ON THE PATH TO SUNSHOT: EXECUTIVE SUMMARY

Solar Energy Technologies Office

U.S. Department of Energy

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1 Study Context and Overview

The U.S. Department of Energy launched the SunShot Initiative in 2011 with the goal of making solar electricity cost-competitive with conventionally generated electricity by 2020. At the time this meant reducing photovoltaic (PV) and concentrating solar power (CSP) prices by approximately 75%—relative to 2010 prices—across the residential, commercial, and utility-scale sectors. To examine the implications of this ambitious goal, the Department of Energy's Solar Energy Technologies Office (SETO) published the SunShot Vision Study in 2012. The study projected that achieving the SunShot price-reduction targets could result in solar meeting roughly 14% of U.S. electricity demand by 2030 and 27% by 2050—while reducing fossil fuel use, cutting emissions of greenhouse gases and other pollutants, creating solar-related jobs, and lowering consumer electricity bills.

The SunShot Vision Study also acknowledged, however, that realizing the solar price and deployment targets would require overcoming a number of challenges. Both evolutionary and revolutionary technological changes would be required to hit the price targets, along with the capacity to manufacture these improved technologies at scale in the United States. In addition, operating the U.S. transmission and distribution grids with increasing quantities of solar energy would require advances in grid-integration technologies and techniques. Serious consideration would also have to be given to solar siting, regulation, and water use. Finally, substantial new financial resources and strategies would need to be harnessed over a relatively short period to enable the rapid large-scale solar deployment. Still, the study suggested that the resources required to overcome these challenges were well within the capabilities of the public and private sectors. SunShot-level price reductions, the study concluded, could accelerate the evolution toward a cleaner, more cost-effective, and more secure U.S. energy system.

That was the assessment in 2012. Today, at the halfway mark of the SunShot Initiative's 2020 target date, it is a good time to take stock: How much progress has been made? What have we learned? What barriers and opportunities must still be addressed to ensure that solar technologies achieve cost parity in 2020 and realize their full potential in the decades beyond? To answer these questions, SETO launched the On the Path to SunShot series in early 2015 in collaboration with the National Renewable Energy Laboratory (NREL) and with contributions from Lawrence Berkeley National Laboratory (LBNL), Sandia National Laboratories (SNL), and Argonne National Laboratory (ANL). The reports focus on the areas of technology development, systems integration, and market enablers.

Three key insights that can be drawn from the series include the following:

1. Increasing use of grid-flexibility options, next-generation power electronics, and other strategies could enable America to get 25% of its electricity from solar.
2. Continued innovation in system-level science and technology will play a critical role in meeting SunShot's cost reduction targets for 2020, and offer potential pathways to even further cost reductions beyond 2020.
3. Driving down solar costs beyond 2020 targets will enable the development of integrated solar systems with higher value at higher levels of deployment. In a world with low-cost solar and increasing solar deployment, the solar industry must pursue multiple strategies to increase the value of solar, both for the grid services and to the American public.

The reports examine key topics that must be addressed to achieve the SunShot Initiative's price-reduction and deployment goals. The *On the Path to SunShot* series includes the following reports:

- Emerging Issues and Challenges with Integrating High Levels of Solar into the Electrical Generation and Transmission Systems (Denholm et al. 2016)
- Emerging Issues and Challenges with Integrating High Levels of Solar into the Distribution System (Palmintier et al. 2016)
- The Role of Advancements in Photovoltaic Efficiency, Reliability, and Costs (Woodhouse et al. 2016)
- Advancing Concentrating Solar Power Technology, Performance, and Dispatchability (Mehos et al. 2016)
- Emerging Opportunities and Challenges in U.S. Solar Manufacturing (Chung et al. 2016)
- Emerging Opportunities and Challenges in Financing Solar (Feldman and Bolinger 2016)
- Utility Regulatory and Business Model Reforms for Addressing the Financial Impacts of Distributed Solar on Utilities (Barbose et al. 2016)
- The Environmental and Public Health Benefits of Achieving High Penetrations of Solar Energy in the United States (Wiser et al. 2016).

Solar technology, solar markets, and the solar industry have changed dramatically over the past five years. Cumulative U.S. solar deployment has increased more than tenfold, while solar's levelized cost of energy (LCOE) has dropped by as much as 65% (Figure 1). As a result, today the solar industry is about 70% of the way towards achieving the Initiative's 2020 goals. New challenges and opportunities have emerged as solar has become much more affordable, and we have learned many lessons as solar technologies have been deployed at increasing scale in the United States and abroad. The On the Path to SunShot series explores the remaining challenges to realizing widely available, cost-competitive solar in the United States.

As it enters the second half of the SunShot Initiative, SETO has begun to consider setting longer-range targets for the program. In conjunction with key stakeholders, SETO will use the results from the On the Path to SunShot series to aid development of its solar price-reduction and deployment strategies for the second half of the SunShot period and beyond.

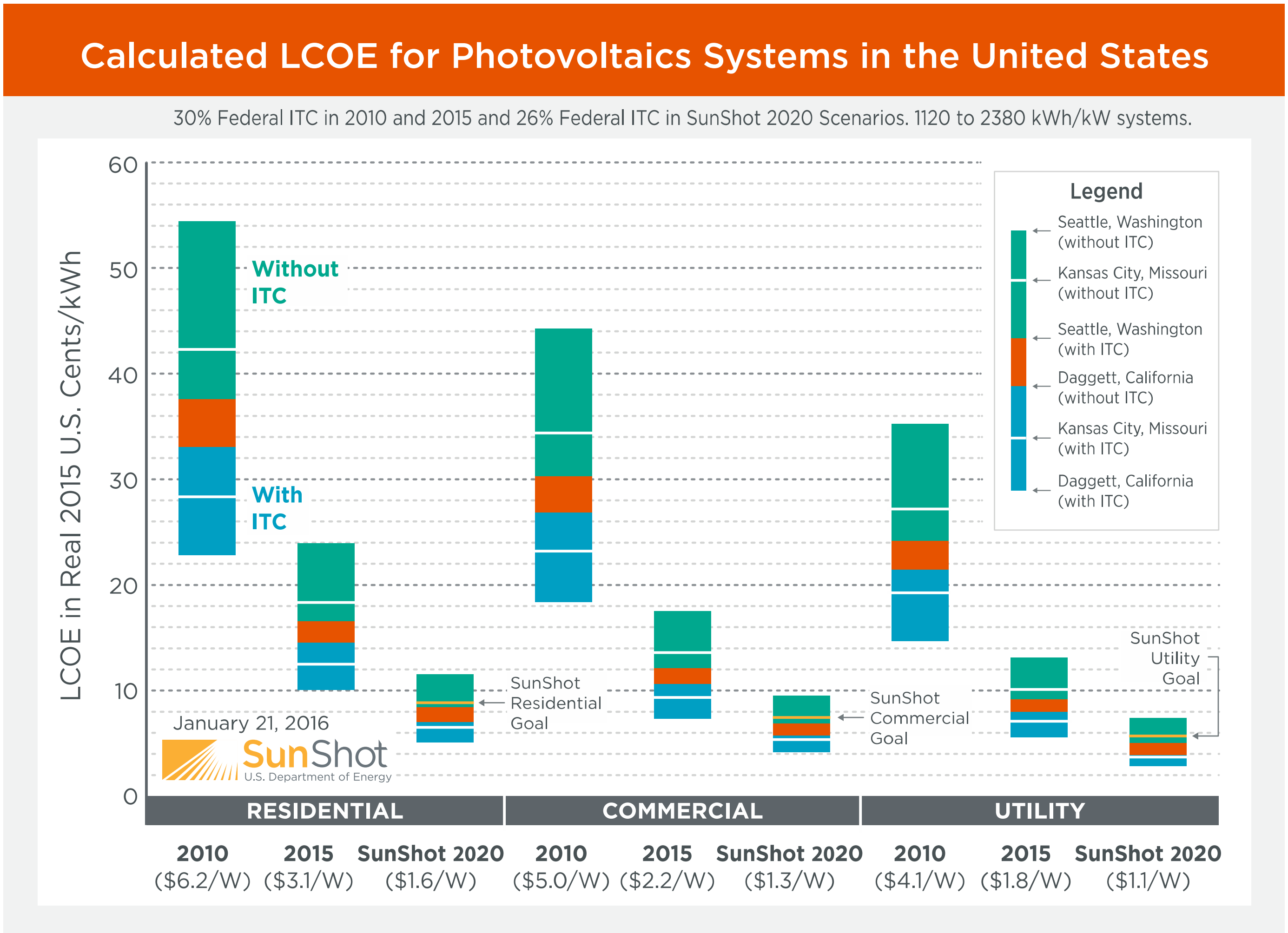

Figure 1. Solar PV LCOE – historical, current, and 2020 targets

In Section 2, below, we provide a brief synthesis of key insights and findings from across all of the On the Path to SunShot reports. For additional context, detailed findings, and important discussions about methods, limitations, and future research needs, readers can download the full reports at the On the Path to SunShot webpage . In Section 3, we conclude with a brief discussion of future SunShot Initiative work.

2 Key Findings

The SunShot Initiative's original targets were set in terms of reduced solar technology prices and electricity costs, which detailed analysis suggests will translate into dramatically higher U.S. solar deployment over the next several decades. The cost of solar electricity in dollars per kilowatt-hour ($/kWh) can be reduced by boosting the amount of energy a solar system produces over its lifetime (kWh), cutting the lifetime cost ($) of that system, or both. Once that cost is at or below the cost of competing energy technologies, solar deployment should proceed rapidly. This is valid, to a point, and has been reflected in market developments to date.

However, as U.S. solar electricity has continued its transformation from a niche to the mainstream, several challenges to this equation have become increasingly clear. First, the cost of a solar system embraces more than the cost of solar hardware and even more than the cost of the various processes required to sell, install, and interconnect the system. Second, solar's cost is dynamically intertwined with the characteristics and costs of all the other ways of satisfying electricity demand within the power system. Finally, some kWhs of solar electricity may be more useful than others—and more useful to some stakeholders than to others—which can have profound implications for cost. All these observations are linked by the concept of value. Value encompasses solar electricity's costs and benefits. For example, solar electricity might have one set of costs and benefits to a homeowner, another to a utility, and yet another to the broader society. It might have more value than natural gas-generated electricity in one time, place, and mix of generating technologies but less value in a different situation. And so forth.

Failure to address this complex web of value-related issues could jeopardize the SunShot Initiative's vision of affordable, widely deployed solar that produces substantial national benefits, including a boost to U.S. solar manufacturing. Conversely, effectively weaving the threads together could spur achievements that surpass the original SunShot vision. Here we extract insights from the On the Path to SunShot reports to highlight critical connections that affect solar costs, deployment, and domestic manufacturing. We also highlight some of the SunShot Initiative's activities that are supporting advances in key areas. Amid the complexity, one common theme emerges—sustained, multifaceted innovation will be needed to achieve the solar future.

2.1 Systems Integration

Increasing the use of grid-flexibility options (improved grid management, demand response, and energy storage) could enable 25% or higher penetration of PV at low costs (see Denholm et al. 2016). Considering the large-scale integration of solar into electric-power systems complicates the calculation of the value of solar. In fact a comprehensive examination reveals that the value of solar technologies—or any other power-system technology or operating strategy—can only be understood in the context of the generation system as a whole. This is well illustrated by analysis of curtailment at high PV penetrations within the bulk power and transmission systems. As the deployment of PV increases, it is possible that during some sunny midday periods due to limited flexibility of conventional generators, system operators would need to reduce (curtail) PV output in order to maintain the crucial balance between electric supply and demand. As a result, PV's value and cost competitiveness would degrade. For example, for utility-scale PV with a baseline SunShot LCOE of 6¢/kWh, increasing the annual energy demand met by solar energy from 10% to 20% would increase the marginal[1] LCOE of PV from 6¢/kWh to almost 11¢/kWh in a California

1. The marginal cost is the incremental cost of an added unit of PV energy.

grid system with limited flexibility. However, this loss of value could be stemmed by increasing system flexibility via enhanced control of variable-generation resources, added energy storage, and the ability to motivate more electricity consumers to shift consumption to lower-demand periods. The combination of these measures would minimize solar curtailment and keep PV cost-competitive at penetrations at least as high as 25%. Efficient deployment of the grid-flexibility options needed to maintain solar's value will require various innovations, from the development of communication, control, and energy storage technologies to the implementation of new market rules and operating procedures.

Wide use of advanced inverters could double the electricity-distribution system's hosting capacity for distributed PV at low costs—from about 170 GW to 350 GW (see Palmintier et al. 2016). At the distribution system level, increased variable generation due to high penetrations of distributed PV (typically rooftop and smaller ground-mounted systems) could challenge the management of distribution voltage, potentially increase wear and tear on electromechanical utility equipment, and complicate the configuration of circuit-breakers and other protection systems—all of which could increase costs, limit further PV deployment, or both.[2] However, improved analysis of distribution system hosting capacity—the amount of distributed PV that can be interconnected without changing the existing infrastructure or prematurely wearing out equipment—has overturned previous rule-of-thumb assumptions such as the idea that distributed PV penetrations higher than 15% require detailed impact studies. For example, new analysis suggests that the hosting capacity for distributed PV could rise from approximately 170 GW using traditional inverters to about 350 GW with the use of advanced inverters for voltage management, and it could be even higher using accessible and low-cost strategies such as careful siting of PV systems within a distribution feeder and additional minor changes in distribution operations. Also critical to facilitating distributed PV deployment is the improvement of interconnection processes, associated standards and codes, and compensation mechanisms so they embrace PV's contributions to system-wide operations. Ultimately SunShot-level PV deployment will require unprecedented coordination of the historically separate distribution and transmission systems along with incorporation of energy storage and "virtual storage," which exploits improved management of electric vehicle charging, building energy systems, and other large loads. Additional analysis and innovation are needed in every area to realize the potential of this integrated vision.

Systems Integration: SunShot Highlights to Date

- Analyzing the interconnection of solar with the grid to help the Federal Energy Regulatory Commission implement the Small Generator Interconnection Procedures, which enable small wholesale energy projects to qualify for a cheaper and quicker fast-track process.
- Testing advanced inverters in high-penetration solar scenarios to help Hawaiian Electric Company respond better to electrical disturbances and clear its interconnection backlog.
- Supporting the invention of a plug-n-play solar installation kit that self-tests and communicates with the utility company.
- Supporting projects that use machine learning to advance solar forecasting.

2. Conversely, distributed PV can provide benefits such as deferring system upgrades, managing voltage using advanced inverters—with or without batteries—and reducing distribution losses.

2.2 Technology Development

Although tremendous progress has been made in reducing the cost of PV systems, additional LCOE reductions of 40%–50% between 2015 and 2020 will be required to reach the SunShot Initiative's targets (see Woodhouse et al. 2016). Understanding the tradeoffs between installed prices and other PV system characteristics—such as module efficiency, module degradation rate, and system lifetime—are vital. For example, with 29%-efficient modules and high reliability (a 50-year lifetime and a 0.2%/year module degradation rate), a residential PV system could achieve the SunShot LCOE goal with modules priced at almost $1.20/W. But change the lifetime to 10 years and the degradation rate to 2%/year, and the system would need those very high-efficiency modules at zero cost to achieve the same LCOE. Although these examples are extreme, they serve to illustrate the wide range of technological combinations that could help drive PV toward the LCOE goals. SunShot's PV roadmaps illustrate specific potential pathways to the target cost reductions.

Energy storage will help enable CSP compete by adding flexibility value to a high-variable-generation (solar plus wind) power system (see Mehos et al. 2016). Compared with PV, CSP systems are more complex to develop, design, construct, and operate, and they require a much larger minimum effective scale—typically at least 50 MW, compared with PV systems that can be as small as a few kilowatts. In recent years, PV's greater modularity and lower LCOE have made it more attractive to many solar project developers, and some large projects that were originally planned for CSP have switched to PV. However, the ability of CSP to use thermal energy storage—and thus provide continuous power for long periods when the sun is not shining—could give CSP a vital role in evolving electricity systems. Because CSP with storage can store energy when net demand[3] is low and release that energy when demand is high, it increases the electricity system's ability to balance supply and demand over multiple time scales. Such flexibility becomes increasingly important as more variable-generation renewable energy is added to the system. For example, one analysis suggests that, under a 40% renewable portfolio standard in California, CSP with storage could provide more than twice as much value to the electricity system as variable-generation PV. For this reason, enhanced thermal energy storage is a critical component of the SunShot Initiative's 2020 CSP technology-improvement roadmap.

Innovation-driven cost and performance improvements, along with strong projected solar demand in the United States and across the Americas, could increase the attractiveness of U.S.-based solar manufacturing (see Chung et al. 2016). Although improvements to standard PV modules have produced deep cost reductions over the past 5 years, the returns on such incremental improvements appear to be diminishing, and more dramatic innovations in module design and manufacturing are required to continue along the path of rapid progress. At the same time, major opportunities exist for innovation to unlock the potential of CSP technologies. This need for innovation could benefit U.S. PV and CSP manufacturers. The United States has been rated one of the world's most competitive and innovative countries as well as one of the best locations for PV manufacturing. It is a global leader in PV and CSP R&D and patent production, and U.S. PV manufacturers are already pursuing highly differentiated innovations.

3. Net demand is equal to normal demand minus generation from variable-generation solar (PV and CSP without storage) and wind. Generation from these technologies is variable because it changes in response to sun and wind conditions, whereas the generation from dispatchable technologies—such as coal or natural gas plants—is not condition dependent.

Technology Development: SunShot Highlights to Date

- Creating the Foundational Program to Advance Cell Efficiency (F-PACE) to increase the efficiency of laboratory and commercial PV cells—building on DOE's decades-long success supporting cell technologies that hold over half the world's efficiency records.
- Supporting CSP technology development and commercialization, such as the novel use of proppants as high-temperature heat-transfer fluids to boost efficiency and energy-storage capacity.
- Helping small businesses with early-stage solar technologies prepare for commercialization and additional private investment through the SunShot Incubator program. For every $1 of public investment, Incubator companies—including some of the industry's most successful enterprises—have earned more than $22 in private follow-on funding. These companies have gone on to create thousands of U.S. solar jobs.

2.3 Market Enablers

Financial innovations—independent of technology-cost improvements—could cut the cost of solar energy to customers and businesses by 30%–60% (see Feldman and Bolinger 2016). Financing is critical to solar deployment, because the costs of solar technologies are paid up front, while their benefits are realized over decades. Solar financing has been shaped by the government incentives designed to accelerate solar deployment. This is particularly true for federal tax incentives, which have spawned complex tax-equity structures that monetize tax benefits for project sponsors who otherwise could not use them efficiently. Although these structures have helped expand solar deployment, they are relatively costly and inefficient. This has spurred solar stakeholders to develop lower-cost financing solutions such as securitization of solar project portfolios, solar-specific loan products, and methods for incorporating residential PV's value into home values. To move solar further toward an unsubsidized SunShot future, additional financial innovation must occur. Development of a larger, more mature U.S. solar industry will likely increase financial transparency and investor confidence, which in turn will enable simpler, lower-cost financing methods. Utility-scale solar might be financed more like conventional generation assets are today, non-residential solar might be financed more like a new roof, and residential solar might be financed more like an expensive appliance. Assuming a constant, SunShot-level installed PV system price, such financing innovations could reduce PV's LCOE by an estimated 30%–60% (depending on the sector) compared with historical financing approaches.

Implementing a range of alternative utility-rate reforms could minimize solar value losses at increasing levels of distributed PV penetration (see Barbose et al. 2016). In conjunction with the technical issues described above, the connections between distributed PV and electric distribution systems hinge on utility business models and regulations. As PV deployment has leapt forward and presaged a truly significant solar contribution, however, it has become clear that utilities' traditional treatment of distributed PV cannot be taken for granted—nor can the future value and deployment of distributed PV. At the heart of this issue is net energy metering (NEM). Under NEM, PV owners can sell to a utility the electricity they generate but cannot consume on site, often at full retail rates. This widespread policy has helped drive the rapid growth of distributed PV, but the success has raised concerns about the potential for higher electricity rates and cost-shifting to non-solar customers, reduced utility shareholder profitability, reduced utility earnings opportunities, and inefficient resource allocation. The resulting reform efforts have revolved largely around changing NEM rules and retail rate structures. Most of the reforms to date address NEM concerns by reducing the benefits provided to distributed PV customers and thus constraining PV deployment. A new analysis estimates that eliminating NEM nationwide, by compensating exports of PV electricity at wholesale rather than retail rates would cut cumulative distributed PV deployment by 20% in 2050 compared with a continuation of current policies. This would slow the PV cost reductions that arise from larger scale and market certainty. It could also thwart achievement of the SunShot deployment goals even if the initiative's cost targets are achieved. This undesirable prospect is stimulating the development of alternative reform strategies that address concerns about distributed PV compensation without inordinately harming PV economics and growth.

Monetizing the environmental health benefits of solar could add ~3.5¢/kWh to the value of solar energy (see Wiser et al. 2016). The monetary impacts due to environmental degradation and public health impacts seem far removed from the apparent "sticker price" of electricity. Yet quantifying these impacts is essential to understanding the true costs and benefits of solar and conventional generating technologies. Compared with fossil fuel generators, PV and CSP produce far lower lifecycle levels of greenhouse gas (GHG) emissions and harmful pollutants including fine particular matter (PM2.5), sulfur dioxide (SO2), and nitrogen oxides (NOx). Achieving the SunShot-level solar deployment targets—14% of U.S. electricity demand met by solar in 2030 and 27% in 2050—could reduce cumulative power-sector GHG emissions by 10% between 2015 and 2050, resulting in savings of $238–$252 billion.[4] This is equivalent to 2.0–2.2 cents per kilowatt-hour of solar installed (¢/kWh-solar). Similarly, realizing these levels of solar deployment could reduce cumulative power-sector emissions of PM2.5 by 8%, SO2 by 9%, and NOx by 11% between 2015 and 2050. This could produce $167 billion in savings from lower future health and environmental damages, or 1.4¢/kWh-solar—while also preventing 25,000–59,000 premature deaths. To put this in perspective, the estimated 3.5¢/kWh-solar in benefits due to SunShot-level solar deployment is approximately equal to the additional LCOE reduction needed to make unsubsidized utility-scale solar competitive with conventional generators today. In addition, water savings from achieving the SunShot goals, could result in the 2015–2050 cumulative savings of 4% of total power-sector withdrawals and 9% of total power-sector consumption—a particularly important consideration for arid states where substantial solar will be deployed. Improving public health and the environment is but one aspect of solar's many costs and benefits. Clearly, however, the assignment of value to such "external" impacts has potential implications for policy innovation and the economic competitiveness of solar and other generation technologies.

4. The $238 billion estimate assumes the savings are based on offsetting the costs of complying with future GHG-reduction regulations, whereas the $252 billion estimate assumes the savings are based on reduced climate change damages (using a central value for the social cost of carbon). These estimates are in present-value terms.

Market Enablers: SunShot Highlights to Date

- Bringing together stakeholders through Rooftop Solar Challenge 2 to standardize solar permitting and interconnection processes, facilitate easy and cheap group purchasing, and create online applications to make going solar faster, easier, and more affordable.
- Supporting a National Rural Electric Cooperative Association project to help 14 rural electric cooperatives develop and deploy a ready-to-use set of standard engineering designs, financing models, and tools to reduce solar adoption costs and ease the integration of solar into their asset portfolios.

3 The SunShot Initiative's Role—2020 and Beyond

Significant progress had been made toward the SunShot Initiative's 2020 solar cost targets. Although additional LCOE reductions of 40%–50% are still required, feasible pathways to those reductions exist. The SunShot Vision Study suggests that achieving the targets could result in solar meeting roughly 14% of U.S. electricity demand by 2030 and 27% by 2050. Achieving such high deployment presents new challenges and opportunities. As the proportion of capacity from variable-generation PV rises to unprecedented levels, the systems that manage U.S. electricity generation, transmission, distribution, and consumption must evolve to maintain grid reliability and cost-effective solar integration.[5] As demonstrated by the On the Path to SunShot series, the technologies and strategies used to facilitate this evolution will affect system-wide costs, and the value of solar energy will change within the evolving system. These changes will be enabled by solar LCOEs falling below the SunShot 2020 goals.

While SETO continues to pursue the 2020 goals, it is also looking beyond that horizon to an even lower-cost, higher-deployment solar future. Thus the On the Path to SunShot series is not only an assessment at the initiative's midway point, but also a starting point for the next phase of solar progress. We now know a great deal about solar technologies and their integration into the U.S. electricity system. However, we also know that, as the technologies and electricity systems change, new opportunities and challenges will arise. The ultimate goal of the SunShot Initiative is to facilitate large-scale solar deployment in the United States to provide the nation with environmental and economic benefits. To achieve this goal, the SunShot Initiative will evolve continually to meet new challenges and exploit new opportunities as they arise.

5. CSP with thermal energy storage presents less of a challenge in this regard and can actually facilitate PV integration.

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