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Solar Energy Technologies Office Multi-Year Program Plan

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Disclaimer

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* Timothy J Silverman was on assignment to SETO in 2020, when much of this document was written.

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Letter from the Director

The past decade has been one of tremendous change and innovation in the solar industry and, indeed, the whole electricity sector. The share of electricity produced by renewables and natural gas has almost doubled, with solar's share increasing more than 30-fold to reach 3% today. Yet an even greater rate of change and innovation is needed to reach President Biden's ambitious goal to decarbonize our electricity grid by 2035. For solar technology, this likely means providing 30%–50% of electricity, with as much as a terawatt of solar capacity by 2035.

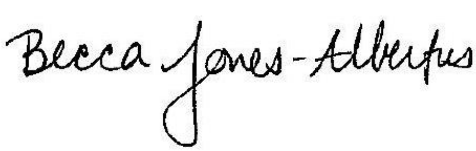
Solar technology has advanced rapidly over the past decade — for example, solar panel efficiencies increased by 30%, trackers became cost-effective, and solar power electronics developed capabilities to provide a broad array of grid services — and the costs of solar electricity have fallen by roughly 80%. These advances provide confidence in our ability to rapidly innovate to meet the Nation's climate goals. At the same time, it is critical that we bring increased focus to reducing soft costs and ensuring equitable access to the environmental, economic, and societal benefits of increased solar deployment.

The U.S. Department of Energy Solar Energy Technologies Office (SETO) plays an important role in setting the agenda for solar energy research, development, demonstration, and deployment, from advancing next-generation technology to tackling sticky market barriers. This Multi-Year Program Plan describes our strategy for the next five years to accelerate the advancement and equitable deployment of solar energy technologies in the United States. This plan lays out goals for 2025 that will support low-cost, reliable solar electricity, rapid solar deployment, and enable solar technology to meet energy needs beyond electricity.

I would like to thank the lead author of this plan, Tim Silverman, who worked with SETO's staff to collect input and draft these goals. This plan reflects the collective expertise of SETO's talented teams, representing countless hours of conversations and analysis. Most of the goals in this plan were presented at the 2020 SETO Peer Review, where we received feedback from solar industry experts, business leaders, researchers, and other stakeholders who will be instrumental in achieving these goals.

Just as the solar industry met and exceeded ambitious targets we set in the past, we know that the creativity and ingenuity of the solar community will enable us to meet these goals and inspire us to be even more ambitious in the years to come.

Thank you for taking the time to read our multi-year plan.



Becca Jones-Albertus

Director, U.S. Department of Energy Solar Energy Technologies Office

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Executive Summary

The U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) does research, development, demonstration, and deployment assistance for solar energy. We advance national progress on climate action, clean energy job creation, and energy justice.

Our vision is for solar energy to play a fundamental role in reaching the Nation's clean energy goals and resolving the climate crisis. Our mission is to accelerate the advancement and deployment of solar technology. Everything we do advances solar technology's ability to provide *low-cost* and *reliable* electricity, *rapid deployment*, and *energy beyond electricity*.

Our program of research, development, demonstration, and deployment assistance is organized into five budget areas: photovoltaics (PV), concentrating solar-thermal power (CSP), systems integration (SI), soft cost reduction (SC), and manufacturing and competitiveness (MC).

The program's activities and specific goals for 2025, and relevant budget areas, are summarized in the tables that follow.

Low-cost electricity
Lowering the cost of electricity from PV
Goal · Levelized cost of energy (LCOE) is less than $0.03/kWh in utility-scale PV systems (PV, SC, MC)
Goal · LCOE is less than $0.08/kWh for commercial PV systems and $0.10/kWh for residential PV systems (SC)
Increasing flexibility to reduce grid integration costs
Goal · Utility-scale PV plus energy storage systems cost less than $1.36/$W_{DC}$ (SI)
Lowering the cost of electricity from CSP
Goal · Solar-thermal electricity with a ≥50% efficiency power cycle is demonstrated (CSP)

Reliable electricity
Supporting the reliability of the power system
Goal · Reliable operation is demonstrated at scale in a power system with 75% power contribution from inverter-based sources (solar, wind, and battery storage) (SI)
Goal · Specific long duration thermal energy storage (TES) system configurations with positive NPV are identified (CSP)
Goal · A pumped TES system has a round-trip efficiency of >50% (CSP)
Enhancing the resilience and security of the grid
Goal · A power system uses PV and storage to demonstrate rapid recovery of critical electricity services after a cyberattack or physical event (SI)

Rapid deployment

Growing the U.S. solar industry

Goal · A well-supported and diverse solar workforce meets the needs of the industry and of disadvantaged communities and grows to employ at least 300,000 workers (SC)

Goal · 1 GW/year of new U.S. PV manufacturing capacity is based on technology that was not yet commercialized in 2020 (MC)

Goal · The solar hardware installed in the United States has at least 40% domestic value (MC)

Reducing the life cycle impacts of solar energy

Goal · New materials, designs, and practices are demonstrated for reducing the environmental impact of PV technology, prioritized based on a life cycle impacts benchmark (PV, SC)

Opening new markets

Goal · 1 GW_{AC} of PV installed in 2025 is combined with another use, such as agriculture or building surfaces (SC, MC)

Ensuring that solar energy benefits all

Goal · 100% of U.S. energy consumers can choose residential solar or community solar that does not increase their electricity cost (SC)

Energy beyond electricity

Reducing industrial emissions using solar thermal technology

Goal · System concepts are defined and key components are validated for solar process heat in carbon-emissions-intensive, high-heat-demand industries (CSP)

Finding the best ways to make solar fuels

Goal · System concepts are defined and key components are validated for producing fuels from concentrated solar energy (CSP)

Office Overview

The U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) is part of the Office of Energy Efficiency and Renewable Energy (EERE). We advance national progress on climate action, clean energy job creation, and energy justice.

This is SETO's Multi-Year Program Plan for fiscal years 2021 through 2025. The Multi-Year Program Plan explains the purpose and the priorities of the office and sets goals for solar energy for 2025. This plan explains how we will accelerate progress toward these goals.

Vision and Mission

Vision

Resolving the climate crisis requires reducing climate pollution in every sector of the economy. Most of the Nation's greenhouse gas emissions come from burning fossil fuels [EPA 2020]. Solar energy is an inexhaustible and climate pollution-free alternative to fossil fuel combustion. Our office advances the technology to use sunlight as a source of clean energy.

The Biden administration is working to put the United States on an irreversible path to a 100% clean-energy economy, reaching net-zero emissions no later than 2050. A first step toward this goal is decarbonizing the electricity sector by 2035. Solar energy will play a fundamental role in reaching these national goals.

Solar electricity is often already cost competitive with conventional power plants. And solar technology is predicted to frequently be the lowest-cost zero-emissions generation option for decades to come. Analysts project that decarbonizing the grid will probably lead to a U.S. electricity generation mix that is 30% to 50% solar [SFS 2021, Phadke 2020, Larson 2020]. An example scenario is shown in Figure 1. Producing this much clean electricity will require us to deploy as much as 1 TW_{AC}, a trillion watts, of alternating-current solar capacity. While about 15 GW_{AC} were installed in 2020 alone, annual deployment must increase by a factor of 2–5 to reach 1 TW_{AC} in 2035 [EIA EPM 2021, SFS 2021].

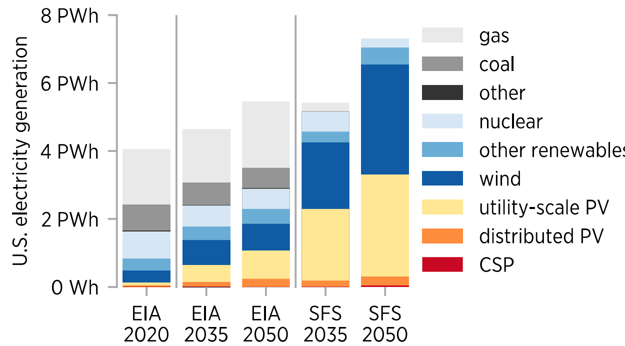

Figure 1. Projections for the electricity generation mix from the U.S. Energy Information Administration (EIA) 2021 Annual Energy Outlook (AEO) and the National Renewable Energy Laboratory (NREL) Solar Futures Study (SFS) show that solar energy will make a major contribution in 2050 [EIA AEO 2021, SFS 2021]. The reference case from the EIA AEO and the decarbonization and electrification SFS scenario are shown. This SFS scenario is 95% decarbonized in 2035 and 100% decarbonized in 2050. A petawatt-hour (PWh) is a trillion kilowatt-hours (kWh).

Shared Challenges

Realizing our vision in a responsible and equitable way means confronting shared national challenges. We must reduce climate pollution in every sector of the economy; increase resilience to the impacts of climate change; protect public health; conserve our lands, waters, and biodiversity; deliver environmental justice; and spur well-paying union jobs and economic growth. We are committed to tackling these challenges.

Solar energy reduces climate pollution and protects public health by replacing fossil fuel combustion with an emissions-free energy source. Reducing natural resource extraction for fuel helps conserve our lands, waters, and biodiversity. Solar power plants can have environmental impacts and we work to understand and minimize these impacts. We are committed to resolving the disproportionate environmental burden that the energy system has placed on communities of color and low-income communities. The U.S. solar industry already employs hundreds of thousands of Americans. Substantial growth in solar jobs is expected as the Nation accelerates solar energy deployment to meet climate targets. We work to make the benefits of these jobs available to disadvantaged communities.

Mission

Our mission is to accelerate the advancement and deployment of solar technology.

We execute our mission by:

- Funding projects,
- Supporting facilities, primarily at the National Laboratories,
- Sponsoring prize competitions,
- Convening experts, and
- Providing relevant and high-quality information to decision-makers and interested parties.

We provide funds through a variety of mechanisms, including:

- Competitive financial assistance, typically cooperative agreements,
- Prize challenges,
- National Laboratory funding calls, and
- Other funding programs.

Our work is a collaboration with:

- National Laboratories,
- Universities,
- The energy industry and adjacent industries,
- Entrepreneurs,
- Investors,
- Nonprofit organizations,
- Federal agencies, and
- State, local, and tribal governments.

Each of these groups has unique capabilities and needs, so specific funding opportunities may target different groups. For example, funding to develop unique facilities for testing and measurement or strategic analysis is focused at national laboratories. Funding aimed at developing leading-edge, high-risk technologies is often focused at universities. Funding opportunities advancing emerging solar technologies are typically open to all stakeholder groups and coordinated through project partnerships to enable a transition to the private sector.

Whenever possible, we make our results available to the public. We encourage awardees to make software tools and data freely available online when this does not compete with the private sector. Our awardees also commit to disseminating their findings, including results and recommendations, to the appropriate audience.

Our mission drives us toward our vision. We are taking the first step toward our vision for 2050 through a set of specific goals for 2025. These goals, and the priorities they embody, are described in detail below.

Federal Role of the Office

Scope

SETO funds projects that *advance* and *deploy* technology for converting sunlight into electricity or industrial process heat.

Advancing solar technology means improving cost, performance, and fundamental understanding. It includes:

- Developing new materials, components, devices, processes, and systems,
- Improving existing materials, components, devices, processes, and systems,
- Validating technology improvements,
- Building tools to improve understanding of new and existing technology,
- Analyzing and improving solar energy’s contribution to the grid, and
- Studying ways for solar technology to complement other technology.

Deploying solar technology means supporting solar technology's practical use in the Nation's energy system. It includes:

- Supporting domestic economic activity and employment,
- Improving the non-hardware "soft costs" of solar energy,
- Expanding access to the benefits of solar energy, and
- Increasing solar technology adoption in support of climate action.

Our work on the electricity grid includes only topics where solar energy integration has a major effect and is carried out in coordination with the DOE Office of Electricity, and other offices across DOE through the Grid Modernization Initiative.

Types of Projects

SETO funds projects that do technology research, development, and demonstration and projects that provide analysis and technical assistance. These project types include different contributions in different parts of the program. For example, demonstration projects are especially important in CSP and systems integration, two technology areas that rely on full-scale validation for advancement. Analysis and technical assistance projects are important for soft costs reduction and for advancing domestic manufacturing.

Our projects last one to five years, and each year of funding may focus on a slightly different set of priorities.

Maturity Level

The earliest-stage work we fund is applied research that solves practical problems. While funding decisions are technology-agnostic, we prioritize projects that can improve solar technology's delivery of our priorities in time to help resolve the climate crisis.

We choose projects at a stage or with a scope that the private sector cannot support fast enough on its own. Our portfolio covers a range, from risky with revolutionary potential to lower-risk with evolutionary potential. Some projects cover all or part of this range. We fund demonstration projects and provide commercialization and deployment assistance.

Energy Justice and Equity

Communities of color and low-income communities have incurred disproportionate environmental and health impacts due to pollution from our Nation's energy system. These communities also have disproportionately high energy burdens and face barriers to accessing the benefits of solar electricity. Solar technology produces energy without fuel cost or emissions and is a key component of delivering energy justice. We work to make the benefits of solar energy available to all. We support efforts to deliver 40% of federal climate investment benefits to disadvantaged communities.

Our office operations prioritize improvements to diversity, equity, and inclusion (DEI). For example, we publicize new employment and funding opportunities in cooperation with minority-serving groups. Our staff cultivate an inclusive atmosphere, with formal training and recognition for DEI work.

We promote DEI in our external interactions. For example, SETO events seek to include diverse and equitable representation of speakers and participants. Our funding opportunities encourage leadership and participation from underrepresented groups.

We include an emphasis on equity in all our funding announcements. We also provide funding for workforce development projects to promote a more equitable solar industry. We sponsor workforce training efforts and fellowships that specifically target underserved groups.

Technology and Market Overview

SETO focuses on solar energy technology that uses sunlight to directly produce electricity using photovoltaics (PV) or to produce heat that drives a thermal power plant or an industrial process using concentrating solar-thermal power (CSP).

The amount of U.S. electricity that is generated by solar technology is increasing. In 2010, less than 0.1% of U.S. electricity generation came from solar energy. **Figure 2** shows that in 2020 this fraction was more than 3%. There is considerable variation in solar energy contribution across states. In California, the state with the most solar capacity, solar technology produced roughly 20% of all electricity generated in the state in 2019. During certain times of the year in California, solar contribution has been even higher, meeting 30% of *daily* demand a few times per year and 40% of *hourly* demand more than 5% of the time [CAISO 2020].

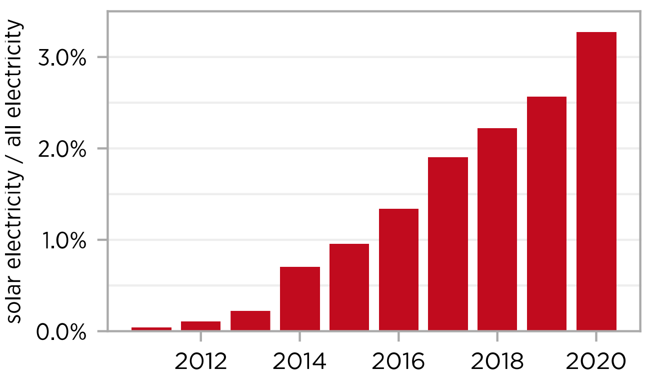

Figure 2. The fraction of annual U.S. electricity generation from solar generation has increased rapidly [EIA EPM 2021].

The cost of solar electricity is decreasing, driven by global economies of scale, technology innovation, and greater confidence in PV technology. **Figure 3** illustrates that levelized cost of energy (LCOE) benchmarks and actual power purchase agreement (PPA) prices for utility-scale PV (UPV) systems have decreased more than 80% since 2010. We produce annual PV cost benchmarks for different locations, both with and without incentives. Our cost targets refer to the benchmark for systems built without incentives in Kansas City, Missouri, a location with average sunlight for the U.S. However, utility-scale PV systems are most often installed in places with high solar resource and with incentives such as the investment tax credit (ITC) [1]. This means that realized energy costs are usually even lower than the LCOE from our average-resource, no-incentive benchmark, shown in red in **Figure 3**. These low costs have driven the deployment of over 95 gigawatts direct current (GW_{DC}) or 76 GW alternating current (GW_{AC}) of PV capacity in the United States as of the end of 2020 [WM 2021, EIA EPM 2021]. About half of this capacity was installed after 2017 [WM 2021] and virtually all of it is connected to the power grid. An additional 2 GW_{AC} of CSP capacity is operational in the United States.

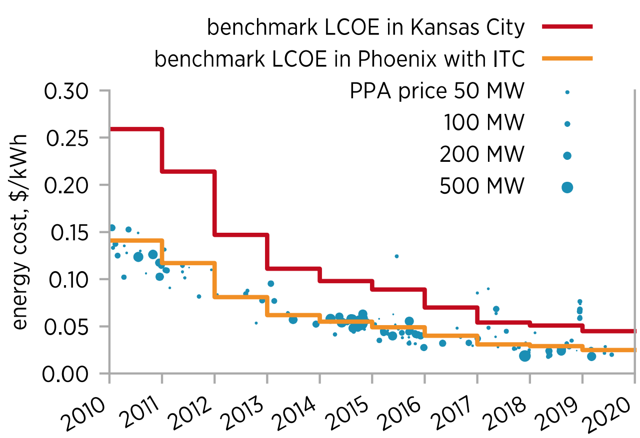

Figure 3. The modeled cost (lines) and actual contracted energy price in power purchase agreements (PPA, circles) for utility-scale PV electricity have declined more than 80% since 2010. PPA prices include incentives such as the investment tax credit [Bolinger 2019].

The solar industry employed about 250,000 people in the United States in 2019. Most of these jobs were in installation, project development, wholesale trade, and distribution. Most of these functions are

[1] The ITC provided a 30% tax credit for PV systems from 2006 through 2019, stepping down to 26% in 2020 and 22% in 2023. In 2024, the credit is 10% for commercial- and utility-scale systems and is eliminated for residential systems.

inherently local and cannot be moved offshore. Solar workers are in high demand and their wages are above the national median wage. The solar workforce approaches, and in some cases exceeds, the ethnic and racial diversity of the U.S. workforce. Solar jobs are available for workers with a range of educational backgrounds and many jobs do not require previous experience. Domestic solar manufacturing, including manufacturing of mounting structures, PV modules, monitoring systems, and inverters, employed over 34,000 people in 2019 [Solar Foundation 2020].

Operating the power system becomes more difficult with increasing contributions from solar power. The power system reacts faster to interruptions owing to the power electronics that connect it to solar generation [AEMO 2019]; the power system needs more flexible resources to accommodate the diurnal and uncertain nature of solar generation [CAISO 2016]; and widespread rooftop PV and other distributed energy resources (DER) are mostly not visible to power system operators and have the potential to cause two-way power flow [EIA AEO 2020]. New operational strategies need to be developed to tackle these challenges and maximize the value of solar generation beyond just providing energy to the power system [Mills 2012]. This fundamental need has led to increased interest in combining solar technology with sensing and communication, analytics and control, and energy storage, and in enhancing the capabilities of PV power electronics.

Technology advancements provide opportunities to increase the value of solar energy as deployment grows. Sensing and communication have advanced to provide higher temporal resolutions and wider spatial coverage [NASPI 2017, EIA 2018, IEEE 2018]. Analytics and control have been improving the fast dynamics of the power-electronics-heavy system [Isik 2018, Kirby 2019, Johnson 2014] and the visibility of DER [Quint 2019]. Battery storage is increasingly being installed alongside PV systems to mitigate the variability of solar energy and provide fast-responding control capabilities [Rudnick 2017, CPUC 2020]. This allows PV systems to increase their support of the reliability and resilience of the grid while delivering affordable energy. CSP systems, which use traditional thermal power generators, can also support the reliability of power system and can provide stored solar energy at the times of day when it is most needed.

Distributed PV systems offer individual energy choice and opportunities for household and community resilience that utility-scale PV cannot provide. These advantages may also extend to local pollution and cost benefits in some cases [Denholm 2014]. Americans who install PV on their homes spend about 70% of the system's cost on non-hardware expenses called soft costs, such as customer acquisition, permitting, and installation labor. Although hardware costs have plummeted over the past decade, soft costs have been slower to decline in the commercial and residential sectors. Not all households have access to residential solar energy due to unaffordability of financing or lack of a suitable roof [Feldman 2015, GTM 2016]. Reducing soft costs is key to making the benefits of solar energy available to all.

Some new uses of solar energy require additional research. Co-locating PV with agriculture or integrating PV into building materials may address land-use concerns in rural areas and land constraints in urban areas [Gross 2020, Horowitz 2020, Adeh 2019]. Applying CSP to industrial processes, like desalination, fuels synthesis, chemicals synthesis, and food processing can extend the benefits of solar energy beyond electricity. Data and analysis, and sometimes new technologies, are needed to test these new uses.

Office Structure

The office has six teams: The PV team is responsible for photovoltaic technology, which converts sunlight directly into electricity. The CSP team is responsible for concentrating solar-thermal power technology, which converts sunlight into heat and then into electricity or industrial process heat. The SI team works on integrating solar energy technology with other energy technologies and the grid. The strategic analysis and institutional support (SAIS) team supports the program's soft cost reduction area, does cross-cutting analysis in support of the office and external stakeholders, and works to expand access to the benefits of solar energy to all. The manufacturing and competitiveness (MC) team supports entrepreneurs and businesses in developing and commercializing innovative solar products. The operations team provides organizational support for the entire office.

Priorities and Strategic Goals

We organize our goals according to our priorities. Everything we do advances solar technology's ability to provide *low-cost* and *reliable* electricity, *rapid deployment*, and *energy beyond electricity*.

Low-cost Electricity

We advance solar technology's ability to deliver electricity to all at a cost that is low and predictable. In parts of the country, solar electricity is already the lowest-cost form of new electricity generation capacity, but solar electricity is not yet cost-effective everywhere. As solar energy makes an increasing contribution to the grid, it becomes more difficult to cost-effectively integrate it. For solar technology to continue delivering low-cost energy, it must not create undue increases in costs for the electricity system. We advance the low cost of solar technology through these activities[2]:

Low-cost electricity
Lowering the cost of electricity from PV
Goal · Levelized cost of energy (LCOE) is less than \$0.03/kWh in utility-scale PV systems (PV, SC, MC) *Goal* · LCOE is less than \$0.08/kWh for commercial PV systems and \$0.10/kWh for residential PV systems (SC)
Increasing flexibility to reduce grid integration cost
Goal · Utility-scale PV plus energy storage systems cost less than \$1.36/W_{DC} (SI)
Lowering the cost of electricity from CSP
Goal · Solar-thermal electricity with a ≥50% efficiency power cycle is demonstrated (CSP)

[2] The budget areas are shown in parentheses. PV stands for photovoltaics, CSP for concentrating solar-thermal power, SI for systems integration, SC for soft cost reduction, and MC for manufacturing and competitiveness.

Reliable Electricity

For solar technology to provide a reliable source of electricity, solar power plants must support power quality, stability, and cybersecurity. Enhancing reliability also includes harnessing opportunities for solar technologies to couple with energy storage and other distributed energy resources to enhance resilience.[3] Because modern CSP plants have built-in inertia and thermal energy storage, they can also directly contribute to a reliable energy system.

We advance reliable electricity through these activities:

Reliable electricity
Supporting the reliability of the power system
Goal · Reliable operation is demonstrated at scale in a power system with 75% power contribution from inverter-based sources (solar, wind, and battery storage) (SI)
Goal · Specific long duration thermal energy storage (TES) system configurations with positive NPV are identified (CSP)
Goal · A pumped TES system has a round-trip efficiency of >50% (CSP)
Enhancing the resilience and security of the grid
Goal · A power system uses PV and storage to demonstrate rapid recovery of critical electricity services after a cyberattack or physical event (SI)

Reliability can also refer to hardware with long and predictable service life. Because long-lasting hardware contributes substantially to affordability, our work in this area is listed under the low cost priority, above.

[3] Resilience is the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. It is related to, but not the same as, reliability.

Rapid Deployment

Meeting the Nation's emissions targets will require clean energy technology that can be deployed quickly. We support this growing deployment in a way that is responsive to the needs of disadvantaged communities, workers, the U.S. solar industry, and the environment.

We support rapid deployment through these activities:

Rapid deployment
Growing the U.S. solar industry
Goal · A well-supported and diverse solar workforce meets the needs of the industry and of disadvantaged communities and grows to employ at least 300,000 workers (SC)
Goal · 1 GW/year of new U.S. PV manufacturing capacity is based on technology that was not yet commercialized in 2020 (MC)
Goal · The solar hardware installed in the United States has at least 40% domestic value (MC)
Reducing the life cycle impacts of solar energy
Goal · New materials, designs, and practices are demonstrated for reducing the environmental impact of PV technology, prioritized based on a life cycle impacts benchmark (PV, SC)
Opening new markets
Goal · 1 GW_{AC} of PV installed in 2025 is combined with another use, such as agriculture or building surfaces (SC, MC)
Ensuring that solar energy benefits all
Goal · 100% of U.S. energy consumers can choose residential solar or community solar that does not increase their electricity cost (SC)

Energy Beyond Electricity

Reducing climate pollution in parts of the energy system beyond the electric power sector is a long-term endeavor. Solar technology could decarbonize industrial process heat, which is currently supplied almost entirely by fossil fuel combustion. And there may be ways to economically produce chemical fuels that can offset or replace fossil fuels.

Mainstream use of solar energy beyond electricity requires progress in these areas:

Energy beyond electricity
Reducing industrial emissions using solar thermal technology
Goal · System concepts are defined and key components are validated for solar process heat in carbon-emissions-intensive, high-heat-demand industries (CSP)
Finding the best ways to make solar fuels
Goal · System concepts are defined and key components are validated for producing fuels from concentrated solar energy (CSP)

Plan

In 2010, solar electricity cost four to five times more than electricity from conventional generation. Cost reduction was critical for solar technology to succeed. Accordingly, until recently, reducing the levelized cost of solar electricity was SETO's main objective. Now that solar electricity is often cost-competitive with conventional generation, the program adds three new priorities: reliable electricity, rapid deployment, and energy beyond electricity. We use a more comprehensive set of targets than cost alone to track progress on these priorities.

We have set goals that go beyond cost reduction to prioritize reliability, rapid deployment, and energy beyond electricity. Several of these goals deal with the integration of solar technology with adjacent domains, such as the power system, energy storage, land use, structures, the economy, and the environment. We still maintain cost reduction goals so that solar energy can be affordable across the country.

These goals are target outcomes for the entire solar community. Many participants will contribute to realizing these goals. Our program is designed to accelerate progress toward these goals using the specific actions and priorities listed here.

SETO's work is funded in five budget areas: PV, CSP, systems integration, soft cost reduction, and manufacturing and competitiveness. Our work in each budget area is relevant to different but overlapping sets of stakeholders. Below, the goals are organized according to the budget area with primary responsibility for the goal, but in practice, some of the goals are pursued across multiple parts of the program.

Photovoltaics

Background

PV technology converts sunlight directly into electricity. This conversion happens in a solar cell, which is typically a semiconductor device. Multiple solar cells are packaged into weatherproof PV modules, and multiple PV modules are connected with other equipment, such as inverters and transformers, to form a PV power plant or system. Virtually all PV electricity produced in the nation is made in PV systems that are connected to the electricity grid. Utility-scale power plants, roughly 5 megawatts (MW) and larger, provide about 60% of the nation's PV capacity [EIA EPM 2021]. The remaining capacity is split between commercial systems, up to hundreds of kilowatts (kW), and small residential systems, up to about 10 kW.

Adding a new PV-only power plant to the grid is often straightforward and economical. But in parts of the grid that already have a lot of solar generation, it is increasingly common to combine PV power plants with battery storage to better match solar generation with electricity demand. In 2019 about 2% of all UPV systems were paired with storage. Over 30% of new UPV projects proposed for construction in 2022 and 2023 are paired with storage [Feldman 2020b].

Crystalline silicon (c-Si) PV made up 94% of the global PV market in 2019. Of this, about two-thirds was monocrystalline silicon and one-third was multicrystalline. The remaining 6% of the market was served by cadmium telluride (CdTe, 5%) and copper indium gallium diselenide (CIGS, 1%) [SPV 2020]. In the United States, 74% of the utility-scale PV installed through 2019 was c-Si technology, and the remaining 26% was CdTe [EIA-860 2020]. Commercial and residential PV are virtually all c-Si [Barbose 2019].

While the market is dominated by crystalline silicon, the same material that the first practical solar cells were made from, major shifts in mainstream technology have occurred since 2010. Median module efficiency increased steadily, climbing 30%

in non-utility systems, from 14.1% to 18.4%, from 2010 to 2018 [Barbose 2019]. Passivated emitter and rear cell (PERC) replaced aluminum back surface field as the most common solar cell type: 79% of 2019 c-Si cell manufacturing was PERC [SPV 2020]. Single-axis trackers were used in 76% of utility-scale PV systems in 2019 and are particularly prominent in sunny areas [EIA-860 2020]. The changes contributed to a reduction in the PV module price of 85%, from $2.51/watt (W) in 2010 to $0.38/W in 2020, and a reduction in the LCOE of 80% over the same time period [Feldman 2021].

Planned improvements continue: Cells and modules may keep getting larger, c-Si cells may move from PERC to double-sided passivated contact or heterojunction designs, and the extra energy produced by bifacial PV systems, which can collect sunlight from both sides of the PV module, may continue to increase. However, mainstream solar cell materials are advancing toward their single-junction efficiency limits. While high-efficiency tandem cells, which stack more than one solar cell in the same device to increase efficiency, have long been in use in space and in concentrating PV, the mainstream PV industry is exploring low-cost tandem cells for non-concentrating terrestrial applications. Low-cost, high-performance materials and processes, some of which do not yet exist, are critical to the commercial success of these tandem products.

On average, PV project developers now expect PV projects to last over 32 years, up from 22 years in 2007 [Wiser 2020]. The fast pace of PV installations is building confidence in the technology's longevity. New products pass the same or harsher accelerated tests compared with old products that have proved to be reliable. But most PV systems are less than three years old. Reliability testing does not always keep up with the frequent product changes that drive cost and performance improvements. PV system health monitoring is growing in sophistication and is beginning to include advanced electrical performance data analysis, aerial thermography, and in-field electroluminescence imaging, but this monitoring needs further correlation with long-term performance data.

SETO addresses PV challenges in cost reduction, performance improvement, and life cycle impacts. Specific technical goals for these efforts are explained in detail below.

Reaching our goals depends on cooperation among academic and National Laboratory researchers, the PV industry, and the energy financing and investment communities. Our awardees make new technology and new practices available to the industry, which is responsible for adopting, financing, and implementing them to reduce the cost of solar electricity.

Goals

Low-cost electricity
Lowering the cost of electricity from PV
Goal · Levelized cost of energy (LCOE) is less than $0.03/kWh in utility-scale PV systems (PV, SC, MC)

Rapid deployment
Reducing the life cycle impacts of solar energy
Goal · New materials, designs, and practices are demonstrated for reducing the environmental impact of PV technology, prioritized based on a life cycle impacts benchmark (PV, SC)

Approach

Lowering the Cost of Energy from PV

Need for continued cost reduction · For solar energy to continue increasing its support of U.S. energy system affordability, PV cost reductions must continue. Today the unsubsidized LCOE of utility-scale PV systems without battery storage is competitive with the LCOE of conventional power plants [Lazard 2020]. But a PV-only system cannot deliver electricity on demand. In areas with a lot of solar power plants, additional solar electricity has less value. In these areas, new PV systems are increasingly combined with energy storage. Decreasing PV-only LCOE mitigates the decrease in value and leaves more room for these additional costs. Many of the mechanisms for decreasing utility-scale PV LCOE can also apply to residential and commercial PV systems.

Goal · Levelized cost of energy (LCOE) is <$0.03/kWh in utility-scale PV systems

- This goal moves the SunShot goal for utility-scale PV LCOE from 2030 to 2025. The goal is reached when a bottom-up cost model shows that unsubsidized LCOE has reached the target. This model describes a 100-MW utility-scale PV system in Kansas City, Missouri, a location with solar resource near the national average.

Competitiveness with other sources · While LCOE is not a measure of electricity value, reducing LCOE to less than $0.03 per kilowatt-hour (kWh) would make the electricity cost from new PV generation similar to a conventional power plant's variable costs, like fuel and maintenance [Lazard 2020]. In cases where PV generation coincides with load demand, this makes new PV power plants directly competitive with existing conventional power plants. But the coincidence of generation with demand changes as more solar and wind power are added to the grid. In areas where a lot of PV generation is already present, PV may need to be combined with low-cost battery storage or other mechanisms for increasing power system flexibility, such as load flexibility or new transmission, to be competitive with new conventional power plants.

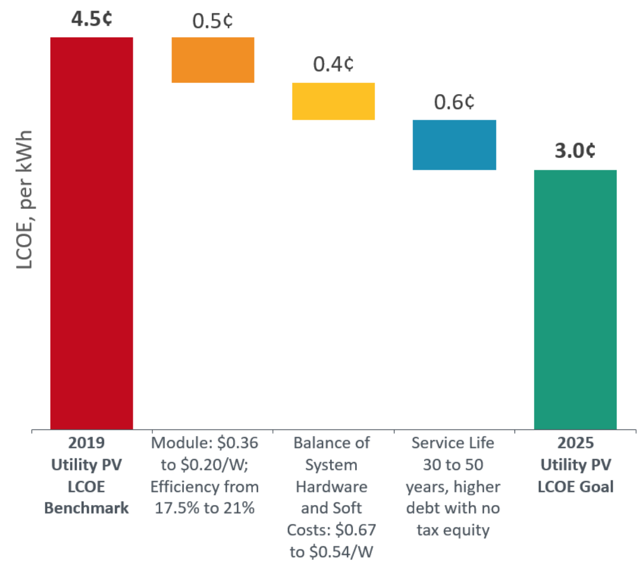

Figure 4. Several performance and cost improvements may contribute to reaching the utility-scale PV LCOE target. LCOE is shown in 2018 real U.S. cents per kWh.

More energy and lower hardware costs · We reduce the cost of PV electricity by increasing the energy a PV system produces over its service life and by reducing the costs to build and operate a PV system. Energy production can be improved through increases in cell and module energy yield and improvements to PV hardware reliability and durability. Costs can be reduced by reducing materials, manufacturing, and operations and maintenance costs. We also support the measurements, characterization, and analysis that translate these results into real-world LCOE reductions. Our work delivers advances that will reach the PV industry in three or more years, covering topics that are outside the focus and reach of industrial R&D alone. Our awardees include the National Laboratories, universities, and the private sector.

One of the most effective ways to increase energy production and decrease LCOE is by improving the efficiency of solar cells and modules. Higher efficiency makes the same amount of electricity available from a smaller, cheaper power plant. Efficiency increases have come from evolutionary improvements to existing technologies, revolutionary shifts to new materials or architectures, and everything in between. Our portfolio delivers progress in affordability by balancing these approaches. Based on the progression of LCOE from 2010 to 2020, we anticipate that the combination of numerous improvements will enable us to reach the 2025 goal. **Figure 4** shows one possible set of improvements.

Absorber materials **·** Only two PV absorber technologies—c-Si and CdTe—are mature enough to directly deliver very-low-cost electricity in 2025, but the 2025 goal is just the first step toward our long-term vision. We support continued improvements to these mainstream products because they can build on the full-scale industry that is already in place. But we also explore emerging technologies, such as perovskite PV, and technologies serving as models that advance long-term scientific understanding of PV, such as III-V materials, made of Group III and V elements in the periodic table. In some cases, these emerging or model technologies may become successors to today's mainstream technology.

Module efficiency and new architectures **·** In c-Si and CdTe PV absorbers, the gap between actual efficiency and theoretical maximum efficiency is closing, and successor technologies are not yet identified. We work to narrow the gap between cell and module efficiency to extract the maximum value from a cell. And we support the development of tandem architectures that can exceed the mainstream efficiency limits by combining multiple solar cell types into one cell or module.

A cell or module with a given indoor-measured efficiency might deliver different amounts of annual energy depending on cell design, module design, system configuration, and system operation. We support continued increases in energy yield through innovations in each of these areas.

Reliability and durability **·** Minimizing LCOE requires making the entire PV system's service life long and predictable, even as product improvements occur multiple times per year. We support improvements to PV reliability through new materials and designs, test and measurement methods, and computer simulations. We also work to identify emerging reliability concerns and quantify and reduce uncertainty in PV system service life with science-based reliability testing and by collecting and analyzing field data on degradation and failure. These improvements reduce uncertainty in the modeled energy output of proposed power plants, reducing the risk associated with investment. Our awardees integrate their findings into the international standards that affect virtually all grid-connected PV globally.

Balance of system costs **·** Over 20% of the hardware cost in a utility-scale PV system is spent on components other than modules and inverters. These balance of system (BOS) components include connectors, wiring, combiners, racks, and trackers. We pursue hardware cost reductions such as new materials, designs, and manufacturing techniques that use less material or less expensive material. BOS innovation can also help PV deliver more energy, longer system life, better durability, and improved safety.

Operating costs **·** Operations and maintenance (O&M) for PV power plants includes monitoring system performance, managing vegetation, cleaning modules, and repairing equipment. We fund work to minimize these costs by studying technologies that can reduce O&M requirements and to perform related activities more cost-effectively.

Reducing the Environmental Impacts of Solar Energy

Quantifying environmental impacts **·** For PV to deliver clean electricity, it must be produced in a way that minimizes waste, energy use, negative effects on human health, and pollution. These consequences of the manufacture and use of PV are not yet routinely tracked. New technology can reduce PV's environmental impact. The information needed to properly prioritize this R&D is not always available.

Publishing a new benchmark **·** We will support an effort to establish a life cycle benchmark for PV. The benchmark will include selected typical and emerging products, such as c-Si PERC, c-Si heterojunction, CdTe, and perovskite, and selected system configurations, such as utility-scale single-axis tracking and rooftop residential.

Building on the success of PV cost benchmarks, a DOE-published life cycle benchmark will effectively disseminate expert analysis to build awareness and acceptance of priorities for reducing impacts. Details of the analysis will be publicly available so others can assess candidate improvements. Because PV is an energy generation technology, energy payback time (EPBT) and energy return on energy invested (EROI) are relevant metrics to assess its net benefit to society. The life cycle benchmark will include metrics like EPBT and EROI alongside more conventional LCA metrics. Producing a benchmark, which includes setting a recommended system boundary and specifying inputs, will give researchers the information they need to tackle the most important life cycle projects.

Technology to reduce environmental impacts **·** In parallel to developing a life cycle benchmark, we pursue technology that is already known to have promise for reducing environmental impacts. This includes new materials, designs, and practices. Choosing new materials and designs upfront can make PV products longer-lasting, less energy-intensive to produce, easier to recycle, and less polluting at the end of life. In some cases, the use of rare, critical, or energy-intensive materials can be reduced, as with reducing kerf loss in silicon, or replaced entirely, as with the replacement of silver with copper. New practices can improve our understanding of environmental impacts to prevent unintended pollution or human health effects, as with improved planning and testing for toxic content in end-of-life PV modules.

Goal **·** New materials, designs, and practices are demonstrated for reducing the environmental impact of PV technology, prioritized based on a life cycle impacts benchmark

- The goal is reached when a life cycle benchmark has been performed and published and technology has been developed according to the priorities identified in the benchmark. The benchmark covers selected typical and emerging products in selected system configurations. The benchmark recommends and rigorously specifies a system boundary that includes manufacture, operation, and decommissioning. The benchmark helps users identify high-priority ways of improving LCA metrics and, similar to the PV LCOE benchmark, is updated annually as technology changes.

Concentrating Solar-Thermal Power

Background

CSP uses a collector field of mirrors to concentrate sunlight onto a receiver. The receiver converts the sunlight to heat and, via a heat-transfer medium, this heat is either converted to electricity, used in an industrial process, or stored for later use. Specially designed industrial processes may someday use concentrated sunlight directly, without an intermediate heat transfer medium, to replace fossil fuels in emissions-intensive industries.

Storing thermal energy is less complicated and less expensive than storing electrical energy. It is straightforward to scale a CSP system's collector field and thermal energy reservoir to provide electricity or process heat for many hours after sunset. Depending on how many hours of stored energy are implemented, CSP plants can act as "peaker" power plants, providing solar electricity when it is most needed; as "baseload" power plants, providing solar electricity at virtually all times of day; or as continuous sources of solar industrial process heat (SIPH), offsetting or replacing the combustion of conventional fuels. Thermal energy storage (TES) technology originally designed for CSP can also be deployed separately in electro-thermal energy storage (ETES) systems in which heat is produced with electricity. ETES plants can store energy produced elsewhere and return it to the grid later as electricity.

CSP plants use a turbine to generate electricity. For grid integration purposes, CSP turbines have the same physical properties as the turbines in a conventional power plant. Combined with their dispatchability, this clears the way for CSP to integrate easily with the power grid.

CSP has not achieved widespread adoption in the U.S. Only direct sunlight can be effectively concentrated using mirrors, so CSP is best suited for the Nation's sunniest areas such as the Southwest. About 2 GW of American CSP plants are operational. Since 2015, an additional 2 GW of CSP capacity has been deployed in the Middle East, North Africa, and China, but no new CSP plant has been built domestically [Feldman 2020]. The minimum practical size for a CSP plant, to optimize LCOE, is currently about 100 MW, requiring hundreds of millions of dollars to build. To see further adoption, CSP technology needs to reach lower costs through technology advancements and increase private-sector investment by reducing the financial risk associated with emerging technology. Some of this technology exists at various stages of maturity but still must be integrated and demonstrated in the field.

There is a path for dispatchable solar electricity and process heat from a CSP plant to be cost-competitive with conventional fuels [Murphy 2019, Kurup 2019, Lazard 2020]. Today the unsubsidized LCOE of a CSP plant with 14 hours of thermal storage is $0.10/kWh, according to detailed cost models. Through technology improvements, component integration, demonstration, and achieving economies of scale, this cost can continue to be driven down. Industrial process heat from CSP technology can also be competitive with process heat from conventional fuels [Kurup 2015].

Some parts of the energy system are challenging to electrify, making them difficult to decarbonize using renewable electricity. CSP could address this challenge using specifically designed plants that drive processes, such as cement production, metals refining, and fuels production, directly from sunlight.

We fund R&D and demonstration to support advancements toward low-cost CSP electricity and industrial process heat. Our R&D efforts include materials and fabrication methods, equipment design and component integration, methods of operation, and analysis of application of CSP toward multiple different applications, such as the electricity grid, water desalination and other industrial processes. Specific technical goals for these efforts are explained in detail below.

Reaching our goals depends on cooperation among academic and National Laboratory researchers, the CSP and adjacent industries, and the energy financing and investment communities. A major asset of CSP is its ability to store energy for later use, so our CSP program is coordinated with the DOE Energy Storage Grand Challenge (ESGC). Our R&D establishes new technologies and reduces investment risk through demonstration. However, private-sector investments are necessary to bring CSP electricity and SIPH technology to scale.

Goals

Low-cost electricity

Lowering the cost of electricity from CSP

Goal · Solar-thermal electricity with a ≥50% efficiency power cycle is demonstrated (CSP)

Reliable electricity

Supporting the reliability of the power system

Goal · Specific long duration thermal energy storage (TES) system configurations with positive NPV are identified (CSP)

Goal · A pumped TES system has a round-trip efficiency of >50% (CSP)

Energy beyond electricity

Reducing industrial emissions using solar thermal technology

Goal · System concepts are defined and key components are validated for solar process heat in carbon-emissions-intensive, high-heat-demand industries (CSP)

Finding the best ways to make solar fuels

Goal · System concepts are defined and key components are validated for producing fuels from concentrated solar energy (CSP)

Approach

Lowering the Cost of Electricity from CSP

Reducing cost with higher temperatures · In 2016, SETO set a goal for CSP with 14 hours of thermal energy storage to provide electricity at an LCOE of \$0.05/kWh by 2030. Reaching this target could unlock CSP deployment in the U.S. Our 2025 goal for CSP LCOE at \$0.065/kWh represents partial progress toward the 2030 goal. Both of these targets are for systems without subsidies in the American southwest with high direct solar resource. As shown in **Figure 5**, multiple performance and cost improvements will be needed to reach the 2030 goal. These include cost reductions for the collector field, receiver, energy storage, and operations and maintenance. The performance improvement shown in the figure is a power cycle net efficiency of at least 50%. The most promising pathway to achieve this is with a high-temperature power cycle such as a supercritical carbon dioxide (sCO_2) Brayton cycle. The cost reductions must be achieved while simultaneously introducing heat-transfer media and components that are compatible with this high-temperature power cycle.

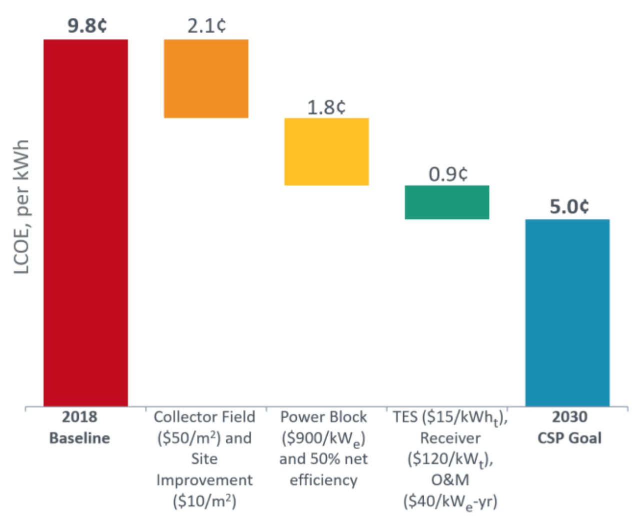

Figure 5. Several performance and cost improvements may combine to reach the 2030 target for CSP LCOE. LCOE is shown in 2018 real U.S. cents per kWh.

Our work developing and demonstrating a high-temperature power cycle aims to realize the third generation of commercial CSP technology, known as Gen3 [Mehos 2017]. Gen3 is the class of technologies that enable solar heat to be collected, stored, and used at temperatures exceeding 565° Celsius, the maximum temperature of conventional molten nitrate salt technology. The goal is for Gen3 technology to deliver heat to an sCO_2 cycle at 700°C or higher. In the example scenario in **Figure 5**, Gen3 technology is responsible for about half the LCOE reduction toward our target.

A major Gen3 CSP technology effort is already underway. The Gen3 program has completed technology development, component validation, and system design projects for receiver, storage, and heat exchanger technology using solid, liquid, and supercritical fluid heat-transfer media. In early 2021, solid particle technology was selected as the most promising heat transfer medium to achieve SETO goals. Efforts are now focused on a megawatt-scale demonstration of this technology before 2025.

High-temperature materials **·** Developing and integrating high-temperature components will require new materials to withstand the demanding thermal and chemical environment of a CSP system. These materials include heat-transfer and storage media and the materials for system components. Our awardees characterize these materials thermophysically, thermomechanically, and thermochemically to ensure their performance, durability, and corrosion resistance. Our awardees also study new manufacturing techniques to enable cost-effective mass production for new parts and special materials.

Power block **·** Our work also reduces power block costs. Supercritical CO_2 turbines can be applied in solar, fossil, and nuclear plants and we collaborate with DOE's Offices of Fossil and Nuclear Energy to advance sCO_2 technology. We also work to realize efficient integration between sCO_2 turbines and a thermal energy storage system, an opportunity that is currently specific to CSP.

Collector fields **·** Low-cost, high efficiency "power tower" CSP systems require solar collector, or heliostat, fields with low cost and high performance. High-temperature solar industrial processes will also rely on high-performance heliostat fields. Nearly half the LCOE reduction in the example scenario in **Figure 5** comes from lower collector field costs. Power tower systems include those to be used in Gen3 power plants and for high-temperature SIPH. Currently, about 45% of incoming solar energy is lost between the collector and the receiver, as illustrated in **Figure 6Error! Reference source not found.**.

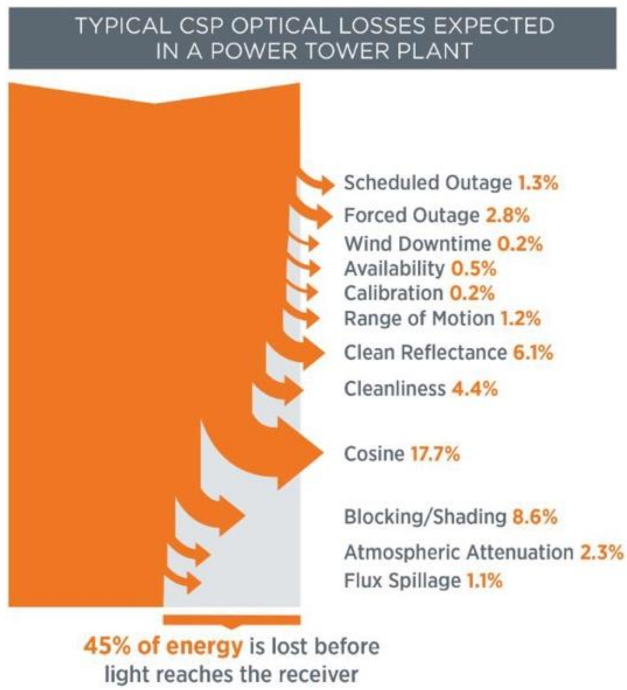

Figure 6. Losses between the collector and the receiver in a CSP system account for 45% of incoming energy.

The heliostat field is an expensive and performance-critical component of a CSP system. Improving the field's cost and performance means less capital is needed to deliver the same energy output. A large collector area (high solar multiple) is a key attribute of a CSP system that has, and effectively uses, long-duration thermal storage.

We pursue heliostat field improvements through better materials, better hardware, and better operational characteristics. Structural cost can be reduced by replacing steel with lower-cost materials or by using lighter-weight reflectors. Improved hardware designs can reduce canting error, tracking error, and soiling losses, all of which reduce efficiency. Operational improvements, such as autonomous control of heliostats, may also help address calibration and tracking issues.

As the industry shifts to higher receiver temperatures, controlling the flux and flux uniformity at the receiver becomes increasingly important. Improvements to these aspects of the heliostat field performance deliver benefits to overall system efficiency.

Integration and demonstration · We reduce the risks associated with investing in new CSP technology by supporting integration and demonstration. Switching to sCO_2 power cycles also substantially reduces the minimum practical size of a plant. Reduced risk and reduced minimum investment lower financing costs and should increase the capital available to invest in CSP technology.

Goal · Solar-thermal electricity with a ≥50% efficiency power cycle is demonstrated

- The goal is met when a prototype of an integrated receiver, storage, and delivery system generating 1 MW or more has been demonstrated. This system must deliver thermal energy to a power cycle's working fluid at more than 700°C, but the turbine is not included in the prototype. The goal applies to any power cycle with a net efficiency exceeding 50%. The sCO_2 Brayton cycle is currently the most promising way to achieve this.

Supporting the Reliability of the Power System

Shifting energy supply and demand · The grid uses stored energy to enhance reliability. Today, batteries supply peaking capacity, energy time-shifting, and operating reserves. As the grid integrates more variable renewable energy, the need for peaking capacity will increase and new needs will arise for daily, multi-day, and seasonal capacity and energy time-shifting [Denholm 2021]. We support work on thermal energy storage systems, which can easily scale to long durations, independently of their peak capacity. These systems could have lower cost than batteries when storing energy for longer than a few hours. We also support work on thermochemical storage concepts that can store energy for many days without loss.

Thermal energy storage · TES allows the amount of stored energy to be adjusted independently of the equipment that uses the energy. Plants using TES can add storage capacity as demand increases, without upgrading the plant itself. Our work in thermal energy storage takes full advantage of technology developed in the Gen3 CSP program, described above. Higher temperatures lead to higher thermodynamic efficiencies and we push the limits of new and existing materials, components, and system designs. Reaching high temperatures requires advanced storage media, component materials, heat exchangers, pumps, and tanks. We support the development and demonstration of these technologies.

Goal · Specific long duration thermal energy storage (TES) system configurations with positive NPV are identified

- The goal is reached when detailed technoeconomic analysis shows that specific thermal energy storage systems attached to power plants or industrial processes have economic benefits that outweigh their costs (positive net present value).

Electro-thermal energy storage · Core TES technology that originated with CSP has a promising application in ETES, where electrical energy is stored as heat and later converted to electricity and returned. ETES plants use many of the same components developed for Gen3 CSP and ETES can be deployed alone or hybridized with CSP plants. As more variable renewable energy is deployed on the grid, demand for storing more than a few hours' electricity may increase. We support the component and system developments necessary to demonstrate pumped thermal energy storage (PTES), a version of ETES that uses a heat pump and heat engine to convert between electrical and thermal energy. Heat pumps raise the temperature of waste heat so it can be stored as useful energy, unlocking round-trip efficiency of >50% in PTES systems.

Goal **·** A pumped TES system has a round-trip efficiency of >50%

- The goal is reached when more than 50% of the electrical energy put into a PTES system is available as electrical output later. We may use a full-scale demonstration or a combination of component-level validation studies to meet this target.

Reducing Industrial Emissions Using Solar Thermal Technology

Moving beyond electricity **·** The office works to make solar energy a cost-effective alternative to conventional fuels for industrial process heat. We pursue cost reductions and process integration improvements to SIPH. Our awardees study a range of temperatures and industrial applications. Developing scalable, low-cost solutions for this variety of applications is a key challenge. High-priority applications include water desalination and synthesis of fuels and chemicals.

Process heat accounts for about 70% of the energy used in U.S. manufacturing and 8% of the nation's total energy consumption [EIA MECS 2014]. Solar energy can provide a clean source of industrial process heat that is free of fuel costs.

New industries may expand to take advantage of low-cost SIPH. These include water desalination and fuels synthesis. Solar desalination replaces electricity or fuel use to address clean water shortages and increasing quantities of specialized wastewater. Solar fuels synthesis represents an opportunity to expand the role of solar energy in the American energy system, offsetting the use of fossil fuels.

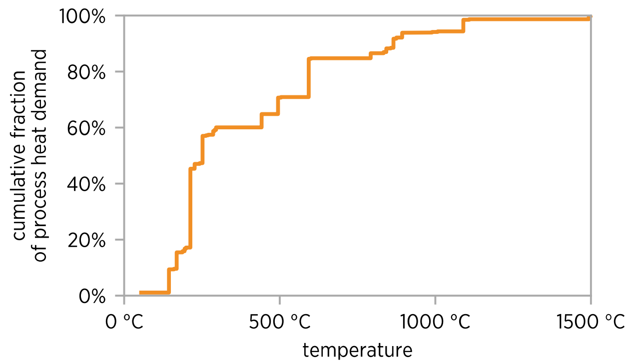

Figure 7. Cumulative process heating energy demand in the United States in 2015 is shown as a function of process temperature [Schoeneberger 2020].

Matching technology to applications **·** Implementing cost-effective SIPH requires analyzing the energy and temperature ranges of industrial demand, summarized in **Figure 7**. These processes range from heating water at 70°C to melting steel scrap at 1,800°C. About half of process heat energy demand is below 260°C and half is above. Candidate applications for SIPH include both low-temperature processes, such as enhanced oil recovery, food processing, and water desalination, and high-temperature processes, such as calcination to produce cement, thermochemical water splitting for producing solar fuels, and ammonia synthesis for producing fertilizer.

We will support the analysis needed to match solar-thermal collection, conversion, and storage technology to industrial processes at different temperatures. We anticipate that systems that are scalable in temperature, thermal power, and storage duration will most cost-effectively meet a range of applications. The technology needed for low-cost SIPH also includes very-low-cost solar collectors and innovative methods of integration with industrial processes.

Goal **·** System concepts are defined and key components are validated for solar process heat in carbon-emissions-intensive, high-heat-demand industries

- The goal is reached when experimental component validation has shown how a suitable industrial process can be driven using concentrated sunlight and a full system concept defines a roadmap for realizing an economically viable version of the process.

Solar thermal fuels **·** Making chemical fuels using concentrated sunlight is not yet commercially viable. Many thermochemical pathways are available and there is not yet a consensus on what fuel and what method is most promising. Renewable hydrogen is a desirable fuel and chemical feedstock. Hydrogen can be produced directly through solar thermochemical mechanisms, although existing catalysts require very high temperatures and operate at low efficiency. High-temperature electrolysis (HTE) of water is another method for producing hydrogen with higher efficiency than ordinary electrolysis. HTE can be hybridized with CSP as a source of heat, electricity, or both. Alternate fuels can also be produced using thermal processes. These include metal oxides, sulfur, ammonia, and versions of fossil fuels or biofuels that have been refined to have higher energy content.

We support solar fuel concepts that can use existing or Gen3 CSP technology. In the coming years, we will support analysis to identify promising thermochemical pathways, development of component technologies, and validation of key components for the most promising pathways. Key components include catalysts and reactors that are specific to solar fuels and cannot be borrowed from CSP.

Goal **·** System concepts are defined and key components are validated for producing fuels from concentrated solar energy

- The goal is reached when experimental component validation has shown how a suitable fuel synthesis process can be driven using concentrated sunlight and a full system concept defines a roadmap for realizing an economically viable version of the process.

Systems Integration

Background

The electric power system is evolving toward a new mix of generation resources, delivery networks, and consumption devices. Inverter-based resources, including solar, wind, and battery storage technology [Ren21 2019] are steadily increasing in deployment, but these resources are much more prevalent in some regions than in others. The electricity network is also evolving, adding sensors and communications, direct current (DC) power lines, flexible alternating current (AC) transmission systems, and solid-state transformers [Burkes 2017, GMLC 2020]. Load consumption types and profiles are being transformed because of deeper electrification of end uses such as electric vehicles [EIA AEO 2020]. Finally, new technologies such as energy storage are advancing for practical applications at different scales [Rudnick 2017]. At the same time, studies show the power system infrastructure runs closer to its operational limits with diminishing thermal and stability margins [NERC 2018]. These trends are fundamentally changing the characteristics of the electric power system: It is experiencing *lower inertia* and *more uncertainty*, and it is using *more distributed energy resources*.

Lower inertia is a result of more inverter-connected generation. The mechanical inertia in the power system is decreasing as conventional synchronous generation is retired and displaced [Matevosyan 2020]. Reduced system inertia has caused concerns about power system reliability [NERC 2017a]. However, with further research and development, the high-speed control capabilities of power electronic devices, such as PV inverters, could enable a more responsive power system, reducing the need for mechanical inertia.

Uncertainties in the power system are increasing because of variable generation, active loads, electric vehicles, system contingencies, and unforeseen and uncontrolled external events [Quint 2019]. Though these uncertainties create major challenges for solar integration, better situational awareness and more flexible controls will also make the grid more adaptive. This can enable generation to meet larger and faster ramps when the solar power contribution is high, while enforcing reliability requirements in a continuously changing environment.

Adoption of distributed energy resources such as rooftop solar generation is increasing. There are over 2.7 million solar generators on the U.S. distribution system today, representing about 40% of total PV capacity, with steady growth expected into the future [WM 2021, Feldman 2020]. This is a shift from the few, large, central resources of the past. Managing many small resources embedded in the power system is a fundamental challenge. But distributed solar generation can also make the power system more scalable, thus more resilient and secure against cyberattack and physical disturbances.

Lower inertia, more uncertainty, and more distributed resources present an opportunity to transition the power system to a new paradigm: a responsive, adaptive, and scalable power system. Solar generation, as a fast-growing resource, can play an essential role in this paradigm shift.

SETO systems integration (SI) research addresses system-level issues in integrating solar generation and other energy technologies into the electric power system to meet customer needs. The technical challenges of solar SI increase with the amount of solar *energy* and solar *power* being produced. Energy is measured as a total contribution over a period of time, and power is measured at a specific moment. Because of their capacity factors [EIA EPM 2020], inverter-based solar and wind resources delivering 20% of a region's annual *energy* may sometimes supply over 50% of the region's instantaneous *power* [CAISO 2020]. **Table 1** shows the peak power and annual energy contributed by solar and wind resources for power systems of different sizes in some areas with the highest wind and solar contributions to date. Wind generation is usually not distributed but solar and wind generation both have lower inertia and more uncertainty compared with conventional generation.

Table 1. Wind and solar technology now make major power and energy contributions to power systems around the world. Contributions for 2019 are shown for the Western Electricity Coordinating Council (WECC), the Electric Reliability Council of Texas (ERCOT), the Southwest Power Pool (SPP), the California Independent System Operator (CAISO), the Australia National Electricity Market (NEM), Ireland, and two islands in the state of Hawaii. [CAISO 2020, ERCOT 2020, SPP 2020, CAISO 2019, AEMO 2019, EirGrid 2019, HECO 2019]

Power system	System size	Peak solar + wind *power* contribution	Annual solar + wind *energy* contribution
U.S. WECC	163 GW	36%	13%
U.S. ERCOT	80 GW	58%	20%
U.S. SPP	51 GW	69%	28%
U.S. CAISO[4]	44 GW	70%	20%
Australia NEM	35 GW	50%	21%
Ireland	7 GW	84%	36%
Oahu	4 GW	58%	22%
Maui	0.5 GW	80%	37%

High solar and wind power contributions have already been achieved in some of the systems shown in **Table 1**. But scaling up these successes is not always easy because of the complex interconnectedness of large power grids and the unique challenges of island power grids. These high solar and wind power contributions usually occurred during low-demand periods (see the California example in **Figure 8**), giving them the benefit of additional backup from conventional power generation. The current strategies are not scalable or cost-effective for future scenarios with system-wide high solar and wind power contributions and diminishing conventional generation. Excessively relying on energy storage is not currently cost-effective, either. Developing scalable and cost-effective approaches for 50% to 75% wind and solar power contribution during medium- and high-demand periods remains a fundamental challenge.

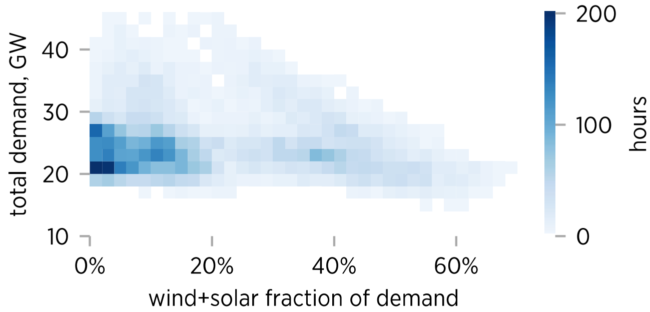

Figure 8. The frequency of occurrence of solar and wind power contributions at different demand levels in CAISO for 2020. Solar and wind make the maximum contribution when demand is low [EIA OpenData].

SETO addresses solar energy SI challenges related to grid system planning, system operation, resilience design, and power electronics and control. These challenges are addressed through research, development, and demonstration of data, analytics, control, and hardware. Specific technical goals for these efforts are explained in detail below.

Our SI work is integrated with related work in other DOE offices. We collaborate with these offices on power system modeling and simulation, power electronics, hybrid systems, sensing and communications, energy storage, and cybersecurity. These activities are organized through DOE initiatives such as Grid Modernization Initiative (GMI) and Energy Storage Grand Challenge (ESGC), and through EERE crosscut activities such as task forces for cybersecurity and hybrid systems.

The GMI is a DOE collaborative effort of multiple offices—Office of Electricity (OE), EERE, Office of Cybersecurity, Energy Security, and Emergency

[4] In 2019, 35% of the solar energy in California was produced "behind the meter" and is excluded from these numbers.

Response (CESER), Office of Fossil Energy (FE), and Office of Nuclear Energy (NE)—on modernizing the reliability, resilience, flexibility, sustainability, affordability, and security of the national electric infrastructure. The initiative integrates the technical capabilities of 14 National Laboratories and more than 100 industry partners [GMI 2015].

The ESGC coordinates energy storage technology development, adoption, manufacturing, supply chains, and relevant policies and workforce development [ESGC 2020]. Energy storage is a crucial complementary technology for solar energy because it addresses short-term uncertainty and daily and annual variability in solar generation.

Goals

Low-cost electricity
Increasing flexibility to reduce grid integration cost
Goal · Utility-scale PV plus energy storage systems cost less than $1.36/W$_{DC}$ (SI)
Reliable electricity
Supporting the reliability of the power system
Goal · Reliable operation is demonstrated at scale in a power system with 75% power contribution from inverter-based sources (i.e., solar, wind, and battery storage) (SI)
Enhancing the resilience and security of the grid
Goal · A power system uses PV and storage to demonstrate rapid recovery of critical electricity services after a cyberattack or physical event (SI)

Approach

Supporting the Reliability of the Power System

Supporting a changing grid · As solar and wind[5] generation become key contributors to the power system, they must actively support the operation of the power system [AEMO 2019, NERC 2020]. Conventional methods of ensuring reliability do not directly apply to a low-inertia power system with high uncertainties and highly distributed resources. With decreasing mechanical inertia and stability support, inverter-based resources and other new technologies must provide these functions using their inherent responsiveness. Uncertainties must be mitigated by flexibility in generation, transmission, and consumption to continue meeting demand and maintaining reliability. Coordinated monitoring and control become essential as distributed resources such as rooftop PV begin to make major contributions.

Advancing inverter capabilities · Inverters and energy storage are key to supporting the reliable operation of power systems with high solar power contribution. Inverters need new capabilities beyond feeding solar DC power to the AC power system [Matevosyan 2019, Zhong 2016]. Inverters must be reliable and long-lasting, and data regarding their degradation and failure must be available. Stability control and grid-forming capability in stand-alone and interconnected configurations are also essential. And inverters must work in control hierarchies that can support adaptive reconfiguration of the power system to support emergency load balancing, islanding, and the system-wide restoration of service known as blackstart. In an inverter-rich power system, fault currents are limited, and thus adaptive protection schemes will need to be redesigned, modeled, and simulated to understand how they can protect both the equipment and the power system as a whole. All these capabilities must be delivered

[5] While solar and wind technology share some system integration challenges, our work emphasizes the challenges that are specific to solar technology.

cost-effectively and without compromising cybersecurity.

Advancing communications and sensing **·** Reliable grid operation with high solar power contribution also needs advancements in data and communication technologies. New sensing technologies are needed to measure voltage and current waveforms in order to capture fast inverter dynamics [IEEE 2018]. These sensors may be integrated with smart inverters. Infrastructure needs to be developed for communication between devices and system-level communication. Collecting wide-area system data is necessary for estimating system inertia and power oscillations, and for increasing visibility and controllability of behind-the-meter solar and DER. Comprehensive solar data repositories can be developed to collect and make available power system models, measurements, event information, and tools for solar research and deployment [DR POWER, BetterGrids].

Understanding dynamics and uncertainty **·** Achieving high reliability with inverter-based generation requires new insights into the dynamics and uncertainty of solar integration with the power system. This requires accurate dynamic modeling and simulation of inverters, energy storage devices, PV, and other DER [Green 2019]. These models need to be integrated with bulk power system models for large-scale analysis and uncertainty assessment of solar plants as well as millions of distributed PV systems. Inverters' effects on power quality, including harmonics, flicker, and voltage sag or swell, must be simulated to understand and mitigate their effects on other equipment in the power system. Advanced signal processing or machine learning techniques are needed for identifying and characterizing unexpected energization, low current, high impedance, or incipient faults and cyberattacks.

Goal **·** Reliable operation is demonstrated at scale in a power system with 75% power contribution from inverter-based solar and wind generation and energy storage

- Reliable operation means that frequency and voltage stay within accepted ranges, including during failures of important generation or transmission assets or during simultaneous outages of many DER assets. This demonstration can use an actual power system or a test bed. The demonstration must include solar power plants and elements such as inverters, energy storage, and the transmission and distribution networks. This demonstration is valid when the power system does not rely on import or export with neighbors. The target is reached when the power generation from inverter-based solar and wind generation and energy storage exceeds 75% or more of the system demand. The scale of the demonstration is a gradual progression during the MYPP period from a small scale such as 1 MW to a utility scale such as 20 MW or higher. Existing and expected SI-funded projects already have field demonstration plans to reach these scales. This would lay solid foundation towards the larger scales in **Table 1** as the ultimate long-term goal for reliable operation of grids with a lot of solar generation.

Increasing Flexibility to Reduce Grid Integration Cost

Adding flexibility through storage **·** Implementing a grid that supports large, fast generation and load ramps requires building flexibility into resource planning, operation, and control. Increased flexibility of generation, load, and network will all be necessary, and this flexibility must be provided at low cost. Energy storage is becoming an important resource for increased flexibility [Rudnick 2017]. Future technology development can support the expanding role of low-cost energy storage. Energy storage can contribute both fast-responding grid services and long-term clean energy supply in tandem with solar generation.

Planning for solar integration **·** Long-term resource planning relies on cost modeling and contingency modeling of the integration of solar generation with energy storage and with the transmission and distribution systems. We support this modeling and the large-scale optimization it makes possible. The result will be integrated resource planning for larger and more cost-effective solar contributions to the electricity generation mix.

Forecasting, analysis, and uncertainty **·** Operation and control of a power system with major solar energy contributions will require improved forecasting, data collection, and analysis [Golnas 2019]. Solar forecasting needs higher spatial resolution and wider temporal coverage, ranging from minutes to days. This enhanced forecasting enables the power system to more effectively adapt to changing conditions, meeting changes in demand at optimal cost. Less forecast uncertainty and better quantification of this uncertainty are essential to increasing flexibility without unnecessary expense. Adequate grid flexibility also depends on real-time collection of data from distributed load and generation over a wide area. Combined with scalable analysis, these data can increase the visibility and controllability of behind-the-meter solar and DER.

More solar generation added to the power system adds more uncertainty in generation. This is especially true at sunset, when a fast increase in load sometimes coincides with a fast decrease in solar generation [CAISO 2020]. The reverse can occur at sunrise. In both cases, the power system needs greater flexibility to balance generation and load. Today's power systems meet this challenge using a combination of fast-ramping conventional generation, energy import or export with neighbors, and curtailment of excess renewable energy. But as solar technology supplies more of the nation's energy, existing practices can become more difficult and expensive to implement. Demonstrating the optimization of solutions to large, fast ramps will show that new practices are in place that enable increasing solar energy contributions.

Goal **·** Utility-scale PV plus energy storage systems cost less than $1.36/W_{DC}$

- The goal is reached when the cost of a utility-scale PV system with four hours of battery storage reaches $1.36/W_{DC}$. The cost is evaluated using a similar bottom-up cost model to the one used for tracking PV-only LCOE, with 100 MW of PV and 60 MW of battery storage. For battery storage, we will incorporate a levelized cost of storage (LCOS), which includes the lifetime cost and benefit of energy storage in addition to the initial installation cost. This effort will be coordinated with the ongoing ESGC initiative [ESGC 2020].

One of the major benefits of energy storage is providing the flexibility necessary for higher solar power contribution. There are also opportunities to improve flexibility from other elements in the power system through integrated resource planning.

Enhancing the Resilience and Security of the Grid

Responding to hazards **·** As the power system relies more on networked communication and distributed generation, and as natural disasters such as hurricanes, flooding, and wildfires increase in severity and frequency, the power system's exposure to cyberattacks and physical hazards increases [NERC 2017b, Robles 2019]. While the power system must continue minimizing outages resulting from these threats, solar technology can help the power system be more resilient when a disruption does occur.

During hazards, the power system can be reconfigured into independent segments that each contain load and generation. With enough DER such as PV systems, there are more opportunities for reconfiguration to enhance grid resilience. The fast-responding power electronics in solar generation and energy storage systems can provide blackstart capabilities to bring new segments more quickly back online. Close coordination between DER and bulk and distribution power systems can be developed to ensure smooth transition between normal and recovery operations.

Realizing fast, adaptive response to physical disruptions or cyberattacks requires new modeling and simulation, new analysis, new inverter capabilities, and field demonstration in partnership with the private sector. We support modeling the effects of all hazards on power system performance arising from and affecting solar systems. These models will be used to test and optimize the grid's response to cyberattacks and physical disruptions, supporting new adaptive protection schemes, grid reconfiguration, emergency load balancing, islanding, and blackstart. An adaptive grid also requires technology to identify faults, attacks, and unexpected energization. Our awardees develop advanced signal processing and machine learning techniques to detect, identify, and mitigate these conditions.

Advancing inverter capabilities · Grid-forming inverters are promising technologies that support fast stability control and automatic switching between networked and standalone modes [Matevosyan 2019]. These inverters must also be cost-effective and support the functions needed to reach the preceding goals: working in control hierarchies with equipment from other vendors and sensing and communicating about their power quality.

To resist cyberattacks, inverters must be inherently cybersecure, implement defense in depth, and support the cyberdefense of the power system they are connected to, following the National Institute of Standards and Technology's (NIST) cybersecurity framework [NIST 2018]. Building a trustworthy, cyber-resilient power system requires developing innovative, dynamic cybersecurity survival strategies for solar generation systems, especially distributed rooftop PV. This system will be able to recognize and reject a cyberattack automatically and autonomously adjust to maintain electric power supply.

Goal · A power system uses PV and storage to demonstrate rapid recovery of critical electricity services after a cyberattack or physical event

- Rapid recovery means that after a cyberattack or physical interruption, electricity service is restored in much less than one day for critical loads in a region with enough solar energy. Cyberattack includes deliberate attempts to disrupt service through an information network or from within a piece of equipment connected to the power system. Natural physical hazards include storms, wildfires, or earthquakes. Manmade physical hazards include human errors or terrorist attacks. The demonstration can occur during a real event, but these are rare and not repeatable. An alternative way of demonstrating this capability is by combining simulation of the power system and emulation of communication and control systems using multi-site federated emulation capabilities.

Soft Cost Reduction

Background

Soft costs are the non-hardware costs of solar electricity. These costs relate to project development; financing; siting; customer acquisition; permitting, inspection, and interconnection (PII); installation labor; and business overhead and profit. **Figure 9** shows how hardware and soft costs have changed. Approximately 35% of utility-scale PV system costs and over 60% of commercial and residential PV system costs are soft costs [Feldman 2021].

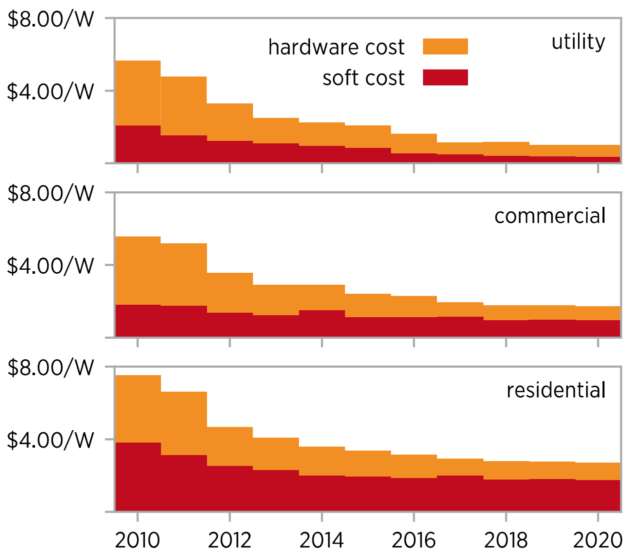

Figure 9. The modeled hardware and soft cost breakdown for different system types.

The components of residential PV soft costs are shown in **Figure 10**. PII and installation labor together account for more than a quarter of residential soft costs. Financing cost, which does not appear in **Figure 10** because it is not part of upfront solar system costs, is about 40% of the LCOE of a residential PV system [Feldman 2021].

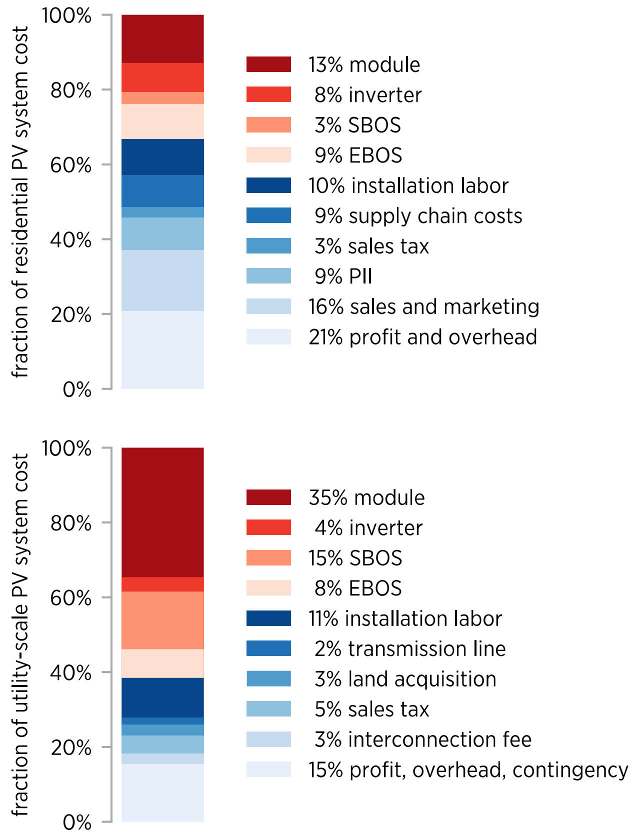

Figure 10. The cost breakdown of a residential PV system (top) and a utility-scale PV system (bottom) show the contributions of soft costs [Feldman 2020]. Hardware costs are shown in red and soft costs in blue. EBOS is electrical balance of system; SBOS is structural balance of system; PII is permitting, inspection, and interconnection.

In conventional commercial and residential PV systems, soft costs have stopped declining and are limiting further PV electricity cost reductions. Further reductions in the cost of PV electricity will depend on new reductions in both hardware and soft costs [O'Shaughnessy 2019].

Residential PV system cost is over two times higher in the U.S. than in Germany and over three times higher in the U.S. than in Australia, mainly due to soft costs [WM GSPSP 2021]. In those countries, permitting and inspection are streamlined and governed by national rules. U.S. regulations and business practices lead to more complex and labor-intensive installation practices. And customer acquisition costs are much higher in the U.S.

[Birch 2018]. Relatively low soft costs abroad suggest that, despite the stalled progress shown in **Figure 9**, it is still possible to reduce U.S. soft costs further.

Location-specific requirements and practices contribute to soft costs. In the United States, there are thousands of local jurisdictions and over 3,400 utilities. Each of these may have different permitting, inspection, and interconnection processes and requirements [Burkhardt 2015]. In PV systems that are combined with storage or other DER, soft costs are higher than in solar-only systems [Feldman 2021].

Deploying PV at large scale may bring increased attention to the optimal use of land. A total of about 1 GW to 2 GW of PV capacity has been deployed with grazing animals or pollinator habitat underneath, on buildings, and floating on artificial bodies of water. These dual-use systems can yield mutual benefits for PV and the other use. Preliminary studies suggest that combining PV with agriculture can increase crop yield, improve efficiency by reducing PV module temperature, and reduce water use [Barron-Gafford 2019]. But dual-use systems are not common, and the benefits are not yet fully understood or quantified.

In UPV systems, avoiding, minimizing, and mitigating site impacts can increase costs. These costs are poorly documented and understood, so are particularly difficult to reduce [Hartmann 2019].

Goals

Low-cost electricity
Lowering the cost of electricity from PV
Goal **·** Levelized cost of energy (LCOE) is less than \$0.03/kWh in utility-scale PV systems (PV, SC, MC)
Goal **·** LCOE is less than \$0.08/kWh for commercial PV systems and \$0.10/kWh for residential PV systems (SC)
Rapid deployment
Growing the U.S. solar industry
Goal **·** A well-supported and diverse solar workforce meets the needs of the industry and of disadvantaged communities and grows to employ at least 300,000 workers (SC)
Reducing the Life Cycle Impacts of Solar Energy
Goal **·** New materials, designs, and practices are demonstrated for reducing the environmental impact of PV technology, prioritized based on a life cycle impacts benchmark (PV, SC)
Opening new markets
Goal **·** 1 GW_{AC} of PV installed in 2025 is combined with another use, such as agriculture or building surfaces (SC, MC)
Ensuring that solar energy benefits all
Goal **·** 100% of U.S. energy consumers can choose residential solar or community solar that does not increase their electricity cost (SC)

Approach

Lowering the Cost of Energy from PV

Reducing regulatory burden **·** Our office supports the analysis and planning that local jurisdictions need to cut red tape and make it easier and more affordable for their residents to go solar. We fund the collection of data, development of tools, and provision of technical assistance that can help streamline permitting, inspection, and interconnection processes, lowering the regulatory burden for PV adoption.

Informing decisions **·** We also research and publish market information that can support more efficient decision-making and associated cost reductions. This information includes, for example, how solar installations affect residential home prices, benchmark costs of different PV market segments, and training materials for first responders.

Reducing soft costs of combining PV with other DERs **·** Adding storage and other DER technology to PV systems can enhance the energy resilience of homes and critical community infrastructure, like police stations, fire stations, and hospitals, in an emergency. These combined PV+DER systems, however, can have much higher soft costs than PV-only systems. For example, adding battery storage to a residential PV system increases soft costs by 50% [Feldman 2021].

We research siting, PII, and operation of PV+DER systems and identify ways to reduce these costs with improvements to technology or information. And we study the resilience value and monetary value of operating such systems.

Reducing barriers to combining PV with new home construction and re-roofing **·** Residential PV systems installed on new houses during construction or on existing houses during roof replacement present major soft cost reduction opportunities [Ardani 2018]. Most rooftop PV systems are implemented as separate roofing and PV products. Integrating PV and roofing products can reduce supply chain and installation labor costs. Integrating the PV and construction industries further reduces customer acquisition, overhead, and labor costs. And PV permitting costs can be reduced when the permitting process is integrated with the permitting process for a roof replacement, construction of a new house, or construction of an entire new neighborhood. Residential LCOE for new construction or roof replacement has a path to $0.05/kWh in 2030. Through collaboration with the construction industry, we are studying the barriers and solutions to installing PV during home construction and re-roofing.

Reducing costs for commercial solar **·** Some aspects of PV system ownership, financing, and procurement are unique to commercial rooftops. We work with commercial building owners to find strategies that reduce cost and encourage adoption of commercial PV. Our research on rate designs and compensation mechanisms helps building owners make informed decisions. We also study under what conditions the colocation of energy storage and electric vehicle charging with commercial PV systems can provide benefits to the building owner or tenants.

Goal **·** LCOE is less than $0.08/kWh for commercial PV systems and $0.10/kWh for residential PV systems

- This goal is reached when a bottom-up cost model shows that unsubsidized LCOE has reached the target. This model describes rooftop commercial and residential PV systems in Kansas City, Missouri, a location with solar resource near the national average.

Growing the U.S. Solar Industry

Building the solar workforce **·** A well-supported and diverse solar workforce will ensure that the industry can hire the range of expertise it needs to grow, adopt updated technologies, and develop more efficient practices. Our office funds solar workforce training and placement for individuals, such as:

- veterans and transitioning service members,
- community college and university students,
- and people who have been incarcerated.

Our approach prioritizes workers hardest hit by discrimination, economic exclusion, and exploitation – including communities of color, legacy fuel workers, and frontline communities most affected by climate and environmental problems. We work to make training, mentoring, placement, growth opportunities, meaningful wages, and labor standards accessible to all workers in the industry. In collaboration with other EERE offices, we also fund solar training, job placement, tools, and resources for professionals in adjacent fields, such as emergency responders and building managers, who are critical to supporting the integration of solar energy into the power system.

Goal · A well-supported and diverse solar workforce meets the needs of the industry and of disadvantaged communities and grows to employ at least 300,000 workers

- The goal is reached when the solar workforce reaches 300,000. We will monitor the availability of jobs and training for disadvantaged communities to ensure the benefits of solar employment are available to all.

Reducing the Life Cycle Impacts of Solar Energy

Improving PV management at end-of-life · Meeting the Nation's energy goals will require rapid solar deployment. This deployment is expected to produce cumulatively tens of millions of metric tons of PV waste by 2050. Like electronic waste, PV waste can contain materials that are rare, valuable, hazardous, or energy-intensive to produce. But PV waste is mostly glass and aluminum, so it is also similar to some construction waste. Today, far more consumer electronics waste is produced than PV waste, but this may change as PV deployment accelerates [EPA 2020b, SFS 2021]. In a sustainable energy system, the materials in PV waste should be recovered and used again. We support analysis to understand and predict the production and handling of PV waste. We will also convene PV stakeholders to understand and resolve the community's end-of-life concerns. We work toward proactive, responsible handling of the PV waste that today's accelerating deployment is producing.

Minimizing land and wildlife impacts · There are federal, state, and local legal requirements that solar energy projects manage the impacts they have on their surroundings. These site impacts include a project's effects on stormwater runoff; wetlands and streams; wildlife and their habitats; historic properties; and public lands. The procedures and costs of fulfilling the requirements to manage these impacts may be different for each site. [Hartmann 2019] We study the impacts of PV on stormwater runoff and develop technologies and methods for collecting data to better understand wildlife interactions with PV facilities. We also are also studying the ecological impacts of co-locating PV with pollinator habitat, grazing, and crops.

Goal · New materials, designs, and practices are demonstrated for reducing the environmental impact of PV technology, prioritized based on a life cycle impacts benchmark

- The goal can be met after a life cycle impacts benchmark is performed and published for commercial PV technology, then new technology has been demonstrated that reduces environmental impact. This goal is shared with the PV budget area.

Opening New Markets

Resolving land-use concerns · As PV deployment increases, some PV projects may face local opposition due to land use conflicts, such as replacing agricultural land [Gross 2020]. Dual-use systems could resolve these conflicts and potentially deliver mutual benefits [Barron-Gafford 2019]. For example, a single piece of land can produce revenue from grazing under PV panels and from the electricity produced by the panels. When the benefits of adding PV exceed the costs, a project has positive net present value (NPV).

Goal · 1 GW_{AC} of PV installed in 2025 is combined with another use, such as agriculture or building surfaces

- Dual use includes PV and agriculture colocation, BIPV, and floating PV. It excludes conventional residential and commercial PV, where PV modules are installed on top of conventional roof material.

We study new system designs, evaluate business practices and business models, and conduct analysis to quantify and improve the benefits of the colocation of solar facilities and other uses for both industries and the local community. These mutual benefits include sources of revenue, such as electricity generation, grid services, crop production, and livestock production. Some benefits are more complex, including changes to water use, the economic and ecological benefits of pollinator habitat, interactions with birds, and interactions with native plants.

Ensuring That Solar Energy Benefits All

Energy consumers who do not have access to rooftop PV can still access the benefits of solar energy. Community solar can offer reduced energy burden to consumers for whom a rooftop PV system is not possible or is not affordable. Residential rooftop PV can be made more accessible through alternative financing or ownership models.

Removing barriers to community solar · Community solar can make low-cost distributed solar energy available to homes and businesses where rooftop solar is not a practical option. This includes about half of all homes and businesses in the U.S. [Feldman 2015]. It is possible for many U.S. consumers to save money on electricity by investing in a solar generation asset through a subscription or partial ownership of a community solar array. We provide networking, collaboration, and technical assistance to stakeholders to expand access to affordable community solar to every U.S. energy consumer by 2025 and enable community solar to provide meaningful benefits to energy consumers, workers, employers, and communities.

Reducing financing costs · Low- and moderate-income households, nonprofit organizations, local governments, and tribal governments often cannot access conventional low-cost financing and tax incentives for solar projects. We fund research on alternative financing models and the development of new tools and methods to evaluate creditworthiness and assess risk, as well as new mechanisms such as short-term contracts for renters, flexible credit agreements, and alternative financing qualification metrics.

Goal · 100% of U.S. energy consumers can choose residential solar or community solar that does not increase their electricity costs

- We measure progress toward this goal by tracking the national fraction of households that have the option to participate in community solar programs or to install rooftop solar that does not increase electricity costs. We evaluate the affordability of projects by calculating their net present value (NPV). Projects that do not increase energy costs have zero or positive NPV.

Manufacturing and Competitiveness

Background

In 2019, about $9 billion were spent on PV hardware in the United States. About $4 billion of this was spent on domestic content and the balance on imported content. **Figure 11**, below, shows how the value of a typical c-Si utility-scale PV system in the U.S. is distributed among its components, and the proportion of domestic content in each component. About 78% of the PV capacity installed in 2019 used c-Si PV modules. The U.S. PV manufacturing industry has the capacity to produce PV modules to meet about half of today's domestic demand [WM USSMI 2019]. The module materials and components are mostly imported content.

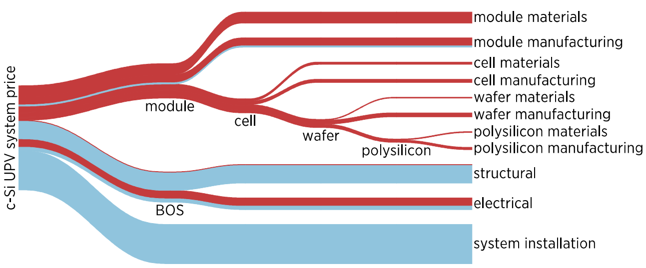

Figure 11. The value of a typical c-Si UPV system in the United States, broken into its components [Feldman 2021, Woodhouse 2020]. The thickness of each line is proportional to its monetary value. "System installation" includes all upfront system costs other than module and BOS. Red indicates imported content, and blue indicates domestic content.

Increasing domestic content in PV hardware will keep more value in the U.S. economy and create valuable manufacturing jobs. Manufacturers consider many factors, including local costs and incentives, when deciding where to site facilities [Smith 2021]. For example, compared to most locations with existing PV manufacturing industries, labor costs are higher in the United States, but electricity costs can be lower [Woodhouse 2020]. New technology could bring more efficient manufacturing processes to the United States that could cost-effectively compete with overseas manufacturers. Reducing reliance on imported goods also reduces cost uncertainty and sensitivity to international supply chain disruptions. Emerging concerns about cybersecurity may also be resolved by using U.S.-made or -assembled hardware for sensitive components such as power electronics.

Half of domestic hardware spending is on non-module hardware: structural balance of system products, including racking and trackers, and electrical balance of system products, including inverters, wiring, and combiner boxes [Feldman 2020, Feldman 2020b, Feldman 2021, WM USSMI 2019]. Most residential racking installed domestically is made domestically. Many of the trackers that are used in utility-scale PV systems are American-made and some American-made trackers are exported. While hundreds of megawatts of domestic inverter assembly and manufacturing exist, this meets only a fraction of domestic demand. New PV system types, such as those combined with agriculture or another land use, could require new hardware that is best made domestically.

The manufacturing and competitiveness budget area supports the development and commercialization of technology that can be manufactured in the U.S., creating jobs and producing local benefits from energy investments. It also supports the commercialization of technology that targets the goals in the other budget areas and can support growth of U.S. businesses. We work to transfer both hardware and software technology into the marketplace.

Goals

Low-cost electricity
Lowering the costs of electricity from PV
Goal · Levelized cost of energy (LCOE) is less than $0.03/kWh in utility-scale PV systems (PV, SC, MC)

Rapid deployment
Growing the U.S. solar industry
Goal · 1 GW/year of new U.S. PV manufacturing capacity is based on technology that was not yet commercialized in 2020 (MC)
Goal · The solar hardware installed in the United States has at least 40% domestic value (MC)
Opening new markets
Goal · 1 GW_{AC} of PV installed in 2025 is combined with another use, such as agriculture or building surfaces (SC, MC)

Approach

Lowering the Cost of Energy from PV

Helping develop and commercialize products · We support hardware and software products that can reduce the cost of solar electricity. Domestically made hardware, especially BOS hardware like racks and trackers, can reduce shipping costs and delays. Innovative software tools can reduce soft costs by enabling faster and more efficient design, grid integration, and operations and maintenance.

Goal · Levelized cost of energy (LCOE) is less than $0.03/kWh in utility-scale PV systems

- The goal is reached when a bottom-up cost model shows that unsubsidized LCOE has reached the target. This goal is shared with the PV and SC budget areas.

Supporting the U.S. Solar Industry

Achieving large-scale domestic manufacturing · Domestic manufacturing of solar hardware creates jobs, produces ancillary economic activity, and promotes clean energy security. Where there is an opportunity to do manufacturing in the US, we aim to maximize it. Establishing the capacity to manufacture 1 GW/year of a new PV technology requires mature, scalable manufacturing techniques that are beyond the scope of small pilot lines. This scale may be able to produce PV modules that are cost-competitive with established PV technologies. Production at the gigawatt scale delivers higher return on federal investment compared to smaller manufacturing projects and serves as the starting point for a vibrant industrial ecosystem. U.S. industry that can reach this scale quickly may realize a first-mover advantage in a new technology. Such rapid innovation and scaling are minimum qualifications for competitiveness in the global PV industry and set up a fast feedback loop between R&D and production. Focusing effort on new technology promotes global leadership in science and technology.

We support proof-of-concept development, technology validation, and technology transfer of new solar technologies. We also advance entirely new technologies and processes. We also work to connect entrepreneurs with the contacts that can help them secure follow-on capital and incentives. We provide financial assistance for innovative solar hardware development and validation. We ask awardees to plan for domestic manufacturing at an early stage. And we form networks and communities, such as the American-Made Network, to support awardees in achieving more rapid innovation cycles. We rely on the private sector to undertake pilot manufacturing and scaling up to prepare for market entry. The selection of a manufacturing facility location depends on state and local considerations and incentives.

Goal · 1 GW/year of new U.S. PV manufacturing capacity is based on technology that was not yet commercialized in 2020

- PV manufacturing capacity is the total annual power rating of what factories can produce. Our target is a domestic industry that makes 1 GW of products in 2025 using new technology. New technology refers to new absorber technology, such as perovskite solar cells, or major modifications to existing absorber technology. It also means new *combinations* of absorbers, including mainstream PV technologies (silicon and CdTe) in tandem with another absorber.

Goal **·** The solar hardware installed in the United States has at least 40% domestic value

- Solar hardware includes PV modules; structural balance of system components, including racks and trackers; electrical balance of system components, including inverters and combiners; and CSP collectors, receivers, and power blocks. Domestic value is calculated based on the country of origin for materials and the country of transformation for manufacturing, as illustrated in the hardware portions of **Figure 11**.

Opening New Markets

Dual-use PV **·** Established PV markets may not be enough to meet the Nation's renewable energy targets. We support domestically made products that can open new markets, including emerging PV system types such as agricultural and building-integrated PV. These markets will require different hardware, including special PV cells, PV modules, mounting, tracking, or other balance-of-system components. Special markets like these may be underserved by the global PV market, so are of particular interest for domestic manufacturing.

Goal **·** 1 GW_{AC} of PV installed in 2025 is combined with another use, such as agriculture or building surfaces

- Dual use includes PV and agriculture colocation, BIPV, and floating PV. It excludes conventional residential and commercial PV, where PV modules are installed on top of conventional roof material.

Analysis

We set our strategy using an analytical foundation. We make key parts of our analysis available to the industry and research communities. Before investing in R&D, we collect data; create baseline benchmarks and tools; prioritize the remaining challenges; and identify research areas that can have the greatest impact. We track progress toward resolving these challenges by updating our benchmarks.

Data **·** We aggregate data about the performance and cost of solar technology and the status of the solar industry. There is often no single source of similar data, which we often make available in public reports, presentations, and databases. Examples include the actual characteristics and installed costs of PV systems [Bolinger 2019, Barbose 2019], the time required for solar permitting [O'Shaughnessy 2020], and the status of U.S. the solar industry [Feldman 2020b].

Baseline benchmarks **·** Baseline benchmarks represent the state of the art in the relevant industries and in the research enterprise. One example is the PV system cost benchmark, which makes a detailed bottom-up calculation of the upfront system cost and levelized cost of energy for PV systems in the main industry sectors [Feldman 2021]. The benchmark also includes the cost of adding storage to a PV system in various configurations. Our office, the solar industry, and the solar research enterprise rely on the benchmark as an analytical basis for prioritizing R&D.

Analysis tools **·** Where appropriate, we introduce public tools that embody our data and benchmarks. For example, the NREL System Advisor Model [Blair 2018] and the Comparative PV LCOE Calculator [Silverman 2018] allow users to compute the economic benefits of potential technology advances.

Setting priorities **·** Based on data, baseline benchmarks, and analysis tools, we choose priorities with the greatest potential to meet our statutory objectives. Where a coordinated system of advances is required, we publish formal roadmaps to organize our priorities. We fulfill these priorities using a mix of risk and technology maturity levels, as described in Office Overview, above.

Tracking progress **·** We continually update the data and benchmarks described above, tracking progress toward our goals. Combined with the Program Evaluation approach described below, these updates provide a closed feedback loop that ensures our research strategy remains relevant and effective.

Program Evaluation

We aim to maximize the national benefits from taxpayer investments in solar R&D. We measure our success by evaluating the performance of our funded projects and our office.

We use data to measure our effectiveness. These data include:

- the definition of funding initiatives (purpose and goals),
- the basis for funding decisions (merit reviews and selection criteria),
- active program management (project reviews and reporting), and
- project outcomes (publications, patents, and students).

We evaluate the effectiveness of funding initiatives through logic models, merit reviews, active program management (APM), and data analysis and dissemination. Logic models describe the partners, activities, target audiences, and outputs for individual projects. These project outputs are linked to short- and long-term outcomes for an entire funding initiative. In accordance with DOE guidelines for financial assistance, subject matter experts conduct merit reviews on applications we receive. We follow EERE Active Project Management (APM) guidelines, including technical milestones, "go/no-go" decision points, and annual site visits for funded projects. We collect and analyze data from these activities to determine historical trends and measure the effectiveness of practices like concept paper review and in-person merit review.

SETO evaluates the outcomes from our funding initiatives using bibliometric analysis, measuring scientific and technological impact beyond publications and patents, and measuring the impact of SETO programs on solar workforce development. We continually revise our metrics and analytical approaches based on the needs of specific funding opportunities. Prize competitions have become increasingly important to our work. We study ways to evaluate the outcomes of prize competitions with the same rigor that we apply to cooperative funding agreements.

In accordance with EERE guidelines, SETO conducts a comprehensive peer review evaluation of all actively funded projects about every two years. The peer review process looks beyond the quality of individual projects and assesses the effectiveness of the entire program.

Statutory Authority

The SETO program is defined in the Energy Policy Act of 2005 [EPAct 2005], the Energy Independence and Security Act of 2007 [EISA 2007], and the Energy Act of 2020 [EAct 2020].

The renewable energy programs, including the solar energy program, "shall take into consideration the following objectives:

- Increasing the conversion efficiency of all forms of renewable energy through improved technologies.
- Decreasing the cost of renewable energy generation and delivery.
- Promoting the diversity of the energy supply.
- Decreasing the dependence of the United States on foreign energy supplies.
- Improving United States energy security.
- Decreasing the environmental impact of energy-related activities.
- Increasing the export of renewable generation equipment from the United States." [EPAct 2005]

The solar energy program includes "research, development, demonstration, and commercial application for solar energy, including—

- photovoltaics;
- solar hot water and solar space heating;
- concentrating solar-thermal power;
- lighting systems that integrate sunlight and electrical lighting in complement to each other in common lighting fixtures for the purpose of improving energy efficiency;
- manufacturability of low-cost, high-quality solar systems; and
- development of products that can be easily integrated into new and existing buildings." [EPAct 2005]

The purposes of the solar energy program are:

- "To improve the energy efficiency, cost effectiveness, reliability, resilience, security, siting, integration, manufacturability, installation, decommissioning, and recyclability of solar energy technologies.
- To optimize the performance and operation of solar energy components, cells, and systems, and enabling technologies, including through the development of new materials, hardware, and software.
- To optimize the design and adaptability of solar energy systems to the broadest practical range of geographic and atmospheric conditions.
- To support the integration of solar energy technologies with the electric grid and complementary energy technologies.
- To create and improve the conversion of solar energy to other useful forms of energy or other products.
- To reduce the cost, risk, and other potential negative impacts across the lifespan of solar energy technologies, including manufacturing, siting, permitting, installation, operations, maintenance, decommissioning, and recycling.
- To reduce and mitigate potential life cycle negative impacts of solar energy technologies on human communities, wildlife, and wildlife habitats.
- To address barriers to the commercialization and export of solar energy technologies.
- To support the domestic solar industry, workforce, and supply chain." [EAct 2020]

The solar program's subject areas include:

- advanced solar energy technologies
- solar energy technology siting, performance, installation, operations, resilience, and security
- integration of solar energy technologies with the electric grid, other technologies, and other applications,
- advanced solar energy manufacturing technologies and practices,
- methods to improve the lifetime, maintenance, decommissioning, recycling, reuse, and sustainability of solar energy components and systems,
- solar energy forecasting, modeling, and atmospheric measurement systems, including for small-scale, large-scale, and aggregated systems,
- integrated solar energy systems that incorporate diverse generation sources, loads, and storage technologies
- reducing market barriers, including nonhardware and information-based barriers, to the adoption of solar energy technologies,
- and transformational technologies for harnessing solar energy. [EAct 2020]

There is additional specific authorization for research in thermal energy storage for concentrating solar power plants; curriculum development and certification for the solar energy workforce; and demonstration of advanced photovoltaic technology in coordination with state governments. [EISA 2007]

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