Sandia National Laboratories Solar Capabilities



CONTENTS

PHOTOVOLTAIC CAPABILITIES

PHOTOVOLTAIC SYSTEMS EVALUATION LABORATORY (PSEL)

PSEL is an integrated testing facility that uniquely combines indoor & outdoor module characterization capabilities with the ability to perform outdoor operational & reliability evaluations of PV systems & components. PSEL has been at the forefront of photovoltaic R&D & model development for more than three decades & leverages many cutting-edge in-house developed test capabilities. The facility is the core physical asset of DOE Designated Capability DC0006 – Sandia Photovoltaic Systems Engineering Support. PSEL hosts the NM Regional Test Center (RTC) & PV Lifetime Projects in addition to Sunlamp projects focused on bifacial & CIGS module technologies.

FACILITIES

- 7 acre fenced site located on Kirtland Air Force Base.
- Most of the site is graded and prepared to accept standardized fixed tilt racking.
- 750 kW grid tie capacity, two transformers
- 7 buildings housing office, lab, shop and R&D spaces.

RELEVANT CAPABILITIES

- Real world PV systems evaluations (DC & AC measurements) & optimization.
- Performance testing of modules, arrays, & power converters.
- Performance characterization of PV cells & photo sensors, including quantum efficiency/spectral response
- Long-term PV system monitoring, including reliability & lifetime assessments
- Calibration of PV reference cells, pyranometers & pyrheliometers.
- Component & systems performance modeling

INFRASTRUCTURE/EQUIPMENT

- Two large dual-axis trackers that are highly configurable for multiple test configurations
- IV data acquisition systems capable of measuring eight modules (tracked) outdoors simultaneously
- Comprehensive PV weather station, including spectrum
- Outdoor calibration facility for irradiance devices
- Equipment for continuous monitoring of PV system outputs on the DC & AC sides of the inverter, currently in use for up to 300kW of small PV systems in a number of simultaneous configurations.
- Indoor module lab: Spire 4600 SLP flash tester, Reltron Electroluminescence unit, Dark IV, FLIR infrared characterization, Atonometrics Light Soaking Station.
- Indoor cell lab: Spectrolab XT-10 continuous solar simulator, Berger Pulsed solar simulator, PV Measurements QEX10 quantum efficiency unit, Cary 5000/DRA2500 spectrophotometer.
- Mobile IV tracers for measuring module & string IV curves in the field over time

PROJECTED GOALS FOR 2030

- Areal expansion to reclaim 8+ acres of adjacent l&, up to 1.5 MW of additional capacity. Could host single axis trackers as well as fixed tilt.

- Mission expansion to use on site PV to evaluate distributed storage, monitoring & modeling.
- Mission expansion to include long-term PV materials degradation studies.
- Restoration of "Sandia Module database", included as part of SAM & open source PV_Lib. Last update to database was in ~2012.
- Expand database to include open source PAN files for PVSyst.

US DOE REGIONAL TEST CENTERS (RTCs)

Launched in 2011, the US DOE Regional Test Center program provides an unmatched, five-site technical platform for the validation of US solar technologies by the national labs. These five climatically distinct and comparably instrumented sites allow for cross-climate performance studies and research on emerging challenges in the areas of PV performance and reliability.

FACILITIES

The RTC program supports five sites in New Mexico, Colorado, Florida, Michigan Tech and Nevada, each with a minimal capacity of 300kW and onsite buildings that provide capabilities ranging from office and storage space to R&D and testing laboratories. The ability of the five RTC sites to deliver high-fidelity, cross-climate data reflects the precision with which the RTCs were designed.

RELEVANT CAPABILITIES

- Fielded performance assessment and validation of diverse manufacturer-provided technologies, including solar cells, modules, power electronics, and tracker technologies
- Boilerplate and customized performance studies that can accommodate side-by-side technological comparisons; also different rack orientations, tilt angles, substrates, etc.
- Standardized installation approach that allows for the rapid design and deployment of new systems
- DC and AC string-level monitoring of PV systems and components
- Irradiance and temperature monitoring at the array level
- Tracker-error monitoring
- High-resolution, high-fidelity data monitoring, including daily data review by Sandia
- World-class soiling and meteorological instrumentation that provides data for performance analysis and research
- Early failure detection and failure analysis of fielded components
- Standardized O&M protocols that provide data to substantiate the value of rigorous O&M.
- Instrumented, multi-climate field sites that can be leveraged to address both mainstream and emerging research challenges

INFRASTRUCTURE/EQUIPMENT

- Three-phase, 480V AC grid tie (although other electrical configurations, such as single-phase 240V or 208V connections, can be made either by connecting to an onsite transformer or by installing a stepdown transformer specific to a system's needs.)
- Highly-calibrated monitoring systems (accuracy of 0.5 %) that collect DC electrical data at < 5-second intervals, averaged at one-minute intervals.
- Data-acquisition system built on a MODBUS network that allow for easy expansion, depending on data and component needs, and programmed to transmit data daily to Sandia.
- Plane-of array (POA) irradiance sensors that include both front and rear-facing sensors (the latter for bifacial modules) to accurately measure the amount of irradiance striking a module's surface
- Back-of-module thermocouples

- Mono-crystalline PV reference, or "baseline" system, against which the performance of other systems can be compared
- Pre-existing, grid-tied racking (so-called "fast-track rack") that can accommodate nearly any size module and includes wire trays and equipment racking to reduce installation time.
- World-class meteorological instrumentation that includes:
    - Irradiance sensors (tracked direct normal, global horizontal, diffuse horizontal)
    - Barometric pressure sensor
    - Anemometer
    - Humidity and temperature sensors
    - Tipping and heated rain gauge
        - Note: data from RTC weather stations and from the baseline PV systems owned by the RTCs are available for public download. [see http://maps.nrel.gov/pvdaq]
- High-resolution electrical monitoring that includes:
    - DC Electrical Monitoring
        - Current shunts to measure DC current at the string level
        - Resistive voltage divers to measure DC voltage
    - AC Electrical Monitoring
        - AC electrical measurements at the inverter level, if the AC data is important to the validation study. If AC data is desired, Sandia will install a revenue-grade shark meter to measure;
        - Active, reactive and apparent AC power
        - Power factor
        - Frequency
        - Line-to-Line and line-to-neutral voltage for all three phases
        - Line currents for all three phases and neutral
        - Ability to accommodate non-UL listed prototypes

SITE-SPECIFIC INSTRUMENTATION

- NM RTC:
    - All equipment at the PSEL facility (listed above) is available to directly support the NM RTC and indirectly support the NV and MI RTCs, which lack onsite laboratories
    - Soiling measurement station (the station collects optical transmittance measurements, which indicate accumulated particulates, from the surface of mini-modules set at different tilt angles)
- FL RTC:
    - Spire 4600 and Sinton flash simulators; EL and IR imaging[1] and other diagnostic equipment
    - Soiling-measurement station
- MI RTC:
    - Soiling-measurement station
    - Snow station that measures the impact of snow accumulation on energy yield (Isc) for modules set at different tilt angles and heights above ground
      Note: although the site does not have onsite flash-testing, the MI RTC can perform outdoor module and string- level IV traces; also modules deployed in MI can be characterized in NM
- NV RTC:

1 This diagnostic equipment, like the PSEL equipment at Sandia, has been leveraged to support the RTCs.

  - Black Photon spectral sensor that provides spectral data important to understanding the performance of high-magnification, concentrated photovoltaic (CPV) systems
    Note: although the site does not have onsite flash-testing, the NV RTC can perform outdoor module and string- level IV traces; also modules deployed in NV can be characterized in NM
- CO RTC:
  - Spire 4600 and 5600 flash simulators; EL and IR imaging and other diagnostic equipment.

PROJECTED GOALS FOR 2030

- Expansion of existing sites onto adjacent l& to allow for greater capacity & greater technological diversity including storage.
- Expansion of program to support more research on the impact of climate on cell degradation, module integrity, etc.
- Expanded focus to include research on optimizing components & systems for specific climates
- Build-out of MI & NV sites (in partnership with local universities) to include diagnostic capabilities
- Expansion of program to leverage RTC technical capabilities to support grid integration studies, in partnership with local utilities
  Expansion of program to include additional sites in US (e.g. Alaska,) & partnerships with overseas RTC-like facilities (operated by research institutions in geographic regions that range from low-latitude to urban to tropical) that would result in a Sandia-managed global database of meteorological & PV performance data

DATA MONITORING & ANALYSIS

Information technology (IT) infrastructure, that is used to retrieve, transmit, store, share, and analyze data, is constantly advancing. The advancements are demanded by increased investments in solar power plants and smart grid technologies that require reliable, intelligent, and secure IT networks. The Sandia research team can provide innovative techniques and technologies that improve PV data monitoring so that it can support maintenance decisions and smart grid operations. The capabilities that support advanced IT infrastructure for PV systems are broken out into two categories: (1) data monitoring and (2) system analysis.

Sandia is capable of developing, deploying, and testing typical commercial off-the-shelf and custom data acquisition (DAQ) systems. The DAQ systems have been used to monitor indoor and outdoor testbeds, weather stations, satellite images, sky images, maximum power point DC and AC electrical parameters, and module and string level I-V curves. The acquired data can be transmitted using various methods that include the transfer of files through folder sharing systems, secure copy, file transfer protocol, hypertext transfer protocol (HTTP), message queue telemetry transport (MQTT), Modbus TCP/IP, Modbus serial, and others. The research team's level of experience with data transmission has allowed them to explore interoperability of the PV monitoring systems. The team has connected PV sensor data streams with other energy resources such as commercial and residential building automation systems, batteries, and centralized databases.

The Sandia research team manages close to 100 (and growing) local (Albuquerque) and remote (Florida, Michigan Tech, Nevada, and others) outdoor PV systems. The management includes extensive oversight and maintenance of the data streams from all the systems to a centralized database. The team has developed an efficient IT infrastructure that allows for automatic ingestion into the database. The data quality is also checked on a regular basis using PECOS python package. PECOS (https://github.com/sandialabs/pecos) python package, was developed by Sandia research staff, provides oversight by automatically evaluating data quality and warns users of issues through daily email reports. The centralized database can be accessed by Sandia staff and routed to outside entities, such as the DuraMat datahub, for collaboration and sharing purposes.

The DAQ systems at Sandia can be used to develop and test sophisticated forecasting, modeling, and classification algorithms. Modeling of PV system has been conducted at Sandia for over 25 years and recently included the creation of PVLIB (https://github.com/pvlib/pvlib-python) modeling package. The research team also has experience using, creating, and deploying machine learning algorithms, such as Support Vector Machines, Multi-Layer Perceptron, Gaussian Process, Deep Learning, Adaptive Resonance Theory (https://github.com/sandialabs/lapart-python), and many others. The algorithms can be deployed in many different environments ranging from small micro-computers to large high-performance computing systems. The intelligent learning can also be distributed across multiple micro-computers to create a network of learning algorithms that learn locally and from remote interactions with other smart monitoring devices.

The available resources and experienced staff provide a unique capability for advanced data monitoring and analytics of PV systems. For continued growth and innovation that will allow the research team to efficiently contribute to the decrease in LCOE, and an overall growth in PV across the United States requires base funding to support infrastructure and basic data management costs.

PROJECTED GOALS FOR 2030

Adequate funding of this capability will allow Sandia to contribute to the advancements in:

- Long-term system reliability,
- Annual energy production improvements,
- Expansion of high-quality data,
- Best practices for distributed energy storage, and
- Unpredictable variability of solar power.

The advancements will reduce the LCOE of solar by helping provide optimal design strategies, improved operations, and help expand PV through increased grid integration.

RELIABILITY ASSESSMENTS OF PV “SYSTEMS”

The solar industry and federal research is focused on initial product quality and accelerated lifetime (primarily solar modules) to simulate long-term reliability, however to our knowledge, this data is not being compared against actual fielded data to evaluate whether the initial product quality certifications or accelerated lifetime tests are valid.

Sandia has developed a unique approach of evaluating the reliability of a fielded PV “system” through analyzing all major components. This was done through the development of the PV Reliability Operations Maintenance data collection best practice, and the PV Reliability Performance Model (PV-RPM) as solutions on how to structure fielded data events for reliability analysis, and analytical techniques to simulate lifetime energy and financial impacts based on the component reliability within the PV system, respectively.

Through these efforts, Sandia has developed data sharing agreements with multiple entities, including independent power producers, owner operators, inverter manufacturers and maintenance providers. This data represents over 50 fielded systems at approximately 2 GWDC and has been in development for 3 years, though initiated through early SETO funding to advance a reliability perspective for PV systems. Sensitivities with data sharing have made the data collection effort difficult as the ideas were well ahead of the solar industry's comfort level, where they believe all data they generate is proprietary.

Funding from SETO has come from all three program areas, originating in systems integration, then moving into photovoltaics and soft costs, depending on the research question surrounding fielded reliability. Focusing on the PV components within a "system" is necessary to advance 2030 technology capability goals to keep improving individual component quality resulting in longer lifetimes. As components behave differently in fielded systems, being able to catalogue, analyze and improve both operations and maintenance with a reliability-centered approach will ensure higher degrees of uptime.

PROJECTED GOALS FOR 2030

- Focusing on the PV components within a "system" is necessary to advance 2030 technology capability goals to keep improving individual component quality resulting in longer lifetimes. As components behave differently in fielded systems, being able to catalogue, analyze & improve both operations & maintenance with a reliability-centered approach will ensure higher degrees of uptime.
- Research results developed from this capability will include formalized best practices for more reliability centered maintenance.
- Baselining component behavior across PV in different climates and configurations can help reveal issues that may not be addressed using current test standards.
- Improved quality and accelerated testing standards will be created based on this feedback loop.

PHOTOVOLTAICS MODULE & SYSTEM PERFORMANCE MODELING

The value of PV technology requires accurate models that can predict the energy production profile (system output over time). Sandia has developed a unique capability in this area. Sandia has a long history developing and validating PV performance models (e.g., Menicucci and Fernandes, 1988; King et al., 2004; King et al., 2009). More recently Sandia started an international collaboration called the PV Performance Modeling Collaborative (PVPMC). This group facilitated by Sandia has hosted eight modeling workshops (two more are upcoming), maintains a technical website (https://pvpmc.sandia.gov) and manages two open source modeling libraries in Matlab and Python (PVLIB). Over 2,800 people are included in the PVPMC mailing list and the website receives over 10,000 page views per month. Sandia is seen globally as a leader in the areas of PV performance modeling and continues to develop and validate new approaches aimed at either increasing accuracy of commercial models or allowing such models to represent new emerging technologies (e.g., bifacial, CIGS, shingled modules, PV roof tiles, etc.). Sandia is also developing and validation new modeling methods in the areas of IV curve fitting, bifacial irradiance, irradiance transposition and translation models, and machine learning methods, among others.

PROJECTED GOALS FOR 2030

- PV technology is likely to perform quite differently than current technology.
- A dynamic research program supported by the US DOE in the area of accurate PV performance modeling is a critical capability that should be supported.
- The lack of accurate performance models leads slower transfer of new technology into the marketplace and general slowing of innovation.

REFERENCES

Menicucci, D. and E. G. Fernandes (1988). User's Manual for PVFORM: A Photovoltaic Systems Simulation program for Stand-Alone and Grid-Interactive Applications. Albuquerque, Sandia National Laboratories. SAND85-0376.

King, D. L., E. E. Boyson and J. A. Kratochvil (2004). Photovoltaic Array Performance Model. Albuquerque, NM, Sandia National Laboratories. SAND2004-3535.

King, D. l., S. Gonzalez, G. M. Galbraith and W. E. Boyson (2007). Performance Model for Grid-Connected Photovoltaic Inverters. Albuquerque, NM, Sandia National Laboratories. SAND2007-5036.

MATERIALS CAPABILITIES

SYNTHESIS & FABRICATION

Our MESA complex includes 2 Fabs specific to silicon and III-V semiconductors, respectively, and each is dedicated to physical phenomena across nano- and micro- scales. The facility contains over 30,000 sq. ft. of Class 1 and Class 100 clean rooms with over 108 analytical support labs offering photolithography, reactive ion etching, CVD deposition, PVD metallization, CMP planarization, ion implantation, and E-beam evaporation to name a few capabilities. The experimental facilities allow fabrication of 6 in. Si wafers with post-processing for hybrid substrates, 3D integration, integrated circuits, and radiation effects. Epitaxial growth of III-V semiconductors produces a range of compositions including nitrides, arsenides, phosphides, and antimonides for a diversity of applications including optoelectronics, photonics, MEMS, VCSELs, and sensors.

We will create new classes of materials including semiconductors, stainless steels, carbon composites, ceramics, and polymers for all facets of modules including cells, encapsulants, coatings, framing, and power electronics. We will focus on Si and thin film packaging materials and next-generation thin film technologies in nano- and perovskite cells and packaging materials.

In the past, our synthesis and fabrication tools have been used to produce CPV modules (spun-off to form Emcore), Microsystems Engineered PV modules (MEPV - spun-off to form multiple start-ups), OPV cells (SETO-AOP), MOF-enhanced thin film cells (SunShot), nano-clay/polymer composite encapsulants (LDRD), solar selective coatings (SunShot), multi-functional coatings (DuraMAT), and solar thermal storage materials (PROMOTES).

ANALYTICAL ANALYSIS

Sandia offers “1-stop shopping” with state-of-the-art hardware and software for materials characterization in order to determine chemical composition and physical signatures at length scales from atoms to macrostructures. For chemical/structural analysis, SEM and TEM are workhorses with energy dispersive spectroscopy (EDS), electron backscattered diffraction (EBSD), wavelength dispersive spectroscopy (WDS), and focus ion beam (FIB) capabilities. Surface analysis capabilities include Auger, x-ray photoelectron spectroscopy (XPS), time-of-flight secondary ion mass spectroscopy (TOF SIMS), atomic force microscopy (AFM), and x-ray absorption fine structure (XAFS). Our aberration-corrected STEM has less than angstrom resolution offering 100X improvement in chemical mapping compared to standard AC-STEM.

Our hardware tools are partnered with the Sandia-developed AXSIA software suite for spectral data analysis allowing for full de-convolution of 3D compositional maps. We use any spectroscopic tool to raster across a sample and collect entire spectrum at each volume element, then use multivariate curve resolution to de-convolute the collection of spectrum into individual components to give a precise chemical composition map.

Our analytical analysis has supported SETO's reliability program for a number of years (SuNLaMP – SI) and has only scratched the surface in PV analysis. In the future, we will understand performance, degradation, and failure analysis at the molecular level. For example, we recently used Photoemission and Low-Energy Electron Microscopy (PELEEM) to study spatial electronic structure variance in CdTe, CIGS, and CZTS cells to improve manufacturing QA (SunShot).

PREDICTIVE SIMULATION

Sandia has developed and operates a host of computational materials science tools including open source hardware, software, and libraries to predict behaviors across length scales. We have at times competed for the title of world's largest computer in hardware for instance with Red Sky, ASCI Red, and now Trinity (in collaboration with Los Alamos). Our software packages include LAMMPS and Socorro for atomistic MD and Quantum DFT analysis, Tramonto and SPPARKS for coarse-grain and mesoscale analysis, and SIERRA and ALEGRA for finite element macroscale analysis.

Our predictive simulation tools will be used to understand existing materials properties without expensive experimentation. We iterate simulated materials behavior with synthesis to speed-up materials development.

In the past, our predictive simulation tools have been used to help synthesize dislocation-free thin film PV cells and to predict position-dependent oxidation by UV and thermal exposure in EVA encapsulants. Currently, we are modeling being stress-strain impacts relating to failure analysis on thin film modules (DuraMAT).

SYSTEMS INTEGRATION CAPABILITIES

DISTRIBUTED ENERGY TECHNOLOGIES LABORATORY (DETL)

DETL provides a highly flexible, reconfigurable laboratory environment that enables the investigation of control, optimization, electrical operation, and communication of distributed energy resources (DER) and other behind-the-meter equipment in real and simulated distribution or transmission grid topologies and conditions. For example, researchers can investigate different grid topologies (e.g., single- and three-phase microgrids) with the integration of a range of DER (e.g., PV inverters, energy storage systems, gensets, fuel cells, flywheels, and electric vehicles) under various grid or production conditions.

RELEVANT CAPABILITIES

The combination of high flexibility, re-configurability and cyber/controls/hardware integration and deep a wide range of related technical areas makes DETL a differentiated platform for development, prototyping and validation of power electronics converters, controllers and protection systems for PV coupled with storage, other DER, in distribution, transmission and microgrid environments. DETL also supports the development, refinement and harmonization of DER performance and safety standards, as well as associated testing protocols. The following highly integrated capabilities are available at DETL:

- PV/DER integration capability up to 1 MVA at 12.47 kV, multiple devices up to 300 kVA at 480V, and 120/240V in grid-connected and microgrid modes; multiple sources (200 kVA grid simulator, onsite diesel genset, energy storage including a 250 kW/1 MWh battery, 200 kW PV field, and 200 kW PV simulator. Fully integrated controller & power hardware-in-the-loop (HIL) capability.
- Comprehensive laboratory SCADA, including System Validation Platform (SVP) to automate test sequences of interconnection and communications/control interoperability, involving grid & PV simulators, and HIL capabilities.
- Virtual Power Plant (VPP) open ADMS R&D platform, specialized in stochastic optimization of DER dispatch and real-time control strategies with communications and cyber constraints.
- X-Net infrastructure, which allows protocol- and architecture-agnostic evaluation of network and device security with arbitrary cyber-attacks scenarios and cyber-defense strategies. X-Net extends DETL capabilities by linking to other Sandia key R&D complementary capabilities including CONET, ETAL, SSM and SWifT(see Complementary Capabilities below).

INFRASTRUCTURE/EQUIPMENT

- Distributed generation equipment: 150 kW of PV available as a configurable DC source, 225 kW diesel generator, and 600 kWh battery bank
- Fully configurable single and three-phase microgrids
- Two PV simulators (40 kW and 200 kW) with hardware-in-the-loop capability, allowing up to 20 separate inverters to interact with distinct or identical DC sources of different module technologies
- 180 kVA AC simulator allowing grid variations in frequency and voltage
- Extensive control infrastructure for automated tests, data acquisition and analysis
- Integration into Sandia's Energy Storage Test Pad, with capacity for electrical, control characterization of large storage systems and power conditioning units up 1 MVA
- Communications infrastructure to assess smart-grid commands using several protocols, such as
- DNP3, SunSpec Modbus and SEP2.0

- Lab-wide TCP networking to isolate equipment for cybersecurity experimentation on different VLANs or physical networks

PROJECTED GOALS FOR 2030

- Ability to conduct large-scale cyber-physical co-simulation including a full complement of power, networking and controls with arbitrary control architecture and communication protocols.
- Ability to demonstrate future high-performance, resilient, safe and secure DER/inverter-based power system operations spanning utility, microgrid, off-grid and military applications.
- Ability to conduct rapid prototyping of controllers for DER devices and systems (including microgrid controllers) using HIL capability.

PV/DER CYBERSECURITY R&D AND STANDARDS

RELEVANT CAPABILITIES

Sandia maintains world-class cybersecurity capabilities applied to a wide range of critical infrastructure, including energy systems. Sandia cyber capabilities that can be leveraged for application to PV include:

- Funded research in three focus areas: (1) Trusted hardware, software, and systems (2) Networks and systems architectures and analysis; and (3) Effective cyber defense systems.
- Extensive computing and information science capabilities, which range from architectures and algorithms to advanced modeling and simulation. These include integration and coupling of cyber Emulytics™ capabilities with hardware-in-the-loop capabilities using Sandia's SCEPTRE environment, which allows for cybersecurity characterization in a physical test bed. This capability uses a live, virtual constructive (LVC) approach to device and systems cybersecurity testing, enabling high-fidelity analysis of potential impacts from cyber-attacks, using a user-defined network architectures and supporting a wide range of SCADA protocols, including Modbus, IEEE 1815, and IEC 61850.
- The Cyber Engineering Research Institute (CERI) is a virtual organization spanning Sandia's Cyber Engineering Research Laboratory at the Albuquerque campus and the Cybersecurity Technologies Research Laboratory at the Livermore Valley Open Campus. CERI facilitates partnerships with academia and industry in order to push the frontiers of science and grow the next generation of cybersecurity talent.

PROJECTED GOALS FOR 2030

- Grid interface technologies that are secure and resilient with respect to cyber threats and fully accepted by industry and utilities.
- From the point of view of distributed solar, work with industry and other stakeholders to identify gaps and appropriate government role to create a core cyber-technology roadmap and framework that serves a blueprint for other DER technologies.
- Cybersecurity standards that ensure that appropriate design and optimization tools and performance assessment methodologies are widely available and continuously improved.

ADVANCED PV/DER POWER ELECTRONICS R&D

RELEVANT CAPABILITIES

Sandia's power electronics R&D capabilities focus on improving capability, efficiency, and reliability of next-generation inverters and converters. Equally important is Sandia's work on developing new break-through power electronics devices for PV and grid applications. A particular emphasis is wide and ultra-wide bandgap semiconductors (SiC and GaN), which are suitable for high power density, voltage, current, and temperature applications. These devices form the basis for potentially revolutionary applications and new topologies for PV, storage and other energy applications over all power and voltage scales. Sandia capabilities that support this core competency include:

- Extensive experience in Si/SiC/GaN device fabrication and performance/reliability for renewable generation, energy storage and other applications. Sandia's Microsystems Engineering and Sciences Applications (MESA) facility embodies a deep expertise in Si and compound semiconductor fabrication, complemented by expertise in materials and device characterization and reliability. In addition, Sandia has a well-established capability in epitaxial growth of GaN by MOCVD.
- Power electronics system design and prototyping – Sandia has unique in-house capabilities to design and prototype converters and inverters, including low-level and grid-related controls.
- The Control & Optimization of Networked Energy Technologies (CONET) Laboratory, a capability for research, development, & testing of coordinating networked & distributed systems for several different operational objectives (see Complementary Capabilities below).

PROJECTED GOALS FOR 2030

- Shepherd the rapid adoption of next-generation power electronics based on ultra-wide bandgap technology to drastically improve performance, reliability, longevity and safety of PV power electronics converters.
- Populate a PV power electronics technology pipeline by taking new topologies and control approaches through the proof-of-concept stage for applications that include medium-voltage converters, grid-forming inverters, and micro-converters.
- Develop break-through power electronics solutions from concept stage and low-TRL level to commercially-ready devices.

SOFT COST CAPABILITIES

SOLAR AND REAL ESTATE VALUATION MARKET ACCEPTANCE

The most accurate empirical evidence that solar adds value to real estate was released in 2017, originating from 6 years of research led by Sandia in developing methods, tools and training materials for valuing solar in a real estate transaction. This research was needed due to estimates of value that were too generalized and not market-specific. This led to a high degree of error due to the challenges of separating the market value of solar using a paired sales approach with low market penetration levels. Sandia developed his capability by leveraging core capabilities in performance modeling as well as data and system analytics techniques developed in-house to support the industry leading PV Value tool. Collaborating with Energy Sense Finance, Sandia is applying data analytic techniques to their new dataset. This provides the industry another benchmark for evaluating solar beyond cost and savings value as "market value" is a new selling point (backed up with empirical evidence) that installers can use to convince customers of the benefits of solar.

PROJECTED GOALS FOR 2030

- By 2030, large amounts of data will be collected from all markets where solar has been installed. This larger dataset will reveal in even greater detail the market differences that impact how solar is valued in a real estate transaction. Solar adoption rates will increase nationally when more local evidence is provided.
- New technologies, aesthetics, and utility incentives/rate changes will continue to impact the multiple value streams offered by solar. Funding of this research as a capability will provide benchmarks on how the market is reacting to solar, which provides a longer view than installed costs and savings 'estimates' over time. Market value recognition can offset potential savings value erosion as incentives decrease.

CONCENTRATING SOLAR POWER CAPABILITIES

NATIONAL SOLAR THERMAL TEST FACILITY (NSTTF)

CURRENT STATE OF THE ART MEASURED CAPABILITY

- Solar Tower: Only research facility of its kind in the US. The tower is a 61 m (200 ft) high concrete structure with three test locations on the north side and the top of the tower. Capabilities include a high speed wind tunnel, 100 ton elevating module, internal cranes, and heat flux characterization equipment.
- Solar Furnace: A high heat flux test bed with 16 kW_t power input and peak heat flux of 6,000 kW/m^2. It is used to investigate thermophysical properties of materials in concentrated sunlight, conduct high-temperature solar thermochemical water- spitting and hydrogen experiments, and determine the performance and failure thresholds of high-temperature ceramic and refractory materials.
- Solar Simulator: It provides electrically produced high flux (up to 1,200 kW/m2) conditions for the accelerated testing of materials under high-temperature/high-flux conditions using four metal-halide lamps and reflectors. It has a spot size of 2.54 cm. and included a programmable, robotic sample holder for multi-sample testing, 24 hours per day, 7 days per week.
- Other Capabilities: The NSTTF houses a large Molten Salt Test Loop (MSTL) for nitrate salt component development, Engine Test Facility for heat engine design and testing, Rotating Platform for direct tracking of collectors, and the High-Consequences Test Facility for unattended, long-term materials testing.

PROJECTED GOALS FOR 2030

- Upgrades to the Solar Tower will provide enhanced abilities to test 6 MW_t power systems by providing adequate electrical power and cooling capacity.
- Upgrades to the Solar Furnace include a world class high speed video imagery setup to capture unique heating events. In addition, the ability to control the power input to the experiments will be upgraded providing cycling capabilities for testing.
- Updates to the infrastructure for the Solar Tower, Heliostat Field, Solar Furnace, and Engine Test Facility will provide a modernized test bed for experiments.
- Capital equipment upgrades to continue supporting CSP testing in the future.

APPENDIX: SANDIA'S SUPPORTING SOLAR CAPABILITIES

BATTERY ABUSE TESTING LABORATORY (BATLAB)

- The BATLab provides comprehensive abuse testing platforms for safety and reliability of cells, batteries and systems from mWh to kWh. It includes cell, module, and battery system hardware deliverables for testing. Testing areas include mechanical abuse (e.g., penetration, crush, impact, immersion), thermal abuse (e.g., over temperature, flammability measurements, thermal propagation, calorimetry), and electrical abuse (e.g., overvoltage/overcharge, short circuit, over discharge, /voltage reversal). BATLab's R&D programs focus on:
- Understanding the mechanisms that lead to energy storage system safety and reliability incidents
- Developing new materials to improve overall energy storage system safety and abuse tolerance
- Performing abuse testing
- Advancing testing techniques
- Performing detailed failure analyses
- Developing strategies to mitigate energy storage cell and system failures
- BATLab is also home to one of the world's largest battery calorimetry laboratories, which uses a variety of calorimetry techniques to characterize energy storage systems. Activities include evaluating materials and strategies to minimize the severity of runaway reactions (Li-ion); analyzing the degradation products, mechanisms, and potential hazards associated with batteries; and modeling, designing, and testing the performance of a battery's thermal management system. Equipment includes six accelerating rate calorimeters (ARCs) for materials and cell-level measurements such as:
- Gas volume measurements for decomposition gas products
- Quantitative gas analysis capabilities from ARC samples
- Performing measurements on 1–150 Ah cells
- The facility also includes two isothermal battery calorimeters, a modulated differential scanning calorimeter, microcalorimetry for materials analysis, and cell prototyping equipment.

CONTROL AND OPTIMIZATION OF NETWORKED ENERGY TECHNOLOGIES LABORATORY

- The Control & Optimization of Networked Energy Technologies (CONET) Laboratory, a capability developed with DOE/OE support, conducts research, development, & testing of coordinating networked & distributed systems for several different operational objectives. CONET focuses efforts in five basic areas, all of which are cross-cut by cybersecurity:
- Coordinated Communications: The CONET Lab has the ability to characterize & imitate multiple networks with devices which can emulate latencies, data drop outs, & data quality issues, to determine the network effects on control systems, & other decision making tools. The CONET Lab can emulate, test, & analyze PMUs streamed data from locations across the western & central U.S.
- Controls for Distributed Systems: The CONET Lab has developed multiple control system prototypes & algorithms, & has utilized PMUs for real-time control to improve grid efficiency, stability, & resiliency by controlling energy storage, wind turbines, PV systems, & high voltage DC
- Optimal Dispatch: The CONET lab plays a critical role in performing demonstrations of several optimization capabilities including stochastic optimization for real-time dispatch of multiple different generation resources; optimization of operational changes to improve resiliency to geomagnetic disturbances or severe storms; & optimization of energy scheduling & dynamic balancing reserve capabilities to increase renewable penetration.

- Protection & Reconfiguration: The CONET Lab plays a valuable role in studying, modeling, developing & testing advanced communication-assisted protection schemes. Elements of a self-healing grid can be tested by advanced algorithms to determine optimal restoration plans.
- Prognostics & Decision Support: The CONET Lab is focused on the need to distill meaningful data from the massive influx especially the ability to harness the data to support real-time decision making, automated actions, & improve operational efficiency, reliability, or infrastructure planning. The processed data can increase system observability, visibility into grid behavior, & situational awareness through state estimation tools, machine learning algorithms, & prediction techniques that are resilient to missing measurements & outliers.

EMULYTICS AND THREAT ANALYSIS LABORATORY

The Emulytics & Threat Analysis Laboratory (ETAL) capability maintained mostly by non-DOE Federal agencies, conducts detailed vulnerability assessments of cyber- physical systems & components such as DER devices, PLCs, PMUs, smart meters, protection systems, building energy management systems, SCADA, network components, etc.

ENERGY STORAGE TEST PAD AND ANALYSIS LABORATORY

The Energy Storage Test Pad (ESTP) is a capability maintained by the DOE/OE Energy Storage Program that accommodates full-scale tractor-trailer-size energy storage systems for characterization & evaluation before fi implementation. Testing conducted at the ESTO are used to better understand, model, & predict the physical performance of integrated energy storage systems, while also offering the ability to assess control algorithms & conduct development tests. ESTP capabilities include:

- Megawatt-size storage & power electronics systems in grid-tied or stand-alone configurations are connected to resistive & capacitive load banks & can be taken through a wide range of operational states.
- Remote-control & data- logging systems facilitate multiple analyses.
- Full integration with DETL and X-Net infrastructure.
- 1 MWh, 250 kW flow battery fully operational as of September 2017.

SCALED WIND FARM TECHNOLOGY FACILITY

The Scaled Wind Farm Technology (SWiFT) Facility focuses on enabling rapid, cost-efficient testing & development of transformative wind energy technology. SWiFT operates with the goals of a) reducing turbine-turbine interaction & wind plant underperformance, b) developing advanced wind turbine rotors, & c) generating & utilizing open-source information to advance simulation capabilities. The facility consists of three variable-speed, variable-pitch modified wind turbines with full power conversion & an extensive sensor suite; two heavily instrumented inflow anemometer towers; & site-wide time-synchronized data collection. SWiFT hosts a control building that handles all central control & operations of the facility (including proprietary work). The following provides additional detail on the control software for the facility’s wind turbines:

- Open Source Code
- Modularized by Subsystem
- EtherCAT up to 1000 Hz
- All DAQ signals available for control
- Running on NI Veristand
- Parameterized Variable Speed & Torque Controller
- Maintains all original safety systems & alarms

SECURE SCALABLE MICROGRID TESTBED

The Secure Scalable Microgrid Testbed (SSMTB) is a microgrid research, development, & testing platform with advanced closed-loop controls, agent-based architecture, & highly integrated communication. This capability was developed with LDRD funding and currently supports DOD research and development focused on power electronics conversion, controls and microgrids

SSM consists of three custom DC microgrids along with some AC component capabilities. These microgrids can be operated individually, merged into one larger microgrid, or organized as a network of microgrids. The platform supports R&D on intelligent (e.g., adaptive, self- healing, & self-organizing) grid control applied to very high penetration of renewables, DER, & microgrids dominated by power electronics systems. SSM can be configured to study AC & DC microgrid architectures with high penetration of variable renewable generation & storage, & contains several scaled power source emulators that model the dynamics of diesel generators, wind turbines, & even hydrokinetic emulators. Examples of testing include application of advanced control concepts for high penetration of renewables, & validation of control schemes for electric ship microgrids.