopted by solar producers, electric utilities, independent system operators (ISOs), and other stakeholders.

So what's that worth?

To quantify the benefit of improved solar forecasting in dollars, NREL performed a study of the ISO New England system. It was found that the value of improving solar power forecasts increases dramatically with increasing solar penetration levels. Read the full study and results at *http://www.sciencedirect.com/science/article/pii/S0038092X16000736*.

Project Spotlight

NREL Contributes to NCAR's Sun4Cast—a Highly Accurate Solar Forecasting Tool

Clouds and other atmospheric conditions have a big impact on the amount of solar energy available at a given time, but they are notoriously difficult to predict. A new solar forecasting system called Sun4Cast, recently released by the National Center for Atmospheric Research (NCAR), offers much more accuracy in predicting these and other factors that affect the availability of solar energy. In tests performed by NCAR, Sun4Cast proved 50% more accurate than current solar power forecasts.

Researchers from NREL contributed their deep expertise to the creation of Sun4Cast by developing a fast radiative transfer model that could be integrated into the widely used Weather Research & Forecasting model. Then to validate the forecasting process, NREL worked with FPL to collect and process measurements from a large PV power plant in Florida.

Sun4Cast was designed to be used by the solar industry and electric utilities for the reliable and cost-effective deployment of solar energy. It provides 0- to 6-hour "nowcasts" of solar irradiance and power production for specific solar facilities. It also supports day-ahead planning with forecasts that extend out to 72 hours. Xcel Energy has begun to use the system to forecast conditions at several of its main solar facilities. This project was funded through the DOE SunShot program.

How can utilities better integrate solar generation onto their grids with solar forecasts?

Project Highlights

WIND Toolkit Data Intended to Support Next Generation of Wind Integration Studies

A final report is now available detailing the creation of the Wind Integration National Dataset (WIND) Toolkit, an update and expansion of the Eastern Wind Data Set and Western Wind Data Set. The WIND Toolkit includes detailed meteorological conditions and turbine power data sets at unprecedented temporal and spatial resolution for 126,000 land-based and offshore wind power production sites or potential sites for seven years (2007–2013). The data were created to realistically reflect the ramping characteristics, spatial and temporal correlations, and capacity factors of the simulated wind power plants and to be time synchronized with available load profiles. The WIND Toolkit was funded by the DOE, EERE, Wind Energy Technologies Office, and it was created through the collaborative efforts of NREL and Vaisala, Inc. (previously 3TIER, Inc.). Download data at http://www.nrel.gov/grid/wind-toolkit.html. Read more about the toolkit at http://www.sciencedirect.com/science/article/pii/S0306261915004237.

Sun4Cast, developed by NCAR with the help of NREL researchers, provides utilities with a 50% more accurate forecast. It also provides predictions in useful time steps—from right now to 72 hours out. A more accurate forecast makes it possible to deploy solar resources more reliably and inexpensively.

NSRDB Expands to Include Solar Data for India

NREL's National Solar Radiation Database (NSRDB) now includes data for a growing list of international countries, including India. The NSRDB is a serially complete collection of meteorological and solar irradiance data sets. The data are publicly available at no cost to the user and provide foundational information to help solar system designers, building architects and engineers, renewable energy analysts, and many others to improve and expand solar energy technologies. Download solar data at https://nsrdb.nrel.gov/.

NREL Staff Lead the Development of International Radiometry Standard

NREL staff members chair two ASTM International standards subcommittees on radiometry and statistics, and they recently led the development of the new standard ASTM G214-16, "Standard Test Method for Integration of Digital Spectral Data for Weathering and Durability Applications." This new standard provides a single method to integrate digital or tabulated spectral data. This will provide greater consistency and simplify the comparison of PV test results from different laboratories, measurement instrumentation, or exposure regimes.

NREL and Wells Fargo Help Start-Up Whisker Labs Bring Innovative Metering Technology to Market

Measuring the energy consumption of individual building systems provides a wealth of information that can be used to improve whole-building energy performance. However, real-time energy data are not available for many buildings, often due to the high cost of metering and data collection. Whisker Labs, a start-up in Oakland, California, developed a solution to this problem with an innovative peel-and-stick energy-metering system. Then, through the Wells Fargo Innovation Incubator (IN^2) program, Whisker Labs was able to work with research staff at the ESIF to test the accuracy of their product using real building loads and reference meters and demonstrate the benefit of this less-invasive submetering technology in a commercial building. Whisker Labs and its sensing technology were recently acquired by Earth Networks, a company that will commercialize their product.

SYSTEM OPERATIONS, POWER FLOW, & CONTROL

Can grid-edge control of distributed energy resources (DERs) be coordinated with utility-level energy management?

Yes, by developing innovative distributed control schemes that enable DERs to coordinate with utility-level control platforms in real time to continuously steer DER operating points to solutions of optimal power flow problems.

Project Spotlight

ARPA-E Project Aims to Coordinate DERs with Utility Operations

NREL is leading a project for DOE's Advanced Research Projects Agency-Energy (ARPA-E) to develop control systems that enable real-time coordination between DERs and bulk power generation. The ARPA-E project, which includes team members from the California Institute of Technology, Harvard University, the University of Minnesota, and Southern California Edison, will develop a comprehensive distribution network management framework that unifies real-time voltage and frequency control at the DER controller level with network-wide energy management at the utility level.

The distributed control architecture will leverage real-time feedback control to continuously steer DER operating points to solutions of optimal power flow (OPF). OPF on a distribution feeder generally means minimizing power losses (caused by excessive currents or voltages) while maximizing the economic benefits to the utility and its end users. However, OPF is a difficult problem to solve, and traditional tools for solving this problem do not offer decision-making capabilities that match the fast dynamics of distribution systems, requiring the problem to be solved centrally at the utility.

To address this issue, NREL developed a new control concept that taps into contemporary advances in time-varying optimization and linear approximations of the alternating-current (AC) power-flow equations. This distilled the control equations to elementary operations that can be implemented with low-cost microcontrollers in the DERs. The control architecture systematically stabilizes the system operation around optimal operational points, and it can operate independently based only on measured feeder voltages. See the paper "Optimal Power Flow Pursuit," at https://arxiv.org/abs/1601.07263.

Regarding providing services to the main grid, the objective is to enable distribution feeders to emulate virtual power plants, effectively providing services to the main grid at multiple temporal scales. As part of this multiyear project, the control architecture will be validated through a PHIL experiment with at least 100 devices at power.

Is it possible to keep the grid stable despite decreasing mechanical inertia provided by traditional generation sources?

Project Spotlight

Inverter Controls Point the Way to Low-Inertia Grids

Today's electric grids rely on central-station power plants that involve a massive generator rotating at the right speed to produce power at a certain frequency—in the United States, 60 cycles per second. These synchronous generators give the grid significant mechanical inertia, enabling it to absorb disturbances with minimal deviations in frequency. Under these circumstances, conventional inverters are controlled to simply lock into the grid and follow it.

But what happens as the world shifts to increasing penetrations of inverter-based energy sources, such as PV systems? The grid could then lack the inertia to maintain stability in the presence of large disturbances. As a result, it may become unclear what device is actually controlling the frequency and voltages on the grid, and the vast number of inverters on the grid may not be able to preserve stability.

For this reason, the electric grids of the future may need inverters that don't simply follow what the grid is doing but actually help the grid preserve system stability. Building on innovations from the University of Illinois, a team at NREL is collaborating with the University of Minnesota; the University of California, Santa Barbara; ETH Zürich; and a commercial partner in the PV inverter industry to further develop a new way to control inverters that can help achieve this goal, a method called virtual oscillator control (VOC).

VOC leverages the properties of coupled oscillators, such as weights hanging from springs, which in turn are connected to a board that is hanging from springs. Set in motion, the weights will soon start bouncing at the same frequency, all in lockstep. For VOC, the trick is to make each inverter respond to the grid much like a nonlinear spring except in the electrical domain: for instance, if the grid voltage or frequency drops or rises, the inverter adjusts its output such that it "pushes" against the voltage or frequency change.

When such inverters are connected to the grid, the grid itself serves as a coupling mechanism between the inverters, thus negating the need for explicit communication. Setting up many inverters on the same circuit will cause them all to work together while maintaining system voltages and frequencies within acceptable limits. VOC responds immediately to changes in grid conditions, just like a spring responds to any stimuli. ESI researchers have demonstrated this approach with an experimental microgrid test bed and plan to extend it to larger simulations in the near future.

VOC-based inverter controls could be an important addition to today's electric grids because they could ease our way into the electric grid of the future. If the world's electric grids do transition from high-inertia grids controlled by rotating machinery to low-inertia grids dominated by power electronics, these distributed controls may be part of the answer to maintaining a stable grid.

NREL is developing new solutions for a stable, low-inertia power system.

What's the best way to control voltage for a solar farm: with the voltage control functions of advanced PV inverters or by using the integrated volt/VAR control of the utility's advanced distribution management system (ADMS)?

For the solar farm studied, using the integrated volt/VAR control of the utility's ADMS proved to be the best solution.

Project Spotlight

Integrated Utility Control Can Provide Improved Grid Voltage Regulation

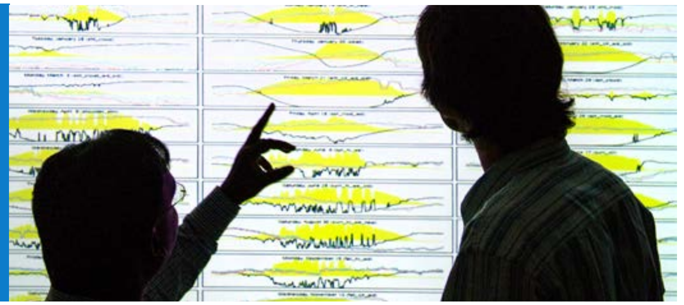
A study performed by NREL, GE Grid Solutions, and Duke Energy has found that when a large solar PV system is connected to the electric grid, a centralized control system at the utility can regulate the voltages on the grid's distribution feeder lines better than advanced inverters alone. The project combined advanced software simulation, novel three-dimensional visualization, and lab-based hardware testing at megawatt scale, all enabled by the one-of-a-kind capabilities of the ESIF.

Duke Energy's grid has a large, 5-MW PV system interconnected to a line approximately 2 miles from the substation. The peak demand on the line is also approximately 5 MW, so at times more PV power is being fed into the line than is being used, leading to voltage control issues and causing the power to reverse flow back into the substation. The unstable voltages and reversed flows can potentially damage customer's devices and interfere with utility operations.

The modeling of Duke Energy's feeder line examined how effective inverter-based volt/VAR control would be compared to a centralized, utility-controlled ADMS, which was provided by GE Grid Solutions. Although the advanced inverters provided some level of local volt/VAR control—particularly in hypothetical scenarios with more PV farther from the substation—the ADMS provided integrated volt/VAR control (IVVC), which noticeably improved operations by reducing voltage challenges and equipment wear and tear. The ADMS also provided conservation voltage reduction (CVR), a scheme to reduce power demand by slightly lowering the voltage on a feeder line.

The research team built a computer model of the feeder line and carried out simulations of system operations over time, used advanced visualizations to understand the results, connected an actual 500-kVA inverter to a full-scale feeder simulation for a real-time simulation, and carried out cost-benefit analyses of each control method.

The project found that all tested configurations of ADMS-controlled IVVC with CVR provided improved performance and operational cost savings compared to the local control modes. Specifically, IVVC with a power factor of 0.95 proved the technically most effective voltage-management scheme for the system studied. This configuration substantially reduced the need for utility equipment to regulate the voltages, and it reduced the observed voltage challenges on the feeder line.



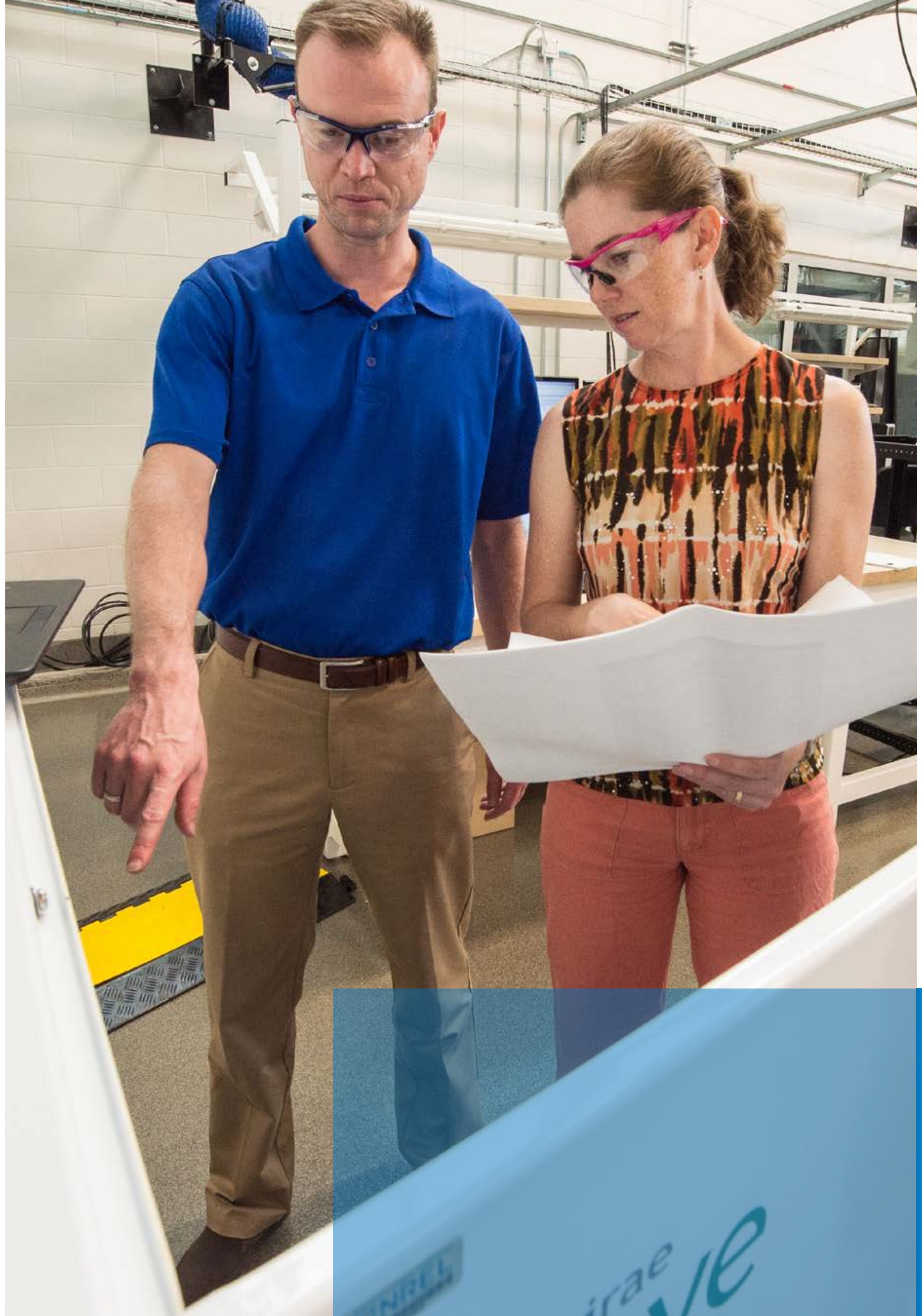
Project Highlights

Study Examines Grid Performance Under Low-Inertia Conditions

Although some ESIF work is focused on the transition to low-inertia grids, other work is examining how today's grid, with some improvements, could tolerate off-normal conditions during periods with low amounts of inertia on the grid, particularly when renewable energy is providing a significant share of the generation. In FY 2016, NREL released the *Western Wind and Solar Integration Study Phase 3A*, which examined the impact of low levels of synchronous generation on the transient stability performance of one region of the grid. Specifically, the report investigated the Western Interconnection with up to 70% instantaneous renewable generation in one region and with low load, resulting in low synchronous generation. The study found that with good system planning, sound engineering practices, and commercially available technologies, the Western Interconnection can withstand the crucial first minute after a grid disturbance, despite high penetrations of wind and solar power.

NREL and Caterpillar Demonstrate Performance of Mission-Critical U.S. Navy Microgrid

NREL worked with Caterpillar to validate a utility-scale microgrid for deployment to a mission-critical U.S. Navy installation. For this particular site, achieving the required power quality and reliability was challenging because the site's PV plant output would often exceed the microgrid load, making it necessary to send power back to the utility when batteries reached full charge. To validate the performance of the microgrid under these complex conditions, the project partners developed rapid (sub-cycle) microgrid switching to keep load online. Then NREL modeled the microgrid's Caterpillar diesel generator sets, battery storage inverter systems, PV inverter, load, and microgrid switch in a real-time digital simulator (RTDS). Using hardware-in-the-loop, NREL validated the system's ability to endure voltage, frequency, and realistic utility grid disturbance events. This work will increase understanding of how microgrids can integrate high levels of solar while still providing high power quality and reliability.



NREL Joins Microgrid Systems Lab Team to Help Accelerate the Deployment of Microgrids

NREL joined the Microgrid Systems Laboratory (MSL) in Santa Fe, New Mexico, as a member institution, with the ESIF serving as a network facility. The MSL is a "fully-integrated innovation center for decentralized energy systems" focusing on microgrid innovation, education, and component certification. The laboratory's partners draw from premier research institutions, utilities, and microgrid industry leaders. In addition to NREL, the MSL research network includes two other DOE national laboratories: Sandia National Laboratories and Los Alamos National Laboratory. Visit http://microgridsystemslab.com/ to learn more.

NREL Helps Wyle Labs and U.S. Army Add New Features to Hybrid Energy System

Under a research agreement with Wyle Labs, NREL worked with the U.S. Army to complete the development and testing of the Consolidated Utility Base Energy (CUBE) System. The CUBE is a power conversion, distribution, and protection device that delivers power from solar, battery, and diesel generators to loads on forward operating bases. By acting as a reliable stand-alone hybrid power system, the CUBE can reduce diesel fuel use, costs, and risks associated with fuel transport in theater. This project expanded on prior work by adding new features and functionality to the CUBE, including the provision to interconnect to local electric grids, the ability to serve unbalanced loads, and the incorporation of a solid-state transformer to reduce size and weight. Evaluation of the new hardware and its control algorithms were completed at the ESIF.

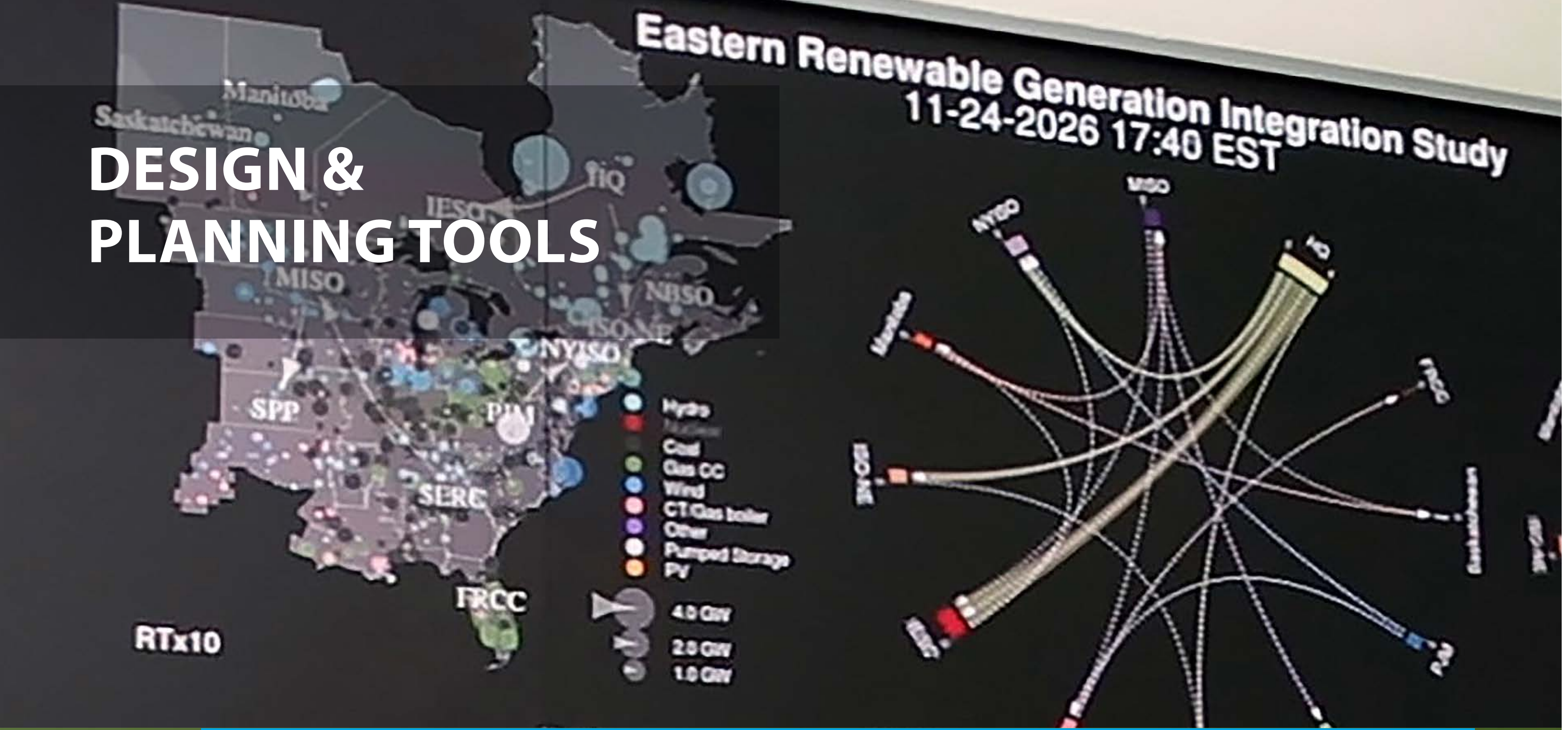
NREL and EPRI Validate Grid-Interactive Microgrid Controller for Resilient Communities

NREL is collaborating with the Electric Power Research Institute (EPRI) to validate the performance of a Spirae-developed advanced microgrid controller capable of managing 1–10 MW of aggregated generation capacity. NREL is validating and testing the functions of the controller in the ESIF by connecting it to a RTDS model of a microgrid. The controller is also being connected to a utility-scale battery inverter, which interacts with the RTDS model through an AC power amplifier, adjusting its output to the simulated electric grid voltage at the point of connection. For one targeted community, the controller is undergoing detailed testing to verify that it meets the technical functional requirements for that community. This project is sponsored by the U.S. DOE's Office of Electricity Delivery & Energy Reliability (OE).

NREL, Raytheon Partnership Receives 2016 Project-of-the-Year Award

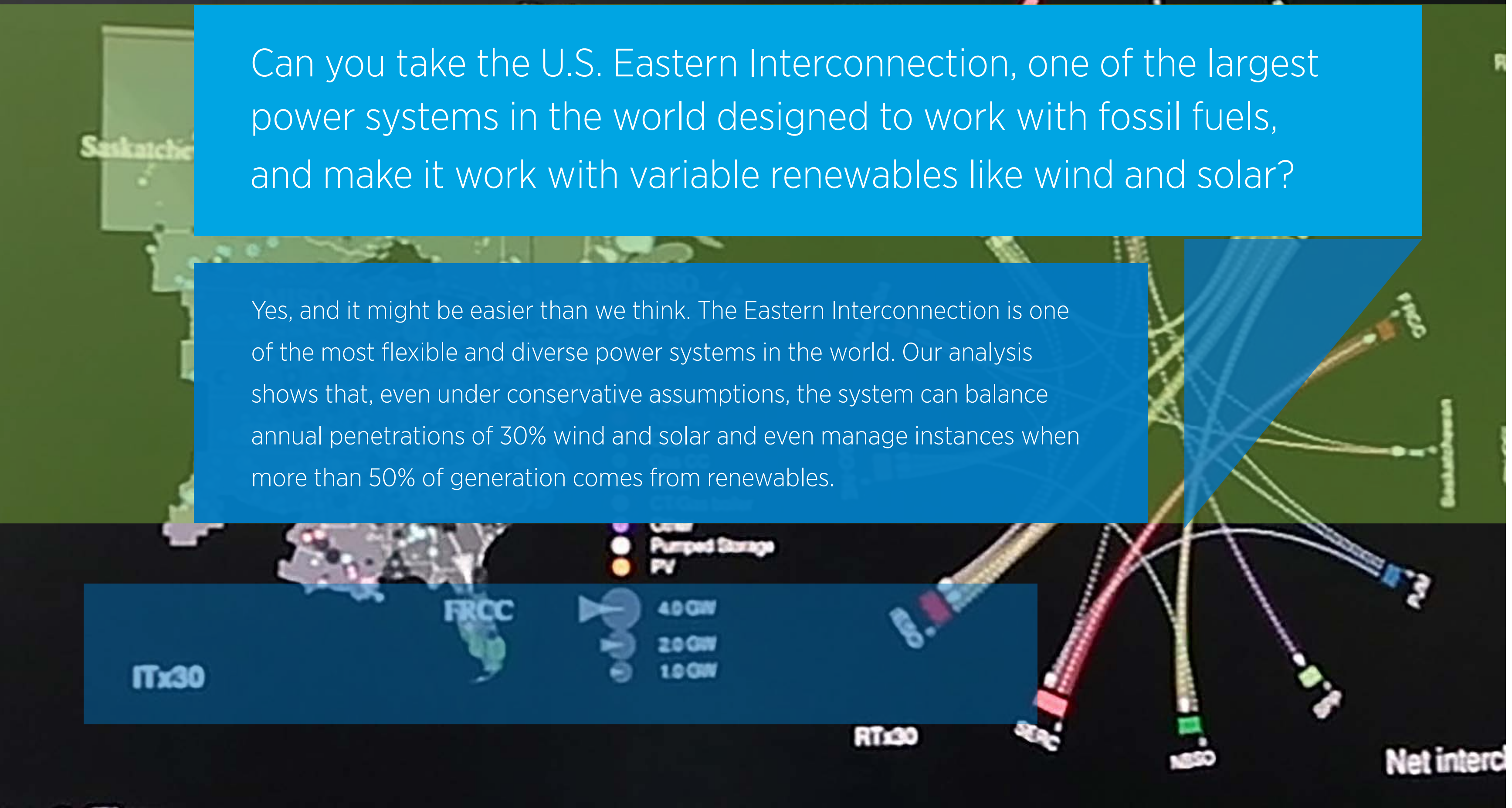
NREL's partnership with Raytheon to demonstrate an advanced microgrid system at Marine Corps Air Station Miramar has received a 2016 Project-of-the-Year Award from the Environmental Security Technology Certification Program. The project successfully demonstrated the microgrid controller's ability to integrate and control the energy storage system, PV system, and facility loads while connected to and islanded from the grid.

DESIGN & PLANNING TOOLS



Can you take the U.S. Eastern Interconnection, one of the largest power systems in the world designed to work with fossil fuels, and make it work with variable renewables like wind and solar?

Yes, and it might be easier than we think. The Eastern Interconnection is one of the most flexible and diverse power systems in the world. Our analysis shows that, even under conservative assumptions, the system can balance annual penetrations of 30% wind and solar and even manage instances when more than 50% of generation comes from renewables.



Project Spotlight

A Roadmap to 30% Renewables on the Eastern Electric Grid

As more variable renewable generation rolls out at all scales across the United States, big questions remain for grid operators. One of the biggest: How much renewable energy can be safely integrated into the grid?

Previous studies designed to answer this type of question relied on simplifying assumptions and investigated operations in one-hour intervals instead of the 5-minute intervals that grid operators use for scheduling resources. To answer questions around renewable energy integration, a new model was needed.

This was the starting point for NREL's Eastern Renewable Generation Integration Study (ERGIS), the first study to model the entire U.S. Eastern Interconnection at 5-minute intervals for a full year. NREL researchers used the ESIF's HPC capabilities and innovative visualization tools to model, in unprecedented detail, how the electric grid of the eastern United States could operationally accommodate up to 30% wind and solar generation.

Results of ERGIS show that the power system can meet loads with variable resources such as wind and PV in a variety of extreme conditions. But to get there, adjustments will be required in operations and regulatory and market structures.

This study was funded by DOE's EERE and OE.

To learn more about ERGIS, get the data sets and visualization tools, and download the full study, visit NREL.gov/ERGIS.

"Our work provides power system operators and regulators insights into how the Eastern Interconnection might operate in future scenarios with more wind and solar energy, More importantly, we are sharing our data and tools so that others can conduct their own analysis."

—Aaron Bloom, NREL project leader for ERGIS

The ERGIS study drew some big attention, with features from *Greentech Media, North American Windpower magazine, Transmission & Distribution World, UtilityDive,* and *Vox*.

Watch: Aaron Bloom, Project Manager for ERGIS, talks about the study: *https://www.youtube.com/watch?v=jx9_4GNkbIQ*.

Project Highlights

NREL Contributes Solar Grid Integration Expertise to On the Path to SunShot

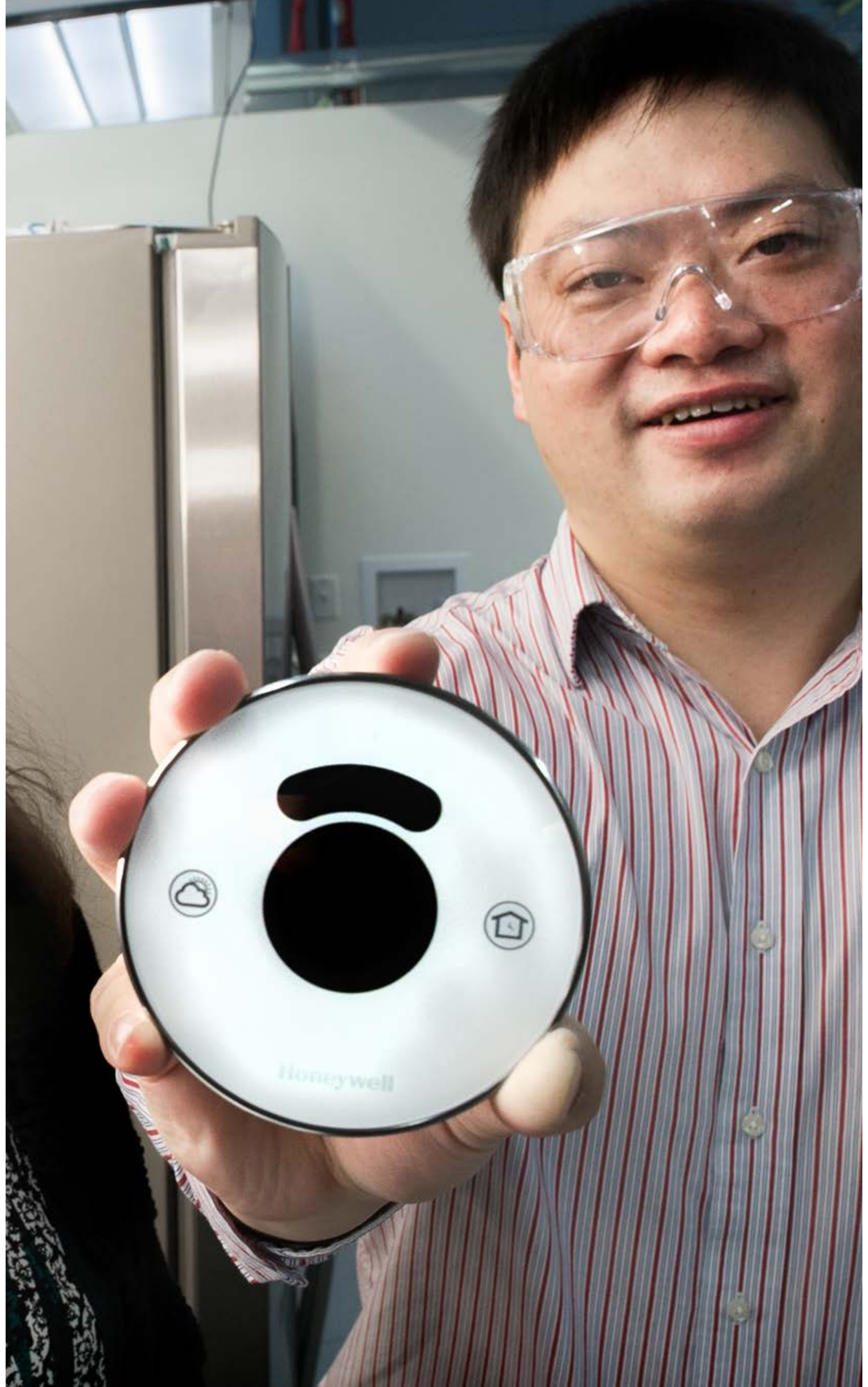
NREL authored several pieces of DOE's newly released On the Path to SunShot report series, including key insights on emerging issues and challenges with integrating solar energy into the electric system. The reports examine the state of the U.S. solar energy industry and the progress made to date toward the DOE SunShot Initiative's goal to make solar energy cost-competitive with other forms of electricity by 2020. The solar industry is currently about 70% of the way toward achieving the Initiative's 2020 goals. The series was produced through a collaborative effort by researchers at NREL, Lawrence Berkeley National Laboratory, Sandia National Laboratories, and Argonne National Laboratory. Download the full report at http://energy.gov/eere/sunshot/path-sunshot.

NREL Develops an Integrated Transmission and Distribution Grid Modeling System

NREL researchers have developed the Integrated Grid Modeling System (IGMS), a first-of-its-kind, large-scale simulation tool specifically designed to integrate transmission and distribution. IGMS is able to capture distributed generation not simply as negative load but as an active participant in large-scale power systems operations. Using high-performance computing, IGMS models hundreds or thousands of distribution systems in co-simulation with power markets and automatic generation control, which keeps the modeled grid in balance with its load. IGMS operates at a massive scale, offering unprecedented resolution from wholesale power markets down to appliances and other end uses. Read a journal article about IGMS at http://dx.doi.org/10.1109/TSG.2016.2604239.

NREL Helps Arizona Public Service Accommodate More Grid-Connected Solar Power

Most utilities turn to simple rules of thumb to evaluate how much solar PV capacity can be installed on a distribution feeder line, but when Arizona Public Service (APS) wanted to allow more PV installations in their service area, they turned to NREL for a more fine-tuned solution. NREL developed open-source tools to perform systematic and detailed quasi-static time-series analyses of distribution feeders with multiple advanced inverters. With such tools, any utility can evaluate a number of mitigation options for voltage regulation problems.



ESIF Engineers Develop a Smart Home Hardware-in-the-Loop Capability

The ESIF has long had a power hardware-in-the-loop capability, which allows actual power equipment to be connected to software models, such as a model of an electric grid, to see how they interact. In FY 2016, ESIF engineers extended that capability by connecting software electric grid models to the ESIF's Smart Home Test Bed, which consists of a PV system and a variety of smart home appliances as well as a home energy management system (HEMS). The electric grid models were executed on the ESIF's supercomputer, Peregrine, to simulate hundreds of additional homes with HEMS and evaluate the system-wide impacts of smart homes. The work mainly involved adding electrical connections and communications interfaces between the smart home devices and Peregrine, with extra preparation to allow for unattended operation.

NREL Advances the State of the Art in Remote, Virtually Connected Energy System Test Beds

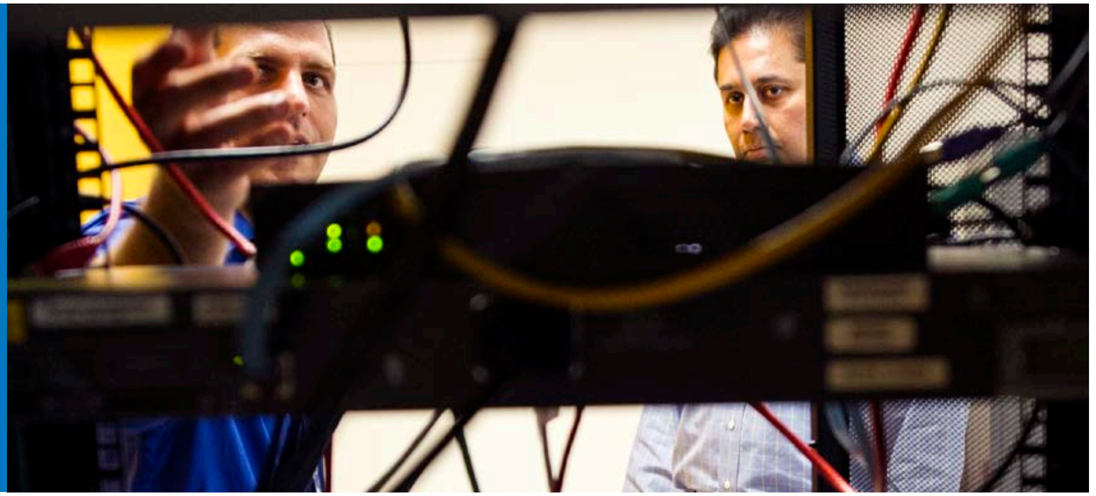
Researchers around the world are pursuing the possibility of "virtually connected test beds," whereby individual hardware-plus-software experiments at distant geographical locations share information to emulate larger, virtually connected systems. However, a fundamental barrier in connecting remote experiments is that the communication delay between locations sets a lower bound on the time resolutions possible in the combined experiment due to the Nyquist criterion. Recently, researchers at NREL developed and validated a novel approach that mitigates the effects of communication delays through the use of an advanced, embedded control technique. The approach was successfully demonstrated through an experiment that connected the NREL ESIF and Power House Energy Campus at Colorado State University at a distance of 115 km. NREL has confirmed that utility-scale renewable technologies can provide grid-support functions when needed. For wind power, NREL simulated a grid-connected wind turbine using the controllable grid interface test facility, which employs a large motor to simulate the turbine's rotor, spinning a generator that is connected to a simulated electric grid at transmission-system voltages.

Watch: More comfortable, convenient homes that use less energy? At the ESIF's Systems Performance Lab, researchers are exploring technologies that will make it possible: *https://www.youtube.com/watch?v=Hzf_zsCyFvw*.

Project Spotlight

Visualization Dashboards Help Identify Grid Hackers

With the cost of cyberattacks against utilities rising and increasing diversity in available information and operational technologies, NREL researchers worked with Splunk Inc. to create dashboards that help to identify cyber events and increase situational awareness. Splunk worked on the ESIF's cybersecurity test bed, which mimics a utility distribution system with two substations and multiple information layers for communications and control. The cyber team developed cyber cases on the test bed while it was operating in various modes. By aggregating, normalizing, and visualizing cyber events using Splunk, NREL was able to identify red flags that indicated cyber attacks. The dashboards developed allow system operators to identify threats, perform event correlations, and have system-wide security metrics in real time. This demonstrated a way to enhance situational awareness by integrating the proprietary cybersecurity event-detection and alarming features of multiple vendor technologies into a standards-based monitoring platform.



INSTITUTIONAL SUPPORT

Project Spotlight

NREL Assists HECO in Bid to Develop and Accommodate More Renewable Energy

How can a state achieve 100% renewably sourced electricity by 2045, especially when that state is an island, unable to rely on neighbors for support? That's the challenge that the Hawaiian Electric Companies (HECO) face as they strive to achieve the goals of the Hawaii Clean Energy Initiative. A partial answer is to develop all economically sound sources of renewable energy in order to provide as great a renewable power resource as can be reasonably achieved with today's technologies.

Hawaii already leads the nation in rooftop solar PV systems per capita, suggesting that the islands need more utility-scale renewable energy to meet the remaining load. To assist HECO with its Power Supply Improvement Plans for the islands of Oahu, Maui, and Hawaii, NREL assessed the resource potential on those three islands for three utility-scale renewable power technologies: onshore wind power plants, PV plants, and concentrating solar power plants.

To assist HECO with modeling any proposed renewable capacity additions, NREL also developed aggregated normalized hourly solar and wind power time-series data for the three islands, drawing on the National Solar Radiation Database and using the Weather Research and Forecasting model to calculate wind-speed data. To help HECO get a better understanding of the technology costs, NREL also reviewed HECO's technology cost assumptions and compared them to the NREL Annual Technology Baseline and Standard Scenarios.

While helping HECO plan for future renewable capacity additions, NREL has been working with the utility to help it better accommodate the many rooftop PV systems on its electric grids, drawing mainly on the features of "smart" PV inverters that can provide grid support. NREL researchers modeled and evaluated a select set of inverters for advanced functionality and also examined how HECO's grid will interact with advanced inverters.

"Our Power Supply Improvement Plan calls for achieving 48% [renewable portfolio standards] by 2020 and more than doubling the amount of rooftop solar systems by 2030. These ambitious goals would not be possible if not for the partnership between NREL and Hawaiian Electric."

—Colton Ching, Senior Vice President, Planning & Technology, Hawaiian Electric

NREL Study Informs FERC on New Market Settlement Rule

The Federal Energy Regulatory Commission (FERC) is proposing to revise its regulations to require that each regional transmission organization and independent system operator settle energy transactions at the same time it dispatches the energy and settle operating reserves transactions at the same time it prices the reserves using real-time markets. This proposed rule was influenced by research at NREL—specifically the recent study Evolution of Wholesale Electricity Market Design with Increasing Levels of Renewable Generation, which showed that, due to the incentives created by hourly integrated settlements, resources can earn significant additional payments by not following dispatch signals. The research demonstrates that if operators use rolling hourly settlements with a 5-minute dispatch, they should reduce the incentive for generators to provide flexibility. By moving to a 5-minute settlement (along with the 5-minute dispatch), an operator will get more flexibility out of the units—and they also earn more profit, creating a win-win scenario for the generators and grid operators.

HIGH PERFORMANCE COMPUTING & VISUALIZATION

How can liquid cooling help data centers and HPCs operate more efficiently?

For cooling, liquids are approximately 1,000 times more effective than air, thus NREL is able to achieve world-leading data center efficiency through the use of liquid-cooled servers and systems throughout the ESIF. NREL is also reducing water use in the cooling towers through a new thermosyphon technology.

Project Spotlight

ESIF's HPC Data Center Pursues Greater Efficiency Through Liquid Cooling

From the day it opened, the ESIF's HPC data center became a hallmark in energy efficiency in that it was the first to employ the HP Apollo 8000 System, a supercomputer jointly developed by HP and NREL. That system is cooled with warm water, and the thermal energy of the resulting hot water can heat the building in the winter. Unused heat is rejected to the atmosphere via evaporative cooling in the summer. But NREL continues to pursue new energy-efficient and water-saving technologies for the ESIF's HPC data center.

For example, NREL is working with LiquidCool Solutions, Inc. (LCS) to demonstrate and characterize the performance of LCS's liquid-submerged technology for cooling computers and servers. LCS employs a dielectric fluid strategically directed onto electronic components in a liquid-tight server enclosure. The fluid's high heat-carrying capacity enables efficient heat removal from temperature-sensitive electronics such as central processing units, graphics processing units, and memory. The dielectric liquid has 1,400 times the heat-carrying capacity of air by volume, making it much more efficient at removing heat from electronics.

An eight-server prototype unit was installed at NREL's Thermal Test Facility to characterize thermal performance of the system, including parameters such as the dielectric flow rate, inlet and outlet temperatures, and computing power. The experiments characterized the cooling capability of the LCS system to maintain acceptable electronic temperatures. In addition, heat recovery up to 140°F was measured while maintaining 90%–95% liquid heat recovery efficiency (depending on the ambient temperature and server workload). The unit is now undergoing operational testing at the ESIF to assess installation and ongoing performance and maintenance in a real data center environment.

While the LCS system is undergoing testing, a number of liquid-cooled servers are commercially available. NREL committed to energy-efficient liquid cooling in 2006, requiring at least 90% of the aggregate IT equipment installed in the data center to be liquid cooled in some manner. In FY 2016, the HPC data center added two RackCDU Direct-to-Chip solutions from Asetek, two Rack Direct Contact Liquid Cooling CHx40 modules from CoolIT, and four ChilledDoor rack cooling systems from Motivair.

Another feature of the energy-efficient ESIF HPC data center is that it eliminates expensive and energy-demanding chillers, instead using evaporative cooling towers, which are energy efficient and much less expensive. While ultra energy efficient, this has a side effect of drawing approximately 2 million gallons of water per year per megawatt of computational electrical load. To reduce that water consumption, NREL and Sandia National Laboratories teamed up with Johnson Controls to investigate the use of the company's novel thermosyphon dry cooling technology, which consists of a shell-and-tube heat exchanger and overhead air-cooled condenser. Hot water from the data center loop flows into the thermosyphon heat exchanger and boils a liquid refrigerant, sending vapor to the condenser, where it condenses back into a liquid and flows down to the heat exchanger, forming a closed loop.

Because the thermosyphon helps to reject heat without consuming water, it is expected to yield significant water savings for the ESIF. Johnson Controls modeled the installation of a thermosyphon upstream of the ESIF's evaporative cooling towers and found that the system would cut the annual water use for cooling by 56%. In fact, the thermosyphon should be able to handle the HPC center's heat output in the spring and fall without the need for evaporative cooling.

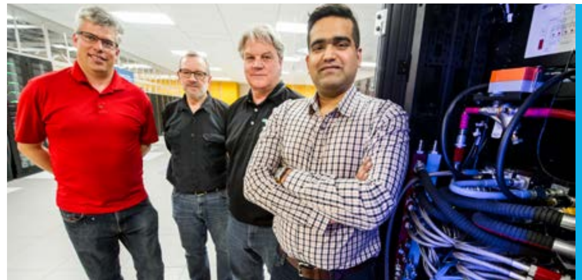
Based on these positive results, a thermosyphon was installed on the ESIF's roof and started operating in August 2016. The system is being monitored for one year to compare the actual results to the modeled results. Sandia will apply the data from the ESIF installation to its own cooling needs.

The Peregrine supercomputer, which is capable of achieving 2.24 petaFLOPS, provided 19.5 million node hours during FY 2016. Due to its extreme energy-efficient design, the ESIF's HPC data center operated at an annual average power usage effectiveness of 1.04 during FY 2016—meaning it required only 4 watts of electricity to provide cooling for every 100 watts used by the computing equipment.

In FY 2016, Peregrine supported 78 modeling and simulation projects across the spectrum of energy-efficiency and renewable energy technologies. For ESI, Peregrine was employed to complete ERGIS (see page 31); to create the IGMS, which models the grid from smart appliances through distribution and transmission, including wholesale power markets; and to run the PLEXOS production cost model and NREL's Resource Planning Model, which finds the least-cost investment and dispatch solution for expanding capacity in a regional power system over a 20-year horizon.

Examples of other applications utilizing Peregrine to support the DOE EERE mission include its use to:

- Model the transport of species through plant cell walls for bioenergy applications
- Perform a large-scale analysis of the U.S. residential building stock for potential energy-efficiency projects
- Run computational fluid dynamics (CFD) and finite element analyses to help design, build, and field-test an engineering prototype of a laser-based geothermal well completion tool
- Employ density functional theory (DFT) to investigate cation degradation pathways in alkaline-membrane fuel cells
- Use DFT to predict the thermodynamic and kinetic behaviors of perovskite and spinel materials of interest for solar thermochemical water splitting
- Investigate third-generation advanced high-strength steels for automotive applications
- Apply high-fidelity CFD simulations to wave energy converters
- Investigate wind power plant optimization at both the wind turbine and plant system level
- Create the NREL Materials Database, an open, multi-property materials design environment with the purpose of enabling and facilitating the discovery of novel materials for renewable energy.



Project Highlights

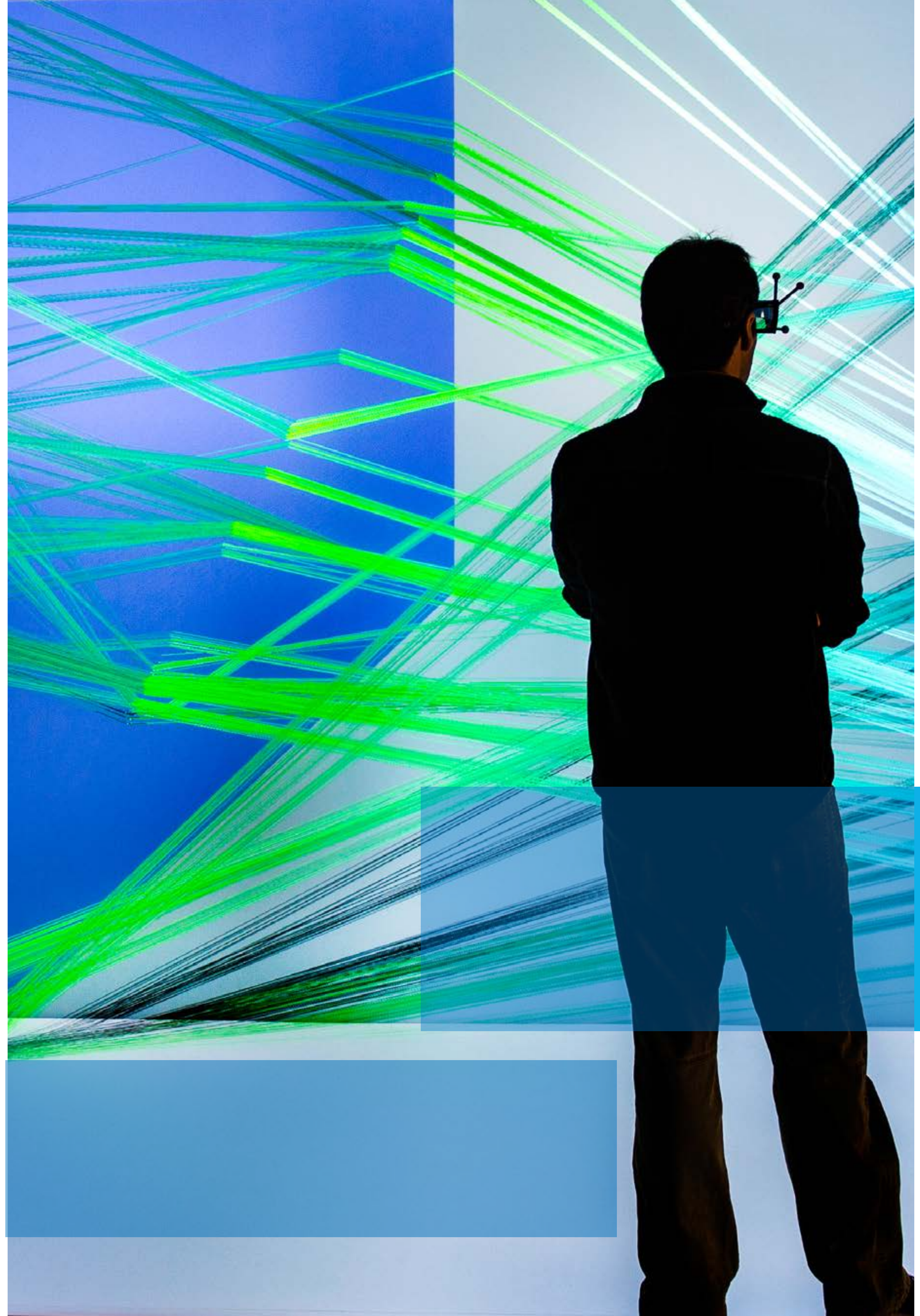
NREL Deploys System That Combines Simulation with Visualization to Create a Better Analysis Tool

NREL's visualization team has deployed a visualization-driven simulation system that tightly couples systems dynamics simulations with an immersive virtual environment. Using this system, analysts are able to rapidly develop and test hypotheses in a high-dimensional parameter space. One of the innovative aspects of this system is that it allows users to both explore existing data as well as launch additional simulations for selected portions of the input parameter space. As soon as the new simulations are complete, their resulting observations are displayed in the virtual environment. This capability has already been used to analyze NREL's biomass-to-bioenergy supply-chain simulations. These simulations model the dynamics and interplay of resource availability; physical, technological, and economic constraints; investor behavior; and government policy, so that analysts can develop insights into points of leverage and potential bottlenecks in the bioenergy industry.

Advanced Visualization Helps Develop Safer Lithium-ion Batteries for EVs

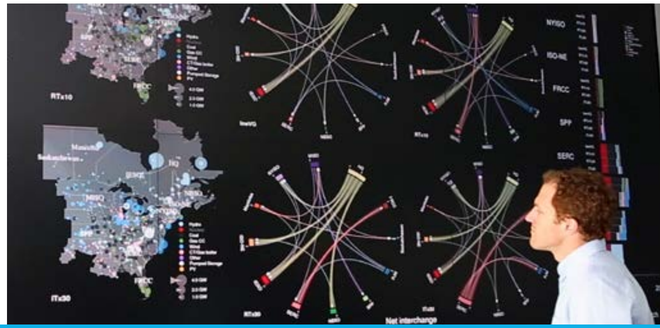
Lithium-ion (Li-ion) batteries are currently the state-of-the-art power sources for EVs, and their safety behavior when subjected to abuse, such as a mechanical impact, is of critical concern. The physical phenomena occurring in Li-ion batteries upon impact are very complicated and take place in different time- and length scales (particle, electrode, cell, and pack). Computational models are an ideal way to study interactions among these multiple domains and provide insights into the design of safer Li-ion batteries. To advance this research, NREL energy storage researchers created a coupled mechanical-electrical-thermal model for simulating the behavior of a Li-ion battery under a mechanical crush. NREL visualization specialists then helped to develop a series of production-quality visualizations to illustrate the complex mechanical and electrical interactions in this model.

Watch: A simulated Li-ion battery takes a hit to show the complex mechanical and electrical interactions that result: ***https://www.youtube.com/watch?v=Hb5JWbcrVEY&feature=youtu.be*****.**



NREL Evaluates LiDAR to Help Wind Power Plant Operators Mitigate Wake Effects

In large-scale power plants, wakes that form behind upstream wind turbines can have significant impacts on the performance of downstream turbines. Wind power plant operators would like to better control wind turbines to mitigate these wake effects, but to make the correct adjustments they need data charting the relationship between the degree of the adjustment and the resulting wake deflection. Light Detection and Ranging (LiDAR) technology has the potential to generate enough data to make such adjustments feasible in real time, but it hasn't been tested for this purpose. To better understand the efficacy of using LiDAR to measure the wake trailing a wind turbine, NREL researchers used high-fidelity computational fluid dynamics to simulate a wind turbine in turbulent flow and simulate LiDAR measurements in this high-fidelity flow. The visual analysis of the LiDAR measurement in the context of the high-fidelity wake showed the limitations of the LiDAR resolution and contributed to the overall understanding of this technology.



The ERGIS study performed at NREL was groundbreaking not only in the large amount of data it analyzed but also in the way those data were brought to life with visualization. NREL visualization researchers used a large-scale display with a combination of multiple coordinated views and small multiples to visually analyze the four large, highly multivariate scenarios.

INTEGRATE PROJECTS

Project Spotlight

OMNETRIC Group Demonstrates a Distributed Control Heirarchy for Power Distribution Systems

With renewable energy expanding at all scales, new tools and technologies are needed to enable the grid to handle high penetrations of these renewable energy systems, particularly the smaller systems installed on utility distribution feeders as distributed energy resources. To address this need, NREL is managing five partnerships under the INTEGRATE project. See the NREL news release on INTEGRATE at http://www.nrel.gov/news/press/2015/18515.

One of these partners is OMNETRIC Group, which facilitates active load management via a DER management system and has designed and demonstrated an open-source-based interoperable platform at the distribution scale. In FY 2016, OMNETRIC Group, in collaboration with Siemens, worked with partners Duke Energy, CPS Energy, and the University of Texas at San Antonio to develop a distributed control hierarchy—based on an open field message bus architecture—that gets away from the traditional centralized control concept, allowing decisions to be made at the edge of the grid with more timely response to changing conditions. The approach allows distributed energy assets to communicate in real time with intelligent grid devices in the field.

The company first developed and validated the architecture at the ESIF, followed by system demonstrations at a Duke Energy microgrid demonstration site, then at Joint Base San Antonio, a joint Army and Navy post in Texas, which has set up a microgrid to power the base's library as a demonstration project. The Texas system combines a solar PV system, a battery storage system, a "sky cam" for weather forecasting, and a microgrid controller. The system functioned well as the microgrid was islanded from the larger grid and then reconnected as designed. The local utility, CPS Energy, is using the results from the demonstration to help inform their broader microgrid development and deployment strategy.

Watch: Smarter Grid Solutions talks grid-edge, real-time control and the advantages of testing at the ESIF for small businesses: *https://www.youtube.com/watch?v=aNoNNlsDDU8*.

Project Highlights

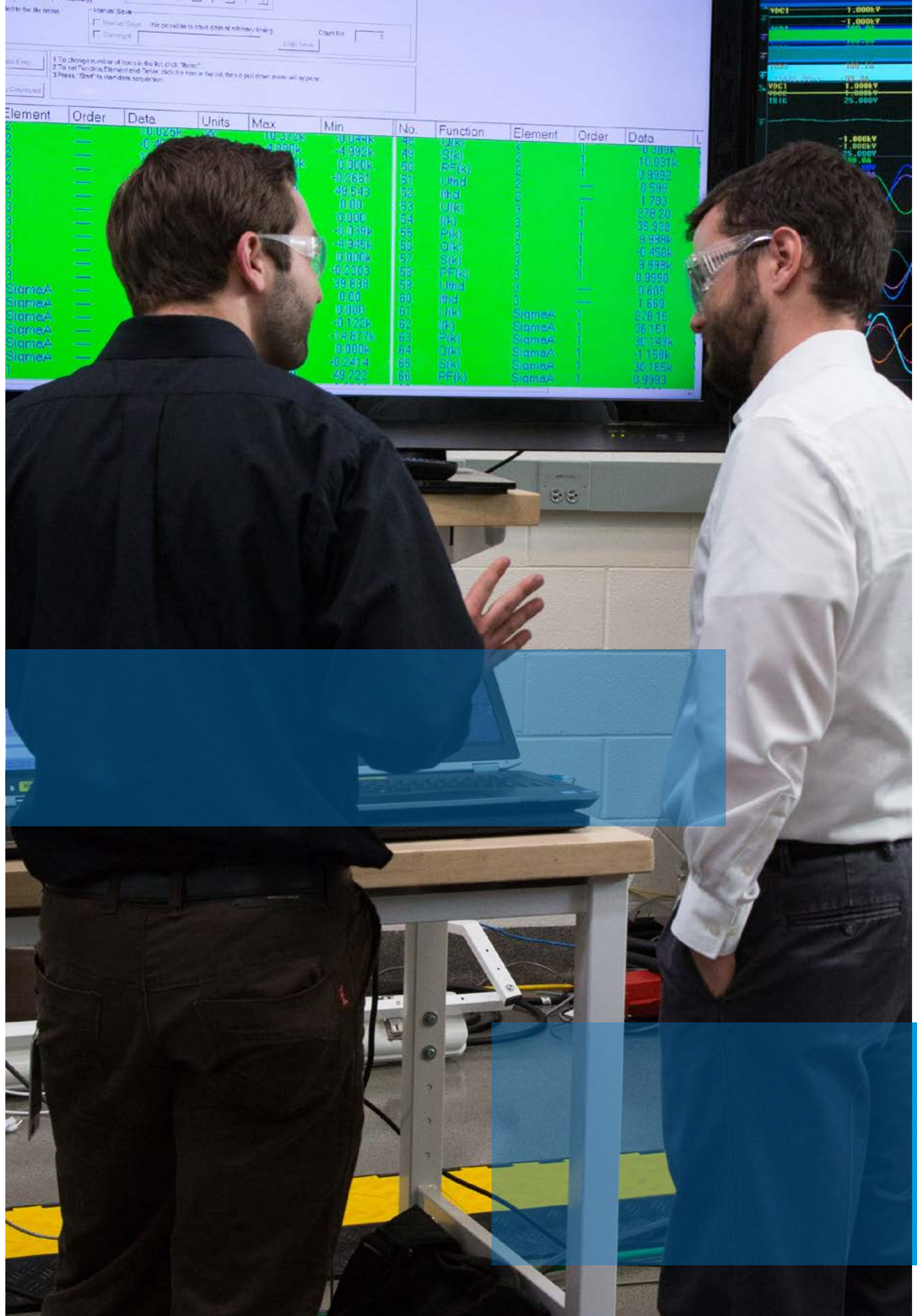
Smarter Grid Solutions Demonstrates Smart Campus Power Control

Another INTEGRATE partner is Smarter Grid Solutions (SGS), which has developed Active Network Management (ANM) technology to coordinate control of DERs with grid constraints in real time. Building on its FY 2015 work that showed ANM could control the power flows among a smart home's DER systems, SGS expanded this effort in FY 2016 to an entire smart campus and smart distribution system, each of which was simulated in the ESIF. The ESIF simulations combined a grid simulator, load banks, inverters, and one actual and four simulated EVs, creating a virtual smart campus that was then interconnected to an actual distribution network. All three simulations deployed under the project validated the ANM system's ability to control power flow, thermal effects, and voltage at multiple scales under scenarios with high penetrations of solar and wind power.

EPRI, Schneider Electric Demonstrate Framework for Distributed Resource Communications

Under another INTEGRATE project, researchers from the Electric Power Research Institute (EPRI) and Schneider Electric are working with the ESIF staff to demonstrate communications and control of DERs through EPRI's distributed energy resource management system with Schneider Electric's ADMS. The project's goal is to develop communication, information, and computation (CIC) layers that support system-level grid control. The open-source CIC framework includes an enterprise integration test environment, a commercial ADMS, open software platforms, an open-platform HEMS, communication modules, and applications. EPRI's CIC infrastructure is enabling the team to improve the interoperability and intelligent control of multiple clean technology devices and resources in a secure fashion.

> "Getting it all to work together in concert is an exciting challenge. Working with real devices and real systems … these opportunities don't come along often particularly for small businesses. The ESIF gives us a chance to develop, demonstrate, and move things into the market quickly. That's extremely exciting."
>
> —Bob Currie, Chief Technology Officer, Smarter Grid Solutions



See more systems operations, power flow, and control research on page 22.

The University of Delaware Characterizes Vehicle-to-Grid Technologies in the ESIF

The University of Delaware, another INTEGRATE partner, has examined the characteristics of two EVs and two charging stations when providing vehicle-to-grid (V2G) services. The project team also installed and validated an aggregator that manages a large fleet of EVs and a distributed group of V2G-enabled charging stations, tracking trips, required energy, and the grid connection status. The work quantified the round-trip efficiency of providing grid services, the vehicles' robustness during transients and faults, the lag between sending a control signal to the vehicles and seeing a response in power output, the maximum rate of increase in power output, and impacts on power quality as the battery discharges. The research also measured the vehicles' response to simulated utility control signals, tested autonomous operation for grid support, and used the vehicles to level power production from a residential PV system.

EPRI Project Examines the Benefits of Smart Consumer Devices

As part of the INTEGRATE project, in FY 2016 EPRI and a team of partners examined how smart, connected consumer devices can act to enable the use of more clean energy technologies on the electric grid. The team investigated the performance of EV supply equipment as well as smart thermostats, water heaters, pool pumps, solar inverters, and BESS. The study found that these connected devices have the potential to provide a wide range of grid services. Using open-access communication protocols at the device level allowed the devices to work collectively at multiple scales, serving as a platform on which a wide range of communications and control strategies may be developed and deployed.

See more devices and integrated systems research on page 6.

PARTNERS

NREL continues to forge new partnerships among industry, academia, and government to leverage the expert staff and exceptional resources that the ESIF offers. Below are partners with active agreements in FY 2016.

3M Company

Abengoa Solar

ACCIONA Solar

American Vanadium

Arizona Public Service

Asetek

Australian National University

BMNT Partners LLC

Bonneville Power Administration*

Bosch

California Energy Commission

Caterpillar, Inc.*

Colorado School of Mines

Combined Power, LLC*

CSIRO*

360 Cyber Secure

Denver Water

Dubai Electricity and Water Authority

Duke Energy

Electric Power Research Institute*

ElementOne, Inc.

Enphase Energy

Environmental Security Technology Certification Program

Expeditionary Warfare Center/Pacific Missile Range Facility

Florida Power & Light*

FuelCell Energy Inc.

GE

General Motors

Giner, Inc.

Google*

Hawaiian Electric Company, Inc.*

Honeywell

Hyundai America Technical Center, Inc.*

Ingersoll Rand

Intel Corporation

Intuitive Machines, LLC

Irradiance

Jefferson County School District

Korea Institute of Energy and Research

Krell Institute

Leclanché

Loop Energy, Inc.

Massachusetts Institute of Technology

Mercedes-Benz USA

National Electrical Manufactures Association

Naval Facilities Engineering Command*

New York State Energy Research & Development Authority*

Ohio Fuel Cell Coalition

OMNETRIC Group

Oorja Fuel Cells

Parker Hannifin Corp.

PDC Machines, Inc.*

Pecan Street Research Institute

Port of Long Beach

Proton OnSite

Raytheon

Sacramento Municipal Utility District

San Diego Gas & Electric*

Santa Fe Community College

Smarter Grid Solutions

SolarCity

Southern California Gas Company*

State Grid Energy Research Institute

SunPower

Technical University of Denmark

Time Warner Cable*

Toyota Central R&D Labs

Toyota North America

University of Central Florida

University of Denver

University of Delaware

University of South Carolina

University of Toledo

U.S. Department of Defense

U.S. Department of Defense, Strategic Environmental Research Program*

U.S. Navy*

WattStick Systems, Inc.

WEB Aruba N.V.*

Western Electricity Coordinating Council

Whisker Labs

Wyle Laboratories*

*These partners have more than one project.

DOE PROGRAM RESEARCH

Energy Systems Integration (Multiple DOE Program Offices)

Distributed Generation Market Demand Model

ERGIS

High-Resolution Rapid Refresh-FCSTS

Human Centered Energy Systems—Thermo-Physiological Modeling and Optimization

INTEGRATE Projects (Collaborative)

EPRI: Cohesive Application of Standards-Based Connected Devices to Enable Clean Energy

EPRI: End-to-End Communications and Control System to Support Clean Energy Technologies

OMNETRIC Group: Open Field Message Bus Reference Architecture Demonstration

Smarter Grid Solutions: Demonstrating Active Network Management integration

University of Delaware: Open V2X at ESIF

Integrated Grid Modeling System

PLEXOS Modeling

Resource Planning Model

ARPA-E

Network Optimized Distributed Energy Systems

BioEnergy

Biology: Biological Studies of Energy Systems

Chemistry and Computational Fluid Dynamics Studies of Energy Systems

Process-Scale Mechanistic Modeling for the Biochemical Conversion of Biomass to Transportation Fuels

Buildings

Circuit-Level Sub-Metering Demonstration for GSA's Green Proving Ground Program

Residential Building Stock Analysis

Volttron Infrastructure Development and Demonstration

Fuel Cell Technologies Office

Catalysts and Electrodes Electrochemical Characterization

Component Testing

Computational Exploration of Mullite as a Diffusion Barrier for High Temperature Refractory Containment Materials

Enlarging Potential National Penetration for Stationary Fuel Cells through System Design and Optimization

Fuel Cell Manufacturing Research and Development

Fuel Cell Research and Development

Hydrogen Compressor Reliability Investigation and Improvement

Hydrogen Dispenser Hose Reliability Improvement

HYSTEP—Calibration for Commercial Fuel Dispensers

Integrate—Electrolyzer Grid Sim

Modeling of High-Performing Pt-Based ORR Catalysts to Facilitate Future Design and Development

Renewable Electrolysis: Integrated Systems Development and Testing

Sensor Research Lab

System, Stack, and Component Operation and Performance

Testing and Technical Assessment

Geothermal

High Power Laser Tool and System for Unique Geothermal Well Completions

Grid Modernization

Capacity Expansion Planning with ReEDs

Development and Deployment of Multi-Scale Production Cost Models

Eastern and Western Interconnection Seams and Optimal HVDC Overlay Study

Transformative Modeling for Solar Technologies on the Bulk Power System

Office of Electricity Delivery and Energy Reliability

Advanced Distribution Management Systems

Testing Multiple Inverter Interactions Using Power Hardware-in-the-Loop

Solar Energy Technologies Office

Commissioning and Use of Long-Pulse Solar Simulator

Computational Modeling and Design of Complex Semiconductors for Energy

Degradation Mechanisms and Development of Protective Coatings for TES and HTF Containment Materials

Dielectric Discharger Test (SuNLaMP)

Direct S-CO2 Receiver Development

Emerging Technologies Characterization

International Photovoltaic Quality Assurance Task Force

Multi-Scale, Multi-Model, Machine-Learning Solar Forecasting Technology

Opportunistic Hybrid Communications Systems for Distributed PV Coordination

Particle Receiver Testing

Solar Resource Assessment from Geostationary Satellites

Solar Energy Technologies (SuNLaMP)

Solar Radiation Measurement

Theoretical Design and Discovery of the Most-Promising Previously Overlooked Hybrid Perovskite Compounds

Theoretical Materials Science for NREL EERE PV programs

Vehicle Technologies Office

Computer-Aided Engineering of Batteries/Microstructure Simulation for Virtual Electrode Design

Electric Drive Vehicle Climate Control Load Reduction

EV-Grid Integration Control and System Implementation

Grid-Connected Electric Drive Vehicle Thermal Load Reduction

Integrated Computational Materials Engineering Development of Advanced Steel for Lightweight Vehicles

Multiscale Multiphysics Lithium-ion Battery Modeling

OPTIMA Simulation Components the Co-Optimization of Fuels and Engines

Reliability of Bonded Interfaces

Simulation of Injector Cavitation Effects on Spray Characteristics

Validation and Development of Coupled Computational Fluid Dynamics and Ignition Kinetics Models for Transportation Fuels

Wind and Water Power Technologies Office

Blade-Resolved Computational Fluid Dynamics Simulations of Wind Turbine Rotors

Eastern Renewable Generation Integration Study

Offshore Advanced Technology Demonstration Projects

SOWFA + Super Controller

Upgrade to GE 1.5 MW Wind Turbine

Wave Energy System Computational Fluid Dynamics Modeling

Wind Flow Modeling

Wind Plant Optimization and Systems Engineering

KNOWLEDGE SHARING

Researchers at the ESIF are working at the leading edge of their field. By sharing their knowledge in many different ways, they are helping to advance the state of the art and also prepare the next generation of energy researchers and engineers. Below are a few of the events held at the ESIF or hosted by researchers at the ESIF in FY 2016.

Webinars

Release of the New National Solar Radiation Database—December 8, 2015

Grid Integration Webinar: Operating the Western Interconnection with 80%–90% Renewables—March 31, 2016

Grid Integration Webinar: Exploring Renewable Energy Integration in California—April 14, 2016

Prevention of Unintentional Islands in Power Systems with Distributed Resources Webinar—August 24, 2016

Workshops & Conferences

iiESI Workshop on Enabling Thermal Energy Flexibility in Integrated Energy Systems in Korea—October 21–22, 2015

Integrating PV in Distribution Grids: Solutions and Technologies Workshop—October 22–23, 2015

Frontiers in Distributed Optimization and Control of Sustainable Power Systems Workshop—January 27–28, 2016

Energy Systems Integration Workshop in Ireland—May 16 & 19, 2016

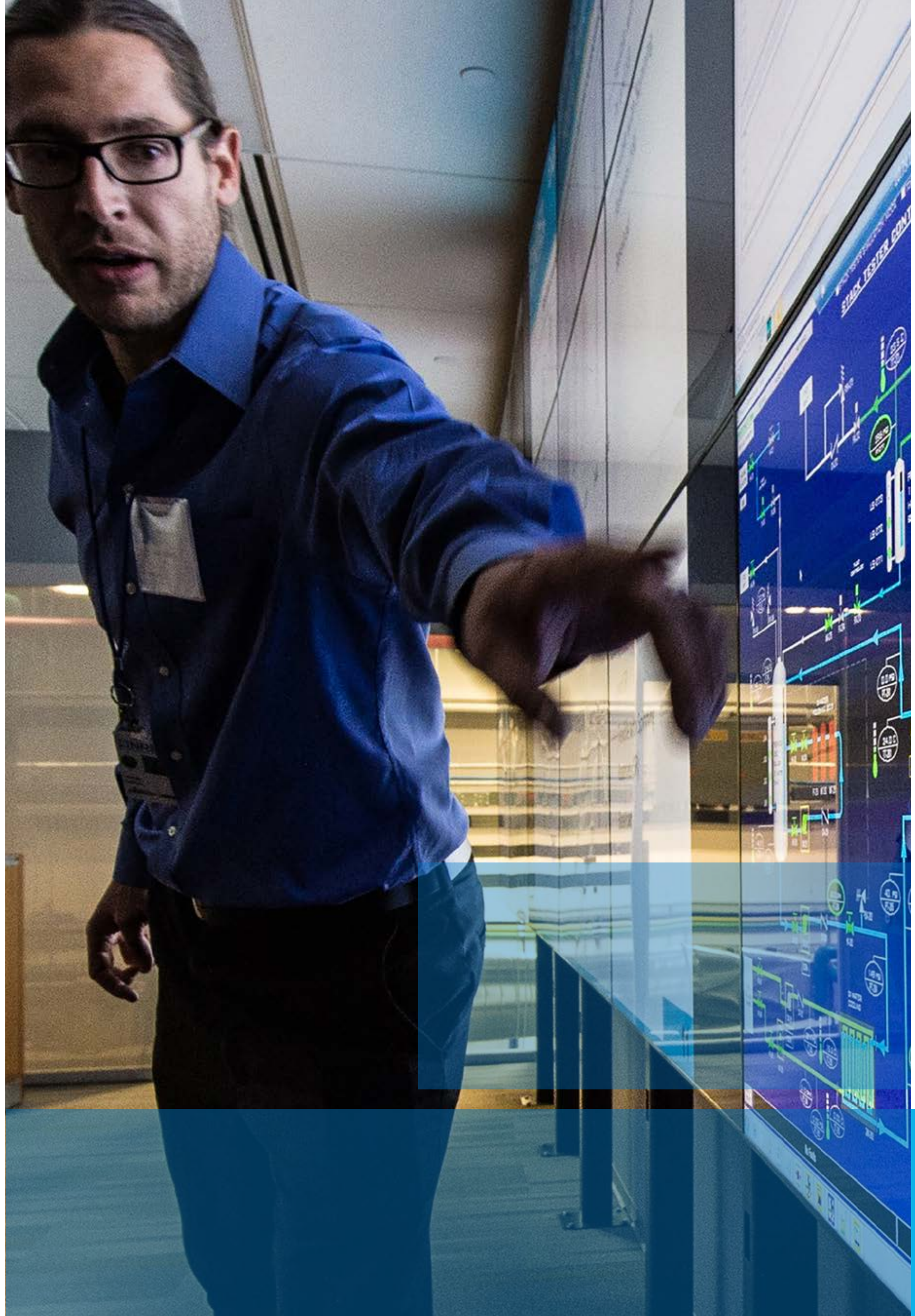
V2X Enabled EVs Expert Meeting—May 18-19, 2016

Advanced Grid Control Technologies Workshops—July 7–9, 2016

Security and Resilience of Grid Integration with Distributed Energy Resources: Lessons Learned and Future Outlook Workshop—July 13–14, 2016

Grid Modernization Initiative Devices and Integrated Systems Workshops—September 13–14, 2016

EV Extreme Fast Charging—September 21–22, 2016



Smart Grid Educational Series

Insecure Field Devices on the Smart Grid: Cyber Risks, Damage Potential, and Practical Solutions—February 25, 2016

Secure and Reliable Grid Integration of Distributed Energy Resources/CAISO Communication via Remote Intelligent Gateway—March 9, 2016

Nonlinear Oscillators and Self-Organizing Power Electronics Systems—March 30, 2016

IoT/PowerMatcher Transactive Energy for Smart Cities—April 13, 2016

Role of Software Defined Networking and WAN Virtualization in Securing SCADA Systems—April 27, 2016

Hardware Security for Smart Grid End Point Devices—May 11, 2016

Industry Outreach for OE CEDS Roadmap Initiative/Cybersecurity in Connected Homes & Buildings—May 31, 2016

Blackridge & Soha Cybersecurity Technologies—June 14, 2016

Smart Grid Virtual Town Hall Meeting to Honor the Late Erich Gunther—June 29, 2016

Cybersecurity Technology & Architecture Dialogue—July 29, 2016

Video Surveillance System Security & NERC CIP Compliance—August 19, 2016

Hitachi Consulting Vision for Environmental Sustainability—September 30, 2016

Download presentations, webinars, and videos at http://www.nrel.gov/esi/seminars-workshops.html.

To be the first to hear about upcoming events, sign up for *Energy Systems Integration News*, a monthly newsletter, at http://www.nrel.gov/esi/esi-newsletter.

Courses & Awards

NREL Hosts Distributed Energy Resources Course for Engineers

NREL hosted the 2016 Summer Course for the Foundations for Engineering Education for Distributed Energy Resources (FEEDER) Consortium on May 31–June 3. FEEDER is a consortium of 8 universities, 2 national laboratories, 8 utilities, and 11 industrial companies. Its primary mission is to significantly advance power systems engineering capabilities in the United States. The FEEDER Consortium is one of the four centers funded by DOE's EERE under its SunShot GEARED (Grid Engineering for Accelerated Renewable Energy Deployment) program, and the course focused on integrating distributed and renewable energy systems into electric power systems. The course was taught by FEEDER faculty from participating universities and staff from NREL's Power Systems Engineering Center.

NREL ESI Engineers Team with University to Develop and Teach Courses on Renewable Integration

Researchers from NREL's Power Systems Engineering Center worked with faculty in the Electrical, Computer, and Energy Engineering Department at the University of Colorado Boulder to develop courses that focus on integrating renewable energy in electric power systems. Developed and taught by NREL researchers, the courses will focus on grid integration and will include: Renewable Energy and the Future of the Power Grid, Power Systems Analysis, Advanced Control and Optimization of Power Systems, and Control of Power Electronics in AC Systems and Microgrids. These courses will be part of a professional master's degree program in power electronics offered through the university.

Four ESI Researchers Receive Outstanding Mentor Awards

NREL's annual ceremony for outstanding mentors of interns and postdoctoral researchers was held on August 30 to recognize the impact these mentors have made on the laboratory's young researchers. NREL Deputy Laboratory Director for Science and Technology Peter Green presented the awards to this year's winners, which include four ESIF researchers: Andrew Clifton, Brian Johnson, Bill Kramer, and Yingchen Zhang.

USER FACILITY UPDATES

Moving REDB Maintenance In-House Saves Big Money, Time

The Research Electrical Distribution Bus (REDB)—a power integration circuit capable of connecting multiple sources of energy—allows NREL and its partners to connect different laboratories and experiments within the ESIF. Because the REDB is unique to the ESIF, when components required electrical maintenance, an external contractor had to be scheduled for long, continuous blocks of time, and experiments requiring laboratory interconnection were often put on hold. However, thanks to an effort in FY 2016 to bring REDB maintenance in-house, NREL is reducing subcontract and schedule risks while also improving safety and quality—and reducing maintenance costs. The change has already saved NREL $500,000 this year. Now, REDB maintenance can be performed around scheduled research by qualified NREL electricians who are already familiar with laboratory safety requirements and culture.

Lab Utilization Reports

With the implementation of new ESIF User Support System functions in FY 2016, it is now possible to collect precise data on ESIF utilization. Reports can be pulled on the availability of resources, lab space, and equipment. With better information on what elements of the ESIF are the most used, it's possible to ensure that future investments are aligned with research needs.

House Power Upgrade

Utility grid power, or "house power," is used frequently in research conducted at the ESIF. Compared to using actual PV arrays, wind turbines, batteries, and loads, which are variable, house power can be used to energize programmable power supplies and loads that emulate these assets in a way that is configurable, repeatable, and scalable. As work at the ESIF continues to grow, the facility was reaching its limit in availability of house power, with load panels in most lab spaces tapped to nearly maximum. To solve this problem and lay the groundwork for future research, three 480-V, 4,000-A switchboards were installed with new medium-voltage service and three 2,500-kVA transformers to supply the switchboards. These upgrades added 7.5 MW to the ESIF's high-bay lab house power.

The ESIF has been designated as a DOE user facility for both proprietary and nonproprietary work, and can accommodate the diverse needs of its many users and partners. Partners and users are able to take advantage of world-class research tools and pay only for the support or equipment time they need. To find out more about conducting research at the ESIF, contact us at 303-384-6528 or martha.symko.davies@nrel.gov.

A visualization room in the ESIF was upgraded to be a backup emergency operations center and display room with equipment and tools virtually identical to a utility control room. The room will support ongoing research as well as serve as a location to assemble and monitor systems and equipment throughout the ESIF.

INVENTIONS

Records of Invention

Title	Primary NREL Center	NREL Number
Wave Generation with Submarine Compressed Air Energy Storage	5D00 - Power Systems Engineering	ROI-16-01
Method for Photovoltaic Maximum Power Point Estimation	5D00 - Power Systems Engineering	ROI-16-06
Estimation of Short-Term Equivalent Inertia in a Wind Power Plant	5D00 - Power Systems Engineering	ROI-16-07
Energy Storage Opportunities and Capabilities in a Type 3 Wind Turbine Generator	5D00 - Power Systems Engineering	ROI-16-08
Spinning Reserve and Frequency Regulation of a PV Power Plant	5D00 - Power Systems Engineering	ROI-16-09
Integrated Distribution Market Operator	5D00 - Power Systems Engineering	ROI-16-11
A Method for Mitigating Communication Latency Errors in Remote Hardware-in-the-Loop Experiments	5D00 - Power Systems Engineering	ROI-16-31
Optimal Power Flow Pursuit	5D00 - Power Systems Engineering	ROI-16-35
Fast All-Sky Radiation Model for Solar Applications (FARMS)	5D00 - Power Systems Engineering	ROI-16-36
Conversion Tools: Sinergi2DSS, Cyme2DSS, GIS2DSS, Sinergi2GLM and Cyme 2GLM	5D00 - Power Systems Engineering	SWR-16-17
FARMS (Fast All-sky Radiation Model for Solar applications)	5D00 - Power Systems Engineering	SWR-16-18
ITEMC (Internet of Things Energy Management Controllers	5D00 - Power Systems Engineering	SWR-16-21
9-Layer Cybersecurity Architecture	5D00 - Power Systems Engineering	ROI-16-70
A Synthetic Procedure for Synthesizing Virtual Oscillators for Inverter-Based Power Systems	5D00 - Power Systems Engineering	ROI-16-74
Virtual Oscillator for Tunable Droop-like Functionality	5D00 - Power Systems Engineering	ROI-16-75

Title	Primary NREL Center	NREL Number
Method and Apparatus to Liquid Cool Computer Mother Boards	5D00 - Power Systems Engineering	ROI-16-79
dynamo	5D00 - Power Systems Engineering	SWR-16-23
Novel Magnetocaloric Refrigeration System	5D00 - Power Systems Engineering	ROI-16-91
A Virtual-Oscillator-Based Power-Tracking Controller for Inverters in a Power-Electronic-Dominated Distribution Systems	5D00 - Power Systems Engineering	ROI-16-99
Dual Active Bridge based DC Transformer LavVIEW FPGA Control Code	5D00 - Power Systems Engineering	SWR-16-25
Three-phase Four-leg Inverter LabVIEW FPGA Control Code	5D00 - Power Systems Engineering	SWR-16-26
A Constraint-Enforcing Virtual-Oscillator Controller for Grid-Tied Battery Energy Storage Systems	5D00 - Power Systems Engineering	ROI-16-100
Analytical Tools for Modeling and Visualizing Impacts of Emerging Technologies in Distribution Feeders	5D00 - Power Systems Engineering	SWR-16-28
Predictive Rapid Active Power Control of Photovoltaic Systems	5D00 - Power Systems Engineering	ROI-16-103
Designing Pricing Strategies for Voltage Regulation in Distribution Systems	5D00 - Power Systems Engineering	ROI-16-107
DERHCAT (Distributed Energy Resources Hosting Capacity Analysis Tool)	5D00 - Power Systems Engineering	SWR-16-32
Kaleidoscope	5D00 - Power Systems Engineering	SWR-16-35
Design of Controllers Realizing Distribution-Level Virtual Power Plants	5D00 - Power Systems Engineering	ROI-16-124
L-TERRA (Lidar Turbulence Error Reduction Algorithm)	5D00 - Power Systems Engineering	ROI-16-04

Patent Filings

Title	Primary NREL Center	NREL Number
An Ocean Wave Energy Conversion System Optimized for Energy Capture and Delivery of Utility Standard Power	5D00 - Power Systems Engineering	PROV/16-01
Distributed Feedback Controllers for Optimal Power Flow	5D00 - Power Systems Engineering	PROV/16-35
Mitigating Latency Errors in Distributed Systems	5D00 - Power Systems Engineering	PROV/16-31
Virtual Oscillator Control for Power Electronics Inverters	5D00 - Power Systems Engineering	PROV/16-74
Managing Photovoltaic Power for Use in Grid Stabilization	5D00 - Power Systems Engineering	PROV/16-06
Distributed Feedback Controllers for Optimal Power Flow	5D00 - Power Systems Engineering	PROV/16-35 A
Virtual Oscillator-Based Power-Tracking Con-troller	5D00 - Power Systems Engineering	PROV/16-99
Fast Power Control	5D00 - Power Systems Engineering	PROV/16-103
Lidar Turbulence Measurement Error Reduction	5D00 - Power Systems Engineering	PROV/16-04

PUBLICATIONS

Most Downloaded Publications

The following were the most downloaded FY 2016 ESIF publications on NREL.gov:

1. "Rooftop Solar Photovoltaic Technical Potential in the United States"
2. *Eastern Renewable Generation Integration Study*
3. *High-Penetration PV Integration Handbook for Distribution Engineers*
4. *Advanced Grid-Friendly Controls Demonstration Project for Utility-Scale PV Power Plants*
5. *Western Wind and Solar Integration Study Phase 3A: Low Levels of Synchronous Generation*
6. *On the Path to SunShot: Emerging Issues and Challenges in Integrating Solar with the Distribution System*
7. *Advancing System Flexibility for High Penetration Renewable Integration*
8. *Final Technical Report: Integrated Distribution-Transmission Analysis for Very High Penetration Solar PV*
9. *Parallel Application Performance on Two Generations of Intel Xeon HPC Platforms*
10. *Experimental Evaluation of PV Inverter Anti-Islanding with Grid Support Functions in Multi-Inverter Island Scenarios*

Conference Papers (Preprints)

Baker, K., E. Dall'Anese, and T. Summers. 2016. "Distribution-Agnostic Stochastic Optimal Power Flow for Distribution Grids: Preprint." Presented at the 2016 North American Power Symposium (NAPS), Denver, Colorado, September 18–20.

Brunhart-Lupo, N., B.W. Bush, K. Gruchalla, and S. Smith. 2016. "Simulation Exploration through Immersive Parallel Planes: Preprint." Presented at the IEEE Workshop on Immersive Analytics (IA), Greenville, South Carolina, March 19–23.

Cheung, W.Y., J. Zhang, A. Florita, B.-M. Hodge, S. Lu, H.H. Hamann, Q. Sun, and B. Lehman. 2015. "Ensemble Solar Forecasting Statistical Quantification and Sensitivity Analysis: Preprint." Presented at the 5th International Workshop on Integration of Solar Power Into Power Systems, Brussels, Belgium, October 19–20.

Ding, F., B. Mather, and P. Gotseff. 2016. "Technologies to Increase PV Hosting Capacity in Distribution Feeders: Preprint." Presented at the 2016 IEEE PES General Meeting, Boston, Massachusetts, July 17–21.

Gallo, G. 2015. "Integrated Agent-Based and Production Cost Modeling Framework for Renewable Energy Studies: Preprint." Presented at the 49th Hawaii International Conference on System Sciences (HICSS), Kauai, Hawaii, January 5–8.

Guntur, S., J. Jonkman, S. Schreck, B. Jonkman, Q. Wang, M. Sprague, M. Hind, and R. Sievers. 2016. "FAST v8 Verification and Validation for a Megawatt-Scale Wind Turbine with Aeroelastically Tailored Blades: Preprint." Presented at the American Institute of Aeronautics and Astronautics Science and Technology Forum and Exposition (SciTech 2016), San Diego, California, January 4–8.

Habte, A., M. Sengupta, A. Andreas, I. Reda, and J. Robinson. 2016. "The Impact of Indoor and Outdoor Radiometer Calibration on Solar Measurements: Preprint." Presented at the European PV Solar Conference and Exhibition (EU PVSEC), Munich, Germany, June 20–24.

Krad, I., E. Ibanez, and E. Ela. 2015. "Analysis of the Effects of a Flexible Ramping Ancillary Service Product on Power System Operations: Preprint." Presented at the CIGRE U.S. National Committee 2015 Grid of the Future Symposium, Chicago, Illinois, October 11–13.

Krad, I., E. Ibanez, E. Ela, and W. Gao. 2015. "Operational Impacts of Operating Reserve Demand Curves on Production Cost and Reliability: Preprint." Presented at the 14th International Workshop on Large-Scale Integration of Wind Power Into Power Systems as Well as on Transmission Networks for Offshore Wind Power Plants, Brussels, Belgium, October 20–22.

Muljadi, E, V. Gevorgian, and A. Hoke. 2016. "Short-Term Forecasting of Inertial Response from a Wind Power Plant: Preprint." Presented at the 2016 IEEE Energy Conversion Congress and Exposition, Milwaukee, Wisconsin, September 18–22.

Muljadi, E., A. Wright, V. Gevorgian, J. Donegan, C. Marnagh, and J. McEntee. 2016. "Dynamic Braking System of a Tidal Generator: Preprint." Presented at the 2016 IEEE Energy Conversion Congress and Exposition, Milwaukee, Wisconsin, September 18–22.

Muljadi, E., V. Gevorgian, A. Wright, J. Donegan, C. Marnagh, and J. McEntee. 2016. "Electrical Power Conversion of a River and Tidal Power Generator: Preprint." Presented at the 2016 IEEE North American Power Symposium (NAPS), Denver, Colorado, September 18–20.

Muljadi, E., V. Gevorgian, A. Wright, J. Donegan, C. Marnagh, and J. McEntee. 2016. "Turbine Control of a Tidal and River Power Generator: Preprint." Presented at the 2016 IEEE North American Power Symposium (NAPS), Denver, Colorado, September 18–20.

Muljadi, E., V. Gevorgian, and A. Hoke. 2016. "Energy Storage Opportunities and Capabilities in a Type 3 Wind Turbine Generator: Preprint." Presented at the 2016 IEEE Energy Conversion Congress and Exposition, Milwaukee, Wisconsin, September 18–22.

Muljadi, E., Y.C. Zhang, V. Gevorgian, and D. Kosterev. 2016. "Understanding Dynamic Model Validation of a Wind Turbine Generator and a Wind Power Plant: Preprint." Presented at the 2016 IEEE Energy Conversion Congress and Exposition, Milwaukee, Wisconsin, September 18–22.

Pavese, C., T. Kim, Q. Wang, J. Jonkman, and M.A. Sprague. 2015. "HAWC2 and BeamDyn: Comparison Between Beam Structural Models for Aero-Servo-Elastic Frameworks: Preprint." Presented at the European Wind Energy Association Annual Conference and Exhibition 2015 (EWEA 2015), Paris, France, November 17–20.

Vignola, F., J. Peterson, R. Kessler, F. Mavromatakis, M. Dooraghi, and M. Sengupta. 2016. Use of Pyranometers to Estimate PV Module Degradation Rates in the Field: Preprint. Presented at the 43rd IEEE Photovoltaic Specialists Conference, Portland, Oregon, June 5–10.

Wang, D., L. Yang, A. Florita, S.M.S. Alam, T. Elgindy, and B.-M. Hodge. 2016. "Automatic Regionalization Algorithm for Distributed State Estimation in Power Systems: Preprint." Presented at the IEEE Global Conference on Signal and Information Processing (GlobalSIP), Washington, D.C., December 7–9.

Wang, Q., H. Wu, J. Tan, B.-M. Hodge, W. Li, and C. Luo. 2016. "Analyzing the Impacts of Increased Wind Power on Generation Revenue Sufficiency: Preprint." Presented at the 2016 IEEE Power and Energy Society General Meeting, Boston, Massachusetts, July 17–21.

Wu, Z., X. Wang, W. Gao, M. Kang, M. Hwang, Y. Kang, V. Gevorgian, and E. Muljadi. 2016. "Frequency Support of PMSG-WTG Based on Improved Inertial Control: Preprint." Presented at the 2016 IEEE Power and Energy Society General Meeting, Boston, Massachusetts, July 17–21.

Xie, Y., and M. Sengupta. 2016. "Diagnosing Model Errors in Simulations of Solar Radiation on Inclined Surfaces: Preprint." Presented at the 43rd IEEE Photovoltaic Specialists Conference, Portland, Oregon, June 5–10.

Xie, Y., and M. Sengupta. 2016. "Fast All-Sky Radiation Model for Solar Applications (FARMS): A Brief Overview of Mechanisms, Performance, and Applications: Preprint." Presented at the European PV Solar Conference and Exhibition (EU PVSEC), Munich, Germany, June 20–24.

Xie, Y., and M. Sengupta. 2016. "Performance Analysis of Transposition Models Simulating Solar Radiation on Inclined Surfaces: Preprint." Presented at the European PV Solar Conference and Exhibition (EU PVSEC), Munich, Germany, June 20–24.

Yang, R., and Y.C. Zhang. 2016. "Coordinated Optimization of Distributed Energy Resources and Smart Loads in Distribution Systems: Preprint." Presented at the 2016 IEEE Power and Energy Society General Meeting, Boston, Massachusetts, July 17–21.

Yao, Y., W. Gao, J. Momoh, and E. Muljadi. 2015. "Economic Dispatch for Microgrid Containing Electric Vehicles via Probabilistic Modeling: Preprint." Presented at the North American Power Symposium (NAPS), Charlotte, North Carolina, October 4–6.

Zhang, C., M.H. Gray, R. Tirawat, R.E. Larsen, and F. Chen. 2016. "Effects of UV Aging on the Cracking of Titanium Oxide Layer on Poly(ethylene terephthalate) Substrate: Preprint." Presented at the ASCE Earth and Space Conference, Orlando, Florida, April 11–15.

Zhang, C., S. Santhanagopalan, M.A. Sprague, and A.A. Pesaran. 2016. "Simultaneously Coupled Mechanical-Electrochemical-Thermal Simulation of Lithium-Ion Cells: Preprint." Presented at the 229th Meeting of the Electrochemical Society (ECS 229), San Diego, California, May 29–June 2.

Zhou, X., J. Tian, L. Chen, and E. Dall'Anese. 2016. "Local Voltage Control in Distribution Networks: A Game-Theoretic Perspective: Preprint." Presented at the 2016 North American Power Symposium (NAPS), Denver, Colorado, September 18–20.

Conference Papers (Published Proceedings)

Ainsworth, N., B. Johnson, and B. Lundstrom. 2015. "Fuzzy-Logic Subsumption Controller for Home Energy Management Systems." In *Proceedings of the 2015 North American Power Symposium (NAPS)*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

Annoni, J., P. Gebraad, and P. Seiler. 2016. "Wind Farm Flow Modeling Using an Input-Output Reduced-Order Model." In *Proceedings of the American Control Conference*.

Annoni, J., P. Gebraad, and P. Seiler. 2016. "Wind Farm Flow Modeling Using Input-Output Dynamic Mode Decomposition." In *Proceedings of the American Control Conference*.

Baggu, M., J. Giraldez, T. Harris, N. Brunhart-Lupo, L. Lisell, and D. Narang. 2015. "Interconnection Assessment Methodology and Cost Benefit Analysis for High-Penetration PV Deployment in the Arizona Public Service System." In *Proceedings of the 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

Baingana, B., E. Dall'Anese, G. Mateos, and G.G. Giannakis. 2016. "Robust Kriged Kalman Filtering." In *Proceedings of the 2015 49th Asilomar Conference on Signals, Systems and Computers*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

Basso, T., S. Chakraborty, A. Hoke, and M. Coddington. 2015. "IEEE 1547 Standards Advancing Grid Modernization." In *Proceedings of the 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

Chakraborty, S., A. Hoke, and B. Lundstrom. 2015. "Evaluation of Multiple Inverter Volt-VAR Control Interactions with Realistic Grid Impedances." In *Proceedings of the 2015 IEEE Power and Energy Society General Meeting*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

Cheung, W.Y., J. Zhang, A. Florita, B.-M. Hodge, S. Lu, H.H. Hamann, Q. Sun, and B. Lehman. 2015. "Ensemble Solar Forecasting Statistical Quantification and Sensitivity Analysis." In *Proceedings of the 5th Solar Integration Workshop: International Workshop on Integration of Solar Power Into Power Systems*. Darmstadt, Germany: Energynautics GmbH.

Churchfield, M.J., E. Quon, and J. Sanz Rodrigo. 2016. "Incorporating Mesoscale and Diurnal Influences to Microscale Atmospheric Boundary Layer Large-Eddy Simulations." In *Proceedings of the Symposium on OpenFOAM in Wind Energy*.

Churchfield, M.J., Q. Wang, A. Scholbrock, T. Herges, T. Mikkelsen, and M. Sjöholm, 2016. "Using High-Fidelity Computational Fluid Dynamics to Help Design a Wind Turbine Wake Measurement Experiment." In *Journal of Physics: Conference Series, The Science of Making Torque from Wind*.

Clark, K., N.W. Miller, M. Shao, S. Pajic, and R. D'Aquila. 2015. "Transient Stability of the US Western Interconnection with High Wind and Solar Generation." In *Proceedings of the 2015 IEEE Power and Energy Society General Meeting*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

Cui, M., J. Zhang, H. Wu, B.-M. Hodge, D. Ke, and Y. Sun. 2016. "Wind Power Ramping Product for Increasing Power System Flexibility." In *Proceedings of the 2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

Cui, M.-J., D.-P. Ke, Y.-Z. Sun, D. Gan, J. Zhang, and B.-M. Hodge. 2015. "A Scenario Generation Method for Wind Power Ramp Events Forecasting." In *Proceedings of the 2015 IEEE Power and Energy Society General Meeting*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

Dall'Anese, E. 2016. "Optimal Power Flow Pursuit." In *Proceedings of the 2016 American Control Conference (ACC)*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

Dall'Anese, E., S.V. Dhople, B. Johnson, and G.B. Giannakis. 2015. "Decentralized Optimal Dispatch of Photovoltaic Inverters in Residential Distribution Systems." In *Proceedings of the 2015 IEEE Power and Energy Society General Meeting*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

Deslippe, J., F.H. da Jornada, D.-V.Fowler, T. Barnes, N. Wichmann, K. Raman, R. Sasanka, and S.G. Louie 2016. "Optimizing Excited-State Electronic-Structure Codes for Intel Knights Landing: A Case Study on the BerkeleyGW Software." In *Proceedings of the International Conference on High Performance Computing*, 402–414.

Ding, F., B. Mather, N. Ainsworth, P. Gotseff, and K. Baker. 2016. "Locational Sensitivity Investigation on PV Hosting Capacity and Fast Track PV Screening." In *Proceedings of the 2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

Fleming, P., J. Aho, P. Gebraad, L. Pao, and Y. Zhang. 2016. "Computational Fluid Dynamics Simulation Study of Active Power Control in Wind Plants." In *Proceedings of the American Control Conference*.

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