What is This?

In the SETO 2020 Peer Review poster session, you will be required to use a template inspired by #betterscienceposter. We understand that this may be a poster format with which you are not familiar and thus, in addition to the instructions, we thought some visual examples may be useful. We have converted several posters from the 2017 Peer Review to the new template for you to peruse.

The posters come in sets of two. The first is what was submitted to the 2017 Peer Review, the second is that same posters information presented in the 2020 Peer Review poster format.

Example 1

Two-dimensional material based layer transfer (2DLT) for low-cost, high-throughput, high-efficiency solar cells

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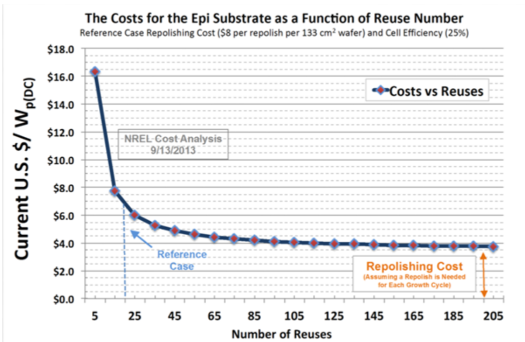
PVRD2 Small Innovative Projects in Solar (SIPS)
08151

TECHNOLOGY TO MARKET

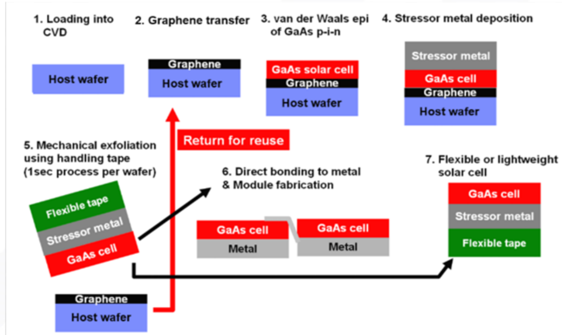
PROBLEM STATEMENT

Although solar cells made from III-V semiconductors have shown the highest efficiency in any single- or multi-junction forms, the cost of large-area GaAs substrates, which are necessary to grow high efficiency III-V solar cells, is extremely high (at least > 100X compared to a Si wafer). The cost reduction of existing lift-off process is limited by the release speed, material loss and cost due to CMP process The process of reusing GaAs substrates with improved speed and without CMP step is needed.



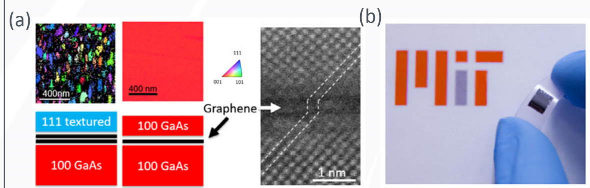
PROJECT OVERVIEW & VALUE PROPOSITION

This project aims to solve the challenges of existing lift-off process and drastically reduce the cost of III-V solar cells, by using two-dimensional material based layer transfer (2DLT). Ultimately, the developed process will produce high efficiency GaAs-based thin film solar cells with infinitely reusable substrates without CMP process. GaAs thin film solar cells can be reduced beyond $4/W. Dramatic cost reduction of high efficiency III-V cells is expected, a crucial step towards SunShot's $0.02-0.03/kWh 2030 LCOE goal with III-V photovoltaics.



TECHNOLOGY OVERVIEW

The team discovered that monolayer graphene is transparent to remote atomic interactions of substrates and epilayers. Therefore, GaAs thin film solar cells can be synthesized on monolayer graphene coated GaAs substrates with the film quality on par to homoepitaxial GaAs solar cells. The thin film GaAs cells will be mechanically exfoliated from the substrate using metal stressor, and subsequently bonded to a low cost foreign substrate. Due to the accurately release interface defined by the graphene layer, the released surfaces of substrate and epilayer will be atomically flat, allowing the regrowth on GaAs substrate with minimal surface preparations and material loss. Infinite substrate reusing is possible.



PROJECT OBJECTIVE & MILESTONES

This project aims to achieve five objectives:

1.Planar epitaxial growth of GaAs on a graphene/GaAs substrate
(Q1) r.m.s < 5 nm, (Q3) r.m.s. < 1 nm

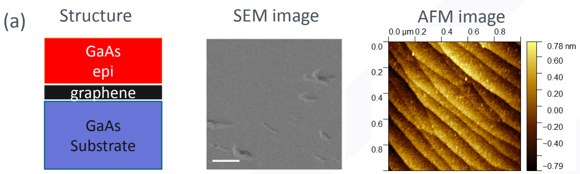
2.Obtain high-quality GaAs epitaxial films on graphene
(Q2) Dislocation density < 1e6 cm^{-2}, (Q3) Dislocation density < 1e4 cm^{-2}

3.Mechanical release of GaAs on graphene
(Q1) 10% simulation accuracy, (Q3) > 70% yield, (Q4) > 99.5% yield

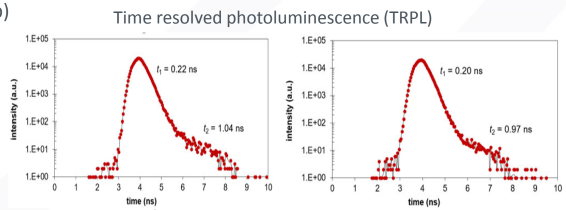
4.Obtain E>20% baseline GaAs single-junction solar cells
(Q1) E > 10% on GaAs, (Q2) E > 10% on foreign substrate
(Q3) E > 20% on GaAs, (Q4) E > 20% on foreign substrate

5.Maximize reusability of the graphene/GaAs substrate
(Q2) > 5 times, (Q4) > 20 times

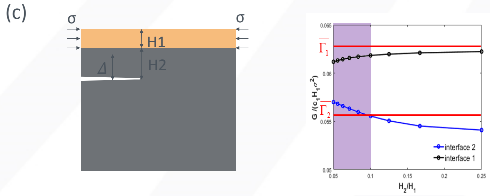
RESULTS



RMS = 0.3 nm



On GaAs wafer τ = 1 ns   On graphene τ = 1 ns



Since the beginning of the project, we already obtained the specular epitaxial surface of GaAs grown on monolayer graphene coated GaAs substrate through remote epitaxy., which is the goal of planar epitaxy growth of GaAs in Q3. We also achieved carrier lifetime of 1 ns from GaAs through remote epitaxy, identical to the value from GaAs substrate, which is a good indication of pristine material quality of the epilayer on graphene. In addition, by modeling the mechanical properties of nickel stressor/graphene/GaAs structure, we are able to predict the stressor conditions needed to exfoliate the remote epitaxial GaAs epilayer. The predictions matches reasonably with the experimental results.

INDUSTRY IMPACT

The process development industrial production oriented and compatible to existing industrial high volume process, utilizing metalorganic chemical vapor deposition (MOCVD) and direct current (DC) sputtering. LG electronics is partnered with our team to obtain World record efficiency of flexible GaAs solar cells. Once the proposed development is achieved, the process can be rapidly adapted into the industrial production. We will commercialize the low-cost thin film GaAs solar cells with LG electronics.

PROJECT NAME: 2D material based layer transfer (2DLT) for low-cost, high-throughput, high-efficiency solar cells

Last 5 digits of project number: 08151
Principal Investigator (PI): Jeehwan Kim
PI Email: jeehwan@mit.edu

BACKGROUND / INDUSTRY IMPACT

- III-V semiconductors have shown the highest efficiency solar cells, but large area GaAs substrates are extremely expensive.
- A process for reusing GaAs substrates with improved speed and without CMP step is needed.

PROJECT OVERVIEW / OBJECTIVES

- Drastically improve current lift-off process and thus reduce III-V solar cell cost by using 2D material based layer transfer

METHODS

- Monolayer graphene is transparent to remote atomic interactions of substrates and epilayers
- GaAs thin film solar cells can be synthesized on monolayer graphene coated GaAs substrates with the film quality on par to homoepitaxial GaAs solar cells
- Thin film GaAs cells will be mechanically exfoliated from the substrate using metal stressor

KEY OUTCOMES / MILESTONES

- Specular epitaxial surface of GaAs grown on monolayer graphene coated GaAs substrate through remote epitaxy. The r.m.s. roughness of the surface is 0.3 nm
- carrier lifetime of 1 ns from GaAs through remote epitaxy, identical to the value from GaAs substrate
- modeling the mechanical properties of nickel stressor/graphene/GaAs structure, we are able to predict the stressor conditions needed to exfoliate the remote epitaxial GaAs epilayer

CONCLUSION / REMAINING RISK

- Still need to produce a baseline GaAs single-junction solar cells with PCE>20%
- Still need to show this is possible with large area devices.

PHOTOVOLTAICS TRACK (Topic name goes here *ex. New Cell and Module Structures/Designs/Processes Topic*)

Growth and **mechanical exfoliation** of high quality **single crystal GaAs** thin films is possible using a **graphene** protecting interlayer on a **GaAs wafer**

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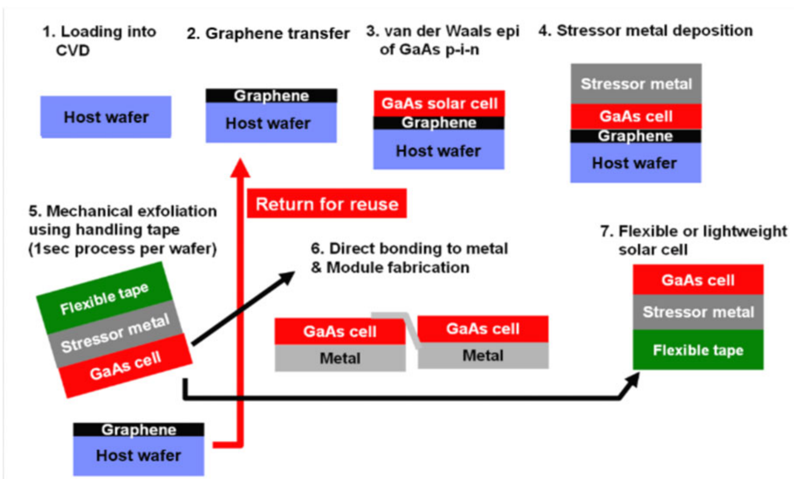
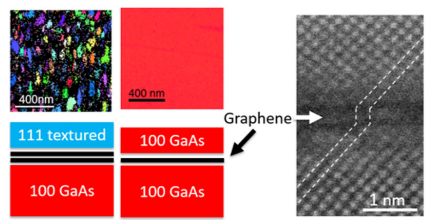
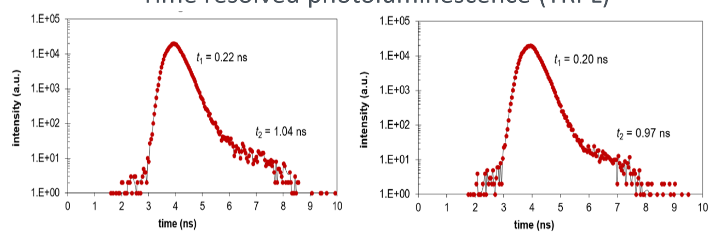




Time resolved photoluminescence (TRPL)



On GaAs wafer τ = 1 ns   On graphene τ = 1 ns

Additional project contributors:

Example 2

Addressing Soiling: From Interface Chemistry to Practicality

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PHOTOVOLTAICS

PROBLEM STATEMENT

Soiling has reduced the energy output of PV systems since the inception of the industry. As discussed in NREL's comprehensive review of PV soiling, (Sarver et. al., Renewable and Sustainable Energy Reviews, 2013, vol. 22, issue C, pages 698-733) while the issues have been discussed in the literature for more than 70 years, "the fundamental properties of dust and its effect on energy transfer are still not fully understood, nor is there a clear solution to the problem. Soiling on modules has huge technical challenges: (1) starting from not understanding the fundamental underpinnings and processes that lead to dust and other contaminants initially sticking to the glass surfaces and ultimately becoming more adhered over time, (2) not being able to accurately predict soiling losses for a given site, and (3) not understanding the impact soiling and cleaning methods have on value-added coatings. Our approach to address these technical challenges is to perform the scientific investigations needed to understand the chemical and mechanical processes involved and to experimentally demonstrate successful mitigation strategies.

VALUE PROPOSITION

Recent evaluations of large PV installations found that soiling rates within the U.S. range from 0.1% to 0.3% per day, with an annual average loss of ~4% for many representative regions. Furthermore, the more insolation rich regions in the U.S./world can have higher soiling rates and may need to be cleaned even daily. Even a 4% loss in energy collection results in gigawatts of lost power (billion in lost revenue) in the U.S. today, and thus may increase LCOE by approximately ¢0.3/kWh. The push to site PV in high-insulation but dusty regions in the U.S. and throughout the world has never been greater and will increase as energy demand grows. Thus, there is a huge market driven pull to have true synergistic efforts that address the main soiling problems now. Soiling being a top priority is demonstrated by the partners that are committed to this project and the ~200 participants worldwide on the soiling PV Quality Assurance Task (PVQAT) for soiling.

PROJECT OVERVIEW

NREL's team has taken a proactive approach to mitigate the inherently high risks of this project. For example, to develop accurate predictive soiling models, we use an approach that has been very successful in identifying critical PV plant performance criteria before and combine this with the high-quality data from over 200 locations from partners like First Solar and SunPower to determine annualized soiling losses. This avoids the complexity of previous less successful attempts that tried to understand specific soiling events, while providing a loss metric that is the most useful for 30 year predictions. In the case of tool development for value-add coatings, the industry indicated priorities are: 1) deployment guidelines that are specific to the location and specific interface chemistries involved, and 2) international long-term durability standards. NREL has expertise with soiling surface chemistry and can establish guidelines for location specific interface property selection due to the synergy with the predictive modeling effort that will provide information on which variables distinguish one location from another. Overall, this project has a technical plan that is industry directed, and focused on impacting LCOE.

TECHNOLOGY OVERVIEW

Partners: Colorado School of Mines, Arizona State University, First Solar, Sun Power, EDF, Enki Technology, 3M, Dubai Electricity and Water Authority (DEWA), DSM, IIT Bombay, ARL Designs LLC, Sun Edison, KAUST, and KACARE.

Predict Soiling Rates
- PV performance data, >200 sites
- Data mine important soiling parameters
- Develop robust predictive models
- Validate models

Evaluate Durability with Soiling
- Deploy samples in field
- Analyze field specimens
- Develop accelerated tests
- Correlate results
- Develop IEC standards with international community

Characterize Soiling Mechanisms
- Deploy specimens at sites
- Collect representative samples
- Characterize soiling materials
- Isolate individual mechanisms
- Characterize surfaces
- Identify complex mechanisms

Outcomes

Reduce Performance Uncertainty
- Predict seasonal, annual and 30 year soiling loss rates for new sites
- Help establish cleaning schedules and O&M costs

Module Coating Standards
- Accelerated tests for validating durability and performance of PV coatings in different soiling conditions

Coating Deployment Guidelines
- Critical requirements for coating performance in different environments
- Help establish cleaning schedules
- Enables techno-economic analysis

Lower LCOE
- Financial institutions reduce rates for borrowing
- Integrators reduce cleaning costs
- Coatings companies have standards to meet
- Companies can focus on developing coatings with the right properties for the environments that make economic sense

PROJECT OBJECTIVE

This project is reducing LCOE in relation to PV module soiling losses, by developing predictive methods for (1) determining soiling losses at new sites; (2) accelerated tests to approve cleaning methods, antireflection (ARC) coatings, anti-soiling coatings, and other mitigation strategies; and (3) an understanding of the chemistry/other mechanisms that drive soiling on module surfaces. The end goal is to provide U.S. PV manufacturers like First Solar and SunPower, integrators like EDF, and coating manufacturers like 3M and ARL Designs with a better understanding of soiling and how to make choices for the coatings, maintenance, and cleaning related to soiling.

MILESTONES

The overall project objectives are to develop predictive models and tools/knowledge for value added coatings that ultimately will reduce performance uncertainty, leading to lower finance rates and thus lower LCOE. These milestones are:

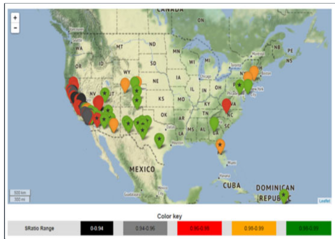
Phase 1 Milestone: The quantified relevant predictive criteria for determining annualized soiling loss are established by multi-variate analysis against all independent variables under consideration, with R2>0.7 and p<0.05 for each independent variable. Publish a Pareto chart that establishes priority variables to determine annualized site-specific soiling losses. The Pareto chart includes methods and sources that were used to quantify the site-specific variables.

Phase 2 Milestone: (1) Make publically available, a soiling rate map that includes the results of the data sets evaluated for ≥ 50 sites and covering climatically diverse and PV relevant regions of the U.S. (2) 2-4 complex soiling mechanisms that have a large impact on PV module performance or system cost and/or with adhesion strengths substantially above typical physisorption (e.g., ≥0.01 μN) for specified environmental conditions were documented through systematic analysis of environmentally controlled model surfaces. At least two publications submitted to peer-reviewed journals.

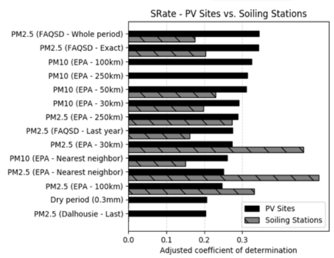
Phase 3 Milestone: A predictive soiling model will be established that has RMSE statistics less than 25% (relative) for all the sites in the validation data set. A publication in a peer-reviewed journal with PV module soiling mechanisms related with site-specific environmental conditions and soiling losses will provide the industry with the guidance (including cleaning or mitigation strategies) needed to make good techno-economic decisions about mitigation strategies. New work item proposal will be submitted to IEC that includes a draft document for abrasion testing on module surfaces.

The project has and continues to meet all progress indicators and phased milestones on time.

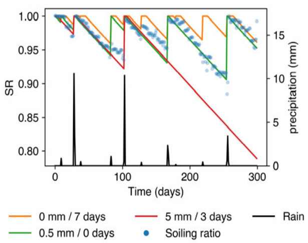
RESULTS



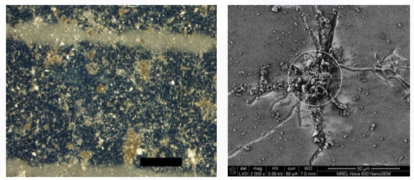
Soiling ratio map for the U.S. using soiling stations and PV production data analysis. in the future, additional vetted results can be added to the map by the general community using these and potentially other methods.



Comparing the results from the PV systems with those obtained for 43 soiling stations. Correlating environmental parameters to deduce soiling losses at PV and new sites is challenging due to a number of factors including non-uniform soiling across a PV site, different transportation mechanisms, soiling stations consider Isc, PV power plants consider Pmp or Imp, which are more subject to soiling and to non-uniform soiling, and soiling stations are all ground mounted, installed mainly in rural areas. Many PV sites are commercial rooftop systems

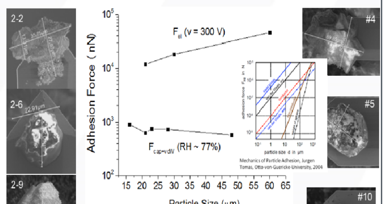


Soiling Ratio (IWSR = 0:970) and the result of the FRP method under three different input combinations: 0 mm cleaning threshold and 7 day refractory period (IWSR = 0:989), 5 mm cleaning threshold and 3 day refractory period (IWSR = 0:925). Devised and validated a method for estimating soiling loss directly from system yield without the need for precipitation data. This stochastic rate and recovery (SRR) method, automatically detects soiling intervals that can be used for fleet-scale assessment of soiling loss to facilitate mitigation planning and risk assessment.



Field samples from around the U.S. and world have found biological on PV modules and glass coupons that are heated with sunlight. This is somewhat surprising because the PV module surfaces often reach temperatures over 60 Celsius. The main species identified so far is clearly capable of adhering to glass and is a member of the *Alternaria* genus. The most likely route of contamination is from airborne spores. More research is needed on low-cost, environmentally sustainable, and gentle cleansers or cleaning methods for PV glass.

To better understand and quantify soiling rates on solar panels, we are investigating the adhesion mechanisms between dust particles and solar glass. In addition to quantifying the adhesion of van der Waals (vdW) and capillary adhesion forces, we have identified two novel issues. Contrary to predictions, real dust particles do not appear to have increased adhesion from vdW or capillary adhesion with increased particle size. This is primarily due to the roughness of the dust particles limiting the contact/interaction area of these short range forces for any given dust particle. Second, the attraction and adhesion force, due to high voltage (e.g. 1000 V) often used by PV utilities, are one to two orders of magnitude higher than vdW/capillary forces, can exist for hours after the sun sets, and may create non-uniform soiling/degradation.



For real dust particles with surface contact areas much smaller than and not correlated with particle diameter, vdW and capillary adhesion does not increase proportionally as particle size increases.

INDUSTRY IMPACT

To have maximum impact on the soiling problem, this project has fully engaged U.S. PV and coating manufacturers to address what they have identified as the most important problems including, for the first time, models that accurately predict annualized soiling losses at new PV plant sites and providing the PV industry with the necessary tools/knowledge for successful long-term deployment of modules with value-added coatings (e.g., antireflection or anti-soiling coatings). The need to bring multiple industrial groups together to perform the highly innovative cross-cutting work of the project can only be done with NREL as the lead to collect and analyze proprietary information and materials and to be able to develop and disseminate the tools that will be useful throughout the PV industry.

The results from this project are primarily focused on developing a scientific basis to help the community improve soiling mitigation strategies and thus lower uncertainty, O&M costs, and LCOE. For example, one outcome is a publically available interactive map that enables PV plant designers to easily obtain relevant soiling loss for their site. Other outcomes will help PV manufactures qualify their modules for harsh soiling environments and help coating manufacturers to develop materials that actually decrease soiling losses. Examples of our dissemination efforts are listed below.

Recent, significant publications:

- Accepted Journal of Photovoltaics, B.M. Deceglie, L. Micheli, M. Muller, "Quantifying Soiling Loss Directly from PV Yield." Paper detailing the process and success in accurately determining soiling rates from PV production data.
- Submitted to Solar Energy Materials and Solar Cells, Sarah Toth, Matthew Muller, David C. Miller, Lin J. Simpson, Helio Moutinho, Bobby To, Leonardo Micheli, "PV Soiling and Abrasion: Initial Observations from 5-Year Photovoltaic Module Glass Coating Study." Initial study results from field tests highlighting the impacts of biological soiling on PV modules from the U.S. and around the world.
- Solar Energy Materials and Solar Cells, H.R. Moutinho, C.-S. Jiang, B. To, C. Perkins, M. Muller, M.M. Al-Jassim, and L. Simpson, "Adhesion Mechanisms on Solar Glass - Effects of Relative Humidity, Roughness, and Particle Shape and Size." Uniquely quantified the adhesion of dust particles due to van der Waals and capillary forces on PV glass surfaces as a function of surface roughness and humidity.
- Progress in Photovoltaics: Res. Appl. (2017)DOI: 10.1002/pip.2860. C.Leonardo Micheli, Matthew Muller, "An Investigation of the Key Parameters for Predicting PV Soiling Losses." Provides details of the different environmental parameters that can be used to accurately predict soiling losses of PV modules.
- To be submitted, Journal of Photovoltaics. D.C.-S. Jiang, H.R. Moutinho, B. To, C. Xiao, C. Perkings, M. Muller, M. M. Al-Jassim, and L. J. Simpson, "Strong Electric Field Attraction and Adhesion Forces of Dust Particles on Photovoltaic Modules." Landmark paper quantifying the impact of high voltage PV modules on the attraction and adhesion of dust particles.
- NREL has made the code used to pull soiling loss rates from PV production data (Software Code: PV Soiling Detection - NREL Software Record SWR-18-02) "open source."

PROJECT NAME: Addressing Soiling: From Interface Chemistry to Practicality
Last 5 digits of project number: 30311
Principal Investigator (PI): Lin Simpson
PI Email: lin.simpson@nrel.gov

PHOTOVOLTAICS TRACK (Topic name goes here *ex. New Cell and Module Structures/Designs/Processes Topic*)

Reveal fundamental **mechanisms of soiling** processes that reduce PV energy output and create **predictive tools and maps** to minimize losses

BACKGROUND / INDUSTRY IMPACT

- Soiling is known to reduce the energy output of PV systems
- In order to mitigate this, more understanding is needed on the how dust and contaminants stick to the glass, how to predict the losses from soiling, and how soiling and subsequent cleaning affect value-added coatings

PROJECT OVERVIEW / OBJECTIVES

- Develop methods to predict soiling losses
- Create accelerated tests to approve mitigation strategies like cleaning methods, antireflection (ARC) coatings, and anti-soiling coatings
- Understand the mechanism driving soil sticking to module surfaces

METHODS

- Quantify predictive criteria for soiling loss by multi-variate analysis against each independent variable
- Correlate soiling data with geographic are
- Investigate adhesion mechanisms between dust and glass such as van der Waals, capillary adhesion, and roughness and voltage driven adhesion

KEY OUTCOMES / MILESTONES

- Published a soiling rate map evaluating data for > 50 climatically diverse and PV relevant US regions
- Identified 2-4 complex soiling mechanism that have highest impact on performance an cost
- Model which industry groups can use to accurate predict soiling losses at new sites and deploy appropriate coatings
- Identified biological contaminants even at high temperatures

CONCLUSION / REMAINING RISK

- Provides PV and coating manufacturers with tools to mitigate soiling losses and deploy modules with effective value-added coatings
- Lower uncertainty, O&M costs, and LCOE

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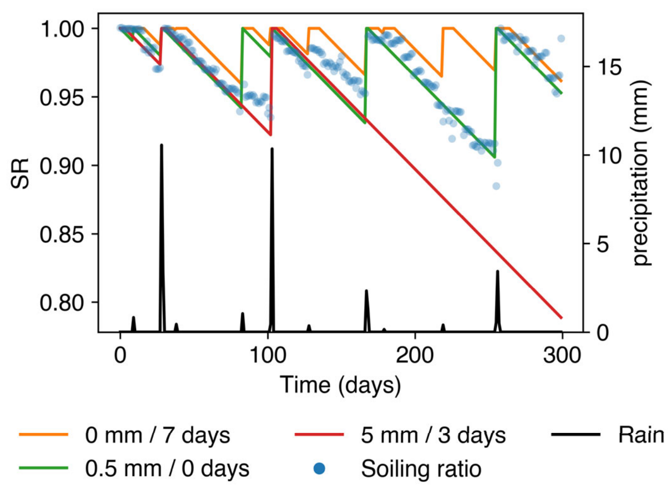

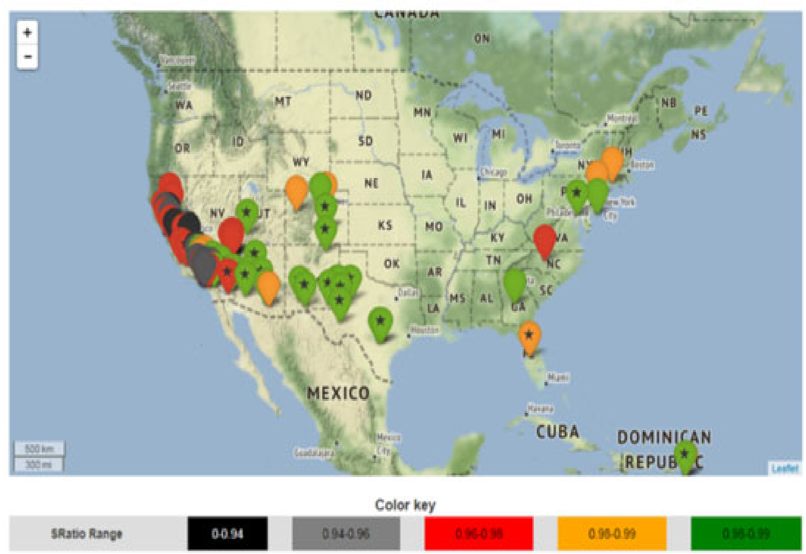

Additional project contributors: Colorado School of Mines, Arizona State University, First Solar, Sun Power, EDF, Enki Technology, 3M, Dubai Electricity and Water Authority (DEWA), DSM, IIT Bombay, ARL Designs LLC, Sun Edison, KAUST, and KACARE.

Example 3

15%-efficiency (Mg,Zn)CdTe solar cells with 1.7 eV bandgap for tandem applications

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Arizona State University
DE-FOA-0001387
07552

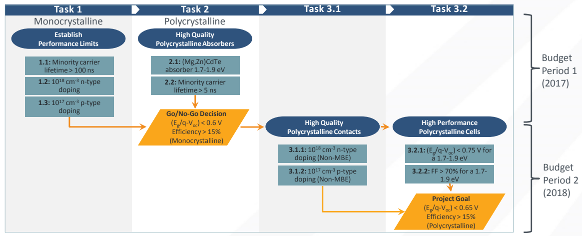
PROBLEM STATEMENT

- With a record efficiency of 26.7 % and efficiencies over 25 % achieved in high-scale manufacturing environment, Si-based photovoltaic solar cells are approaching their theoretical efficiency limit (29.4 %)

→ Limited room for further improvement

- Multijunction tandem devices offer a pathway to higher efficiencies: >30% achievable with dual-junction solar cells
- However, in order to keep the low cost associated with the use of c-Si wafers, **inexpensive materials with the required 1.7 eV bandgap for current-matching with a c-Si bottom subcell need to be developed**

PROJECT OVERVIEW



PROJECT OBJECTIVES

1. Establish the performance limits of 1.7 eV II-VI alloys using MBE-grown monocrystalline materials

→ 1.7 eV monocrystalline II-VI devices with η>15 % and (E_g/q-V_{oc})<0.6 V

2. Develop high material quality 1.7 eV polycrystalline II-VI absorbers

→ Lifetime > 5 ns

3. Develop electron and hole contacts for these absorbers, leading to the achievement high efficiency 1.7 eV polycrystalline II-VI solar cells

Project Goal:
1.7 eV polycrystalline II-VI devices with η>15 % and (E_g/q-V_{oc})<0.65 V

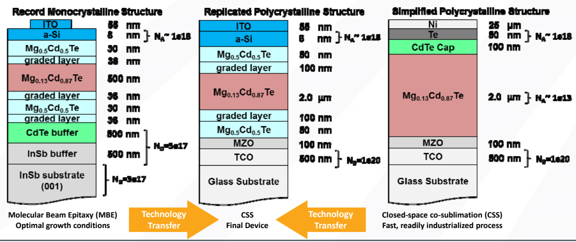
VALUE PROPOSITION

- c-Si and polycrystalline CdTe are the two most mature photovoltaic technologies on the market, both cost-effective and manufactured at the GW-scale
- The bandgap of II-VI alloys such as CdTe can be engineered by adjusting the concentration of the different elements in the compound

→ In particular, CdTe can be alloyed with Zn or Mg in order to obtain a 1.7 eV bandgap material, suitable for a top subcell in a current-matched II-VI/Si tandem architecture

→ **$Cd_{0.60}Zn_{0.40}Te$ and $Cd_{0.87}Mg_{0.13}Te$ are promising candidates**

TECHNOLOGY OVERVIEW

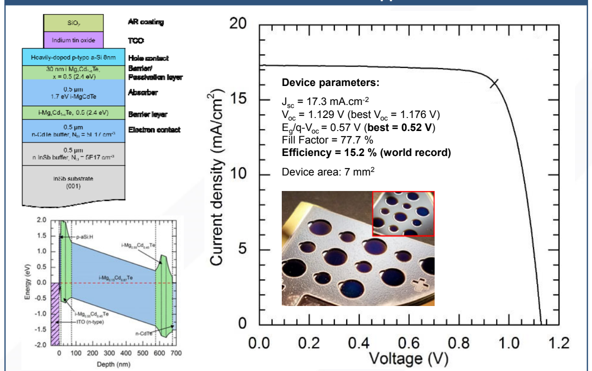


MILESTONES

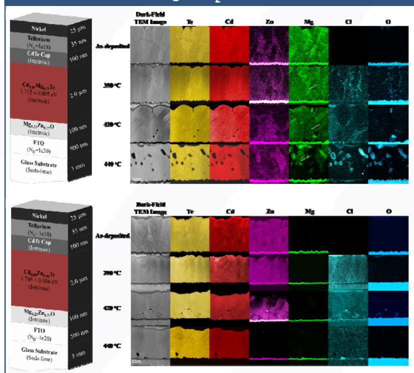
Task 1	Task 2	Task 3.1	Task 3.2
Milestone 1.1: 100 % complete Monocrystalline 1.7 eV CdMgTe with lifetime >120 ns Milestone 1.2: 90 % complete > 10^{18} cm^{-3} n-type doping of mono-CdMgTe (or other high E_g contact material with < 0.4 V conduction band offset) Milestone 1.3: 90 % complete > 10^{17} cm^{-3} p-type doping of mono-CdMgTe (or other high E_g contact material with < 0.4 V valence band offset)	Milestone 2.1: 90 % complete Grow (closed space co-sublimation) polycrystalline CdMgTe and CdZnTe with a bandgap of 1.7-1.9 eV Milestone 2.2: 100 % complete Lifetime > 5 ns for 1.7-1.9 eV polycrystalline CdMgTe and CdZnTe	Milestone 3.1.1: 25 % complete > 10^{18} cm^{-3} n-type doping of polycrystalline Cd(Mg,Zn)Te (or other high E_g contact material with < 0.4 V conduction band offset) Milestone 3.1.2: 25 % complete > 10^{17} cm^{-3} p-type doping of polycrystalline Cd(Mg,Zn)Te (or other high E_g contact material with < 0.4 V valence band offset)	Milestone 3.2.1: 25 % complete 1.7-1.9 eV polycrystalline CdMgTe and/or CdZnTe with (E_g/q-V_{oc}) < 0.75 V Milestone 3.2.2: 75 % complete 1.7-1.9 eV polycrystalline CdMgTe and/or CdZnTe with Fill Factor > 70 %
Go/No-Go decision: 100 % complete **1.7 eV mono-CdMgTe with (E_g/q-V_{oc}) < 0.6 V and efficiency > 15 %**		**Final Milestone: 25 % complete** **1.7 eV poly-Cd(Mg,Zn)Te with (E_g/q-V_{oc}) < 0.65 V and efficiency > 15 %**	

RESULTS

Work on MBE-grown monocrystalline CdMgTe shows no inherent limit to the approach



For poly-Cd(Mg,Zn)Te, Mg and Zn out-diffusion during $CdCl_2$ treatment needs to be addressed



- Mg loss onsets at the grain boundarie
- Bulk loss progresses from the front to the back

→ Non-homogenous Mg content

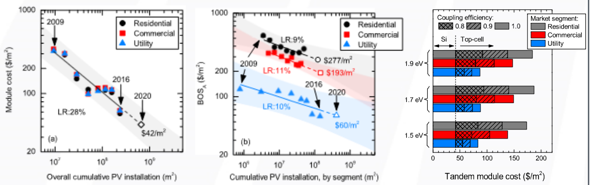
- Significant Mg/Zn interdiffusion at the MZO/CdMgTe interface
- Formation of voids in the absorbers

- Zn loss originates at the back of the device and progresses towards the front
- Bulk loss only, no evident segregation

→ Conservation of one alloy

- No interdiffusion at the MZO/CdZnTe interface
- Formation of voids in the absorbers

INDUSTRY IMPACT



- Cells and modules cost have experienced a faster cost decrease compared with Balance-Of-System (BOS) and overall PV system costs

→ Modules represent a shrinking part of the overall system cost

→ Efficiency, even at a higher cost, is a powerful lever in order to reduce the Levelized Cost of Electricity (LCoE)

→ Very high efficiency approaches, such as tandem modules, can enjoy a sizable price premium, especially for area-restricted applications

- First Solar, the top American PV module manufacturer, is also the leading manufacturer of II-VI (CdTe) photovoltaic products

→ II-VI/Si tandem products would strongly benefit First Solar

PROJECT NAME: 15% Efficiency (Mg,Zn)CdTe solar cells with 1.7 eV bandgap for tandem applications

Last 5 digits of project number: 07552

Principal Investigator (PI): Zachary Holman

PI Email: Zachary.Holman@asu.edu

BACKGROUND / INDUSTRY IMPACT

- Silicon-based photovoltaics have limited room for improvement as they near the 29.4% theoretical limit
- A dual-junction tandem device could achieve >30% efficiency
- To achieve these efficiencies and keep costs low, need to develop an inexpensive material with a 1.7 eV band gap

PROJECT OVERVIEW / OBJECTIVES

- Pursued the promising candidate materials $Cd_{0.60}Zn_{0.40}Te$ and $Cd_{0.87}Mg_{0.13}Te$
- Set goal of polycrystalline material with:
  - 1.7 eV bandgap
  - n > 15%
  - $(E_g/q - V_{oc}) < 0.65$ V

METHODS

- Establish the performance limits of 1.7 eV II-VI alloys of monocrystalline (Mg,Zn)CdTe
- Develop high quality 1.7 eV polycrystalline II-VI absorbers with a >5 ns lifetime
- Develop electron and hole contacts for these absorbers to make high efficiency PV devices

KEY OUTCOMES / MILESTONES

- Work on monocrystalline CdMgTe grown by molecular beam epitaxy shows no inherent limit to this approach – achieved goals in efficiency, lifetime, and $(E_g/q - V_{oc})$
- Polycrystalline materials show progress towards goal values but further work is needed

CONCLUSION / REMAINING RISK

- These materials have been demonstrated as promising tandem materials in single-crystal devices
- In polycrystalline materials, out-diffusion of Mg and Zn during $CdCl_2$ treatment needs to be solved

PHOTOVOLTAICS TRACK (Topic name goes here *ex. New Cell and Module Structures/Designs/Processes Topic*)

Demonstrated the potential of **(Mg,Zn)CdTe** materials to pair with Silicon in **tandem photovoltaic devices** that could reach **>30% efficiency**, exceeding Silicon's theoretical limit

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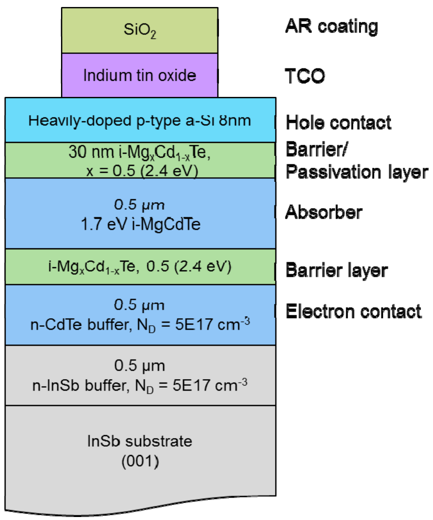
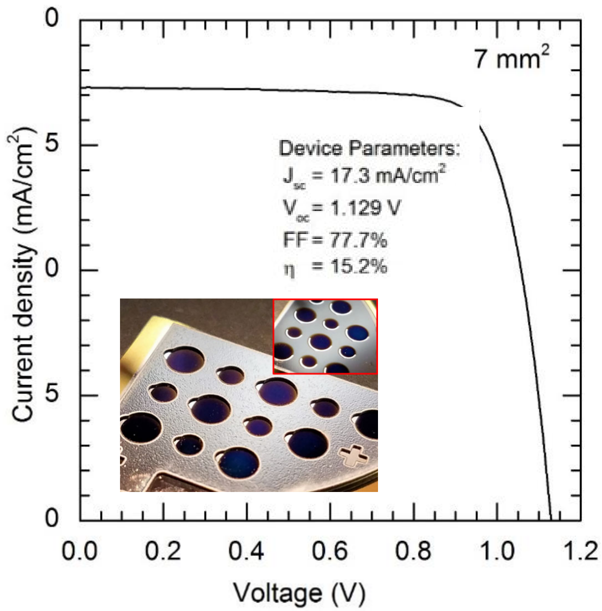
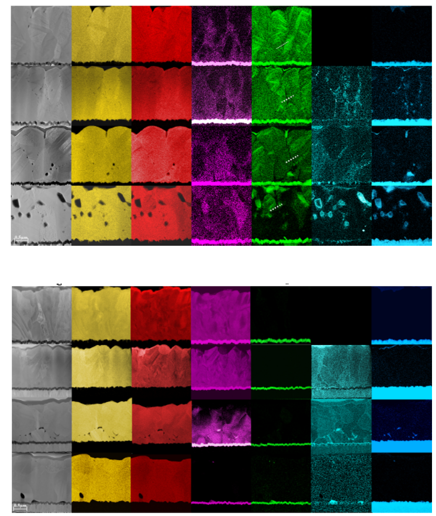






Additional project contributors:

Example 4

Voltage Regulation and Protection Assurance using DER Advanced Grid Functions

Jay Johnson
jjohns2@sandia.gov
Sandia National Laboratories
ENERGISE
32931

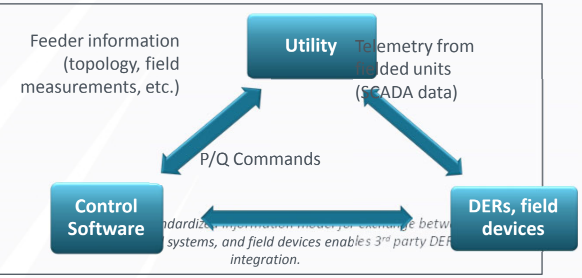
SYSTEMS INTEGRATION

PROJECT OVERVIEW

This project is creating open-source components for a commercial platform to addresses the spectrum of distribution circuit and DER management, including: state estimation, voltage regulation, protection, economic optimization, communications and cybersecurity. This solution will safely allow PV penetrations of 50% or greater by providing real-time visibility into distribution circuits and optimizing the active and reactive power (P/Q) DER settings to meet voltage regulation, protection and economic objectives in the presence of forecast uncertainty.

PROJECT OBJECTIVES

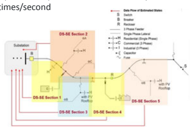
- Provide real-time feeder visibility/visualization
- Operate DERs to keep feeder voltages within ANSI C84.1-2006 limits
- Maintain protection with high penetrations of DER on distribution circuits
- Minimize economic costs using multi-objective optimization
- Create information exchange recommendations
- Generate cyber security recommended practices



TECHNOLOGY OVERVIEW

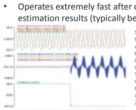
Georgia Tech and Sandia technologies will be released as open-source code or algorithms and incorporated into a commercial software product developed by BPL Global. The core technologies being developed are:

1. Distribution System Distributed Quasi-Dynamic State Estimator
   - Generates the voltage profile and power flow estimation with scalable solution from feeder telemetry
   - Operates on partitioned distribution system with solutions at up to 60 times/second



See: A.P. Meliopoulos, G. Cokkinides, B. Xie, C. Zhong, J. Johnson, "Full State Feedback Control for Virtual Power Plants," Sandia Technical Report, SAND2017-10178, September 2017.

2. Estimation-Based Protection
   - Detects faults and protects the system by isolating the faulted section of circuit
   - Signals reclosers, breakers, or other switching operations
   - Operates extremely fast after collecting state-estimation results (typically below 1 ms)



See: Y. Liu, A. P. S. Meliopoulos, R. Fan, L. Sun and Z. Tan, "Dynamic State Estimation Based Protection on Series Compensated Transmission Lines," in IEEE Transactions on Power Delivery, vol. 32, no. 5, pp. 2199-2209, Oct. 2017.

3. Persistence forecasting
   - Uses historical data and clear sky index to generate PV power forecast
   - 1-15-sec time-step with a 10-min horizon
   - Forecast uncertainty characterized by historical record to be used in the optimization

See: J. Johnson, et al., "Design and Evaluation of a Secure Virtual Power Plant," Sandia Technical Report, SAND2017-10177, September 2017.

4. Robust optimization taking into account forecast uncertainty
   - Construct an uncertainty set Ω for the DER power injections
   - Define DER power injections in terms of u^t

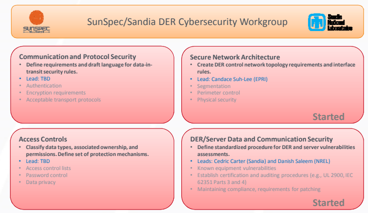
$$\Omega^t(\bar{X}^t, \hat{\sigma}^t, \delta^t) := \left\{ u^t \in \mathbb{R}^I : \sum_{i \in I} \frac{|u_i^t - \bar{X}_i^t|}{\hat{\sigma}_i^t} \le \delta^t, u_i^t \in [\bar{X}_i^t - \hat{\sigma}_i^t, \bar{X}_i^t + \hat{\sigma}_i^t], \forall i \in I \right\}, \Omega := \prod_{t \in T} \Omega^t$$

where I is the set of all DERs with uncertain injections for time intervals in T
u^t: vector of uncertain DER power injections
$\bar{X}_i^t$: nominal value of the DER power injection
$[\bar{X}_i^t - \hat{\sigma}_i^t, \bar{X}_i^t + \hat{\sigma}_i^t]$: range of uncertainty
δ^t: Budget of uncertainty set

See: D. Bertsimas, E. Litvinov, A. Sun, J. Zhao, and T. Zheng, Adaptive Robust Optimization for the Security Constrained Unit Commitment Problem, IEEE Transactions on Power Systems, 28, 1, 52-63, 2013.

DER CYBER SECURITY

- The SunSpec/Sandia DER Cyber Security Working Group was initiated as part of this project and has already gathered hundreds of stakeholders to discuss DER cyber security.
- The workgroup covers security for DER devices, gateways, and other networking equipment, owned or operated by end users, aggregators, utilities, and grid operators.
- **Primary Goal: Generate a collection of best practices that act as basis for a national or international DER cyber security standard.**
- Secondary Goal: facilitate DER cyber security discussions between stakeholders to exchange perspectives and (hopefully) gain broad buy-in from the industry for the recommendations. https://sunspec.org/sunspec-cybersecurity-workgroup/

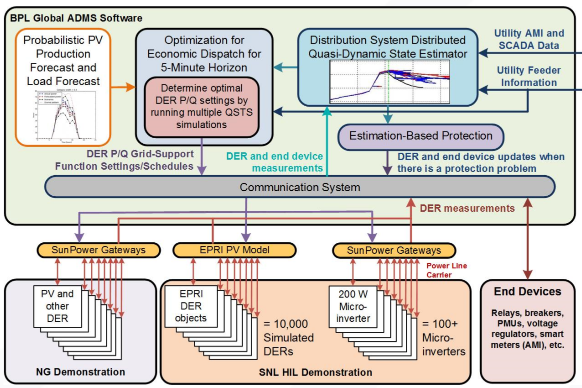


DER Cyber Security Working Group working groups and activities.

SYSTEM ARCHITECTURE AND OPERATIONS

Programmable Distribution Resource Open Management Optimization System (ProDROMOS)

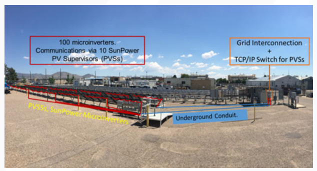
(Prodromos is Greek for "forerunner" and the prodromoi were a light cavalry army unit in ancient Greece used for scouting missions.)



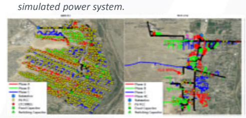
1. Distribution System Distributed Quasi-Dynamic **State Estimator** (DS-DQSE) ingests feeder telemetry, DER and customer data, and generates the voltage profile and power flow estimation.
2. The **Estimation-Based Protection** (EBP) scheme detects faults and protects the system by isolating the faulted section of the distribution circuit by recloser/breaker/switching operations.
3. The **forecasting** component provides short-term (e.g., 10 minute) forecasts of PV power output and load using recent system states and statistical irradiance modeling in conjunction with PV performance models.
4. A **dispatch optimization engine** determines the necessary active and reactive (P/Q) power settings for groups of DERs to maintain voltage and distribution protection systems for the next time period (~1-5 minutes) considering the economic impact of curtailment and non-unity power factor operations.
5. The **communications system** uses the SCADA and DER control network to update DER operations and get new data from the power system.

DEMONSTRATION WITH POWER HARDWARE-IN-THE-LOOP

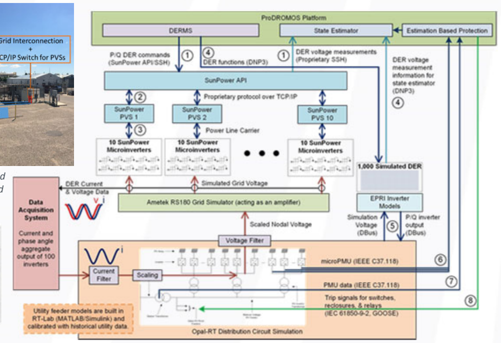
The ProDROMOS system will be demonstrated using a power hardware-in-the-loop system (PHIL) at the Distributed Energy Technologies Laboratory (DETL) at Sandia and in a field demonstration on a National Grid feeder with a utility-scale PV installation.



100 Microinverter installation at DETL. The active and reactive power of each of the devices can be changed to provide voltage regulation and protection on the simulated power system.



Example utility feeder models augmented with additional PV systems for high PV penetration simulations with the ProDROMOS system.



PHIL power and information flows with the ProDROMOS system controlling real and simulated DER.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Team Partners: SunSpec Alliance, Georgia Institute of Technology, SunPower, BPL Global, National Grid, Public Service Company of New Mexico

PROJECT NAME: Voltage Regulation and Protection Assurance using DER Advanced Grid Functions

Last 5 digits of project number: 32934

Principal Investigator (PI): Jay Johnson

PI Email: jjohns2@sandia.gov

BACKGROUND / INDUSTRY IMPACT

- We developed open-source codes and algorithms which can be plugged into commercial software products in order to address the spectrum of distribution circuit and DER (distributed energy resource) management

PROJECT OVERVIEW / OBJECTIVES

- Provide real-time feeder visibility/visualization
- Operate DERs to keep feeder voltages within ANSI limits
- Maintain protection with high penetration of DER on distribution circuits
- Minimize costs using multi-objective optimization
- Create information exchange recommendations
- Generate cyber security best practices

METHODS

- Our system, ProDROMOS (Programmable Distribution Resource Open Management Optimization System) can:

1. Ingest telemetry and customer data
2. Use this to estimate faults and protect the system
3. Generate 10 minute forecasts of PV power output
4. Use forecast to determine power and voltage settings
5. Communicate with SCADA and DER to continually update

KEY OUTCOMES / MILESTONES

- ProDROMOS will be released as an open-source code and incorporated into a commercial software product developed by BPL Global
- ProDROMOS will be demonstrated at the Distributed Energy Technologies Laboratory (DETL) at Sandia and at the National Grid feeder in a utility-scale PV installation

CONCLUSION / REMAINING RISK

- By developing a standardized information model for exchange between the utility, control systems, and field devices, ProDROMOS allows for 3rd party DERMS integration
- This could safely enable >50% PV penetration

Created **open source** tools to manage distributed energy resources (DER) that can **safely** enable >**50% PV penetration** into grids by optimizing settings and providing **real-time** visibility

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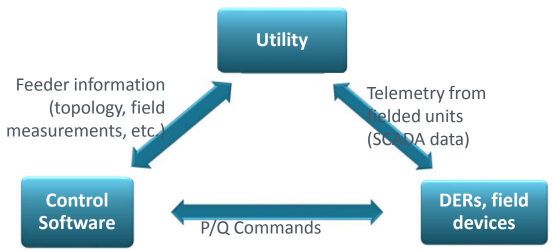

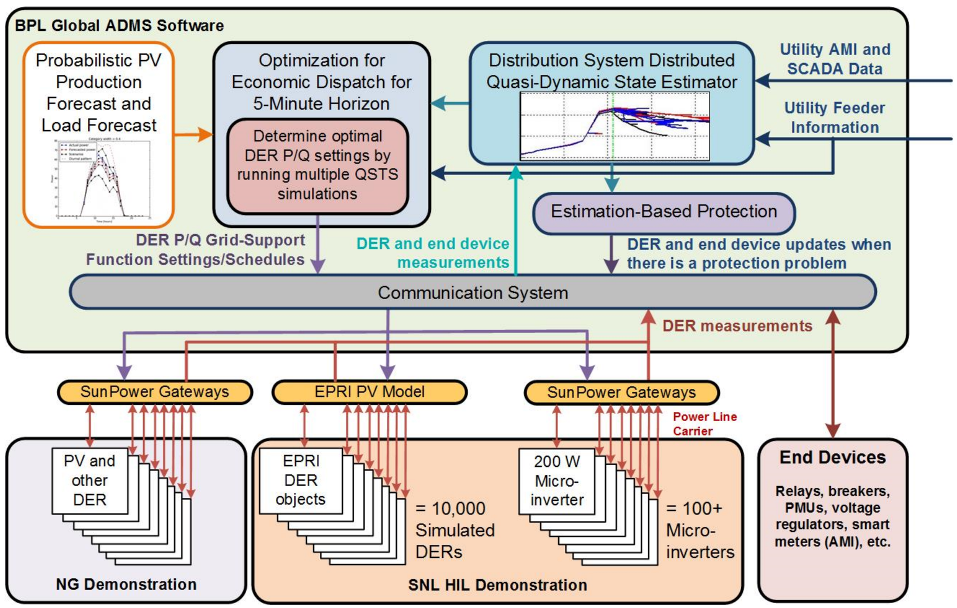

Additional project contributors: SunSpec Alliance, Georgia Institute of Technology, SunPower, BPL Global, National Grid, Public Service Company of New Mexico