Chapter 10 – Advancing Solar Technologies: Research, Development, and Demonstration

10.1 INTRODUCTION

Preceding chapters of this report show that solar energy has the potential to play a significant role in meeting global electricity needs in a low-carbon future. However, beyond modest levels of penetration and absent substantial government support or a carbon policy that favors renewables, contemporary solar technologies remain too expensive for large-scale deployment. Therefore, to realize solar energy’s sizable potential, large cost reductions are still needed. Several pathways to such reductions exist. In the case of solar photovoltaics (PV), progress in the short term will likely come from improving today’s incumbent technologies — notably, solar cells based on crystalline silicon and a number of thin-film materials (see Chapter 2). Gains will flow from incremental increases in cell and module efficiencies, further scaling and streamlining of manufacturing processes, and innovations in installation hardware and practices. Over the longer term, much larger cost reductions may be achieved through the development of novel, inherently less costly PV technologies, some of which are now only in the research stage. Progress toward reducing the cost of concentrated solar power (CSP) technologies will likely follow a similar trajectory. In the near term, accumulating experience should enable today’s designs to be built and operated at lower cost. Ultimately, however, more significant cost reductions will require the development of new materials and system designs that can meaningfully shift CSP’s fundamental efficiency frontier.

To realize solar energy’s sizable potential, large cost reductions are still needed.

The challenges that confront government efforts to stimulate technology change — whether on the supply side or on the demand side — are different and arguably greater in commercial sectors such as energy, health, transportation, and agriculture than they are in sectors such as defense, space, homeland security, or intelligence where cost is not a central objective. These challenges include balancing competing objectives (e.g., low carbon emissions, environmental sustainability, energy independence, and job creation); dealing with a fickle legislature that does not always, or even usually, provide the stable funding that is so necessary for efficient technology development; and attracting and retaining public officials who understand private markets and for-profit investment decision-making. Finding an appropriate and effective balance in government efforts to support solar technologies is a difficult but crucially important task.

This chapter focuses on the broad issue of investment in solar energy research, development, and demonstration (RD&D) with a particular emphasis on identifying needs and promising approaches, and on the role of the U.S. federal government as a partner to industry and academia in pursuing them. After briefly reviewing the history of U.S. government support for solar RD&D, we discuss current
U.S. Department of Energy (DOE) solar RD&D funding objectives, and identify areas where we believe DOE should focus future PV and CSP RD&D activity. Concluding sections discuss DOE efforts to support solar demonstration projects and future opportunities for the Department to leverage its infrastructure to amplify the impact of its solar programs.

Finding an appropriate and effective balance in government efforts to support solar technologies is a difficult but crucially important task.

10.2 HISTORY OF U.S. GOVERNMENT SUPPORT FOR SOLAR RD&D

The federal government has a long history of supporting solar RD&D activity. Today, most of this support is managed through the Solar Energy Technology Office (SETO) within DOE’s Office of Energy Efficiency and Renewable Energy (EERE). Since the early 1970s, DOE has invested more than $7.9 billion in solar energy, most recently through SETO/EERE-supported programs. Figure 10.1 shows the breakdown of this investment between PV and CSP technologies. Cumulatively, the PV and CSP programs have received approximately $5.0 billion and $2.9 billion respectively since the early 1970s.\(^1\),\(^2\) DOE also supports research relevant to PV and CSP technology development outside of EERE, with funding through its Office of Science and the Advanced Research Projects Agency–Energy (ARPA–E). Data on these expenditures, which are often targeted to individual projects rather than at the program level, are not included in Figure 10.1.

\(^1\)Figures include DOE’s budget request for 2016 and 2009 appropriations under the American Recovery and Reinvestment Act of 2009.

\(^2\)Figures do not include Office of Science funding for basic research relevant to PV and CSP.\(^3\)
As Figure 10.1 shows, DOE began providing significant funding for PV and CSP technology research during the late 1970s in response to the first oil crisis. Funding declined along with oil prices during the early 1980s and rose modestly throughout the early 1990s. Funding increased more substantially in 2007 and reached a peak in 2009, when additional spending on energy R&D was authorized as part of a broader effort to stimulate the U.S. economy under the American Recovery and Reinvestment Act of 2009.

Total DOE funding for solar energy research has fluctuated from year to year, often significantly. A number of factors are responsible for this variation, including changes in global energy prices, the state of the economy, changes in renewable energy policy, and decisions regarding overall federal research priorities.

Nevertheless, it is important to appreciate that large year-to-year budget swings have made it very difficult for research institutions to assemble and retain the talent necessary to execute the long-term basic research programs needed to develop breakthrough solar technologies.

**RECOMMENDATION**

DOE should avoid significant short-term fluctuations in solar RD&D funding to allow universities and national laboratories to recruit and retain the talent needed to support long-term research programs.

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**BOX 10.1 THE TENSION BETWEEN PROTECTING INTELLECTUAL PROPERTY AND DISTRIBUTING KNOW-HOW**

Government support for RD&D compensates for the private sector’s tendency to under-invest in promising technologies whose commercial value is viewed as too uncertain to warrant development by private firms. The guiding principle is that public support is justified because the public will benefit in the long term from investing in a portfolio of such technologies.

The universities and not-for-profit laboratories that generally perform government-funded early-stage research have long been allowed to claim patents, including some patents of great value, that spring from their work. This policy is justified by the notion that it provides an economic incentive for researchers or, more commonly, for their licensees to make the substantial investments necessary to commercialize results from early-stage research.

For later-stage RD&D activities, which inherently carry much lower technology risk and have explicit commercial objectives, the situation is more complicated. When government supports late-stage RD&D, it frequently expects significant industry cost sharing. Understandably, the private firms that participate in such cost-sharing arrangements expect — and typically receive — intellectual property rights in return. These firms may therefore gain the opportunity to benefit commercially from early-stage public R&D investments at little or no cost, while non-participating firms — and by extension the general public — lose that opportunity. Public concerns about such arrangements are justified, especially when foreign firms are among the beneficiaries.

This tension, between granting intellectual property rights as a way to provide incentives for private firms’ participation and disseminating the benefits of public technology investments as broadly as possible, affects all government “technology push” programs that seek to encourage late-stage RD&D. DOE’s solar programs are not exceptions.
Since 2010, important changes have occurred in DOE’s budget for solar RD&D. Figure 10.2 shows that the proportion of SETO’s budget dedicated to solar system integration, balance-of-system (BOS) cost reductions, and solar manufacturing innovation and competitiveness has been increasing. From a comparison of SETO budgets for 2015 and 2010, it is apparent that the proportion of the overall budget that is dedicated to core PV and CSP technology programs has fallen from 80% to 33%. This shift in funding priorities has coincided with the launch of DOE’s SunShot Initiative, a collaborative, national-level effort to make solar technologies cost-competitive with other forms of electricity generation by 2020.

Recent changes in SETO’s funding priorities have been prompted by significant reductions in PV module costs over the past several years. As discussed in Chapter 4 of this report, today’s modules cost between $0.60 and $0.70 per peak watt ($W_p$), meaning that current PV technology is already approaching the Sunshot Initiative’s $0.50–$0.55 per-W_p cost target for 2020. Given this progress, SETO has progressively refocused investment away from PV technology programs and toward reducing BOS “soft costs” (i.e., non-hardware BOS costs associated with installing and connecting PV systems), while also fostering innovation in manufacturing competitiveness. The remaining SETO budget for PV R&D is spread across a variety of established cell innovations.

**Figure 10.2 Budget Breakdown for DOE’s Solar Energy Technologies Office**

Note: Budget figures are in constant 2014 dollars. Figures are as enacted in each year except 2016, for which only requested budget data exist. Large year-to-year changes in the allocation of funding within SETO may be a response to the fast-paced development and commercialization of solar technologies. The chart does not include approximately $24 million in annual funding for the Fuels From Sunlight Energy Innovation Hub.

http://energy.gov/eere/sunshot/sunshot-initiative
technologies based on crystalline silicon (c-Si), thin-film amorphous silicon, and cadmium telluride (CdTe), as well as several others that have been under development for some time using copper indium gallium diselenide (CIGS) and copper tin zinc sulfur selenide (CZTSSe) in addition to multi-junction, dye-sensitized, and organic devices.

The small size of SETO’s PV Energy Systems budget, and the relative conventionality of the technologies it supports gives the impression that SETO has determined that the contemporary PV technology paradigm, based on a rigid glass-covered PV panel (probably made using c-Si technology) surrounded by a metal frame, provides a sufficient long-term basis for scaling up PV deployment. While our study group agrees strongly with the need to reduce BOS costs, we consider the SETO SunShot-focused strategy of achieving a reduction on the necessary scale within the contemporary paradigm to be too conservative and unduly short term. New technologies that can provide

**New technologies that can provide the foundation for a new paradigm and enable a step-change in PV system costs are needed.**

the foundation for a new paradigm and enable a step-change in PV system costs are needed. A much larger part of the SETO budget should be directed to developing the promising ideas already at hand, and discovering others.

Figure 10.3 shows the distribution of SETO funding to different types of RD&D entities in 2013. In that year, about one-quarter of the total SETO budget supported university-based

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**Figure 10.3 Breakdown of SETO Funding by Type of Recipient for FY2013**

<table>
<thead>
<tr>
<th>Type of Recipient</th>
<th>Percentage of Budget</th>
</tr>
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<tbody>
<tr>
<td>University</td>
<td>20%</td>
</tr>
<tr>
<td>National Laboratories</td>
<td>60%</td>
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<tr>
<td>Industry</td>
<td>10%</td>
</tr>
<tr>
<td>Other</td>
<td>10%</td>
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</tbody>
</table>

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Chapter 10 – Advancing Solar Technologies: Research, Development, and Demonstration 235
research, approximately 40% was directed to the national labs, and the rest was used to support industry-led RD&D. This funding distribution, with its heavy emphasis on applied research of nearer-term commercial relevance, reinforces the impression that SETO is underestimating the need for investment in fundamental technology. In its place, SETO — and by extension the federal government — is assuming a funding burden with respect to relatively mature technologies that firms should reasonably be expected to bear themselves so as to gain competitive advantage (see Box 10.1).

**FINDING**

In recent years, DOE has rebalanced the distribution of federal funding for solar RD&D, providing increased resources for areas where the industry should be motivated and well positioned to innovate, even absent public support.

Moreover, we note that advances in reducing BOS and integration costs, if they are closely tied to the contemporary technology paradigm, could quickly become irrelevant when a new paradigm emerges. Industry may have no option but to invest in such advances for near-term competitive reasons, but the case for government to do so is harder to make. DOE should therefore carefully assess and quantify the effectiveness of its support for RD&D efforts that target commercially relevant, nearer-term issues. Unless federal support has the potential to deliver a distinctive impact beyond what industry can deliver on its own, we suggest that scarce public resources should be largely redirected to support work on emerging high-potential, high-risk technologies that could fundamentally improve solar energy’s competitiveness.

**RECOMMENDATION**

*DOE should focus its solar RD&D investments on supporting fundamental research to advance high-potential, high-risk technologies that industry is unlikely to pursue.*

Without question, the success of increased RD&D investment cannot be guaranteed. Promising technology pathways based on novel thin-film materials, for example, are currently limited by relatively low conversion efficiencies and poor stability. Few have been demonstrated at the module scale. Nonetheless, if these or other as-yet-undiscovered pathways can be successfully pursued, they have the potential to dramatically improve PV competitiveness and thus to reduce the cost of moving to a low-carbon future.

Before going on to discuss future RD&D opportunities for PV and CSP, we note that DOE’s 2016 budget request includes an increase in funding for SETO generally and a large increase in funding for PV research specifically. If Congress funds the DOE 2016 budget request, it would represent an appropriate and welcome reversal of the long-term trend toward less emphasis on transformative research.
10.4 DIRECTIONS FOR FUTURE RD&D

This section describes important areas for future government-supported RD&D for PV and CSP. In both cases, the motivation and objective must be to achieve dramatic reductions in overall system costs per unit of energy produced. For PV, we point to the likely need for a break with the contemporary rigid module paradigm. Enabling this will require new device and substrate materials, as well as efficient device and module designs with inherently lower cost, and greater flexibility of deployment. For CSP, we argue for a step-change in system efficiency based on operating at significantly higher temperatures, with a corresponding emphasis on point-focus, rather than conventional trough systems.

RD&D Opportunities in PV Technology

Materials and Cells

Creating improved PV technologies will require the contemporaneous development of new materials and device designs that can deliver optimized solar power conversion efficiency (PCE).

A number of properties and characteristics are desirable for materials used in PV devices (these concepts are described in more detail in Chapter 2 and Appendix B):

- **Optical and electrical properties**, including high theoretical efficiency based on strong optical absorption of the solar spectrum, and low carrier and transport losses.
- **Scalability**, specifically, high crustal abundance with scalable production pathways that are not constrained by the economics of byproduction (see discussion in Chapter 6) and that require few steps for synthesis.
- **Utility**, including stability under typical operating temperatures, illumination conditions, and environmental conditions (air/water exposure) over the more-than-25-year lifetime of a PV installation (concerns related to the toxicity of PV-active materials are elaborated in Box 10.2).

We believe high priority should be given to developing a new PV technology paradigm based on modules that use low-cost substrates and that are also light, mechanically robust, and self-supporting.

In particular, we believe high priority should be given to developing a new PV technology paradigm based on modules that use low-cost substrates and that are also light, mechanically robust, and self-supporting. These attributes would allow for a very different approach to managing BOS requirements, with lower hardware and “soft” costs than can be achieved with existing module technology. To dramatically reduce module costs, however, lightweight modules must be produced using scalable, high-throughput manufacturing methods, possibly involving deposition techniques such as inkjet printing, screen-printing, and spray coating. Continuous (sometimes known as “roll-to-roll”) deposition on thin-film substrates, or large-area batch processing techniques on light, rigid substrates may prove to be important in combination with these techniques.
Cruelly, RD&D efforts to develop a new, low-cost PV technology paradigm in a reasonably short span of time must be coordinated to ensure that successful materials and device designs can be rapidly advanced to the point of large-scale manufacturing.

**RECOMMENDATION**

**DOE should coordinate RD&D efforts at all points along the development chain to provide for rapid manufacturing scale-up.**

Inefficient PV technologies require a larger area and a greater number of modules to produce a given amount of power; in addition, many BOS costs, such as those related to land acquisition and site preparation, scale with installation area. Therefore, system costs depend strongly on cell and module efficiency. Figure 10.4 illustrates this effect in the case of a contemporary, grid-connected, utility-scale c-Si PV system. Given typical module and BOS costs for such a system, two important features of Figure 10.4 stand out. First, at power conversion efficiencies below roughly 10%–15%, system cost (in dollars per Wp) falls rapidly with increasing module efficiency. Above this range, the marginal benefit of further efficiency improvements diminishes, as system cost is dominated by BOS components, such as inverters, that are independent of installation area. Increased power conversion efficiency is
Note: Figure 10.4a shows the contribution of module and BOS costs to total system costs. BOS cost components can be divided into two categories: area-dependent (e.g., land, materials and labor for wiring and mounting) and area-independent (e.g., inverters, permitting, interconnection, and taxes). One-quarter of BOS costs at 15% power conversion efficiency (PCE) are assumed to scale with area, consistent with estimates for a contemporary fixed-tilt, utility-scale system. At 15% PCE, modules constitute 36% of the total system cost of $1.80/Wp. A constant module price of $0.65/Wp is assumed. Figure 10.4b shows that higher module efficiencies reduce the importance of area-dependent costs and hence total BOS costs. At low efficiencies, the fraction of total system cost attributable to BOS costs approaches unity due to the larger system area required. In Figure 10.4c the marginal cost reduction from increasing PCE by a fixed quantity (e.g., one percentage point) decreases with increasing absolute efficiency.
therefore an important target for emerging, low-efficiency PV technologies, but assuming conditions typical of the southwestern United States (i.e., high insolation and low land costs) it becomes relatively unimportant above approximately 15%. Where land costs are high, efficiency remains important even at higher efficiencies, but the general conclusion still holds: efficiency gains above a certain level provide a low marginal cost reduction for a large PV installation. For a given BOS cost, what matters most is module cost per peak watt.

**Modules**

Much RD&D work on PV modules focuses on manufacturability. Reliably demonstrating module-level processes, however, often requires relatively large operational scale, which most university labs cannot achieve. National labs are well placed to support research on module integration and to oversee new pilot-scale manufacturing lines for emerging technologies.

Figure 10.5 highlights one key challenge of module integration — achieving module efficiencies that are close to the efficiency of individual cells. Record module efficiencies range from roughly 60% to 90% of cell efficiencies, and tend to be higher for older technologies. This long transition from efficient cell to efficient module accentuates the need for continued investment in module technology development.

**RECOMMENDATION**

Federal RD&D efforts should support pilot-scale demonstration of high-throughput processing techniques (e.g., roll-to-roll methods) for emerging thin-film PV cells and integrated modules.

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An important lesson from the recent sharp fall in c-Si module prices is that, with very large manufacturing scale, module costs can be driven very low. In a context where global demand for PV modules easily justifies investment in large factories, new technologies will compete with each other — at least in part — based on how rapidly their costs fall with increasing manufacturing scale. Likewise, as the scale of deployment needed to displace fossil generation leads to very large PV installations, module technologies will also compete on the basis of low area-dependent BOS costs. This should prompt efforts to develop substrate and device materials that are low-cost, compatible with large-area deposition techniques, and suited to rapid and inexpensive deployment in large installations.

**RECOMMENDATION**

DOE should fund RD&D for new PV materials and device architectures if they enable fundamentally lower-cost manufacturing and installation processes.
**BOX 10.3 THE PEROVSKITE STORY**

The rapid emergence of hybrid organic-inorganic perovskites as a promising thin-film PV technology is an example of a global RD&D success in the making.

The class of materials known as hybrid perovskites was first studied in the early 1990s. Basic materials characterization and device engineering showed high potential for use in light-emitting diodes (LEDs) and transistors, but PV applications were not explored. In the mid-2000s, perovskites were used for the first time in dye-sensitized solar cells (DSSCs) in place of typical organic dyes. Employing a typical DSSC device structure and piggybacking on insights from that field, solid-state perovskite solar cells soon achieved promising efficiencies on the order of 10%. This development sparked a surge of interest in PV applications for perovskites, as researchers working on other emerging PV technologies applied their characterization techniques and processing methods to the perovskite material system. Record cell efficiencies for perovskite solar cells have increased to more than 20% since 2011 — an unprecedented rate of improvement.

Despite these impressive developments, however, perovskites remain firmly in the early stages of RD&D. Key issues still remain in perovskite material and device development. For example, the use of toxic lead is a concern: further research is needed on the bioavailability and toxicity of lead specifically in perovskite materials, possible options for risk mitigation by encapsulation and recycling, and non-toxic substitutes (e.g., tin). Long-term stability and device lifetimes are unproven, and degradation mechanisms remain poorly understood. Improved stability could reduce encapsulation needs, allow more versatile module form factors, and lower module and BOS costs. In addition, more work is needed to demonstrate scalable and reliable processing of perovskite thin-film devices, and the myriad and inevitable challenges of module integration have yet to be resolved. Continued RD&D support may well determine whether perovskites or other emerging PV technologies realize their high potential and achieve cost-effective deployment within the next few decades.

**Grid Integration and Energy Storage**

As discussed in Chapter 8, integrating the intermittent output of PV installations into a system that reliably responds in real time to unpredictable fluctuations in electricity demand presents a very significant technological hurdle to utilizing solar power on a very large scale. For this reason, technologies that can help smooth the output of intermittent PV generators and make them operate more like dispatchable resources, and otherwise help ensure grid reliability at high levels of PV penetration, are important targets for federal RD&D. Economical bulk energy storage systems represent a key enabling technology for large-scale PV deployment, as they improve the economic competitiveness of PV at high levels of penetration and mitigate the decline in value factors that would otherwise occur with increased penetration (for reasons discussed in Chapter 5) by enabling solar generators to shift their output away from hours of peak sunlight. We describe energy storage systems that are relevant for the electric power sector in Appendix C and solar-to-fuels technologies in an associated working paper.
In part due to the availability of combustion turbines, demand management, and geographic averaging, current levels of PV penetration across the United States have not yet reached the point where the absence of large-scale storage capability is constraining further deployment. Therefore, the appropriate balance of government support for storage technologies should emphasize fundamental research over deployment at the present time.

**RECOMMENDATION**

Research on bulk energy storage should be strongly supported at a level commensurate with its importance as a key enabler of intermittent renewable energy technologies.

The appropriate balance of government support for storage technologies should emphasize fundamental research over deployment at the present time.

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Pumped hydro is a mature and efficient energy storage technology, but it is only applicable in specific geographic regions, most of which have already been exploited in developed nations.
Although we argue that SETO should rebalance its RD&D portfolio toward breakthrough cell and module technologies, and away from BOS generally, we recognize the need for federal support to advance BOS improvements in certain areas. In particular, innovative power electronics are needed to facilitate PV integration with the electricity grid at high levels of penetration. Further, efficient and reliable microinverters and techniques such as maximum power point tracking,* which is so far widely used only in battery charge controllers and grid-connected inverters, could be introduced at the module level to increase power conversion efficiency for modules and arrays, and thereby improve PV economics at all scales. “Smart” inverters and electronics, particularly at the residential and commercial level, would also enable greater central control over the output of distributed, grid-connected PV generators and help grid operators maintain system stability at high levels of PV penetration while also, perhaps, reducing cycling costs for thermal plants (see discussion in Chapter 8). We note that many innovations in power electronics are not tied to contemporary system designs and may be equally applicable to many types of future PV systems. We are enthusiastic about DOE efforts in this field.

**RECOMMENDATION**

**Government-supported RD&D to advance BOS technologies should continue to pursue innovations in power electronics that can improve system efficiency.**

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**RD&D Opportunities in CSP Technology**

Advances in CSP technology can be framed in terms of the interplay between RD&D on materials, system components, and system design. An important part of this interplay is the feedback from system design to the research agendas for CSP materials and components.

Priorities for the CSP RD&D agenda are informed by the costs and efficiencies of the major components of current systems. In Chapter 3 (Figure 3.2), we show the energy flow through a typical CSP plant to identify the major system inefficiencies. By far the two largest losses occur in the power block (40% efficiency) and the collector/receiver (42% efficiency). Together, losses at these two points account almost entirely for the overall 16% efficiency of the CSP plant. In a typical installation, the collector/receiver and power block are also the two most expensive components, accounting for 44% and 17% of total plant cost respectively. These cost and efficiency breakdowns suggest an RD&D focus on the collector/receiver and power block components in today’s CSP designs.

Of course, the relative efficiencies and costs of major CSP system components are sensitive to overall system design. For example, point-focus designs (such as solar towers) lend themselves to higher temperatures and thus more efficient and lower cost power blocks and thermal energy storage systems. The higher operating temperatures, in turn, lead to a set of new materials research problems.

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*Maximum power point tracking (MPPT) is a feedback control technique whereby the power transferred from a source having output impedance to the input of a loading device is maximized by dynamically adjusting the voltage and/or current at the input of the loading device.

*These are simulation results for a 150-MW solar tower plant with 11 hours of storage located in Dagget, California. See Appendix D for details.
Finally, new materials can open the door to new system components and system designs. For example, the discovery of new thermal energy storage fluids or heat transfer fluids could enable the use of much more efficient power blocks, while also requiring new research on materials for use in other system components (e.g., pumps).

The major advantage of CSP as an electricity-generating technology is that it affords relatively simple and low-cost opportunities to integrate thermal energy storage, and can operate in hybrid configurations with other thermal processes.

As we point out in Chapter 3, the major advantage of CSP as an electricity-generating technology is that it affords relatively simple and low-cost opportunities to integrate thermal energy storage, and can operate in hybrid configurations with other thermal processes. As a result, CSP systems can be designed to provide dispatchable electricity and to incorporate storage (or effective storage) ranging from minutes to days. RD&D to improve and exploit this unique capability should also be a priority.

Another attribute of CSP systems noted in Chapter 3 is that they are economic only when deployed on a large scale. Pilot-scale demonstrations can play an essential and cost-effective role in moving from laboratory research on materials and components to full systems. The need for pilot-scale demonstration facilities is discussed further in Section 10.5 and illustrated by the history of CSP RD&D (Box 10.4).

The next sections discuss RD&D opportunities and challenges for different aspects of CSP technology — specifically, high-efficiency solar energy collection and receiving systems (including novel CSP system configurations), efficient and cost-effective thermal energy storage systems, advanced high-temperature power cycles, and novel system designs for CSP integration and hybridization.

**BOX 10.4 THE HISTORY OF CSP RD&D**

DOE supports CSP as a unique technology that can deliver solar-generated electricity on demand through thermal energy storage (Chapter 3). Federal support for CSP in the United States dates back to DOE’s formation in 1977. Two significant early projects, Solar One and Solar Two, involved pilot-scale demonstrations of tower technology. In 1981, DOE, Southern California Edison, the Los Angeles Department of Water and Power, and the California Energy Commission worked together to build Solar One, a 10-megawatt (MW), pilot-scale facility located in Barstow, California. Solar One demonstrated a tower configuration for steam generation of electricity using hot oil circulating through the tower and thermal storage in rocks. It operated from 1982 through 1986. In 1995, DOE and a consortium of utilities led by Southern California Edison built Solar Two, which made use of some of Solar One’s remaining infrastructure. This pilot-scale tower was designed to demonstrate the use of molten salts in the thermal energy receiver and for storage. Solar Two ran successfully between 1996 and 1999. Since CSP designs, unlike PV cannot be effectively tested at small scale, this sort of pilot-scale system demonstration is very important as a means to mitigate the risks of constructing a facility at the very large scale typical of utility generation plants being built today (see Chapter 3).
High-Efficiency Solar Energy Collection and Receiving Systems

As discussed previously, the most expensive and second least efficient component of a typical CSP plant is the collector/receiver, which gathers solar energy in the mirror field and converts it to thermal energy. Key RD&D priorities for the mirror field include lower cost manufacturing and installation, less costly and more accurate tracking systems, more efficient mirrors, and engineered surfaces to prevent fouling in desert environments — all improvements that would enable future plants to achieve tighter light focusing and higher temperatures. Basic research at universities on surface modification and thin films may lead to breakthroughs in the latter two areas, and applied research undertaken by universities, national laboratories, and industry researchers can lead to lighter-weight, easier-to-manufacture mirror designs. Most of the applied research to reduce mirror weight and manufacturing costs, however, will appropriately fall to industry as it scales up new CSP technologies.

As described in Chapter 3, a point-focus CSP architecture (e.g., solar tower) can generally achieve higher power conversion efficiencies than the older trough technology, since point-focus designs deliver a higher-temperature heat source to the power block. Based on this inherent efficiency advantage, we recommend that most future CSP research target point-focus technologies or new, novel configurations rather than incremental improvements to trough designs.

Although a higher-temperature heat source increases the heat-to-electricity conversion efficiency of CSP systems, it also creates material-related challenges. One such challenge is to develop suitable receiver materials and heat transfer fluids that are capable of handling high temperatures without degrading and can also get through the night without freezing. Another challenge is to develop construction materials and designs for components such as pumps and pipes that are capable of withstanding exposure to high temperatures. These challenges point to important new directions for basic and applied research in this field.

**RECOMMENDATION**

Future CSP RD&D should emphasize high-temperature, point-focus technologies that hold promise for improving system efficiency and cost-effectiveness.

Efficient and Cost-Effective Thermal Energy Storage Systems

One of the unique characteristics of CSP technologies is that they offer easy and cost-effective opportunities to incorporate significant thermal energy storage. Many problems in thermal storage must be addressed, however, to exploit this synergy fully. Much recent research has focused on developing molten salt compositions suited to parabolic trough and point-focus applications. This work leverages extensive past research on molten salts for high-temperature nuclear reactors. Progress with molten salts has enabled operation at higher temperatures and provided for greater thermal energy storage density. However, problems with freezing at the low-temperature end of the process and thermal decomposition at the high-temperature end of the process may...
require new thermal energy storage materials depending on the overall CSP configuration used. A particular issue here is to keep material costs low, since large quantities of storage material will be needed.

In addition, better understanding is needed of material properties at the high (greater than 500°C) temperatures contemplated in new CSP designs. Specific topics include the radiative heat transfer properties of molten salts, including absorption but also scattering and emission; chemical compatibility (corrosion, dissolution) of structural materials in high-temperature molten salts; and rugged and compact heat exchangers for operation with high-temperature molten salts. Basic research is also needed on other high-energy-density and long-term storage approaches, perhaps in the form of chemical energy and phase change materials.

**RECOMMENDATION**

New thermal energy storage materials and concepts should be developed and further explored in future CSP RD&D activities.

**Advanced, High-Temperature Power Cycles**

Power cycles that are both more efficient and cheaper (as well as smaller scale, if possible)\(^vi\) are needed. Advanced, high-temperature power cycles have the potential to produce electricity at higher efficiencies and lower cost than the traditional cycles used in fossil-fuel plants. Since high-temperature power cycles are inherently more efficient, they might be economic at smaller scales than current Rankine-cycle systems. If high-temperature power cycles can be implemented cost-effectively at smaller scales, this would both reduce capital cost requirements and alleviate an existing difficulty in point-focus CSP plants with respect to the need to focus mirrors over long distances. Finally, alternative power cycles might reduce or eliminate the need for process (cooling) water, which is often in short supply in the typically arid regions that have the largest solar resource.

In FY2015, SETO’s CSP subprogram began collaborating with DOE’s Offices of Fossil Energy and Nuclear Energy and with EERE’s Geothermal Technologies program on a crosscutting initiative through the Advanced Solar Power Cycles RD&D activity to advance supercritical carbon dioxide (CO\(_2\)) electricity production technology. Air and supercritical CO\(_2\) Brayton cycles may offer significant advantages over today’s power cycles; they are described in Chapter 3 of this report (Section 3.6).

**RECOMMENDATION**

DOE should continue to invest in RD&D on high-temperature power cycles that hold promise for significantly boosting the conversion efficiency and reducing the cost of CSP power plants.

\(^vi\)For a discussion of power cycles, see Box 3.1 and Section 3.6 in Chapter 3.
**Novel CSP Design, Integration, and Hybrid Configurations**

Research on novel CSP configurations can exploit the inherent advantages of CSP technology — namely, that it allows for the natural integration of energy storage and easy hybridization with fossil power plants — and may enable the efficiency limitations of current systems to be overcome. In particular, novel configurations can provide a platform for integrating innovations in the three research opportunity areas discussed previously (i.e., high-efficiency collection and receiving systems, efficient and cost-effective energy storage systems, and advanced power cycles). An example is the direct solar-to-salt design described in Chapter 3 (Section 3.6 and Figure 3.12), which — by combining the traditional elements of receiver and thermal energy storage container — simultaneously addresses several issues with respect to efficiency losses, materials design challenges, thermal storage, and operational temperature.

Finally, numerous research opportunities exist for exploiting the thermal energy collected in CSP plants to provide energy for thermochemistry and process heat. Because this study is focused on solar electricity generation, we do not discuss these applications in detail other than to note that by stopping short of the electricity production step, they eliminate power block losses altogether. An example is the use of steam produced by concentrated solar thermal plants for enhanced oil recovery. In such applications, the thermal energy collected by the solar plant can either supplement fossil energy sources or replace them. Concentrated solar thermal energy can also be used as a heat source for reforming, cracking, and gasification processes. With potential advances in the future, it might also be used for water splitting to produce hydrogen.

There are a variety of ways in which the thermal energy collected by CSP plants might be exploited efficiently in thermochemical and other thermal processes. These processes and designs need to be considered for further development and possible commercialization as part of a broader CSP RD&D portfolio.

**10.5 Demonstration Support for Solar Technologies**

The federal government has long provided support for energy technology demonstration, including for early light water nuclear reactors, and more recently for efforts to demonstrate...
Loan Guarantee Programs

Over the past several years, the loan guarantee programs administered by DOE’s Loan Programs Office (LPO) have been held up as an important example of demonstration support for solar PV and CSP technology.19,20 Fourteen individual solar projects have received LPO support, all as part of the Section 1705 Loan Program. In total DOE has provided $5.85 billion in loans for CSP projects (including $5 billion as the sole lender) and $4.74 billion in loans for PV projects (including $3.28 billion as the sole lender). All of the CSP and PV loans are currently in good standing. DOE has also provided $1.085 billion in loans for solar manufacturing; of this total, $596 million is classified as discontinued (including $528 million drawn by Solyndra Inc.), which indicates termination of the loan or guarantee, an ongoing bankruptcy proceeding, or (possibly pending) sale of the guaranteed note.21

A key objective of any technology demonstration program should be to develop insights regarding, among other things, the cost, technical performance, and reliability of new technologies when deployed at commercial scale. Sharing this information with the private sector should build confidence in the technologies being demonstrated and help reduce perceived technology risks to the point where private capital becomes available to support deployment. While DOE loan guarantees have certainly enabled the development of several very large (i.e., commercial-scale) PV and CSP installations, with combined capacity totaling 1,200 megawatts (MW), it is not clear that the current loan program has been effective in achieving desired technology demonstration objectives, particularly since DOE has not produced any comprehensive public reporting on the costs and performance of the technologies the program has supported.

FINDING

Many of the solar projects supported by DOE’s loan guarantee programs to date are of a scale well beyond that needed for effective commercial demonstration; moreover, very high loan repayment rates suggest an overly conservative loan guarantee project portfolio.

The fact that only 2.2% of DOE’s PV and CSP generation loan book is now in default indicates that the risk profile of projects supported by the federal loan program has been very conservative. Furthermore, several projects that have received federal loan guarantees, including several PV generation projects, significantly exceed the project size needed for effective technology demonstration.22

RECOMMENDATION

DOE should assess what has been learned regarding cost, performance, and reliability for solar technologies that have received support in the form of federal loan guarantees and make this information available to the private sector.

Moving forward, DOE has stated that its loan guarantee programs will no longer be available to the types of large-scale PV and CSP facilities they have supported to date.23 We believe this change is appropriate.
Pilot-Scale Test Facilities and Simulation Infrastructure

We do not, however, advocate a complete retreat from federal support for solar technology demonstration projects. Instead, DOE should redirect resources toward technology test beds and pilot-scale facilities, while also supporting demonstration projects through cost sharing. This would allow a wider range of solar technologies to move through the demonstration phase of development. Specifically, DOE should support a set of pilot-scale test beds in which new CSP and PV concepts can be evaluated at much lower cost than in a commercial-scale demonstration. For PV, the focus of these pilot facilities should be on new thin-film technologies and novel manufacturing methods; for CSP, the focus should be on system verification and some component manufacturing and testing (e.g., new mirror supports).

DOE has an opportunity to leverage its own facilities such as the National Laboratories to establish test beds and pilot-scale demonstrations. These can be much smaller than the full commercial-scale demonstration plants currently being supported by the Department’s loan guarantee programs, but still large enough to provide for the useful and relatively rapid demonstration of new technologies. For CSP, the appropriate scale for such facilities is likely in the range of 5–20 MW_{e}.^{viii} PV facilities can be smaller, perhaps as small as 1 MW. Such facilities can be utilized for relatively low-cost validation and demonstration or to verify new PV and/or CSP technologies. We expect the risk associated with scale-up to full-size commercial units from pilot-scale demonstrations to be larger for CSP systems than for PV systems; we also expect that pilot tests will be needed on a larger scale for CSP than for PV. DOE has previously used this model for the support and demonstration of new technologies in other areas, such as coal gasification. Before adopting this approach, however, the costs to maintain and operate pilot-scale facilities must be considered to ensure that they offer a practical and cost-effective model for validating and demonstrating new solar technologies.

**RECOMMENDATION**

DOE should direct demonstration support toward a greater number of smaller projects and facilities, such as test beds and pilot plants, that are genuinely demonstration-scale in nature and that involve truly novel PV and CSP technologies.

DOE has a second important opportunity to further leverage its own infrastructure in the area of simulation. The Department has extensive capacity for and experience with simulation, and integrating this infrastructure into current and future solar RD&D work, particularly on advanced materials and device development, would be of appreciable value. Examples of efforts that harness DOE’s broad simulation capacity already exist, among them the Consortium for Advanced Simulation of Light Water Reactors, and we believe a similar initiative for solar could be productive.

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^{viii} Here the subscript “e” refers to the nameplate electric power generating capacity of the plant in watts.
10.6 CONCLUSIONS

Recent years have seen very significant progress toward reducing the cost of solar electricity, but further cost reductions are needed for solar technologies to be competitive beyond modest levels of penetration. The cost competitiveness of today’s primarily crystalline-silicon-based technologies is likely to continue to improve, but only incrementally. Furthermore, the solar energy industry is both capable and highly motivated to capture the remaining opportunities. Realizing solar energy’s larger long-term potential to become a major source of global electricity supply, however, still demands a step-change in solar costs, and achieving this step-change requires the development of inherently lower-cost new technologies. Here there is a role for government-supported RD&D. To advance PV generation options, we call for new thin-film technologies, based on Earth-abundant materials, that can be manufactured using low-cost processes and in form factors that reduce BOS costs. For CSP, we point to the need for more efficient energy-capture systems, higher-temperature materials, and improved power-cycle efficiencies.

DOE’s current budget for solar RD&D places a great deal of emphasis on work aimed at meeting a set of short- and medium-term cost goals for currently commercial solar technologies. Progress toward these goals will, of course, be welcome. However, this work is unlikely to yield the step-change in costs that will ultimately be needed if solar energy is to play an important role in meeting the challenge of climate change. Therefore, we believe that DOE should redirect its solar RD&D investment toward broad support for fundamental research to advance those nascent high-risk, high-potential technologies that, if successfully developed, could yield the required cost reductions.

We also advocate reforms in DOE’s support for solar demonstration projects that would enable more rapid assessment of a broader range of new technologies. Such reforms should emphasize cost sharing ahead of loan guarantees and should support the establishment of pilot-scale and test-bed facilities to enable rapid and low-cost technology demonstrations.

Finally, it will be difficult or impossible to achieve the progress needed in solar electricity generation without significant, sustained support for basic research and development. Solar energy has the potential to be the major source of electricity globally. Realizing that potential will require the combined efforts and resources of government, industry, and academia.

We believe that DOE should redirect its solar RD&D investment toward broad support for fundamental research to advance those nascent high-risk, high-potential technologies that, if successfully developed, could yield the required cost reductions.

ix See, for example, the many pathways described in the International Technology Roadmap for Photovoltaic 2014.
REFERENCES


6 DOE annual budget justifications 2011-2016 obtained from http://energy.gov/cfo/reports/budget-justification-supporting-documents


21 http://lpo.energy.gov/our-projects/


The hyperlinks in this document were active as of April 2015.