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2018 Solar Energy Technologies Office Funding Opportunity Announcement Supporting Research

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This paper provides the technical background for the 2018 Solar Energy Technologies Office (SETO) Funding Opportunity Announcement (FOA). Find more information about the FOA here.

1 Advanced Concentrating Solar Power Collectors

The collector subsystem is a major portion of concentrating solar power (CSP) costs (contributing approximately 30% to direct capital costs in state of the art plants). Two forms of collectors have seen significant commercial deployment: heliostats for central receiver 'Power Towers', and parabolic troughs. SETO has previously funded R&D into both these forms of collectors as well as parabolic dishes and linear Fresnel systems. Heliostats will be emphasized below, both for brevity, as well as their ability to readily integrate with high temperature Generation 3 CSP systems. Analogous analysis can be performed for any form of CSP collectors.

Sandia National Laboratory's 2011 Power Tower Roadmap[1] aggregated information from a variety of sources to pin then-current state of the art heliostat costs at approximately $200/m^2 and closer to $240/m^2 for relatively small heliostats. The Solar Energy Technologies Office set a 2020 collector cost goal of $75/m^2.[2] Moderate Technology Readiness Level (TRL) prototypes have begun to approach this targeted cost value. Data from cost surveys performed by the National Renewable Energy Laboratory (NREL) indicates that commercial heliostat systems continue to follow a learning curve, as costs are approaching $100/m^2. To reasonably compare proposed collector concepts to commercial products and other R&D concepts, novel technologies must account for all costs related the collector design, including reflector modules, drives, pedestal support, foundation, controls and wired connections, field wiring, manufacturing facilities, installation and check out, *etc*. When the approach's influence on a specific cost is uncertain, appropriate ranges should be quantified.

As with every CSP subsystem, the efficiency with which energy is moved is of critical importance. For commercial power tower heliostat fields, the annual subsystem efficiency is on the order of 50-60%.[3] Low TRL collector R&D concepts may often appear to be unrealistically efficient when all categories of loss are not accounted for. Novel concepts must account for efficiency losses related to mirror reflectivity, cosine losses, sun shape, shading by adjacent collectors, collector accuracy/intercept factor, field availability, and mirror cleanliness, and wind induced optical error, among other loss mechanisms. The annual efficiency of a collector field is far more important than design point efficiency.

Critical to any new collector design is the influence of wind and the environment on the system. Ideally systems will be operable at high wind speeds and survive at any reasonable speed. Accounting for this often drives cost optimization and limits the viable solution space for new concepts.

A key element of SETO's strategy to reduce the levelized cost of electricity (LCOE), has been to pursue high temperature CSP, with receiver temperatures of interest at approximately 750°C. These high temperatures may enable high efficiency, low cost advanced power cycles. However, temperatures in this range may lead radiative losses to begin to dominate receiver system efficiency. This effect can be countered by several strategies including advanced solar selective coatings and cavity receivers. Of particularly interest to collector design is offsetting receiver loss by maximizing the average concentration ratio impingent on the receiver.[4] By increasing concentration ratio – without increasing costs – well beyond current commercial power tower plants (which achieve a concentration ratio on the order of 800 suns) new collectors can enable increased simplicity in high-temperature receivers. A first order approximation of this relevance of increased concentration ratio is

[1] Kolb, Gregory J., et al. "Power tower technology roadmap and cost reduction plan." *SAND2011-2419, Sandia National Laboratories, Albuquerque, NM* 7 (2011).
[2] Tilley, Drake, Bruce Kelly, and Frank Burkholder. *Baseload nitrate salt central receiver power plant design final report*. No. DOE-ABENGOA--3596. Abengoa Solar LLC, Lakewood, CO (United States), 2014.
[3] National Renewable Energy Laboratory (US). *Assessment of parabolic trough and power tower solar technology cost and performance forecasts*. DIANE Publishing, 2003.
[4] Ho, Clifford K., and Brian D. Iverson. "Review of high-temperature central receiver designs for concentrating solar power." *Renewable and Sustainable Energy Reviews* 29 (2014): 835-846.

provided in Figure 1. It is important to note that there are mechanisms to increase concentration ratio that do not depend on technological innovation (i.e., smaller heliostat fields can more readily focus flux due to relaxed geometric aiming requirements). SETO is most interested in concepts that improve solar field components or design over state of the art technology. While increasing concentration ratio is an important area of innovations, technologies that can drastically improve the efficiency or cost of solar concentration are of vital importance to achieving the stated cost targets.

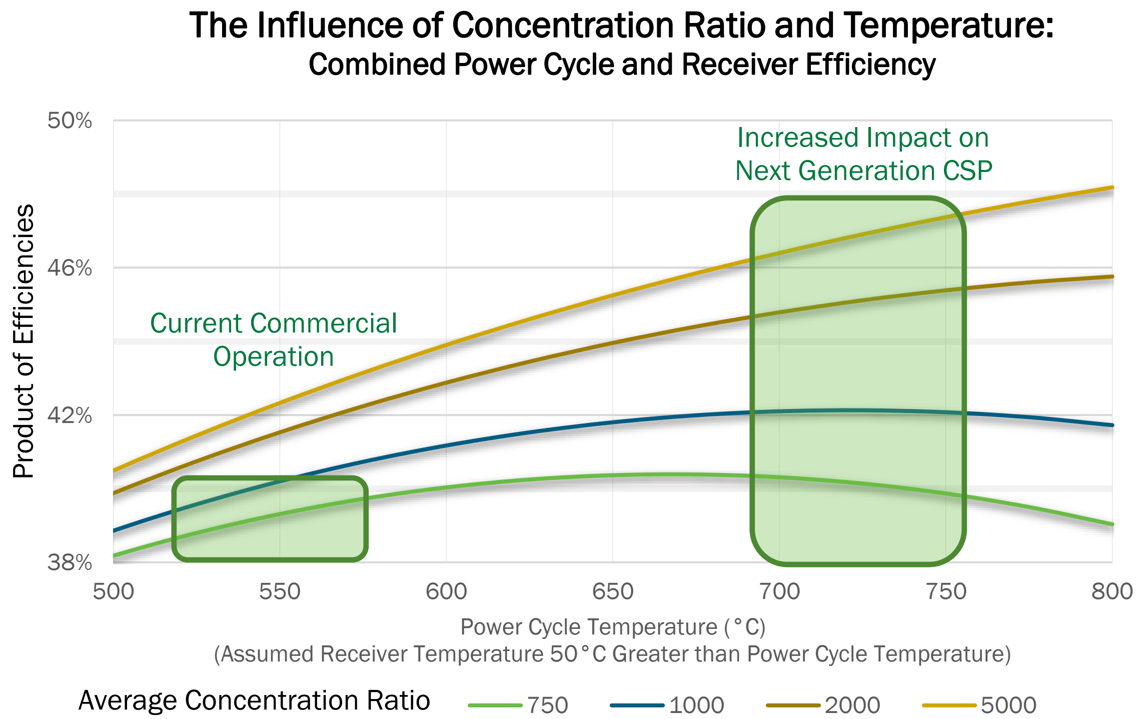

Figure 1. Comparison of combined receiver efficiency and power cycle efficiency as a function of temperature for several concentration ratios. The receiver is assumed to be a flat panel using state of the art solar selective coating (solar absorptivity = 0.95, black body emissivity = 0.80). The location's DNI is representative of the Southwest United States (800 W/m^2). The power cycle is assumed to operate at 75% of the Carnot limit. The SETO programmatic objective of developing a relevant power cycle above 700°C creates a new need for higher concentration ratio collector systems. This plot does not account for other optical, thermal, and parasitic losses in a CSP system.

With these objectives in mind, high impact R&D may fall primarily into one or more of the following three categories:

Collector Unit Innovations: The critical hardware employed for each individual collector. This hardware primarily drives the cost, efficiency, and concentration ratio of the collector field.

Collector Deployment: CSP Power Tower designs can typically require over 100,000 heliostats. This creates a unique challenge and opportunity: the assembly and installation of each collector, including site preparation, must be optimized to minimize labor cost and total deployment time of the CSP plant.

Collector Support (O&M): Critical technology development must occur outside of innovations targeting exclusively design point operations. Technology innovations may primarily focus on supporting the operations or maintenance of the collector subsystem. This can include aiming technology or strategy, control systems, maintaining optical (reflective) performance, collector downtime, wind mitigation *etc.*

2 Advanced Power Cycles for Concentrating Solar Power

The power block subsystem converts the collected thermal energy from the CSP receiver and/or thermal energy storage into electricity. The theoretical efficiency limit for thermodynamic power cycles is defined by the Carnot equation: $\eta \leq 1 - \frac{T_{cold}}{T_{in}}$

Therefore, higher inlet temperatures (T_{in}) and lower heat sink temperatures (T_{cold}) are desirable to improve cycle thermodynamic efficiency and, in turn, reduce CSP plant cost. However, CSP plants are typically situated in highly arid regions, necessitating a capability to operate with dry cooling. Because the cost of CSP stems primarily from fixed capital costs that do not vary based on generation, high conversion efficiencies are particularly important to enabling a low LCOE. The chief pathway that has been identified to achieve a baseload CSP LCOE of 5¢/kWh describes power blocks that **cost ≤ $900/kW$_e$** (including the heat exchanger interface between the heat transfer fluid and the power cycle) and operate at a **net thermal-to-electric efficiency of ≥ 50%**. Power cycle concepts targeting higher cost or lower efficiency should quantitatively justify how they can nevertheless enable the 2030 CSP cost targets. Costs significantly below $900/kW$_e$ may be possible, and are of particularly interest. Innovative technologies should take into account that DOE's default financial model assumes a 30 year plant lifetime and development plans should include lifetime validation.

Highly innovative CSP Power Cycle technologies can be divided into two categories:

Supercritical CO_2 Power Cycles

The supercritical CO_2 (sCO_2) cycle is a uniquely beneficial power cycle for CSP due to the following characteristics:

- Predicted higher cycle efficiency than the Rankine Cycle for turbine inlet temperatures above 550°C.
- Ability to readily incorporate air cooling as ultimate heat sink with minor impacts on cycle efficiency
- Compactness of turbomachinery and general simplicity of cycle design, leading to easier build, installation and operation
- Ability to interface better with high temperature HTF at smaller scale, as the supercritical Rankine cycle has not been proven feasible at the 100 MW$_e$ scale; additionally, supercritical steam cycles at temperatures above 620°C have not been built at commercial scale.
- Potential to reduce the cost of the power block compared to commercial steam Rankine cycles, due to compact turbomachinery
- Operational simplicity compared to steam generation that can potentially lower O&M cost

Particular innovations for sCO_2 power cycles for CSP may include:

1. **Component innovations supporting sCO_2 cycle variations advantageous to operation of a complete CSP plant**

   The sCO_2 recompression closed Brayton cycle (RCBC) is the configuration of interest for much recent research into sCO_2 cycles.[5] However, variations from this null case are needed to optimize the cycle for

[5] Brun K., Friedman P., & Dennis R. (Eds.), (2017) Fundamentals and Applications of Supercritical Carbon Dioxide (SCO_2) Based Power Cycles 1st Edition. Woodhead Publishing

the CSP application. The following discussion highlights scenarios aligned with this case, which may be improved upon.

Thermal energy storage (TES) is an important feature of CSP plants. Sensible thermal energy storage needs a significant temperature change (ΔT) of the HTF. The ΔT requirements (change in working fluid temperature at the primary heater) for reasonable TES cost (targeted to be 15 $/kW$_{th}$) is of the order of 250-300°C, which conflicts with the 150-180°C ΔT requirement needs imposed by the sCO_2 RCBC with ~700°C turbine inlet temperature. This necessitates either alternate cycle designs, like the partial cooling cycle (which allow for a slightly larger ΔT), or the use of low-cost (near-) isothermal energy storage methods (motivating even smaller ΔT). A second limitation is the requirement of high turbine inlet temperature (TIT) for high sCO_2 cycle efficiency (*e.g.*, TIT of 715°C for 50% efficiency at a compressor inlet temperature of 35°C). The cost of the CSP plant increases with HTF exit temperature requirements owing to the need of advanced alloys for piping (or containment) to transport fluid from the receiver to the TES storage.

A further challenge is due to the height of commercial CSP power towers, which can exceed 500 feet at the ~100 MW scale. The required piping then runs from the base of the tower to large 150-foot diameter salt storage tanks for hundreds of feet. The cost of manufacturing and installing high nickel alloy pipe may push plant costs impractically high. Therefore, significantly increasing power cycle efficiency at temperatures below 700°C would be uniquely advantageous, resulting in a reduced maximum HTF temperature. This would ultimately reduce the cost of HTF pipping and improve receiver efficiency.

Beyond these described challenges, other sCO_2 power cycle technology innovations which could support a reduced CSP LCOE (compared to the sCO_2 RCBC null case) through unique adaptations to the HTF constraints, TES system, cycle layout, *etc*. are sought.

2. Component Innovations for the sCO_2 Recompression Closed Brayton Cycle

The RCBC sCO_2 cycle is still in relatively early stages of research and development. Many opportunities to make transformative developments to the cycle's technology exist. Innovations are sought which could make drastic improvements to the cycle's cost, efficiency, reliability, and resiliency. Cost improvements may include the opportunity for the entire cycle to cost significantly less than the target of $900/kW$_{e.}$ Some examples of potential areas of innovation are discussed below:

- In the case of nominal radial compressor/axial turbine shaft designs, improvements in the expander-compressor in-line integrated drive train may be enable by elimination of oil lubricated bearings. In the case of integral geared designs, opportunities may exist to minimize efficiency losses in multiple casings.

- The power consumed in compressing sCO_2 is a significant use of turbine output – approximately 30% for a 14 MWe turbine (for a 10 MWe recuperated Brayton compression cycle). The compressor inlet temperature is a major driver of power cycle efficiency. It was originally thought that in the hot desert environment of typical CSP plants, the appropriate compressor baseline design would be based on the daytime average temperature (incremented by the temperature drop due to air cooling). However, a subsequent analysis of a modeled baseload CSP plant with 14 hours of TES and ambient temperature in a selected location (Dagget, CA) indicated an average annual temperature for a ~6000 hour annual operation of ~20°C, below the critical temperature of CO_2 of 31 °C. Therefore, it is essential to design the compressor for near critical compressor inlet temperature (or substantial periods operating at a temperature <31°C). Outside of some subsea operations, wet gas compression has not been very successful, as compressor power variations and instabilities have limited performance.

- To reduce the compressor work, replacing the main compressor with a quasi-isothermal compressor may be an attractive strategy. The isothermal compressor can be combined with the pre-cooler to reduce the complexity. In addition, the isothermal Brayton cycle can maximize efficiency in the simple cycle mode. A quasi-isothermal compressor is also believed to increase cycle efficiency by several points for a given turbine and compressor inlet temperature. A significant challenge is in incorporating an internally cooled compressor diaphragm economically, and within the small sized CO_2 compressor.

- Primary heat exchanger: The primary heat exchanger design for CSP is challenging owing to the need to accommodate two high temperature, potentially corrosive fluids in the primary and secondary channels. This has led to a need for new materials, coatings, manufacturing processes, and innovative PCHE designs to attain the 200 $/kW$_e$ (100 $/kW$_{th}$) goal.

- To enable the use of lower cost alloys for the expander and the recuperator, it would be beneficial to reduce the turbine inlet temperature (without losing efficiency) and increase the pressure drop across the expander (to limit the high temperature recuperator inlet temperature to 500°C). For example, Alloy 718 has been the workhorse of gas turbine, compressor and combustor industry for years while being limited to 650°C. Limiting the turbine inlet temperature to 650°C may provide an opportunity to lower the cost for the turbine, recuperators, and interconnecting piping, and make use of vast industry experience in fabrication using such alloys.

3. Materials and Manufacturing for sCO_2 Cycle Components and Interconnections

The sCO_2 cycle is being developed today due, in large part, to materials and manufacturing advancements that have made the temperatures and compact components of the cycle viable. Recent research and development has proven specific high nickel alloys' general compatibility at the peak temperature, pressures, and thermal cycling rate of the cycle.[6] However, piping, forgings and parts made of identified high-nickel alloys are generally very costly. Opportunities to prove lower cost alternative materials in piping or components throughout the cycle are of particular interest.

Another pathway towards substantial cost reduction of power cycle components may involve leveraging innovative manufacturing solutions, which could generally reduce material usage requirements, the number of processes steps, and enhance the automation and reliability of buildout. Potential solutions should recognize the relatively small size of turbines, compressors, and heat exchangers for the sCO_2 power block, and should target manufacturing processes beyond the traditional, casting, forging and machining steps to dramatically reduce the cost ($/kW$_e$) and schedule. Some processes that have already shown promise in additive machining include laser beam sintering, direct energy deposition, laser engineered net shaping, electron beam machining, sheet lamination. However many scientific issues around these processes have not been fully resolved. Manufacturing technologies which could enable a step shift in component cost or capability are of particular interest. Research and development into new materials or manufacturing capabilities for CSP should justify how the innovation can be applied to CSP applications and quantify the potential benefit in meeting cost, efficiency, or other metrics.

[6] B. A. Pint and R. G. Brese, (2017) "High-Temperature Materials Chapter 4 in *Fundamentals and Applications of Supercritical Carbon Dioxide Based Power Cycles*, K. Brun and P. Friedman, eds., Elsevier, London, pp.67-104.

4. Operations and Maintenance Innovations

Due to the typically remote location of CSP plants, technologies enabling operations and maintenance (O&M) cost reductions are critical to every CSP subsystem, including the developing power cycle. Areas of particular interest include:

- Automating the sCO_2 power block control systems for limited or minimal operator action (especially for CSP plants operating for 20+ hours a day in remote locations)
    - Integration of the control system with the CSP thermal transport system
    - Enabling remote monitoring and operations
- Innovations which could enable a power cycle O&M cost target of $10/kW-year + $2/MWh (approximately a quarter of the fixed, and the majority of the variable total targeted CSP O&M cost).

Novel Power Cycles to Enable CSP Cost Reductions

While the sCO_2-based cycle is attractive for CSP due to the reasons outlined above, other alternative thermal-to-electric conversion processes may be attractive if they can be integrated at low-cost and high-efficiency. Particularly, modular, small-scale heat engines may allow CSP systems to operate at a small distributed scale, take advantage of more simplified thermal systems, enable, or more readily meet the cost and efficiency objectives of the CSP program. Innovative concepts should clarify how they would be able to integrate with a solar thermal energy input, as well as indicate a power cycle efficiency target, power cycle cost target. These quantified values should be compared to the technoeconomic needs of the proposed market. It is particularly important to identify challenges and propose solutions in integrating thermal energy storage with novel power cycles.

3 Concentrating Solar Power Thermal Transport System and Components

The thermal transport system of a CSP plant is typically connected to a thermal-to-electric energy conversion technology and must be designed considering the effects on and limitations of the power cycle. Typically, the temperature limitations of the heat transfer media (approximately 400 °C for synthetic oils or 565 °C for molten nitrate salts) have dictated the power cycle efficiency that CSP could leverage. Optimizing the capability of thermal transport in terms of the temperature, scale, cost, efficiency, and responsiveness with which heat can be collected, stored, and delivered to a specific power block or other application can lead to an increased value for the heat delivered or a reduced levelized cost of heat / electricity. Technology innovations in components or entire systems that can realize a unique and impactful combination of the above listed characteristics are sought in pursuit of the 2030 CSP cost targets. With an application identified, the appropriate temperature, scale, and responsiveness of the system are bounded. The efficiency and cost of the system are limited by innovations in heat transfer, materials, and material degradation.

Materials

For high temperature thermal transport systems, the cost of containment infrastructure and required lifetimes (30 years for the baseline 2030 target financial assumptions) typically leads to a significant challenge in cost-effectively preventing degradation. Multiple strategies to prevent containment material degradation may be employed separately or simultaneously. Ideally, systems will be designed so that degradation cannot occur in the first place. This is often the approach pursued by deploying protective coatings. However, the nature of the thermal transport system is such that a high geometric area must be protected, inevitably leading to defects and cracks. Such approaches must consider the challenges involved in maintaining a pristine, hermetic protective coating during assembly and in-field welding. Other attempts to stop corrosion by stopping mass transport, such as utilizing non-wettable surfaces, may offer similar performance with the added benefit of increases robustness.

For this reason, dynamic, auto-responsive systems are of high merit if they are reliable and low-cost. A non-exhaustive list of potential strategies includes:

- Self-healing protective coatings
    - Alumina-forming alloys
    - Auto plating from HTF
- Dynamic chemical equilibrium capable of responding to hot spots
    - Systems capable of 'buffering' against extensive damage
    - Protective equilibria that can be sensed and corrective action taken before irreparable damage occurs.

If the chemistry of containment can be solved one must still address the fact that mechanical integrity of the containment boundaries typically degrades with temperature. This is a challenge that is certainly not unique to CSP; however, finding solutions from other fields/industries that fit into CSP's cost structure presents a challenge. If novel materials are proposed, additional challenges remain, even if the requisite properties and cost can be validated. For example, the ability to join components must be well established to garner industry acceptance. This includes joining composite materials to their self, as well as to dissimilar materials, such as traditional alloys. Proving the combination of chemical compatibility, mechanical integrity, and cost requires sophisticated approaches. The better of these approaches employ probabilistic cost inputs for the materials feed, they cite historical cost trends and pressure from inflation, and they build manufacturing, handling, and shipping cost estimates from ‘nearest neighbor’ materials and fields/other industries.

Thermal System Design

Elegant, rigorous methodologies for analyzing tradeoffs of the entire transport system are typically required for novel system designs. Figures of merit are often employed to attempt to respect competing performance factors. These science-based equations attempt to respect the fact that improving one property of a heat transfer media can lead to an undesirable decrease in another property. For example, increasing the heat capacity of a molten salt heat transfer fluid can often also lead to an increase in the melting temperature of that salt. Areas of persistent challenge often standardize on a shared figure of merit so that the 'best in class' may be readily known.

The heat transfer efficiency contributes to the overall system efficiency in several ways. High efficiency can benefit the system by minimizing the size and complexity of the thermal transport system. High temperature heat is valuable but costly to create, move, and contain. For example, transporting heat at temperatures above 650 °C often requires a switch from stainless steel to high nickel content alloys. Thus, the thermodynamic benefit in terms of the work afforded by the higher temperature heat needs to be offset by highly effective heat transfer to minimize material cost. One strategy to avoid excessive cost of materials is to localize the production of that heat near to its end-use, such as with a chemical energy conversion process. Such approaches need to respect the first and second laws of thermodynamics, the principles of kinetics, and the technoeconomic consequents. In general, the strategies that employ the fewest unit operations possible are also the more cost effective.

It is important to note that heat transfer media comprised of either solid or gas are expected to affect minimal chemical degradation of containment materials, in addition to suffer little decomposition of the media itself. This is because both solids and gasses are typically poor solvents or ‘carriers’ for structural alloy elements, and negligible mass transport occurs between the two phases. Solids may contribute to depletion of components from the structural material through erosion whereas gasses will not. Whereas solids and gasses are less likely to deplete elements from structural materials their heat transport and materials handling challenges are perhaps greater.

Solid particles demonstrate many beneficial material compatibility properties. However, containing, transporting and transferring the thermal energy with particles at temperatures relevant to CSP is a significant challenge. Solutions must consider the multi-physics design space of fluids, radiation, convection, conduction and particle friction and compaction. Such solutions must balance, for example, the heat transfer benefits of fine particles, with their material handling challenges necessary to control them in a dynamic high flux environment.

Inert gasses as heat transfer media suffer from low thermal conductivity and heat capacity, which necessitate high pressures to achieve acceptable performance. While the corrosivity is not a problem, the high pressures introduce containment material thermal stresses, creep and fatigue. This is particularly important in the receiver where high intensity flux creates a large temperature delta across tube walls. If the solar receiver itself is considered as a heat exchanger, it may benefit from novel designs (like microchannels) that may improve heat transfer and thermal stresses. However, these strategies may require novel manufacturing approaches such as diffusion bonding or additive manufacturing. The reliability and scalability of such fabrication techniques should be seriously considered and shown to be reliable.

Solar Receiver Design

The optical to thermal conversion of energy at the receiver is fundamentally a heat exchanger unique to the CSP application. This is potentially a costly component with unique failure risks and energy loss mechanisms. Extreme mechanical and thermodynamic conditions in CSP systems are typically seen in the receiver subsystems both by the heat transfer media as well as by any components exposed to the high solar flux. Energetic losses can occur due to reflection, re-radiation, convection, conduction, and parasitic flow losses.

SETO has extensively explored viable solar selective coatings.[7] These coatings maximize optical absorptance in the solar (primarily visible) spectrum while minimizing emissions in the black body (infra-red) spectrum. The principal challenge with these systems is to either: a) produce a low-cost coating that employs a kinetic strategy to inhibit degradation in solar selectivity and then recoat periodically; or, b) produce a low-cost coating that employs a thermodynamic strategy to 'grow-in' solar selectivity by allowing the mechanism of degradation to become the mechanism of *in-situ* synthesis. Seemingly viable options for both strategies exist. Other avenues may exist for efficiently moving optical energy into a heat transfer medium, thermal storage, or a power cycle. These may include paradigms where the majority of absorption does not happen at the receiver surface, volumetric absorption of light, intentional wavelength shifting, etc. High-impact research would allow higher receiver efficiency at high temperatures, at low concentration ratios, or simplify the complexity of the thermal transport systems. The receiver is inherently limited by a design's ability to accept and transport incident heat with minimal parasitic losses. As a solution point, SETO targets receivers with efficiency greater than 90% and lifetimes greater than 10,000 cycles.

Thermal Energy Storage

Thermal energy storage (TES), providing energy on demand, is vital to the value proposition of CSP. The state of the art commercial TES system uses a two-tank system, wherein a hot tank of salt stores energy to be delivered to a power cycle, and a cold tank to store the salt prior to travel through the receiver. This salt may also directly serve as the heat transfer fluid (HTF). This concept is commercially viable below the HTF's decomposition temperature (about 565 °C for currently used nitrate salts) and above its freezing temperature (220 °C for 'solar salt' – a mixture of potassium and sodium nitrate/nitrite). For a new, direct HTF/TES media the characteristics of the fluid must be optimized in context of the entire thermal transport system's tradeoffs (cost, efficiency, temperature range, responsiveness, and scale). A well-designed CSP TES system is one that has a high energetic efficiency, η, as well as a high *exergetic* efficiency, ζ, as defined,

$$\eta = \frac{Q_{out}}{Q_{in}} \qquad \text{(Eq. 1)}$$

$$\zeta = \frac{Q_{out}}{Q_{in}} \times \frac{W_{out}}{W_{in}} \approx \frac{Q_{out}\left(1-\frac{T_\infty}{T_{PB}}\right)}{Q_{in}\left(1-\frac{T_\infty}{T_{RO}}\right)} \qquad \text{(Eq. 2)}$$

where Q_{in} is the total energy transferred from the HTF to the storage system during charging, Q_{out} is the total energy transferred from the storage system to the HTF during discharging, T_{PB} is the temperature of the working fluid at the inlet of the turbine in Kelvin, T_{RO} is the temperature of the HTF at the outlet of the receiver in Kelvin, and T_∞ is the ambient temperature nominally taken to be 298K.[8]

Innovations are sought in the containment of TES media, energy or mass exchange into and out of the TES system, and novel TES systems and materials. For many CSP systems, the heat transfer media can double as thermal energy storage media. Innovations in the manner the media is stored, as well as its movement, are most critical. Other embodiments may be better supported by an indirect TES. In either embodiment heat may be stored sensibly (through temperature change), latently (via phase change), or thermochemically (within molecular bonds).

[7] Wang et al. Journal of Applied Physics 123, 033104 (2018);
[8] Stekli, J.; Irwin, L.; Pitchumani, R. "Technical Challenges and Opportunities for Concentrating Solar Power With Thermal Energy Storage," *ASME Journal of Thermal Science Engineering and Applications*; Vol. 5, No. 2; Article 021011; 2013; http://dx.doi.org/10.1115/1.4024143.

Sensible. Cycling sensible energy storage in a CSP configuration is typically associated with a large change in temperature for the storage substance. If not carefully planned, poor coupling of sensible TES with the temperature requirements of the available power blocks (**Table 3**) can result in losses in exergetic efficiency. These losses vary based upon the operational constraints of each specific sensible TES configuration. Nonetheless, sensible energy storage is relatively both simple and reliable, its major hurdles being high temperature stability of the storage media, materials compatibility, and cost reduction.

Latent. Cycling latent energy storage is typically associated with a smaller change in temperature for the storage substance. As the storage is exercised the substance undergoes a change in its physical state (such as freezing/melting). When the temperature associated with the phase change is carefully paired with the appropriate power block, improved exergetic efficiencies can be realized. Latent energy storage is also relatively both simple and reliable, its major hurdles being materials compatibility, rapid and efficient heat transfer during discharge, and cost reduction.

Thermochemical. Cycling thermochemical energy storage can be associated with narrow temperature changes and operating temperatures that can be adjusted based upon the conditions of the targeted chemical reaction. While these systems typically have the highest energy densities, challenges include obtaining high exergetic efficiency across a charge/discharge cycle, useful storage material lifetime, rapid and efficient heat transfer, reducing costs and system complexity, and improving reliability and longevity in service.

High temperature TES design requires consideration of the thermo-mechanical stresses placed upon the storage system due to temperature cycling. These stresses may be exacerbated by the dissolution, corrosion, or general degradation that may occur on the inside and the outside of the storage vessel. The TES material itself must be of high thermal stability over extended lifetimes (30 years). These considerations should be taken into account by all potential innovations for TES, regardless of energy storage type.

Just as any innovation in the power cycle is dependent on the simultaneous success on many components and a specific working fluid, the thermal transport system must respect the limitations of a variety of components and the heat transfer media. For the specific embodiment of a thermal transport system under investigation, researchers should first address the most critical or limiting challenges before proceeding to other interesting optimizations or components.

4 Addressing Solar Integration Challenges in Electric Distribution System

As the penetration of solar energy on the electric transmission and distribution grid continues to increase, it becomes imperative to identify the associated technical, economic and regulatory challenges, and to develop impactful solutions in order to ensure compatibility with the existing grid and a smooth transition to a secure, reliable and resilient grid of the future.

The SETO Systems Integration subprogram has identified the following research areas as crucial for integration of solar energy onto a modernized electric grid. These are:

- **Planning and Operation** – fundamental understanding of the impacts of increasing penetration of solar energy on grid reliability and power quality, addressing the variability of solar generation and two-way power flows,
- **Solar + X** – developing best practices for interconnecting and integrating solar with energy storage and synergistic distributed energy resources (DER) technologies to achieve higher asset utilization and value,
- **Power Electronics** – researching power electronic technologies such as smart PV inverters for flexible power flow control,
- **Sensing and Communication** – enhancing situational awareness of solar generation at the grid edge using advanced information, communication, and data analytic technologies and,
- **Codes and Standards** – informing the standardization of interconnection, interoperability, and cybersecurity for PV and other DER systems.

Current research and development (R&D) efforts funded by the SETO Systems Integration subprogram include: The Sustainable and Holistic Integration of Energy Storage and Solar PV (SHINES), Enabling Extreme Real-Time Grid Integration Of Solar Energy (ENERGISE), SunShot National Laboratory Multiyear Partnership (SuNLaMP), Solar Forecasting II, and Grid Modernization Laboratory Consortium (GMLC) research activities including the recently launched Resilient Distribution Systems (RDS) program.[9]

__Priority Research Areas__

Resilience to large-scale inter-regional blackouts due to storms, earthquakes and unplanned outages, and faster service restoration in their aftermath is in our national interest. Innovations in this area can lead to faster restoration to local power service, and prevent and mitigate social emergencies, huge financial losses, and possible loss of life, even if it is a temporary stoppage of electric power service. As recent natural calamities have shown, some blackouts can last days, weeks, or even longer, completely shutting down commercial activities and critical services such as telecommunication networks, financial markets, water supplies and hospitals.

The end-to-end electric power grids, their communications and control systems need be well maintained and securely protected. Over the last two decades, power outages in the United States have increased in size and frequency[10]-[11]. Severe weather is already the leading cause of power outages in the United States, accounting

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[9] https://energy.gov/eere/solar/systems-integration-competitive-awards
[10] "Impact of Power System Blackouts", M. M. Adibi, and Nelson Martins, Power Point Presentation at 2015 IEEE Power & Energy Society General Meeting
[11] "Leveraging Distributed Resources to Improve Resilience", R. Arghandeh, M. Brown, A. Del Rosso, G. Ghatikar, E. Stewart, A. Vojdani, and A. von Meier, IEEE Power & Energy Magazine, September/October 2014

for 87% of outages according to the 2013 report of the Executive Office of the U.S. President. Several studies estimate that outages and power quality disturbances cost the economy several billion dollars10-11. Some estimate more than $80 billion annually on average, and sometimes as much as $188 billion in a single year. Distribution networks are the most vulnerable parts of the electric grid[12]. In addition, it has been estimated that 90% of electricity customer outages in the United States are related to distribution network problems.11

Solar PV and DER systems not only provide the customers with choices for economical energy supplies, but also have unique features to provide grid-support functions for reliability and resilience, either individually or as a fleet of assets. Recent advances in smart PV inverter technologies, smart grid, and intelligent control algorithms make it possible for the DER systems to take a more active role in providing grid services during normal operation, and participate in black-start scenarios during system-wide outages.[13]-[14]-[15] Distribution management and outage management, while having been well-established within the framework of conventional distribution systems, can incorporate behind-the-meter (BTM) solar and DERs through DER management system (DERMS) to enhance system resilience and to enable faster local service restoration. New technologies - smart grid, smart meters, smart inverters, sensors, micro-PMUs, energy storage, building load control, electric vehicles, etc. - working together can offer ample alternative solutions to provide flexibility and resilience against large scale outages, minimize the area affected, and enable faster restoration to small areas within a blackout region.[16]-[17]-[18]-[19]-[20]

Advances in the following research areas can help enable distributed solar photovoltaic (PV) to contribute to grid reliability and resilience:

- Adaptive Solar Grid Integration,
- Solar Observability, and
- Solar + X.

These will be discussed in detail in subsequent sections. It should be noted that research to be pursued in these areas should leverage current and past work done in the industry and advancements and insights from projects under GMLC and others funded by DOE-EERE Vehicle Technologies Office, DOE-EERE Buildings Technologies Office, DOE-ARPA-E, DOE Office of Electricity Delivery & Energy Reliability, DOE Office of Science, the US Advanced Battery Consortium, as well as the Department of Defense.

Topic Area 1: Adaptive Solar Grid Integration

Objective

As solar PV, energy storage, and other DER systems are increasingly deployed in the distribution system, the existing interconnection requirements often limit the hosting capacity and utilization of these distributed assets. For example, PV systems are treated as passive, grid-following devices despite smart inverters already providing many grid-support functions. The worst-case scenarios considered in interconnection studies can be

[12] "Achieving Resilience at Distribution Level", G. J.-Estévez, A. N.-Espinosa, R. P.-Behnke, L. Lanuzza, and N. Velázquez, IEEE Power and Energy Magazine, May/June 2017

[13] "Next-Generation Energy Technologies Are Constrained by Outdated Markets. Here's How to Fix Them", S. Kann, GreenTech Media, October 2017

[14] http://www.eiscouncil.com/App_Data/Upload/BSPI.pdf

[15] CleanStart-DERMS, GMLC Resilient Distribution Systems Lab Call Awards, https://energy.gov/under-secretary-science-and-energy/resilient-distribution-systems-lab-call-awards

[16] "Solar Plus: A Holistic Approach to Distributed Solar PV", E. O'Shaughnessy, K. Ardani, D. Cutler, and R. Margolis, National Renewable Energy Laboratory Report

[17] "Evaluation of Inverter-based Grid Frequency Support using Frequency-Watt and Grid Forming PV Inverters", M. Elkhatib, W. Du, Wei; R. Lasseter, IEEE Transactions on Power Delivery

[18] "CERTS Microgrid Research and Lessons Learned", Power Point Presentation, B. Lasseter , University of Wisconsin – Madison

[19] "Getting Out In Front: Distribution System Planning for a Modern Grid", August 29, 2017 Webinar by Advanced Energy Economy

[20] "Economic Modeling of Distributed Resources in the Real Grid", B. D. Bunte, IEEE SmartGrid WG Power Point Presentation

readily mitigated by dynamic control features natively provided in individual PVs (or a fleet of PVs from multiple customers at multiple locations).

Research and field validation are needed for adaptive solar integration technologies that can enable distributed solar PV to contribute more to grid reliability and resilience by providing solar dispatchability and grid-support functions – including energy, capacity, and reliability and resilience services. Through the intelligent control of the distributed assets, flexible interconnection requirements can increase the overall hosting capacity for solar and DERs in the distribution system, support diverse customer interconnection choices, improve system reliability and resilience, and reduce PV curtailment.

Approach

The technical approach will focus on developing flexible interconnection requirements and dynamic hosting capacity concepts for solar PV, energy storage and other distributed energy resources (DERs), as opposed to today's prevalent firm interconnection requirements and static hosting capacity analysis.[21–22–23] Example projects may include, but are not limited to, hardware and software innovations in PV smart inverter control and DERMS that allow more flexibility to interconnection and operation of small scale PV and other DER systems at significant penetration levels. Solutions must consider all DER options available as well as power systems engineering alternatives, and demonstrate the benefits of the proposed methods in the hosting capacity planning. It should also be shown how the solutions will be able to respond to fast changing conditions under normal operations and provide power to critical loads during grid outages – with consideration of other DER options and distribution system constraints.

Consider the well-known steady-state power flow equations.[24] The apparent power in the first equation, a complex variable, is written in terms of its active and reactive power components, using rectangular coordinates, in equations 2 and 3. All power terms are expressed as a function of the nodal voltage magnitudes and their phase angles, and the associated line parameters. The subscripts *i* and *j* denote the nodes at which power is injected or withdrawn, *N* and denotes the number of buses.

Typically, these equations will have to be expanded to include multi-phase nature of unbalanced distribution networks, and modeling of the three-phase transformers and grid control devices such as voltage regulators and capacitor banks. In the presence of solar PV, energy storage, and other DERs, the controlled buses in these equations will also include the distributed technology devices. New control mechanisms that can manipulate a single or clustered sets of PV and DERs will provide opportunities to modify the power injections and withdrawals at these nodes in order to maintain required voltage profiles and optimal power flows.

$$S_i = V_i * I_i^* = V_i \sum_{j=1}^{N} V_j^* Y_{ij}^*)$$

$$P_{G_i} - P_{L_i} = \sum_{j=1}^{N} |v_i||v_j|(G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij})$$

$$Q_{G_i} - Q_{L_i} = \sum_{j=1}^{N} |v_i||v_j|(G_{ij} sin\theta_{ij} - B_{ij} cos\theta_{ij})$$

To further explain, the figure below shows a high-level depiction of an example distribution network. In this figure, it is assumed that the distribution feeder has a very high penetration of solar generation, and it includes a microgrid, two nano-grids, many electric vehicles and energy storage units. Under current interconnection

[21] "High-Penetration PV Integration Handbook for Distribution Engineers", Technical Report, NREL/TP-5D00-63114, January 2016.
[22] "Distribution Feeder Hosting Capacity", EPRI Technical Update 3002004777, April 2015
[23] "Distribution Grid Hosting Capacity: Unlock dynamic grid hosting capacity with flexible interconnection and active network management", Jeremiah Miller, Solar Power International, September 2017.
[24] "Comparison between Load Flow Analysis Methods in Power System using MATLAB", K. Singhal, International Journal of Scientific & Engineering Research, Volume 5, Issue 5, May-2014 1412

agreements and allowable configurations, PV can be used only within its installation site and when the feeder is energized. Within microgrids or nano-grids, PV can only operate, in most cases, when another generator (or energy storage) establishes the reference voltage and frequency. Such a network does not allow sharing of the solar generation, especially during blackouts when electric power is much needed and the sun is shining. Clearly, new research and innovations are required that can unlock the advantages of high penetration solar generation during blackouts.

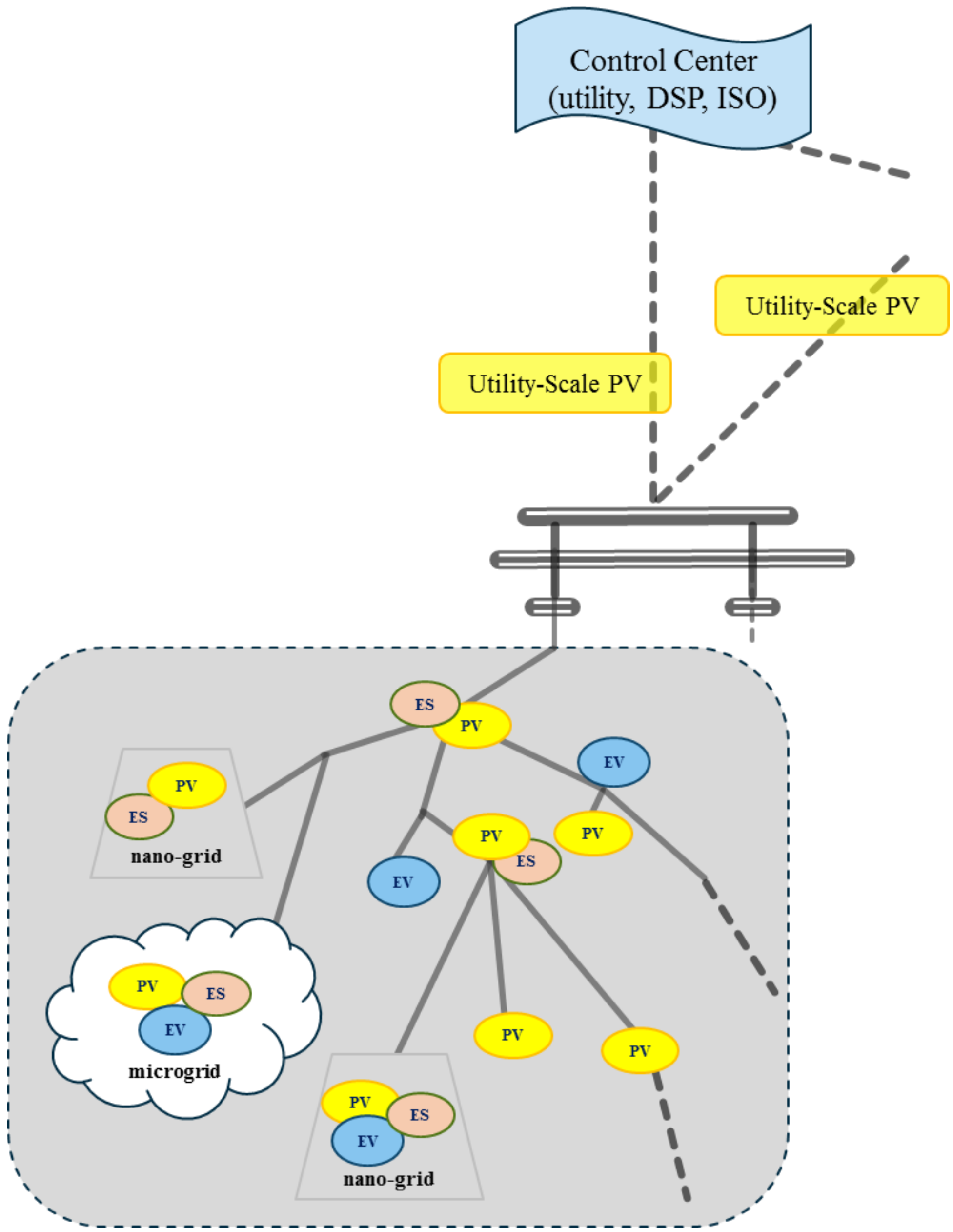

Figure 2. A high-level depiction of an example distribution network with significant penetration of solar PV, energy storage, and DERs. Smart clustering techniques can allow DER assets to be organized to provide grid reliability and resilience services.

Outcome

Research in this area is expected to result in new flexible PV interconnection methods and adaptive control mechanisms for distributed solar PV and DERs, taking advantage of the control capabilities of these devices. The solutions will be able to respond to fast changing conditions under normal operations and to provide local grid resilience and faster local service restoration. By adaptive and dynamic integration of solar PV generation, energy storage, and DERs, which are in close proximity to the load, the solutions will be able to provide the ability to withstand and reduce the magnitude and/or duration of disruptive events, which include the capability to anticipate, absorb, adapt to, and/or rapidly recover from such event.

Specific outcomes may include the following:

- A framework of flexible interconnection and dynamic hosting capacity methods for distributed PV and other DERs,
- Smart clustering techniques to manage solar PV and DERs in providing grid services under normal operation conditions,
- Smart clustering techniques to manage solar PV and DERs in enabling/enhancing resilience of local grid against power outages, by minimizing their impact, shortening the local service restoration time, and potentially providing auxiliary power to critical loads,
- Advances in hardware (e.g. smart inverters) and software (e.g. DERMS) technologies supporting the above framework and smart clustering techniques,
- Analysis to show reduced solar grid integration costs and increased opportunities for DERs to contribute to the reliability and resilience of local community as a whole (compared to current back-up power alternatives).

Topic Area 2: Solar Observability

Objective

The increasing deployment of distributed solar and other DERs brings about serious challenges in terms of their visibility, control, communications and advanced analytics. Solar observability, or situation awareness, is required across multiple spatial scales (from behind-the-meter through the distribution substation and beyond) and at multiple time scales (from microseconds to minutes and hours). Today's utility planners and operators typically do not map BTM solar generation onto the feeders and analyze their contributions and impacts for lack of sensing, communication, and data management capabilities in their grid infrastructure.

There have been significant advances in smart grid technologies including information, communications, and sensor, and control. For example, some vendors are working on fault line sensors to help accurately detect fault types and locations.[25] Others are working to advance micro-PMU technologies that can provide hundreds of measurements per second.[26] Still others are doing research and development in smart inverter technologies that provide sophisticated grid-support functions.[27]-[28] However, these technologies have not been fully integrated

[25] http://www.tdworld.com/smart-grid/florida-power-light-orders-20000-distribution-line-sensors
[26] https://uc-ciee.org/downloads/i4E%20micro-PMU%20talk%20Oct%2019.pdf
[27] "Synthesizing virtual oscillators to control islanded inverters", B. Johnson, M. Sinha, N. Ainsworth, F. Dorfler, and S. Dhople. IEEE Transactions on Power Electronics. Volume 31 (8). pp. 6002-6015. 2016.
[28] "Frequency Response Assessment and Enhancement of the U.S. Interconnections towards Extra-High Photovoltaic Generation Penetrations — an Industry Perspective," Y. Liu, S. You, J. Tan, Y. Zhang, Y. Liu, IEEE Transactions on Power Systems. In revision.

to enhance local situation awareness of BTM solar PV and DERs for normal operating conditions as well as in service recovery. PV systems often communicate to utilities, aggregators, and other grid operators over the public internet. As a result, the power system cyber-attack surface has significantly expanded. At the same time, solar energy systems are getting equipped with a range of grid-support functions that - if controlled or programmed improperly - present a risk of power system disturbances. As the experience and sophistication of cyber adversaries grow, so too must the US power system's defenses, situational awareness, and response and recovery strategies. [29_30]

Therefore, research, development, and field validation are needed for solar observability or situational awareness technologies at the grid edge to support planning and operation with high PV penetration. Primary focus areas include PV-integrated sensor technologies, secure and robust communication, advanced data analytics (including machine learning) and detection of cyber-intrusion. Projects may also be considered with secondary focus areas, which enhance grid-edge observability of solar systems by integration with additional planning, operations and business unit systems.

Approach

The technical approach will focus on developing and integrating observability technologies with solar PV and DERs to support planning and operation of distribution systems. Observability here is defined as a mechanism by which sufficient information about solar PV and DERs is acquired to accurately monitor and reliably operate the distribution system. Primary research areas include sensor technologies, secure and robust communications, advanced data analytics that can be easily included in PV system design and integration. To compensate for the lack of up-to-date and accurate multi-phase network models for distribution feeders, machine learning techniques can be incorporated.[31] These machine learning algorithms will include BTM solar and other measurement types and are robust in a range of temporal and spatial scales. With the proliferation of (sometimes low-cost) sensor and telecommunication technologies, it is critical to consider interoperability, standardization, and uniform infrastructures.

Secondary research areas will consider: real time autonomous and local-decision making methods to address solar generation and load variability – without the need for massive data communication; [32] integrating solar observability to DERMS software using standardized interfaces; advancing data analytics that are tailored for systems with high penetration of solar PV and DERs.

On the cyber security front, the research will leverage established industrial control and power system cyber security prior work to implement state-of-the-art cyber security best practices. The research should address the potential cyber security vulnerability in PV and DERs and develop and commercialize innovative technologies to harden PV systems, protect networks from penetration, detect intrusions, and effectively respond to cyber security breaches.

Outcome

Research in this area is expected to result in new software and hardware solutions and data analytical methods for solar observability that inform system operators and/or automated devices to make correct planning and operation decisions.

Specific outcomes may include the following:

[29] "An Attack-Resilient Middleware Architecture for Grid Integration of Distributed Energy Resources", Y. Wu, G. J. Mendis, Y. He, J. Wei, and B.H. Hodge, IEEE Global Communications Conference, Exhibition and Industry Forum 2016 (GLOBECOM), December 4-8, 2016, Washington, DC.
[30] "Roadmap for Photovoltaic Cyber Security", J. Johnson, SANDIA REPORT, SAND2017-13262, December 2017
[31] Nick Allen, et al, "Data-driven Management of Distribution Systems with High Penetration of DER", Whitepaper by SLAC
[32] https://www.greentechmedia.com/articles/read/moving-the-open-standard-for-grid-edge-controls-from-pilots-to-markets#gs.xQ==TqA

- Sensor technologies that are easily and cost effectively included in PV system design, especially smart inverters and low-cost smart meters;
- Secure and robust communications that enable solar visibility;
- Advanced data analytics and applications that exploit new features in solar observability;
- Cyber security technologies that harden PV systems and protect distribution networks;
- Integration of all of the above

Topic Area 3: Solar + X

Objective

The impacts of solar power on the distribution grids are fundamentally due to two key characteristics solar generation: a) constrained solar availability—the fact that the solar energy is available only during daytime, with the highest amounts of energy primarily from mid-morning till late afternoon whereas for a typical load profile in a residential or commercial installation, demand increases during early morning, levels off during the day, increases during early evening and tapers off later in the night, and b) variability – that solar power changes with solar irradiance and cloud transients. As penetration of solar increases, it is imperative that these two attributes are handled in a fashion that maintains grid reliability, resilience, and power quality while reducing curtailment of available solar power and enabling sustainable performance to achieve cost efficiency and societal benefits of solar and grid technology investments.

The widespread adoption of smart distributed technologies - behind the meter and on the customer premises - offers new opportunities for dispatchable solar, i.e. solar power on demand and in desired amount. A "Solar + X" solution – consisting of customer owned and co-located distributed PV, energy storage, smart building load, electric vehicles, and optimized local control software, etc. – not only can reduce the total integration and operation cost of these assets, but also has the potential to provide grid services (including energy, capacity, and reliability and resilience services). A study carried out by LBNL and NREL reports that demand charge savings from a combined BTM PV and storage system are greater than the sum of PV and storage deployed alone[33]. Many challenges still remain. In the areas of resilient operation, interoperability, control coordination, communication, and scalability, there is lack of holistic design before assets are deployed, resulting in added integration cost, non-optimal DER asset utilization, and operation complexity.

Research and field validation are therefore needed for innovative approaches to integrate BTM solar PV with synergistic DER technologies in a holistic manner to support dispatchability and provide grid services – especially the resilience service. Such an integrated solution should be scalable to significantly higher levels of DER penetration with standardized and proven external and internal interoperability capabilities. The solution thus developed is expected to have minimal interconnection review and approval process by the utility due to the standard nature of capabilities, communication, control and data exchange attributes, and is also expected to facilitate the determination of the optimal distribution circuit upgrades by the utility and the needed modifications to behavior of loads for enabling high penetrations of solar.

Approach

The technical approach will focus on integrating BTM PV with energy storage and smart load control to perform the following functions: (1) identify and store solar generation in excess of local load during high supply and low usage periods, and release the stored energy during peak load hours when the power from solar

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[33] "Solar + Storage Synergies for Managing Commercial-Customer Demand Charges", P. Gagnon, A. Govindarajan, L. Bird, G. Barbose, N. Darghouth, and A. Mills, National Renewable Energy Laboratory and Lawrence Berkeley National Laboratory.

plants are reduced, providing supply shifting on a daily basis; (2) decrease the variability of solar power output, provide a robust and sustainable path in mitigating potential adverse impacts of high solar penetration; (3) organize the resource capabilities to provide grid services and be compensated for them; and (4) organize the resource capabilities to provide power to critical load during outages.

The solution as envisioned will have the following features:

- Be grid-connected,
- Continue operation in a “resilient” mode to provide critical power during outages,
- Consist of the solar PV, energy storage, smart loads, electric vehicles acting as both load and storage,
- Utilize coordinated control of smart inverters, load management, and smart charging/discharging,
- Be interoperable internally and externally using industry standard protocols that satisfy communication and control capabilities as required by the local utility, home/building energy management systems, and DERMS,
- Have the capabilities to respond to electricity market price signals and incorporate solar and load variabilities in determining optimal behavior of the local system.

Projects may consider traditional firm DER interconnection requirements as well as emerging flexible interconnection approaches (such as those sought in Topic 1) and innovative compensation mechanisms. In an effort to minimize the overall system cost for solar integration and look beyond battery storage as the only solution space, more utilizations of estimation of solar and load, of advanced data analytics, and of artificial intelligence are anticipated in order to enhance system operations. Additional considerations may include solutions that support zero-energy homes and buildings with high level of BTM solar integration and utility partnership field validations utilizing flexible interconnection agreement. Project should have an assessment of economic viability of the system or component in the application as part of the project, with potentials for new automation tools for modeling and trade-off analysis of PV curtailment versus distribution infrastructure upgrade.

Outcome

Research in this area are expected to result in holistic “Solar + X” designs that increase the BTM solar PV dispatchability and provide grid services by integrating with customer-owned co-located DER technologies, such as, energy storage, building controls, and electric vehicles. Such integrated solutions will be scalable to significantly higher levels of DER penetration, reduce system integration cost, and increase asset utilization and thus customer value.

Specific outcomes may include the following:

- “Plug-in” DER platform for connecting and integrating small scale PV, storage, smart load, and electric vehicles,
- Control optimization algorithms for BTM solar and DER, using either firm or flexible DER interconnection requirements,
- Standardized grid services that can be provided by the onsite DERs, especially resilience services,
- New automation tools for modeling and trade-off analysis of PV curtailment versus distribution infrastructure upgrade.

5 Preparing the Solar Workforce for the Industry's Future Needs

Summary

The solar industry has experienced significant expansion since 2010, in terms of both capacity additions to the grid and employment. Consequently, a large number of solar hiring managers report difficulty due to a lack of experience or technical knowledge in applicants, insufficient qualifications of applicants, and the high volume of new workers that are required. In addition, studies suggest that more value (e.g. in terms of profit margins) can be realized by industry players if a greater focus is placed on recruiting from larger talent pools than are currently being accessed by employers, simultaneously easing hiring difficulties and improving firms' value propositions.

Further, a robust and well-informed power systems workforce is critical for increasing the reliability, resiliency, and affordability of the future grid. Although the utility sector has historically been considered a staid profession, new and emerging technology has upended the status quo. Integrating technology such as solar and other distributed energy resources into the grid increasingly requires advanced skills at the intersection of digital and power systems. In this context, digital systems refer to technologies that leverage two-way information flow and big data via communications and information technology infrastructure.

New technologies, such as smart inverters and PV-integrated sensors, have the potential to increase the reliability and affordability of electricity. These benefits can be amplified by training and workforce development initiatives that cost-effectively transition technology from R&D to operations. This opens up new market opportunities for solar as the grid is better able to derive various services from distributed generation.

In this paper, we discuss all of these issues and provide ideas, based upon other successful workforce programs and experience from programs funded by the U.S. Department of Energy, on features new programs may wish to incorporate to increase their impact.

Part 1: Expanding Participation in the Solar Workforce

Veterans of the U.S. armed forces, with the large range of hard and soft skills that come with their career paths, are ideal individuals to engage in the solar industry at a greater level than ever before. Previous and continuing efforts in the space of veterans' workforce development have led to resources and programs such as Warriors to Work, Hiring Our Heroes, and Solar Ready Vets. These programs each engage with the veterans and active duty communities in different ways to provide tools, training, and/or placement in internships and apprenticeships in target industries, but there are still additional opportunities for growing the community of veterans employed in the solar industry (e.g. e-learning to provide software skills without regard to a worker's geographic location, or innovative combinations of these programs to maximize their best traits). Skilled veterans are a boon to any industry and a talent pool the solar industry should draw from in even greater quantities, and in more diverse ways, than it has previously.

As the solar industry enters new markets across the country, the solar industry needs to expand its efforts to grow participation in training and job placement programs. Many firms have commonly reported difficulties in recruiting sufficient quantities of talented employees, suggesting that the industry lacks a pool of qualified workers that live and work in the communities they hope to serve.

Strategies for New Solar Training Initiatives: Veterans

The Solar Energy Technologies Office has identified a number of strategies, both specific to veterans training programs and relevant to any workforce development initiative, listed below. These items are provided for the purposes of continuing thoughtful discussion on the topic and encouraging others to benefit from a number of lessons learned in the field.

1. New training programs would ideally **have strong partnerships with – or be already embedded in – the solar industry**, to enable placement of participants into jobs as frequently as is possible. Additionally, this guarantees program administrators will have **sufficient up-to-date knowledge regarding the state of the solar industry and open job categories that are growing** and in need of expanded training efforts.

2. Programs that **empower veterans that are already working in the solar industry** have the potential to significantly improve veterans recruiting efforts at individual companies, providing transitioning service personnel with a mentor who can guide them through the various intricacies of the transition process and help them build a professional network in the civilian workforce.[34]

3. Typically, workforce development programs limit their scope to training and resource provision for individuals seeking employment in an industry. However, there is potential value to be captured by also **engaging with employer firms with training opportunities for existing staff, especially in the context of veterans hiring**. Providing guidance to civilian hiring managers and Human Resources (HR) staff at solar firms regarding the differences between civilian and military career structures has the potential to provide veteran job applicants with a smoother and more informed hiring process.

4. Existing programs in transitioning service member training for the solar industry (e.g. Solar Ready Vets) have focused specifically on the hardware side of the industry (e.g. installation). One field currently not pursued by these programs, but which certain specializations of military personnel may have significant value to add, is that of **cybersecurity for the benefit of the electrical grid**. There are a number of unique challenges and opportunities in cybersecurity for the solar industry that are explored in greater depth in other reports.

5. It is important to ensure that those exiting the military who need the most help contributing to the solar industry are also those that are being helped: as such, any new program in this space should **start with an analysis of Military Occupational Specialty (MOS) codes that are most relevant to the solar industry as well as an analysis of MOS codes that historically have seen the most unemployment and underemployment in recent years**. A program with the greatest impact is one that targets participants that may be well-suited to a job in the solar industry based upon their background, but that still need some additional training to truly be competitive.

Envisioning the Solar Workforce of the Future: Expanding Participation in the Solar Industry

According to the Office of Management and Budget, the *FY 2019 Administration Research and Development Budget Priorities*, it is currently a priority of the U.S. government to support "actions that place an emphasis on expanding the Science, Technology, Engineering and Math (STEM) workforce to include all Americans."[35] A full citation of these STEM training priorities can be found in the link below. Other industries have derived significant economic benefits from increasing participation in their workforce from broader talent pools and, as such, the solar industry has an opportunity to benefit from new workforce initiatives. Solar employers frequently cite difficulty in finding fully qualified employees, suggesting that the existing talent pools being tapped by the industry may not be sufficient in providing the skilled labor solar needs. As such, an opportunity exists for programs that grow and expand the labor pool.

[34] *Veterans in the Workplace*. (U.S. Chamber of Commerce Foundation, 2016).
[35] Mulvaney, M. (August 17, 2017). *FY 2019 Administration Research and Development Budget Priorities* [M-17-30]. Retrieved from https://www.whitehouse.gov/sites/whitehouse.gov/files/omb/memoranda/2017/m-17-30.pdf

Part 2: Digital Adaptation Training for Distributed Energy Resources on the Grid

The increasing penetration of solar electricity systems can create new challenges and opportunities for integrating solar assets into the electric grid. At high levels of penetration, the variability of solar generation must be addressed through grid and/or complementary technology integration, such as advanced power electronics, controllable loads, electric vehicles, and storage, which make the relationship between supply and demand more flexible.

These changes have contributed to the rapid evolution of the power systems sector, as operations, planning, and data management models shift to identify new best practices to increase efficiency while accounting for emerging risks, such as cybersecurity. However, despite the ample opportunities to be part of a dynamic industry, the power systems sector is struggling to recruit and retain talent in entry-level to management positions. This exacerbates the issues associated with adapting to new technology in the marketplace. Training and workforce development are critical to de-risk new technology and utilize available energy infrastructure. New initiatives should focus on the training and workforce needs of the utility of the future. Training and workforce efforts may range from system-level interventions, such as developing new credentials and incentives program, to more direct interventions, such as content generation and use of novel pedagogical approaches.

Topical Areas of Interest

The communications and measurement capabilities of the grid are rapidly increasing and distributed energy resources (DERs), such as solar, are causing the grid to become a much more dynamic system. New technology has the potential to increase the reliability, resiliency, and affordability of the grid if incorporated into operations, planning, and data management practices. Training and workforce development can fill this emerging skills gap at the intersection of power systems and digital systems. The electricity industry needs a cross-disciplinary workforce that can understand, design, and manage cyber-physical systems. In this context, digital systems refer to technologies (such as Internet of Things, advanced sensors, controls, data analytics) that leverage two-way information flow and big data via communications (such as wireless internet, cloud services, mobile) and information technology infrastructure. There are opportunities and risks associated with new and emerging technology in operations, planning, and data management. Successful workforce initiatives may not cover this full scope.

Operations. The future grid, often referred to as the smart grid or grid edge, is characterized by two-way flows of electricity and information. This requires new approaches to control, monitoring, and protection.[36] Training and workforce development efforts for operators, engineers, and management should directly address the implications of new technology on grid operations by integrating it into simulations, incorporating in hands-on learning opportunities, and providing background information. In addition, leveraging these technologies requires the appropriate communications and information technology infrastructure to be in place.[37] This may lead to new job roles that straddle the operations and information technology divide.

Planning. DERs and other technologies also have significant implications for transmission and distribution system planning. Training and workforce development initiatives are needed to translate these implications into specific job functions. For example, training is needed to highlight the best practices for interconnection requests and reduce the costs associated with this step, including ensuring resources exist for all parties involved in the solar permitting process (e.g. project developers). Similarly, distribution system planners need

[36] Farhangi, H. (2010). The path of the smart grid. *IEEE power and energy magazine*, *8*(1)
[37] PNNL. 2015. The Emerging Interdependence of the Electric Power Grid & Information and Communication Technology. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24643.pdf

to understand how to use DER resources strategically for non-wires alternatives to defer capital project and maintenance costs. In addition, training efforts could help utilities leverage tools such as agent-based models and machine learning to predict temporal and spatial trends in distributed solar adoption by incorporating social and behavioral factors.[38]

Data Management. Utilities report that costs, regulatory uncertainty, integration of new technology, and internal resistance to change are the top obstacles for evolving a utility's business model[39]. Training can facilitate this transition by increasing familiarity with new technology to de-risk adoption. In addition, the emergence of big data in the electricity sector opens up significant opportunities to transform the way that utilities do business. Training is needed to ensure that utility professionals, from engineers to in-house data analysts, understand how and when to use data to make decisions. Utilities can use data streams to optimize maintenance and replacement schedules for grid infrastructure. In addition, utilities can also use big data to provide consumers with more relevant and timely information. For example, new technology, such as distributed energy resources and advanced metering infrastructure that leverage real-time communications, can generate data that make utility programs more efficient and economic.

In addition, utilities can open up market opportunities by sharing data with researchers and industry, but doing so requires a staff capable of safely and securely building the necessary data infrastructure and access schemas for sharing relevant data sets.

Cross-Cutting Risks

Grid edge technologies, such as the ones discussed above, are not without risk. The digitization of the grid presents major cybersecurity challenges and there are reliability risks associated with balancing new and legacy technology. Training and workforce development initiatives can de-risk new technology by addressing these challenges directly.

Cybersecurity risks. As the use of communications technology on the grid increases, cybersecurity risk also increases. Cybersecurity risk ranges from viruses that slow down computers to malicious power injection attacks that put linemen's lives at risk. In 2018, 81% of utility professionals reported that physical and cyber security was their top issue. [39] This need increases demand for expertise as well as new job roles. There is a high demand for cybersecurity professionals in power systems – but a limited supply of experts who understand both cybersecurity as well as power systems. This gap can open up vulnerabilities at the intersection of information technology (IT), which includes servers and networks, and operational technology (OT), which includes sensors and control mechanisms.[40,41]

Technology integration. There are numerous challenges associated with integrating legacy and new technology in the grid. For example, the emergence of a large quantity of microgrids could have significant impacts on the larger electricity grid. Sudden drops in demand could necessitate similar drops in generation in a short timeframe, which could undermine system reliability. In order to ensure reliability as technology evolves, power systems professionals may need higher levels of education and training than in the past. For example, the Center for Energy Workforce Development (CEWD) includes IT fundamentals, communication systems basics, and integration of new technology with legacy technology as key competencies for today's power engineers.[42]

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[38] Robinson and Rai. 2015. Determinants of spatio-temporal patterns of energy technology adoption: An agent-based modeling approach. Applied Energy, 151, 273-284.
[39] Utility Dive. 2018 State of the Electric Utility Survey Report.
[40] Hawk, C. & Kaushiva, A. (2014) Cybersecurity and the Smarter Grid. *The Electricity Journal*. http://dx.doi.org/10.1016/j.tej.2014.08.008.
[41] Idaho National Lab. 2017. Cyber Threat and Vulnerability Analysis of the U.S. Electric Sector. https://energy.gov/sites/prod/files/2017/01/f34/Cyber%20Threat%20and%20Vulnerability%20Analysis%20of%20the%20U.S.%20Electric%20Sector.pdf
[42] CEWD 2011 http://www.cewd.org/Documents/EngCompModel.pdf

Workforce pipeline. Utilities may need to hire more engineers with masters and doctorate degrees.[43] However, there are insufficient numbers of American students choosing to pursue advanced degrees in power systems. While approximately 80% of undergraduate power systems students are domestic, only 35% of graduate students are.[44] Average enrollment of domestic students pursing advanced degrees (MS and PhD) in power engineering decreased by 4.5% in the last two years and part-time enrollment decreased by 10%. This may be due to perceived higher job security, since most domestic students pursue a graduate degree part-time while employed. Utilities, in particular, often restrict hiring to U.S. citizens, highlighting the need for workforce development programs in the electric power industry to be aware of such demographic trends in the student pool.

Future Workforce Initiatives

As the rapid evolution of the solar industry and grid-edge continues, more cost-effective technologies will be available. Without proper training, their ultimate impacts will be limited. As discussed above, the digitization of the grid affects all aspects of the electricity industry. New digital technologies open up opportunities for additional data to be collected, which then need to be processed and analyzed. This report highlights specific opportunities in operations, planning, and data management – but this is not an exhaustive list.

Future workforce initiatives should address the skills needed for the utility of the future as well as the realities of the workforce of today. A successful initiative should identify the most important issues to address and an appropriate solution. A single initiative may or may not cover the span of issues identified above. There are numerous opportunities to improve training and workforce development in the power systems sector, some of which are highlighted below:

- ***Credentials*** – Issues with retention and turnover are exacerbated by a lack of standardization across the industry. Without consensus-based standards and credentials to accompany them, it can be difficult to assess the skills of potential and current employees. In addition, increased standardization could help institutionalize the types of skills needed for new technology and define new job roles that are needed. These types of efforts are best accomplished when the implementers (e.g. utilities, HR departments) are involved in the discussion from the beginning.

- ***Incentives*** – Any workforce initiative also needs to ensure that appropriate incentives are in place to ensure that the professional development is providing value. For example, human resources departments need to understand credentials and needed skills to ensure hiring practices are in line with workforce needs. HR departments could be incentivized to adopt best practices. In addition, incentives are needed to encourage employees to pursue the most important training, rather than what's easiest and most convenient. For example, professionals could be incentivized to cross-train for other job roles to improve inter-organization cooperation. The workforce pipeline needs to understand what will improve their employability and increase their promotion potential. For example, the Solar Career Map developed by IREC highlights advancement routes across the solar industry.[45]

- ***Content Development*** – As technology is developed, new training materials are needed that translate research into operational terms. These training materials facilitate adoption by clarifying who needs to be involved, where it fits in the order of operations, and the additional tools and technology needed outside of an R&D context. As a result, training is needed across the management chain, from CEOs to entry-level. The energy industry's regulatory environment does not always incentivize new technology adoption, even if it is cost-effective. New technology introduces risk, which can be at odds with the

[43] Quadrennial Energy Review 2017
[44] Chaudhuri, N., Hines, P., Kavasseri, R., & D. Ray. (2017). Electric Power Engineering Education Resources: 2015-16 US and Canadian University Survey Results. Report from the Power and Energy Education Committee of the IEEE Power & Energy Society. https://www.ieee-pes.org/images/files/pdf/peec-survey/2015-16_PES_PEEC_Survey_Report_Final_10-11-2017.pdf
[45] IREC. Solar Career Map. http://irecsolarcareermap.org

reliability goals of utilities and commissions. Training can de-risk this process by broadly exposing best practices from pilots and demonstrations to utility staff to increase comfort with new technologies.

- ***Pedagogical Approach*** – Research on education in the workplace indicates that it is detrimental to limit professional development to traditional lecture-based courses. Developments in e-learning, the value of experiential learning, and the role of informal learning are all important to address in any workforce initiative. E-learning is a promising strategy for improving access to training at low cost.[46] It reduces travel costs, scales easily (as evidenced by massive open online courses or MOOCs), and can be self-paced to accommodate a variety of learning styles. In some cases, an online simulation may be insufficient to understand a new technology – for example, a microgrid simulation is not the same as seeing one operate in real life. However, for many technologies related to the digital transition (especially those focused on data analysis), e-learning is fully capable of providing the needed experiential learning opportunities.

In addition, successful workforce initiatives rely on evaluation, stakeholder engagement, and sustainability to have a lasting impact:

- ***Evaluation*** – At a high level, these types of workforce initiatives aim to improve baseline understanding and increase strategic technology adoption and usage. Formal evaluation is critical to ensure that the effort is effective and efficient. Evaluation can be used to assess a pilot before scale-up, improve the design of the program, and as a continued effort to assess impact. Using a third-party evaluator with relevant expertise is considered best practice.

- ***Stakeholder engagement*** – Stakeholder engagement is critical to ensure there is early buy-in for the initiative and continued appetite. Needs assessments and market surveys can be used to assess the level and interest of relevant stakeholders over time.

- ***Sustainability*** – Workforce initiatives should also consider the long-term sustainability of their program model beyond government funding. For example, content development efforts should consider how to keep content up to date over time. In addition, workforce initiatives should consider how new efforts fit into the existing marketplace.

The above highlights some, but not all, of the opportunities for workforce initiatives at the intersection of digital and power systems. In the context of solar, training and workforce initiatives can facilitate and de-risk digital technologies and distributed energy resources. These technologies have the potential to increase the reliability, resiliency, and affordability of the grid if incorporated into operations, planning, and data management practices.

[46] Noe, Clarke, and Klein. (2014). Learning in the Twenty-First-Century Workplace. Annual Review of Organizational Psychology and Organizational Behavior.

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