Quadrennial Technology Review 2015

Chapter 4: Advancing Clean Electric Power Technologies

Technology Assessments

U.S. DEPARTMENT OF ENERGY

Quadrennial Technology Review 2015

Solar Power Technologies

Chapter 4: Technology Assessments

Introduction

Solar energy offers a number of strategic benefits to the United States. Replacing fossil-fuel combustion with solar energy reduces emissions of human-induced greenhouse gases and air pollutants. Sunlight is a free resource. Thus, once solar technologies are installed, they have very low operating costs and require minimal inputs—this provides insurance against conventional fuel supply disruptions and price volatility. In addition, growing the domestic solar energy industry could establish the United States as a global leader in solar technology innovation and support a growing number of solar-related jobs.

Despite these benefits, solar energy currently supplies only a small fraction of U.S. energy needs, largely because it historically has cost more than conventional energy sources. However, solar manufacturing costs and sales prices have dropped dramatically over the past few decades, and solar technologies are approaching energy-price parity with conventional generating sources in some regions of the United States and abroad. Further, experience accumulated by solar manufacturers and developers, utilities, and regulatory bodies has shortened the time and expense required to install a fully operating solar system. These gains have come partly through research and development (R&D) and partly through U.S. and global solar market stimulation. An additional strong, coordinated effort could enable solar energy technologies to become increasingly cost competitive with conventional electricity-generation technologies in the United States over the next decade.

Since 2010 alone, the installed price of solar energy has dropped by as much as 50%. In that time, the average price of a photovoltaic module has dropped from $2.08/W to $0.66/Watt.[1] Analysis has shown that solar energy cost reductions of 40% relative to 2015 levels could make solar power economically competitive with traditional energy sources throughout the United States.[2] Further technological and market advancements are needed to achieve these goals, building on the remarkable progress to date.[3] Work within the areas of photovoltaics (PV), concentrating solar power (CSP), systems integration, technology to market, and soft costs will help reduce the installed cost of solar and enable high levels of solar energy to be integrated into the electrical grid. The following describes current research, development, demonstration, and deployment (RDD&D) activities, important RDD&D opportunities going forward, and the strategic focus for these sectors:

- **PV and CSP:** Further advances in current state-of-the-art technologies promise to substantially improve performance and reduce costs, enabling much broader deployment. Transformative PV and CSP technology R&D has the potential to yield even greater cost reductions, efficiency improvements, and improved reliability standards. The development of next-generation PV technologies could carry innovation beyond grid parity, and CSP technologies, including thermal energy storage (TES), can provide dispatchable power generation and enable greater deployment of other renewable energy (RE) sources.
- **Systems integration:** Solar energy is a variable resource and therefore requires technologies and strategies that enable effective integration for high levels of penetration to ensure safe, reliable, cost-effective, and widespread solar deployment.

- **Technology to market:** To ensure a robust marketplace, appropriate strategies for commercialization, market readiness, and domestic manufacturing supply chains will be important for creating a dynamic solar marketplace.
- **Soft costs:** Recent technological advances have drastically reduced the cost of solar hardware, making soft costs a greater share of the overall cost of solar. These costs could be reduced by market transparency, workforce training, local solutions, and process improvements to make solar deployment faster, easier, and cheaper. Further improvements in solar hardware, such as Building-Integrated PV or higher efficiencies, also help reduce area- and structure-related balance of system costs.

Owing to advancements in these sectors, rapid growth has occurred in the United States and global marketplaces as costs have declined and demand has increased. While there have not been fundamental changes in the solar technologies available commercially, the efficiencies of these products have advanced steadily with evolutionary technology and manufacturing improvements, contributing to the observed dramatic cost reductions. This section briefly discusses the solar market and solar energy's technical and resource potential. Subsequent sections address R&D strategy and priorities, the development and status of solar technologies and markets, projected solar deployment and impacts, and solutions for high-penetration of renewable energy into the electricity grid.

U.S. Market Overview

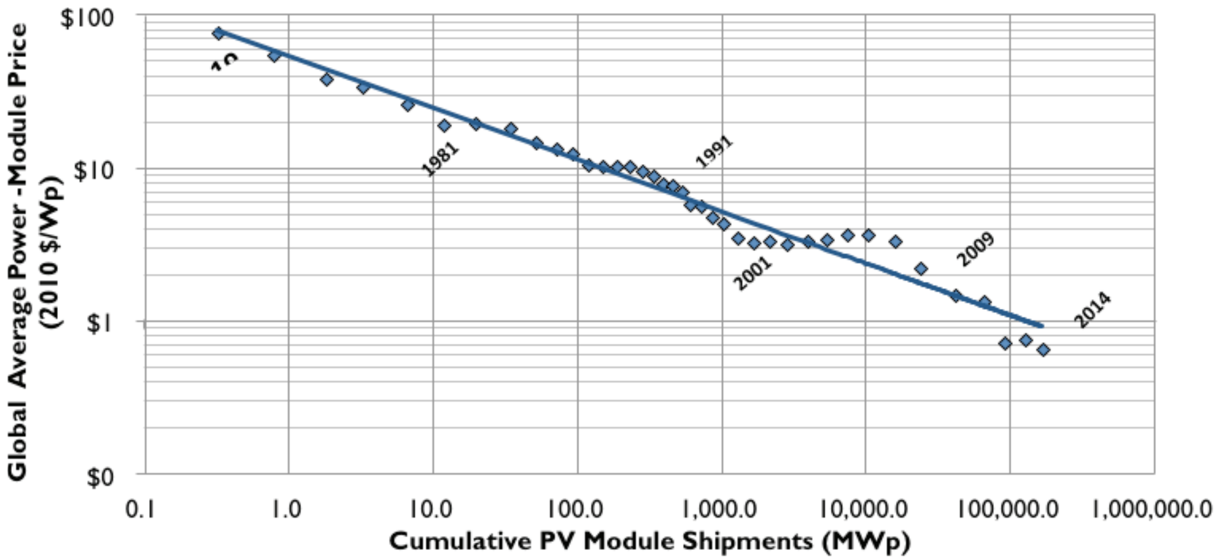
The Energy Information Agency reported 9.3 GW of solar capacity and 18.3 TWh of generation for 2014 (EIA 2015). However, EIA figures do not include distributed systems, which account for a significant share of the solar market. Other analysts report solar energy provided 2% (20 GW) of the U.S. electricity-generating capacity, an 11-fold increase since 2008, when distributed systems are included.[4] While solar power remains a relatively small source of energy, the roughly 2% of U.S. electricity capacity met by solar in 2014 is comparable to the amount supplied by nuclear energy in 1960, which subsequently grew to 11% by 1980 and to 19% by 1990.[5] This dramatic growth in solar deployment has led to impressive job growth in the sector. The solar energy industry has been one of the fastest-growing U.S. industries over the last five years. There are now more than 173,000 jobs in the solar sector, and these jobs are growing at almost 20 times the rate of the U.S. economy.[6]

This growth in deployment is supported by rapidly declining costs. In 2012, PV modules cost about 1% of what they did 35 years ago (Figure 4.P.1). Best-in-class installed PV prices in 2014 were about $3.50/watt-direct current (Wdc) for residential systems, with a median of about $4.30/Wdc,[7] and prices continue to decline following the global trend of continuous price and performance improvements. Overall costs have decreased by over 60% since 2010.

Improvements in the solar sector go far beyond PV cost and deployment. Over 1.6 GW of CSP is now online in the United States, and more than a dozen world-record solar-cell efficiencies have been broken in the past few years (Figure 4.P.5). PV inverters with advanced functionality that can help support the electrical grid are available and could potentially enable even greater deployment. A few states are working to prepare their electrical grids to accommodate a renewable load of upwards of 50%.[9] U.S. communities are using innovative group purchase programs to reduce the cost of residential solar by more than 20%, and some cities now conduct permitting entirely online, cutting down the time to go solar from weeks to minutes, making it easier for many Americans to choose solar. In the United States, deployment continues to grow at a rapid rate, with compounded annual growth of 76% over the past 10 years, as costs continue to decline.[10]

Figure 4.P.1 Module Experience Curve, Detailing Changes in Price Every Time Module Shipments Increase by a Magnitude of 10.[8]

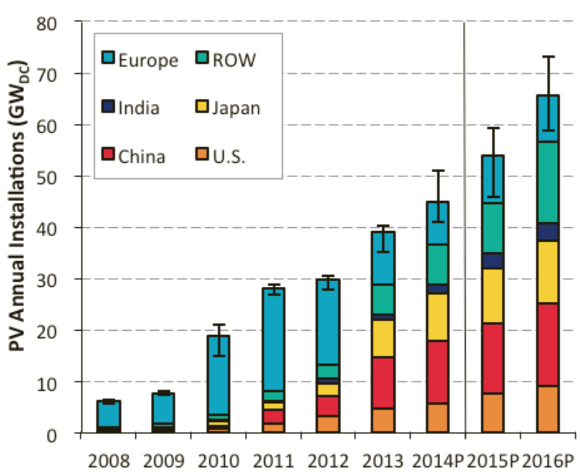
Credit: Paula Mints, SPV Market Research



Global Market

Despite its tremendous growth, U.S. solar deployment has lagged behind deployment in European and Asian countries, primarily because these countries instituted strong solar-promoting policies, while solar policies in the United States were limited and inconsistent. In considering the potential for future growth, it is useful to examine historical growth rates in global markets. Figure 4.P.2 shows the regional PV installations from the United States, Japan, Europe, China, India, and the rest of the world. Between 2008 and 2013, global PV installations achieved a compound annual growth rate of 46%, and the annual installations in 2013 were nearly 40 GW. At the same time, the majority of PV manufacturing has shifted from western countries, including the United States and Germany, to Asia. The United States accounted for 30% of global PV module shipments in 2000 but only 3% in 2012, while China's share grew from 1% to 48%.[11]

Figure 4.P.2 Annual Global PV Installations



Historically, CSP market growth has been sporadic on the global scale. After a number of CSP plants were built in California in the 1980s, almost 15 years passed before the next commercial CSP plant was built in the United States, followed by the construction of a number of new plants in the United States, Spain, India, and the United Arab Emirates during 2007 through 2014. By the end of 2014, global CSP capacity was 4 GW, with 1659 MW installed in the United States and the majority of the remainder residing in Spain.[12] The CSP market has become more diverse in terms of technology and geography in the past few years, although it has not grown at the same rates as solar PV.

Technical and Resource Potential

Although solar energy's contribution to the U.S. energy supply has been small to date, its technical potential is enormous. For example, one estimate suggested that the area required to supply an amount of electricity equivalent to all end-use electricity in the United States using PV is only about 0.6% of the country's total land area.[13] PV can also be installed on rooftops with essentially no land-use impacts. About 17,500 terawatt-hours of annual CSP electricity generation—more than four times the current U.S. annual demand—could be sited in seven southwestern states on land that was screened for use restrictions and technical requirements, such as insolation and land slope.[14]

Solar energy contains a direct component (sunlight that has not been scattered by the atmosphere) and a diffuse component (sunlight that has been scattered by the atmosphere). This distinction is important because only the direct solar component can be focused effectively by mirrors or lenses. The direct component typically accounts for 60%–80% of surface insolation in clear-sky conditions and decreases with increasing relative humidity, cloud cover, and atmospheric aerosols (e.g., dust, urban pollution). Technologies that concentrate solar intensity—such as CSP and concentrating PV (CPV)—perform best in arid regions with high direct-normal irradiance (DNI). Solar technologies that do not concentrate sunlight, such as most PV and passive solar heating applications, can use both the direct and diffuse components of solar radiation and thus are suitable for use in a wider range of locations and conditions than concentrating technologies.

Figure 4.P.3 shows the mean U.S. solar resource available to a standard fixed-tilt PV system that is facing south and tilted at an angle equal to each location's latitude. The PV solar resource includes both direct and diffuse solar radiation. The map illustrates the solar resource in units of the mean radiant energy (in kilowatt-hours), reaching one square meter of that PV during one day (kWh/m^2/day), calculated by using hourly insolation data and models.[15]

The solar resource available to PV is greatest in the southwestern United States, but it is generally at or above 4 kWh/m^2/day in all U.S. states except Alaska and coastal regions of the Pacific Northwest. The annual output of a PV system in Boston, for example, is only 17% less than the annual output of a similar system in Los Angeles. For reference, the annual output of a PV system in Munich, Germany, is 40% less than that from an identical PV system in Los Angeles and 9% less than a system in Seattle, yet Germany has outpaced the United States in solar penetration.[16]

The solar resource available to CSP is highest in the southwestern United States and falls off in eastern and northern states where the direct solar resource is lower. CPV technologies have access to a similar solar resource as CSP. Standard PV systems with tracking systems can access a higher solar resource than that shown in Figure 4.P.3 because the modules are oriented to maximize their use of direct solar radiation, but they can still effectively convert diffuse solar radiation to electricity.

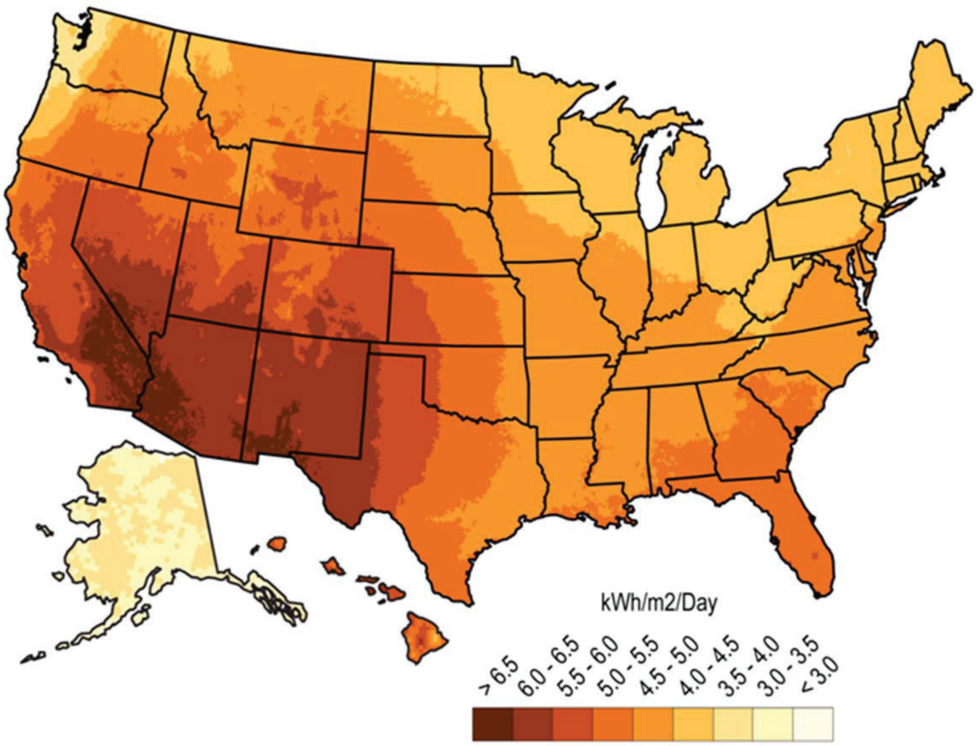
RDD&D Strategy and Priorities

Photovoltaics Strategy and Priorities

While PV module costs have decreased dramatically, module costs must still be reduced by 20%–30% to enable cost competitiveness without subsidies (Figure 4.P.4). An increase in module efficiency also can enable lower balance-of-system (BOS) costs.

The next generation of R&D challenges to support increased PV deployment include further reductions in the cost of PV electricity as well as reliability and life-cycle sustainability. Accordingly, impactful PV R&D has

Figure 4.P.3 U.S. Solar Resource Potential

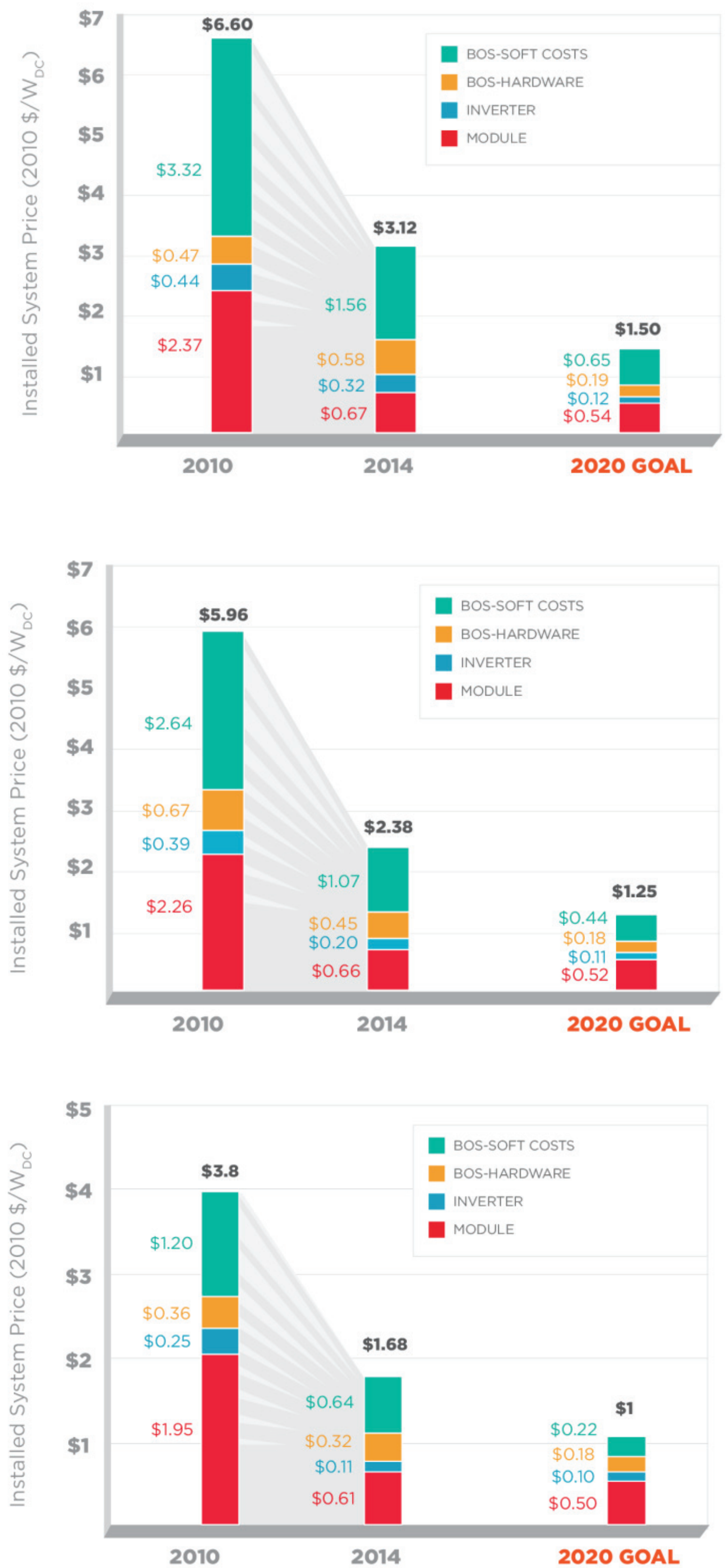


focused on work ranging from early-stage solar cell research to the point of commercialization. It includes work on materials, processes, and device structure and characterization techniques. Just a few examples of high impact R&D opportunities include a combinatorial approach to find new earth-abundant absorber materials, new silicon solar cell structures using organic and metal oxide heterojunctions, high efficiency III-V on silicon multi-junction solar cells, the development of a two-photon photoluminescence technique to separate bulk and surface lifetimes in thin films, and model systems for cadmium telluride (CdTe) solar cells to probe fundamental efficiency limits.

Currently the United States remains a leader in PV R&D, with a strong record of impact over the past several decades. Current investments represent a sustained commitment to high-impact research and expertise across PV technologies, including thin films, silicon, multi-junction, organic PV (OPV), and new material development. The majority of funding occurs in the following strategic areas:

- **Next-generation PV:** This activity area encompasses research with the potential to dramatically lower costs and/or increase efficiencies of PV modules beyond strategic targets of $0.50/W and 20%, respectively, by facilitating the entry of novel competitive technologies into the PV marketplace.
- **Advancing PV efficiency:** Projects focus on improving the power conversion efficiency of established solar cell materials, including silicon, CdTe, copper indium gallium diselenide (CIGS), and III-Vs as well as addressing technological barriers to further advancement.
- **Improving PV life-cycle sustainability:** As more solar energy is deployed, creating techniques to recycle modules and improving the viability of PV modules made from earth-abundant materials will become increasingly important.

Figure 4.P.4 Cost Reduction Goals for Photovoltaic Systems (Residential, Commercial, and Utility Scale)



Concentrating Solar Power Strategy and Priorities

Current R&D projects include programs with near-term to long-term horizons spanning the various CSP technologies. Ongoing R&D efforts could deliver transformative technologies within the next three to five years while lowering capital costs substantially. These include highly efficient reflector materials integrated with low-cost collector structures, lean solar field manufacturing and assembly approaches, self-aligning and tracking controls for collectors, self-cleaning mirrors, novel receiver designs, solar selective coatings for enhanced collection efficiency, corrosion-resistant materials and coatings, high temperature heat transfer fluids (HTFs), and cost-effective thermal energy and thermochemical energy-storage technologies. High-temperature, higher-efficiency power cycles, such as the supercritical carbon dioxide (s-CO_2) Brayton cycle demonstrated at the 1–10 MW scales and the solar-integrated air Brayton cycle, will also be very significant.[17] These next-generation power-cycle technologies have broader relevance beyond the solar industry to the nuclear, fossil fuel, and geothermal industries, among others.

Topics of CSP research include the following:

- **Solar field efficiency improvements/cost reduction:** The solar field constitutes up to 40% of the total system costs for CSP technologies. To reduce the cost of the solar field dramatically while improving optical accuracy and ensuring durability, requires continued R&D. To accomplish these goals, R&D efforts are necessary to develop high optical accuracy reflectors, reduce collector structure weight and material, develop lean and rapid methods for manufacturing, assembly, and installation, develop highly efficient tracking and control methods as well as accurate metrology tools, and reduce collector soiling and the water required for operations and maintenance (O&M).
- **Receivers and HTFs:** To significantly increase the operating temperatures, efficiency, and lifetime of solar receivers while lowering costs requires continued R&D. Supporting the development of fundamentally new receiver designs and novel solar selective coatings and exploring high-temperature receiver corrosion and HTF stability are also important areas for R&D.
- **Power conversion and systems:** Power plant components and systems for CSP benefit from mature and well-understood technology found elsewhere in the power-generation industry. The most common cycle employed by conventional CSP plants is the subcritical steam Rankine cycle. Gross thermal-to-electric conversion efficiencies for current technologies are typically 35%–45%. The primary driver for improving CSP power cycles is to increase solar-to-electricity conversion efficiency. Because CSP facilities are typically located in desert areas where water is a scarce resource, high-efficiency cycles using dry cooling are needed. Examples of high-efficiency cycles include systems that use topping and bottoming cycles, fossil augmentation, or other solar hybridization options. Other R&D opportunities include supporting the development of high-temperature power cycles, such as the s-CO_2 and solar-integrated air Brayton cycles, solid-state power conversion techniques for use as topping cycles, and hybrid power systems.
- **Thermal Energy Storage (TES):** A distinguishing feature of CSP is its ability to include TES at the point of power generation to handle the variability of solar availability. R&D on sensible, latent, phase-change, and thermochemical energy storage and related aspects is being conducted by industry, national laboratories, and universities to help engineer HTFs for high-temperature stability and thermophysical properties and to develop novel TES methods to meet technical and cost targets.

Systems Integration Strategy and Priorities

Because the deployment of PV systems in the electric distribution grid has aggressively accelerated in the past few years, utilities, regulatory agencies, and developers have been faced with a significant number of integration challenges, including variability, voltage regulation, unintentional islanding, and reverse power flows. Addressing these challenges will require substantial RDD&D to improve system reliability overall while encouraging the widespread deployment of solar technologies. RDD&D of technologies, focused in the following areas, are already proving to be impactful; however, they will become increasingly critical as greater amounts solar energy are deployed:

- **Grid performance and reliability:** To achieve high penetration at the distribution level (less than 69 kV) and on the transmission grid requires: developing state-of-the-art utility modeling, simulation, and analysis tools to address technical issues surrounding grid planning, operations, and reliability; developing advanced grid-friendly PV interconnection technologies; accelerating cost-effective deployment of PV generation on the distribution and transmission grid; developing validated inverter, solar system planning, operations, and feeder models to enhance PV integration analysis techniques; demonstrating the feasibility of high-penetration PV scenarios under a wide range of system conditions through laboratory and field testing; and advancing interconnection and performance standards and codes to enable high levels of PV integration with grid reliability.
- **Dispatchability:** To ensure that PV and CSP power plants at utility and distributed scales can be dispatched in a fashion comparable to or better than conventional plants can be addressed with a two-pronged approach: (1) extensive analyses to understand the impact of high solar penetration on the bulk power system and distribution system operations; and (2) research on understanding and enhancing the dispatch capability of PV power plants and investigating the value of varying energy-storage capabilities. Standardized methods for testing grid performance of PV plants are needed. Additionally, RDD&D exploring and demonstrating the value of energy storage will have an impactful role as both storage and solar energy prices decline.
- **Power electronics:** Power electronics are intelligent devices that can maximize the power output from PV arrays and interface with the electric grid (or end-use circuits) while ensuring overall system safety, reliability, and controllability. A technical challenge for power electronics is the optimal trade-off among these three design drivers of performance, reliability, and cost. To accomplish these goals, the following are needed: cost reductions and efficiency improvements through innovative circuit design, development of advanced components, and optimal control; development of power electronics technologies to improve energy yield while reducing BOS hardware costs, process costs, and installation time; development and field demonstration of smart inverter functionalities; and development of accelerated life testing methods and physics of failure models to predict faults and improve reliability.
- **Communications:** To inform grid operations effectively with high-level integration of solar energy, visibility is required across multiple spatial scales (from the end-user load through the distribution substation and beyond) and at multiple timescales (from microseconds to hours and days). Advances in information, communications, and sensor technologies are needed to adequately monitor the behavior and manage the impact of the solar technologies integrating into the grid. Enterprise-level integration of PV-management systems with grid-management systems is also critical to provide important information to grid operators. The implementation of standard communication protocols in inverter hardware and enterprise software and demonstration of end-to-end system integration and interoperability on actual distribution feeders with utilities will also enable growth in the solar market.

Technology to Market Strategy and Priorities

Commercially focused technologies must be nurtured across varying stages. While the earlier stage opportunities described in the Photovoltaics Strategy and Priorities section and Concentrating Solar Power Strategy and Priorities section have the ability to create transformation technologies, businesses with later-stage technologies should also seek to introduce innovative techniques to improve manufacturing processes and reduce technology costs. These development and demonstration activities often can be more quickly commercialized in the market. In addition to funding commercialization-stage activities and beyond, market and cost analysis is necessary to inform strategic direction and reveal market barriers that can be addressed through RDD&D. Internal decision making can be improved with reference to bottom-up cost analyses. Analyses are crucial to educating stakeholders in this rapidly evolving industry and for addressing conversion technologies and systems as well as supply-chain and location-specific competitive advantages.

To effectively move technologies into markets requires RDD&D in the following three thematic areas:

- **Technology commercialization and business innovation:** Commercialization of innovative PV and CSP device concepts and manufacturing pilot lines as well as innovations in hardware installation, grid conversion technologies, and novel business models and software platforms for reducing soft costs.
- **Manufacturing innovation and scale-up:** Innovation in industry involving manufacturers, universities, industry supply-chains, and a unit-process service line. RDD&D consortia could serve significant roles in these. PV and CSP supply-chain improvements as well as innovation in system component manufacturing will assist in achieving cost reductions.
- **Cost analysis, technology, competitiveness, and market uncertainty:** Analyses of competitiveness, funding metrics, and performance targets are important for strategic planning, and require analysis of technology costs, location-specific competitive advantages, policy impacts on system financing, and the cost of energy produced—both "levelized" (LCOE) and as dispatched in operational systems.

Soft Costs of Solar Deployment Strategy and Priorities

Soft costs, or non-hardware balance of system costs, can vary significantly because of a fragmented energy market system that presents a highly variable landscape for those looking to deploy solar energy.[18] The same solar equipment may vary widely in its final installation price owing to process and market variations across jurisdictions. This creates barriers to more rapid industry growth. Development and adoption of standards at the local level and applying regional approaches would create a more uniform and accessible business environment. These costs can be lessened through the standardization of procedures and processes for activities and events such as permitting, installation, inspection and interconnection.

Additionally improved data, analytics, and tools can also help reduce the costs of installing solar. For example improved site assessment tools have the potential to reduce customer acquisition costs by $0.08/W.[19] Improved access to data on systems costs and performance will be necessary to characterize project risk and lower the cost of capital. Similarly, improved pricing data has the potential to increase market transparency, improve consumer protection and decrease customer acquisition costs. Soft cost reduction activities are organized within the following four areas:

- **Empowering state and local decision makers:** Many solar markets are currently fragmented due to knowledge gaps among state and local officials and policymakers. Increased uniformity through shared best practices have successfully reduced project costs related to permitting and compliance. Indeed, variation in local processes have produced PV price differences of 0.64–$0.93/W across disparate solar markets.[20] Reducing this variation through consistent and improved permitting techniques has been successful in improving project economics and increasing deployment.
- **Harnessing big data analysis and technical solutions:** Soft costs result from the time and effort people spend to accomplish solar-deployment tasks.[21] Automation, increased access to information, and software and information-management tools can reduce the time and effort needed to complete a solar installation. Recent efforts in social science have enabled researchers to test, measure, and validate local deployment program effectiveness, accelerating innovation in business and market development while advancing foundational knowledge of social science dynamics.[22]
- **Training an innovative solar workforce:** The solar industry has grown at a rapid pace, with industry employment growing by 86% since 2010.[23] Ensuring that the industry has access to high quality trained workers has been essential to the growth of the market and deployment of solar systems. Recent efforts to expand the number of certified installers has resulted in the training of over 30,000 certified solar installers.[24] However, continued training and workforce opportunities will be critical to greater

deployment, as the solar industry has projected 20% job growth in the near term, and 77% of solar firms reported having difficulty hiring qualified candidates in 2014.[25]

- **Developing solar finance and business solutions:** National laboratories, universities, nonprofits, and talented start-ups have led exciting workshops, gathered stakeholders for work sessions, and built a suite of new tools to support solar growth.[26] Groups are working with financial institutions, project developers, and manufacturers to release standardized contracts and methods for assessing risk portfolios publicly and unlock new streams of capital to support solar project finance. Looking forward, expanding the availability of high-quality data, information, tools, and resources to support the solar industry will be important for providing financing at a low cost of capital, and for lowering process and operation costs related to solar deployment.

Development and Current Status of Technologies and Markets

Photovoltaics Development and Status

Technology History and Overview

PV systems can be classified into three subsystems: modules, power electronics, and BOSs. PV modules are made up of interconnected PV cells that convert sunlight directly into electricity. PV cells are fabricated from semiconductor materials that enable photons from sunlight to “knock” electrons out of a molecular lattice, leaving mobile electron and “hole” pairs that diffuse or drift in an electric field to separate contacts, generating direct-current (DC) electricity. This “photoelectric effect” most commonly has been generated with materials such as crystalline silicon (c-Si) and a range of thin-film semiconductors.[27] The proportion of sunlight these technologies can convert into usable energy determines their efficiency. PV efficiencies have increased dramatically as demonstrated in Figure 4.P.5.

Several c-Si, thin-film, and multi-junction PV technologies have been demonstrated commercially on a large scale. In addition, several emerging PV technologies may be technically and economically competitive in the future.[28] This subsection briefly describes these types of PV module technologies as well as potential third-generation technologies as follows:

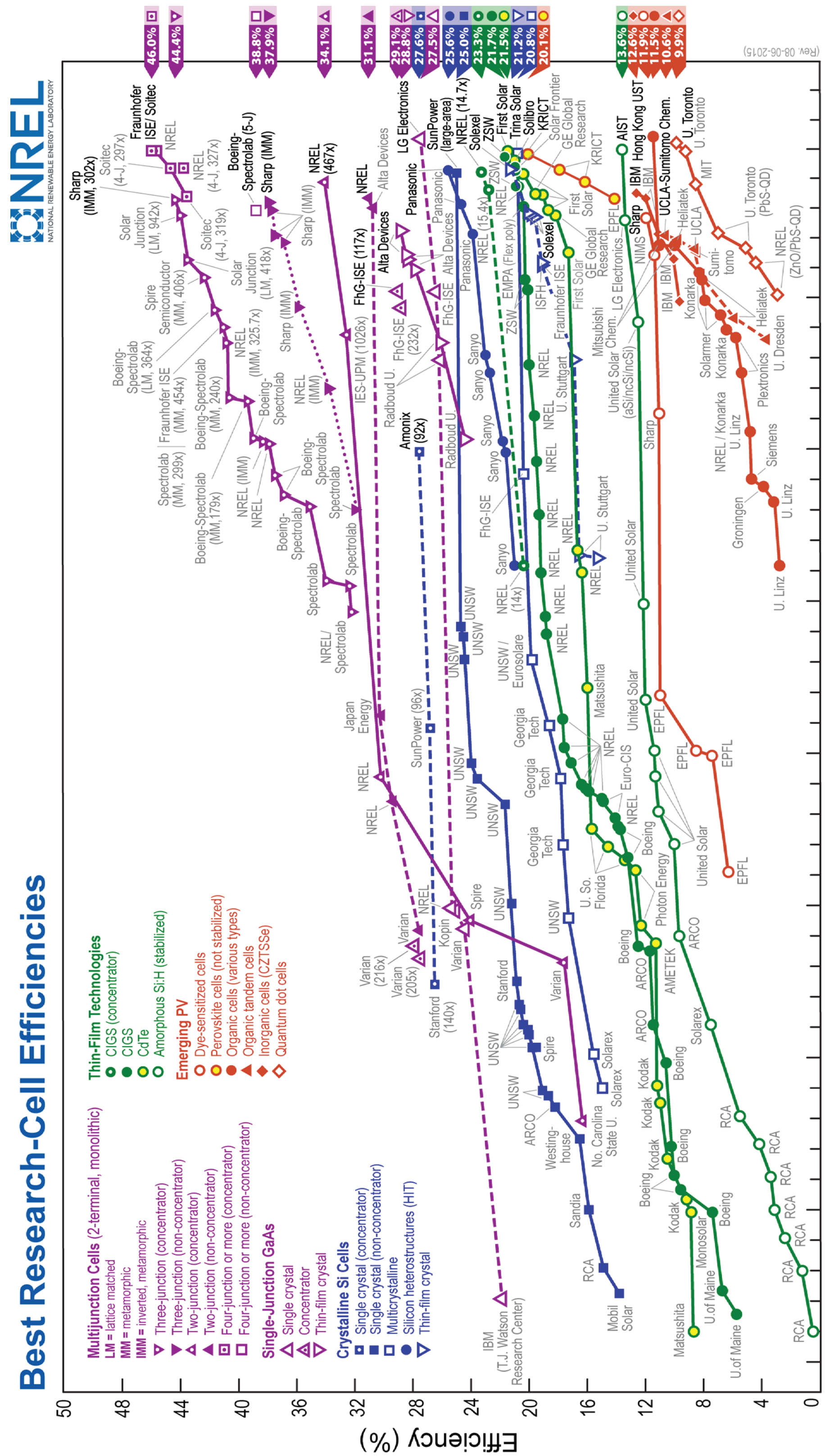
- **C-Si:** This technology constitutes the majority of the PV market, and it has a long history of reliable performance;[29] c-Si modules have demonstrated operational lifetimes of more than 25 years.[30] There are two general types of crystalline, or wafer-based, silicon PV: monocrystalline and multi-crystalline. Monocrystalline semiconductor wafers are cut from single-crystal silicon ingots. Multi-crystalline semiconductor wafers are cut from directionally solidified blocks or grown in thin sheets (i.e. several hundred microns thick). Monocrystalline ingots are more difficult, energy intensive, and expensive to grow than simple blocks of multi-cSi. However, monocrystalline silicon produces higher-efficiency cells. For both types, the silicon is processed to create an internal electric field, and positive and negative electrical connections are added to wafers to form a cell. Standard cell processes are used to complete the circuit for both mono- and multi-crystalline cells, and multiple cells are linked and encapsulated to form modules.

  The rated DC efficiencies of standard c-Si PV modules are about 15%–18%. A number of new or nonstandard cell architectures—such as back-contact cells—are growing in importance because they offer significantly higher efficiency. Nonstandard cell architectures tend to use high-quality monocrystalline wafers and more sophisticated processing to achieve module efficiencies of about 18%–22%.

- **Thin film:** Thin-film PV cells consist of a semiconductor layer a few microns (μm) thick, which is about 100 times thinner than current c-Si cells. Most thin films are direct bandgap semiconductors, which

Figure 4.P.5 World Records for PV Cell Efficiencies

Credit: National Renewable Energy Laboratory



means they are able to absorb the energy contained in sunlight with a much thinner layer than indirect bandgap semiconductors, such as traditional c-Si PV. The most common thin-film semiconductor materials are CdTe, amorphous silicon, and alloys of CIGS. The semiconductor layer is typically deposited on a substrate or superstrate inside a vacuum chamber. A number of companies are pursuing lower-cost, non-vacuum approaches for manufacturing thin-film technologies. Glass is a common substrate/superstrate, but thin films can also be deposited on flexible substrates/superstrates, such as metal, which creates the potential for flexible lightweight solar modules. CIGS solar cells are sensitive to water vapor and thus are traditionally encapsulated in glass to maintain performance. Eliminating the need for glass with "ultrabarrier" flexible glass replacement materials is an important next step for flexible solar applications. CdTe and CIGS thin-film experimental cell efficiencies have increased to about 19-21% in the last few years. For thin film modules, efficiencies can reach 12-17%, and are now often about equal to the efficiency of multi-cSi modules in normal operating conditions.[31]

- **Multi-junction:** Multi-junction technologies are typically used for space applications and in CPV systems. CPV uses concentrating optics made out of inexpensive materials such as glass, steel, and plastic to focus sunlight onto a relatively small, but extremely efficient, PV area. This approach offers several significant benefits. First, it minimizes the amount of active semiconductor material (the material that converts sunlight into electricity) needed to produce a given amount of electricity. On an area basis, the active semiconductor material is the most complex and expensive component of many PV modules; this is particularly true for multi-junction cells. Multi-junction cells are capable of much higher efficiencies than single-junction silicon or thin-film cells, because each junction of a multi-junction cell collects a different part of the solar spectrum. Multi-junction cells are typically a stack of three to five different cells on top of one another. This higher efficiency comes at a higher manufacturing cost, thus multi-junction devices are too expensive to use in terrestrial applications without concentration. The downside to CPV, especially for higher concentration levels, is that, to maintain the concentration of sunlight on the cell, the module must accurately track the sun throughout the day. Tracking results in a more complex and expensive installation. Recent improvements to multi-junction PV cells have produced cell efficiencies of 46% in the laboratory. Use of CPV systems for utility-scale electricity generation is regionally constrained owing to its dependence on DNI.
- **Third-generation PV:** Third-generation PV refers to technologies that are being developed but are still in early stages of research. Dye-sensitized solar cells, which use dye molecules adsorbed onto a nanostructured substrate and immersed in a liquid or gel electrolyte to absorb solar radiation, have demonstrated laboratory efficiencies as high as 11.9%. OPV solar cells, based on polymers or small molecules with semiconductor properties, have demonstrated laboratory cell efficiencies above 8%; organic modules have the potential for low-cost manufacturing using existing printing and lamination technologies.[32] Quantum dots—nanospheres with physical properties similar to both bulk semiconductors and discrete molecules—have the potential to achieve higher efficiencies through multiple exciton generation, but they have not yet been used to produce efficient PV cells. Perovskite cells, made of materials exhibiting a perovskite crystalline structure, are one of the most promising emerging solar technologies. A recent innovation, perovskites have seen rapid improvements in efficiency, growing from just 3% in 2009 to over 20% in 2014.[33] The perovskite material is relatively earth abundant and has the potential to be manufactured at low costs. However, perovskite cells currently suffer issues with short- and long-term stability, and are sensitive to water and water vapor.

Materials and Manufacturing

Numerous methodologies and individual technologies exist for creating PV cells and modules. Substantial increases in the manufacturing capacity of PV components and systems will be required to meet the growing demand for solar energy. However, domestically and globally, these solar industries have demonstrated an ability to scale up production volumes rapidly and realize associated cost reductions, particularly over the past decade. The PV industry is expanding its manufacturing capacity, helped by new market entrants bringing capital as well as technology, manufacturing, and supply-chain management experience, often from other successful industries—such as computer semiconductor, liquid crystal display, and specialized material industries. Manufacturing scale-up should not limit high levels of PV deployment.

The availability of raw materials has not been found likely to limit solar deployment. For example, material feedstock for c-Si PV is virtually unlimited, and supply constraints are not likely to limit growth. Despite this, c-Si cells typically use silver for electrical contacts, which could be subject to price spikes if there are supply shortages.[34] The use of different contact materials is an area of active research and could reduce supply price risk. Additionally, the availability of some elements may limit the growth of some PV technologies. Of particular concern is tellurium used for CdTe and indium used for CIGS.

Tellurium is primarily extracted as a by-product of electrolytic copper refining, and global supply is estimated at approximately 630 MT/year.[35] Tellurium supply is expected to increase over time on the basis of increasing global copper demand,[36] use of extraction methods with higher efficiencies,[37] and direct mining from known ores[38] or from existing copper mine tailings. However, it takes approximately 60–90 MT of tellurium to make 1 GW of CdTe, over 10% of the current annual supply.[39]

Indium is primarily extracted as a by-product of zinc refining, and global supply is estimated at about 1300 MT/year.[40] It takes approximately 25–50 MT of indium to produce 1 GW of CIGS, but indium is in greater demand than tellurium.[41] Nearly all of the indium supply is used to make transparent conductive oxide coatings, such as those used for flat-panel liquid crystal displays. Global indium supply is projected to increase to meet demand for non-PV applications and potentially for PV applications as well.[42]

Resource constraints can be mitigated by reducing material requirements (i.e., reducing the thickness of semiconductor layers, increasing PV efficiency) and increasing material supply (i.e., increasing annual ore extraction and refining, improving process utilization and in-process recycling). For example, recent studies have suggested that CdTe supply could increase by a factor of eight by reducing semiconductor thickness, increasing module efficiency, and improving resource extraction efficiencies.[43] There are similar pathways for decreasing indium intensities and improving extraction efficiencies. These factors could combine to increase the thin-film materials availability from a few gigawatts per year at present to hundreds of gigawatts per year over the next few decades. However, competition with non-PV applications for rare materials could significantly restrict supply, particularly for indium, and it could increase both material prices and price volatilities.[45]

Concentrating Solar Power Development and Status

Technology History and Overview

CSP technologies use mirrors or lenses to focus sunlight onto a receiver. The receiver contains a fluid that transfers the thermal energy to a heat engine that drives an electrical generator. A key characteristic of CSP is its built-in thermal inertia, which can provide stability in plant output during slight changes in solar radiation, such as when a cloud passes overhead. Also, solar-field components can be oversized relative to the power block so that energy captured during the day can run the power block and provide additional heat energy to the TES medium. This stored energy then can be used to run the power block during cloudy periods and at night, significantly increasing the capacity factor of the CSP power block. The Solana plant, for example, has more than six hours of storage.[46] Additionally, because CSP uses thermal energy, it can also incorporate fossil-fuel backup/hybridization for higher levels of stability and dispatchability and increased duration of energy output. Currently, these attributes allow CSP plants to obtain capacity credits similar to those for fossil-fuel power systems and provide a firm energy resource that improves grid operations.

CSP is composed of a diverse mix of technologies, at different stages of maturity, which convert sunlight into thermal energy and then use this thermal energy to generate electricity. There are three primary forms of CSP: parabolic troughs, power towers, and dish/engine systems. These technologies have distinctive benefits and constraints as follows:

- **Parabolic troughs:** These systems are currently the most proven CSP technology owing to a commercial operating history starting in 1984 with the Solar Energy Generating Systems plants in the Mojave Desert of California. Parabolic trough plants consist of large fields of mirrored parabolic trough collectors, an HTF/steam-generation system, a power system such as a Rankine steam turbine/generator, and optional TES and/or fossil-fuel-fired backup systems. The solar field is made up of large modular arrays of one-axis tracking solar collectors arranged in parallel rows, usually aligned on a north–south horizontal axis. Each solar collector has a linear parabolic-shaped reflector that focuses the direct-beam solar radiation onto a linear receiver (absorber tube) located at the focal line of the parabola. The collectors track the sun from east to west during the day, with the incident radiation continuously focused onto the linear receiver within which an HTF is heated to approximately 390°C. After circulation through the receivers, the HTF flows through a heat exchanger to generate high-pressure superheated steam (typically 100 bar at 370°C). The superheated steam is fed to a conventional reheat steam turbine/generator to produce electricity. The spent steam from the turbine is condensed in a standard condenser and returned to the heat exchangers via condensate and feed-water pumps to be transformed back into steam. Wet, dry, or hybrid cooling towers can be used for heat rejection from the condenser; the selection will influence water use, cycle performance, and cost. The current design-point solar-to-electric efficiency—the net efficiency in the ideal case when the sun is directly overhead—for a parabolic trough plant ranges from 24% to 26%, and the overall annual average conversion efficiency is about 13%–15%.
- **Power towers:** Power towers (also called central receivers) have a shorter operational history than trough systems but are beginning to be deployed. Because of their higher operating temperatures, power towers have the potential to achieve higher efficiency and lower-cost TES compared to current trough technology. Power towers use heliostats—reflectors that rotate about both the azimuth and elevation axes—to reflect sunlight onto a central receiver. A large power tower plant can require from several thousand to more than 100,000 heliostats, each under automated control. The two principal power tower technology concepts are defined by the HTF in the receiver: steam or molten salt. In direct-steam power towers, feed water pumped from the power block is evaporated and superheated in the receiver to produce steam, which feeds a turbine generator to generate electricity. Current steam conditions for direct-steam generation towers range from saturated steam at 250°C to superheated steam at over 550°C. Several characteristics of direct-steam power towers make them attractive: their straightforward design; use of conventional boiler technology, materials, and manufacturing techniques; high thermodynamic efficiency; and low parasitic power consumption. Like many CSP technologies, steam towers can be hybridized with natural gas to provide additional operating flexibility and enhanced dispatchability.

  In a molten-salt power tower, salt at about 290°C is pumped from a cold storage tank to a receiver, where concentrated sunlight from the heliostat field heats the salt to about 565°C. The hot salt is held in a storage tank, and when electric power generation is required, hot salt is pumped to the steam generator, which produces high-pressure steam at nominal conditions of 100–150 bar and up to 540°C. The now cooler salt from the steam generator is returned to the cold salt storage tank to complete the cycle. The steam is converted to electrical energy in a conventional steam turbine/generator. Thus, passing clouds that temporarily reduce DNI do not affect turbine output. The combination of salt density, salt-specific heat, and temperature difference between the two tanks allows economic storage capacities of up to 15 hours of turbine operation at full load. Such a plant could run 24 hours per day, 7 days per week, in the summer and part-load in the winter to achieve a 70% solar-only annual capacity factor. The Gemasolar plant in Spain is designed for such performance.[47]

The annual average solar-to-electric conversion efficiency of a power tower is about 14%–18%, with direct-steam towers slightly higher than molten-salt towers. The design-point efficiency is about 20%–24%. As discussed for troughs, annual average efficiency represents overall real-world performance, whereas design-point values are useful for comparing the performance of individual components. The choice of wet, dry, or hybrid cooling towers can influence water use, cycle performance, and cost.[48]

- **Dish/engine systems:** Dish/engine CSP technology uses a collection of reflectors assembled in the shape of a parabolic dish to concentrate sunlight onto a receiver cavity at the focal point of the dish. Within the receiver, the heater head collects this solar energy, running an engine-driven generator to produce electricity. Similar to heliostats, all dishes rotate along two axes to track the sun for optimum capture of solar radiation. There are currently three major types of engines used at the core of dish/engine technology: kinematic Stirling engines, free-piston Stirling engines, and Brayton turbine-alternator based engines. Current dish/Stirling systems generate 3–30 kW of electricity, depending on the size of the dish and the heat engines used, and have demonstrated the highest recorded CSP design-point solar-to-electric efficiency (31.4%). Unlike trough or tower systems, dishes typically cannot utilize TES. Currently no dish systems are operational commercially, and the largest developer of dish systems, Stirling Energy Systems, filed for bankruptcy in 2011.

Materials and Manufacturing

The long-term availability of materials and manufacturing capacity is critical for increased deployment of CSP plants. In general, the materials required for CSP plants are not subject to rigid supply limits, but they are affected by changes in commodity prices. Necessary materials include glass, steel, and aluminum, which are readily available. HTFs are synthetic oils that are widely used in large volumes in the global chemical industry, or they are nitrate salts. Much of the world's nitrate salts is derived from deposits in the Atacama region of Chile. Proven reserves are 29.4 million MT, although this figure is based on exploration of only 16% of total reserves.[49] Although alternative salts for storage and/or HTFs could be used, if nitrates remain the salt of choice, increased CSP deployment could require expansion of nitrate salt production, possibly including synthetic production via the Haber-Bosch process, which is used worldwide for fertilizer production.

The CSP supply chain is overwhelmingly domestic, from materials to manufacturing. Most, if not all, materials necessary to build a CSP plant have been sourced or manufactured within the United States. CSP plants require a number of components; some are similar to other industrial components and others are unique to the industry. In addition to the structural and reflector components, CSP plants require manufacturing of receiver components and the power block. All developed countries and many developing countries have boiler-manufacturing capabilities and are capable of fabricating components, such as steam boilers and pressure vessels. The manufacturing capability that exists to build conventional fossil-fuel boilers can be readily adapted to fabricate multiple gigawatts per year of steam or molten-salt receivers.

For parabolic troughs and power towers, the current power block is also very similar to those used in conventional fossil-fired plants; thus, manufacturing capabilities for these power blocks and other system components are available worldwide. The development of new turbomachinery—such as that required for new supercritical CO_2 or air-Brayton solar turbines—will also use materials and manufacturing processes common to the existing gas and steam turbine industries.

Systems Integration Development and Status

Analytical History and Overview

As costs have fallen and solar has developed into a viable energy source on a large scale, concerns about integrating the technology into the grid have emerged because of the variability in the solar resource, and a systems-based approach may become necessary to facilitate optimal solar deployment. An improved understanding of the technical capabilities and potential of the grid has helped to improve the feasibility of large-scale solar deployment as well as potential technical barriers for solar energy.

Numerous studies have been conducted to address these technical and analytical challenges.[50] These studies also identified the R&D needed to build the foundation for a high-penetration RE future while enhancing operation of the electricity grid. Researchers have posited that grid integration issues are likely to emerge much more rapidly than most analysts initially expected and that commercially viable renewable technologies could form more than 80% of total U.S. electricity generation in 2050 if paired with flexible transmission and distribution systems.[51] Integration issues are already beginning to become apparent in Hawaii and could emerge in other locations within the next few years as solar power becomes more prominent.

Integration issues (e.g., voltage regulation, unintentional islanding, and protection coordination) must be addressed from the distributed PV system side and from the utility side for high-penetration PV scenarios. New techniques must be developed to enable PV to operate safely with the utility system and act as a grid resource that benefits the grid and the PV owner, beginning with today's unidirectional grid and progressing to the smart grid of the future.[52]

Historically, the viability, benefits, and challenges of integrating high penetrations of wind and solar power have been important tools in developing strategies for RDD&D of technologies. Furthermore, continued systems analysis will have important impacts on optimizing the make-up and operation of electricity fleets.

System Hardware History and Overview

Power Electronics are important devices used to maximize the power from PV arrays and serve as the interfaces to the electric grid. While numerous R&D opportunities (described in the Systems Integration Strategies and Priorities section) have the ability to find the optimal trade-offs among safety, reliability, and controllability design—the primary drivers of performance, reliability, and cost—inverter functionality has historically been limited to switching PV DC currents to AC currents. However, recent advances in inverter functionalities have included the development of smart inverter functionalities that can use volt/var control functionalities to actively manage PV on the distribution grid, accelerated life-testing methods, and physics-of-failure models to predict faults and improve reliability. Advanced inverters are becoming both increasingly critical for grid performance and increasingly common in the marketplace.

Advanced power electronics are not the only devices that can facilitate greater deployment of solar. Though traditionally limited by cost or technical limitations, recent technology advancements and cost reductions for both PV and energy storage technologies have shown the need for improved understanding of the processes for integrating solar energy with energy storage. Much of the current research has aimed to understand and optimize solar and storage at greatly increased penetration levels. As the industry matures, processes to standardize interoperability and communication among various components in the integrated solution and with external systems such as utility grid management software will become increasingly important. Additionally, solutions to improve understanding of the various levels of controls, , and to choosing optimization parameters (e.g. timescale, grid characteristics, building load profile) will help to enable the expansion of solar plus storage solutions. Energy storage could prove to be an important complement to solar PV as costs decline and interoperability and communication protocols improve.

Technology to Market Development and Status

In 2000, the United States manufactured nearly 30% of the world's PV modules. Today, it has less than 2% of global solar manufacturing capacity. Work to increase U.S. market share by filling funding gaps at two stages in the process of bringing new technologies to market (the prototype commercialization stage and the commercial scale-up stage) will be important if the United States is to be a leader in solar deployment and manufacturing. These activities also have the opportunity to reduce costs overall. Opportunities and activities in manufacturing and business innovation are discussed in greater detail in the Technology to Market Strategy and Priorities section.

Soft Costs Development and Status

Historically, the cost of PV modules has constituted the majority of the cost of a PV system. In 2008, modules accounted for 50% of system cost. By 2010, all hardware accounted for approximately 50% of system cost. Owing to recent module cost reductions, hardware costs can now account for as little as 33% of a system's cost. The remaining soft costs vary widely by location and market sector. As a result, soft costs have become a key target for cost reduction. Specific cost reduction activities and opportunities are described in the Soft Costs of Solar Deployment Strategy and Priorities section.

Projected Solar Deployment and Impacts

The deployment of large amounts of solar energy will have a tremendous impact on U.S. electricity markets. Several studies have attempted to project these impacts. This section summarizes results of these studies in terms of solar deployment, LCOE, regional and national impacts, and electricity system cost and rate impacts, assuming aggressive cost reduction trends continue.

Deployment

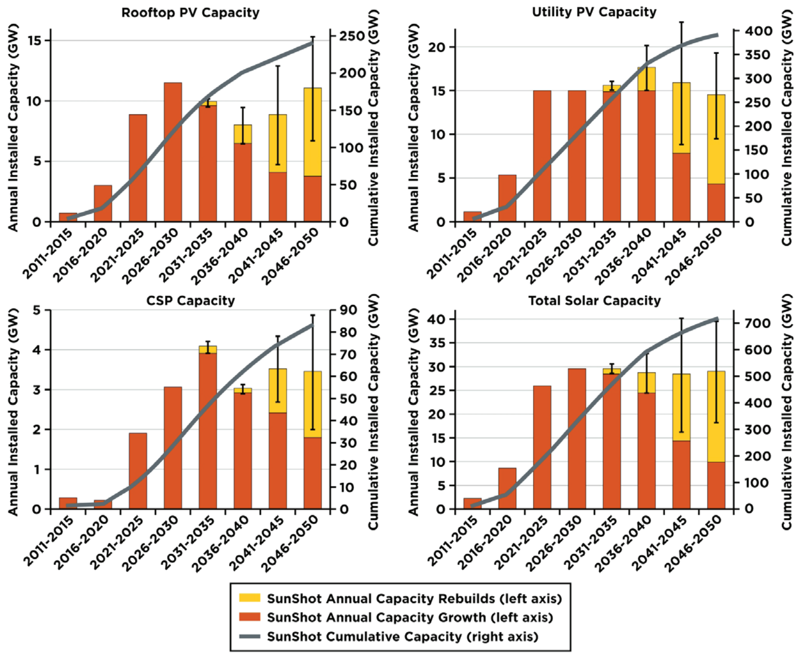
Analyses have been conducted showing that solar energy could become cost competitive with traditional energy sources by 2020 without subsidies.

Figure 4.P.6 shows annual and cumulative U.S. installed solar capacity in one of these scenarios (DOE, 2012). This study assumes that a range of annual installed capacities is required to meet both the solar market growth and end-of-life replacements or retrofits. This study found that solar power could grow to approximately 700 GW of capacity by 2050, satisfying 56% of demand in the Western Interconnection, 28% in the Electric Reliability Council of Texas (ERCOT) Interconnection, and 18% in the Eastern Interconnection if these cost reduction goals are met. This analysis was based on substantial reductions in cost for solar energy with systems reaching an LCOE of $0.06/kWh. While solar costs have decreased substantially continued reductions in module and balance of system costs for PV systems, and overall capital costs for CSP systems in order to reach the levels of penetration assumed in the analysis.[53]

Many other analytical scenarios have indicated that solar technologies will become increasingly prevalent between 2020 and 2050. Table 4.P.1, for example, shows the variation in 2050 installed (utility and rooftop) PV and CSP capacity between the six low-demand core 80% RE scenarios and the high-demand 80% RE scenario, defined in the Renewable Electricity Futures Study (NREL, 2012). Similarly, this analysis indicated that solar technologies could contribute 13%–22% of total generation in 2050; the ranges in PV and CSP capacity deployed in 2050 are 149–294 GW and 33–126 GW, respectively, across these scenarios. Note that the greater capacity factor of CSP systems leads to greater annual energy production per unit of installed capacity compared to PV systems.

The large range in solar deployment among the modeled scenarios demonstrates the strong influences future decisions will have on solar penetration levels. Solar resources are developed more aggressively if it is assumed that RE achieves significant cost and performance improvements (e.g. the Evolutionary Technology Improvement (ETI) scenario), electricity demand increases over time (high-demand 80% RE scenario), and the technical potential of all renewable resources is limited (constrained resources scenario).

Figure 4.P.6 Capacity Additions under the Modeled High Solar Energy Scenario [54]



Regional and National Impacts

Solar technologies that do not concentrate sunlight, such as most PV applications, can use both the direct and diffuse components of solar radiation and can be economically deployed over a wider range of locations and conditions than concentrating technologies that depend on high DNI. The U.S. solar resource has significant geographic variation, as shown in Figure 4.P.7. The southwestern United States has both a high DNI fraction and generally high total solar radiation, leading to higher PV capacity factors than elsewhere in the country. For example, a

Table 4.P.1 Capacity Additions under Renewable Electricity Futures Study[55]

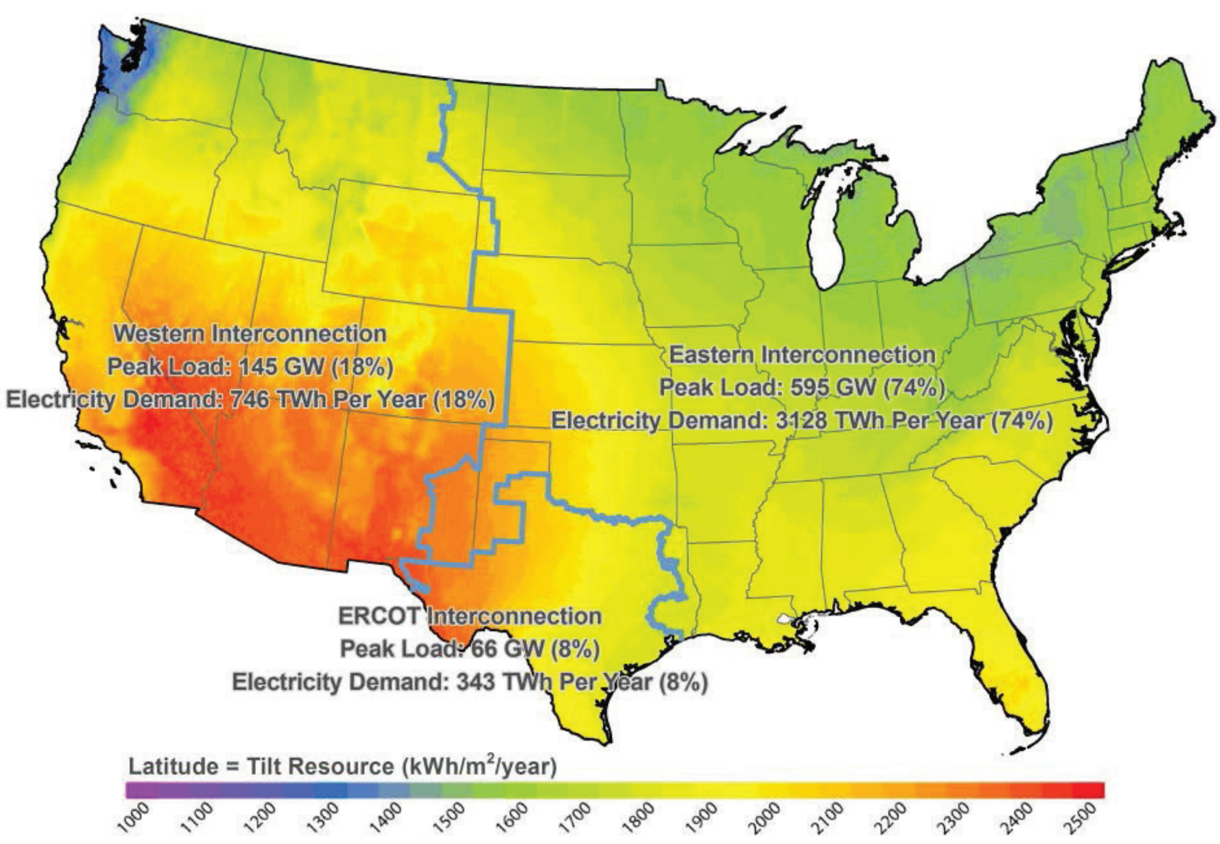
	PV			CSP		Total	
Scenario	Utility PV Capacity (GW)	Rooftop PV Capacity (GW)	Generation (%)	Capacity (GW)	Generation (%)	Capacity (GW)	Generation (%)
High-Demand 80% RE	293	128	12.7%	79	6.4%	493	19.1%
Constrained Transmission	124	170	10.4%	33	3.4%	327	13.9%
Constrained Resources	118	85	7.9%	120	13.9%	324	21.9%
80% RE-Evolutionary Technology Improvement	86	85	6.6%	126	14.1%	297	20.6%
Constrained Flexibility	64	85	5.6%	89	10.4%	238	16.0%
80% RE-Incremental Technology Improvement	83	85	6.4%	56	6.6%	225	13.0%
80% RE-No Technology Improvement	5	85	2.9%	1	0.1%	91	2.9%

one-axis tracking PV module installed near Los Angeles will generate about 23% more electricity than the same module installed near New York City.[56] Electricity demand and wholesale electricity prices also have significant geographic variation. The Western Interconnection represents about 18% of peak and annual demand, the ERCOT Interconnection represents 8% of demand, and the Eastern Interconnection represents 74% of demand.

Under the modeled SunShot scenarios, PV is widely deployed in all U.S. states.[58] Rooftop PV markets in particular develop in all U.S. states, while utility-scale PV is predominantly deployed in southern states, reflecting the combination of good solar resources and the general correspondence of PV output with peak afternoon summer air-conditioning load. On a capacity basis, the largest PV markets are in California, Texas, and Florida, reflecting the relatively good solar resource and relatively high electricity demand. CSP is primarily deployed in the arid southwestern United States, where DNI is highest. The primary CSP markets are in California, Arizona, and Texas, reflecting the high DNI resource and access to load centers in southern California and eastern Texas.

Demand satisfied by other RE in the high penetration of solar scenario is also interesting to examine. Figure 4.P.8 shows the fraction of end-use electricity demand satisfied by solar and wind resources within each interconnection in 2030 and 2050 under the SunShot scenario. In 2030, solar is preferentially deployed in the Western Interconnection (meeting 31% of annual electricity demand) and the ERCOT Interconnection (14% of demand). PV satisfies about 9% of electricity demand in the Eastern Interconnection, and CSP supplies a small fraction of demand. There are good wind resources in each interconnection, and about 6% of electricity demand is met with wind in each interconnection. However, since CSP is built with several hours

Figure 4.P.7 Solar Potential in the United States[57]



of storage, making it a dispatchable resource, the variable RE (PV and wind) fraction is less stratified between interconnections, represented by 22% of electricity demand in the Western Interconnection, and 20% and 13% of electricity demand in the Eastern and ERCOT Interconnections, respectively.

By 2050, solar generation could reach 56% of demand in the Western Interconnection, 28% in the ERCOT Interconnection, and 18% in the Eastern Interconnection in the SunShot analysis. CSP provides the largest share of solar generation in the Western Interconnection, and the resulting variable renewable generation (PV and wind) is similarly less stratified across interconnections (29%, 27%, and 23% in the Western, ERCOT, and Eastern Interconnections, respectively). At these levels of regional market penetration, system operation is clearly a concern. However, CSP with storage can be operated as a dispatchable resource to help integrate variable renewable resources (CSP storage is discussed in greater detail in the Concentrating Solar Power Development and Status section).

Although solar meets a higher proportion of demand in the Western and ERCOT Interconnections, the larger population and electricity demand in the Eastern Interconnection leads to significantly higher PV capacity additions there. The majority of PV capacity is installed in the Eastern Interconnection (63% by 2030, 70% by 2050), and the majority of CSP capacity is installed in the Western Interconnection (87% by 2030, 81% by 2050).

Electricity System Cost and Rate Impacts

Recent modeling has indicated that low-cost solar technologies can have a beneficial impact of direct electric-sector costs. These direct electric-sector costs include the cost of investing in renewable and conventional generation capacity as well as costs for O&M, fuel, and expanding transmission capacity. Figure 4.P.9 shows the electric-sector costs under reference and modeled scenarios, calculated by using 2010 U.S. dollars adjusted with a 7% real discount rate. In the reference scenario, solar costs decline slowly beginning in 2010. In the SunShot scenario, solar costs decrease rapidly between 2010 and 2020.

Figure 4.P.8 Regional Deployment under the Modeled Scenario.[59]

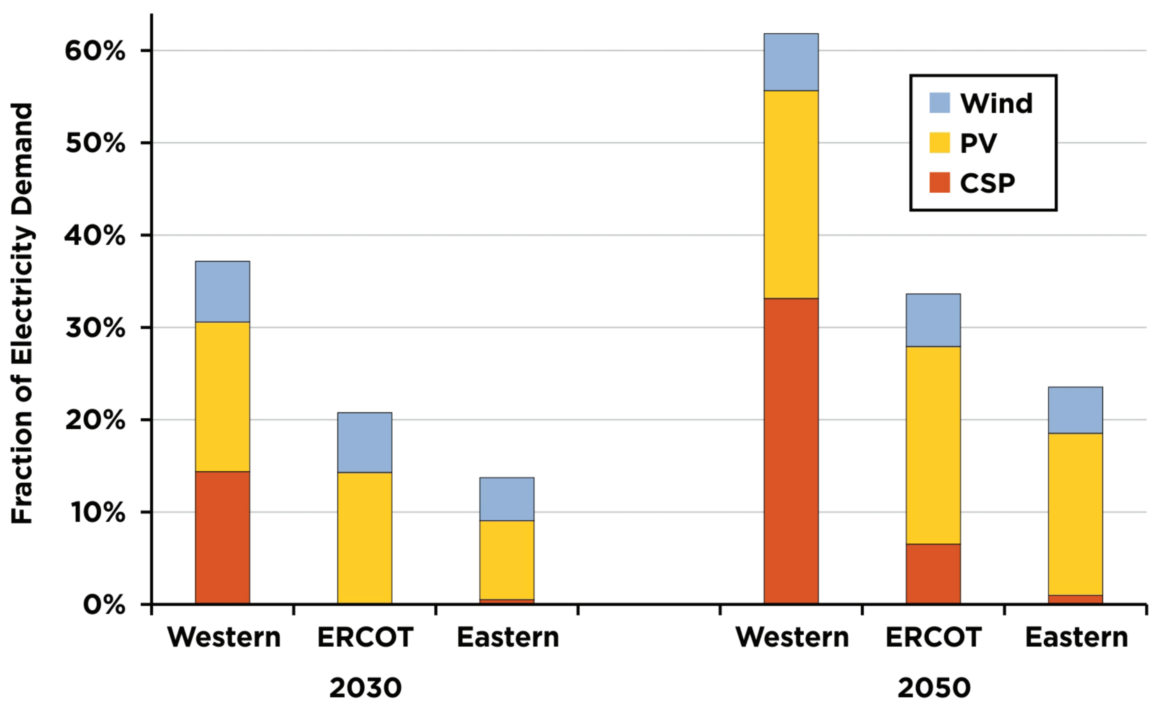
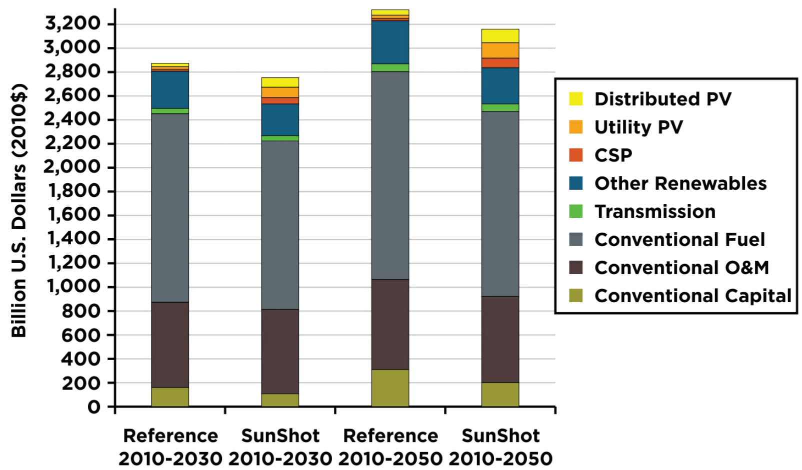


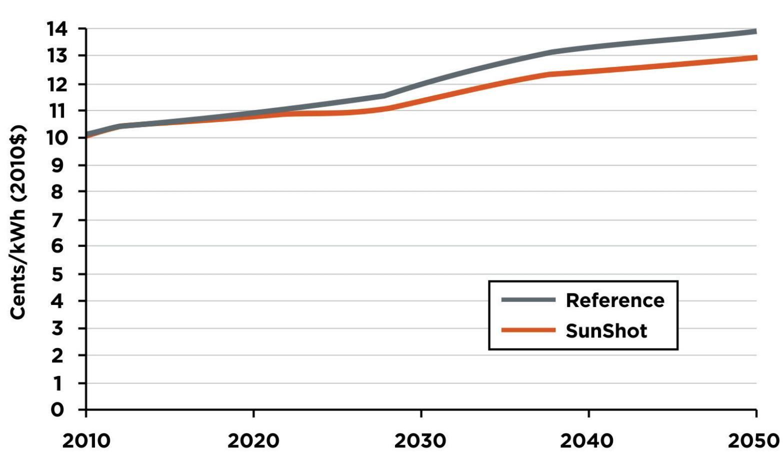
Figure 4.P.9 Electricity Costs under Reference and SunShot Scenarios.



Under these assumptions, the cost of developing solar resources is more than offset by annual fuel savings and reduced capital and O&M expenditures from other technologies. On the basis of AEO 2010 projected fuel prices that are adjusted for higher or lower fuel demand within each scenario, annual fuel savings in the high solar scenario reach $34 billion by 2030 and $41 billion by 2050, relative to the reference scenario.[60] For both scenarios, transmission costs are significantly less than the costs of investing in new generation capacity, O&M, and fuel. This analysis indicates that if solar becomes a widely deployed and cost-competitive technology, it can enable a reduction in overall electricity sector costs.

Figure 4.P.10 shows mean retail electricity rates (2010 dollars) charged to end users through 2050. Mean U.S. retail rates are about 5% lower in the SunShot scenario by 2030 and 7% lower by 2050 relative to the reference scenario. This corresponds to a 0.6 cents/kWh reduction in retail rates by 2030 in the modeled scenario and a 0.9 cents/kWh reduction by 2050 relative to the reference scenario. The lower costs in the modeled scenario result in about a $6 savings per household per month by 2030 and about a $9 savings per household per month by 2050. Real electricity rates increase by about 40% in the reference scenario on the basis of the assumed increase in real natural gas and coal prices in AEO 2010. Across all market sectors, the lower electricity prices in the hypothesized scenario translate into about $30 billion in annual cost savings by 2030 and $50 billion in annual savings by 2050, providing solar prices can be reduced to $1/watt for utility scale systems by 2020.

Figure 4.P.10 Utility Rates under Modeled Scenario



Retail electricity rates include the cost of generation, transmission, and distribution. The costs of generation and transmission are captured in the Regional Energy Deployment System model. Distribution costs are based on average historical costs for the entire U.S. electric-power sector, which is assumed to remain regulated. End-use rooftop PV investments do not significantly impact wholesale electricity rates.

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[52] The current power system was designed to deliver electricity from centralized generators to end users. This system was not designed to incorporate sources of distributed generation, and thus power was only designed to flow in one direction. While the grid is evolving to incorporate both distributed and intermittent sources of generation, the current system is not currently equipped to handle increasing penetrations of distributed PV.

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Acronyms

CPV	Concentrating Photovoltaic
CSP	Concentrating Solar Power
DNI	Direct Normal Irradiance
OPV	Organic Photovoltaic
PV	Photovoltaic
Var	Volt ampere reactive

Glossary

Cadmium telluride	a polycrystalline thin-film photovoltaic material.
Copper indium gallium diselenide (CIGS)	A polycrystalline thin-film photovoltaic material (sometimes incorporating gallium (CIGS) and/or sulfur).
Earth-abundant materials	materials that are commonly found in the earth's crust and can typically be manufactured at a lower cost than rare earth materials. For example, copper zinc tin sulfoselenide is an earth abundant material that has the potential for use in a solar cell.
Multijunction	A high-efficiency photovoltaic device containing two or more cell junctions, each of which is optimized for a particular part of the solar spectrum.
Passive Solar	refers to building design where the walls, floors, and roof of a building are designed to capture solar energy in the winter and reject solar energy in the summer and to use thermal storage to moderate winter and summer temperature swings.
Receiver	the focus area of a CSP unit. Mirrors reflect light onto the receiver, which heats fluid to create electricity
Selective Coating	a coating applied to CSP machinery to improve resiliency of materials in high temperature and oxidative environments.
Thin film	A layer of semiconductor material, such as copper indium diselenide or gallium arsenide, a few microns or less in thickness, used to make photovoltaic cells.
Var	Volt ampere reactive, a unit of reactive power
Wac	Watts, alternating current. Used in this assessment to describe the capacity of a solar system after the electricity has been converted from a direct current to an alternating current
Wdc	Watts, direct current. Used in this assessment to describe the capacity of a solar system before the electricity has been converted into an alternating current from a direct current