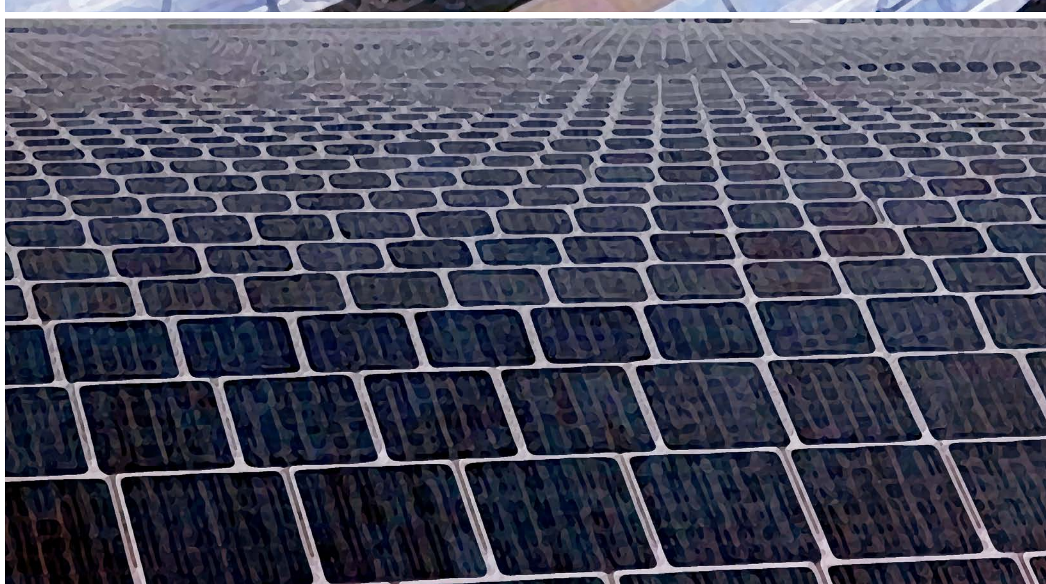
SunShot
U.S. Department of Energy

SunShot Vision Study

February 2012



2. Solar Energy Market Evolution and Technical Potential

This chapter provides context for the SunShot scenario by reviewing the evolution of global and U.S. markets for photovoltaics (PV) and concentrating solar power (CSP). It also examines the maximum potential of U.S. solar markets as determined by the potential of solar technologies to convert available sunlight into electricity and thermal energy.

The global PV market has accelerated over the past decade, with PV shipments averaging 53% annual growth and reaching 17 gigawatts (GW) in 2010, bringing cumulative shipments to about 40 GW. In 2010, the United States accounted for 8% or about 1,400 megawatts (MW) of PV market demand and 6% or about 1,000 MW of supply. The technical potential of the U.S. PV market is large. In fact, one estimate of the land area required to supply all end-use electricity in the United States using PV is only about 0.6% of the country's total land area or about 22% of the "urban area" footprint (Denholm and Margolis 2008a).[10]

The technical potential for CSP is also large. After implementing filters that account for insolation, slope, and land-use restrictions, the technical potential of the U.S. CSP market is about 7,500 GW of potential generating capacity—several times higher than the entire U.S. electric grid's capacity—in seven southwestern states (Turchi 2009). However, CSP market growth has been historically sporadic. After CSP plants were built in California in the late 1980s, almost 15 years passed before the next commercial CSP plant was built, followed by a surge of new plants in the United States and Spain during 2007–2010. At the end of 2010, global CSP capacity was about 1,300 MW, with about 39% in the United States and 57% in Spain; parabolic trough technology accounted for about 96% of the global total and tower technology for 3%.

2.1 Evolution of U.S. Solar Markets

This section discusses market evolution for PV and CSP, including changes in global and U.S. supply and demand and the current status of U.S. solar technology manufacturing. Also discussed are the factors affecting solar market evolution and recent solar industry employment statistics. Putting all the information together, a picture emerges of a solar industry that has come a long way over the past few decades, setting the stage for SunShot-scale deployment during the next several decades.

[10] This calculation is based on deployment/land in all 50 states.

2

2.1.1 PHOTOVOLTAICS

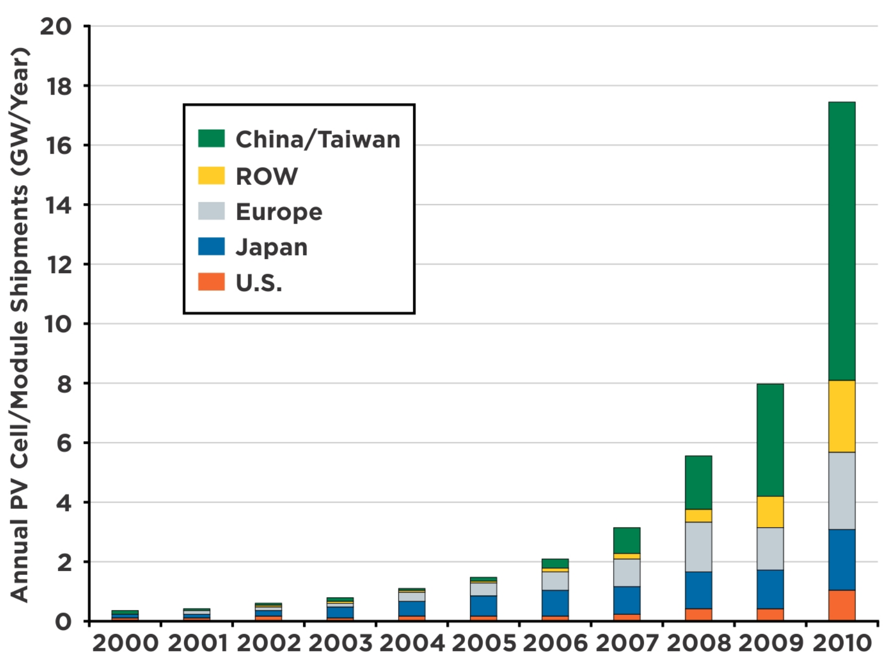
While the global PV market grew rapidly during the past decade, the U.S. market position declined based on more rapid growth in Asia and Europe. During the past couple of years, federal and state policies have helped to drive PV market demand growth and a renewed interest in PV manufacturing in the United States.

Global PV Supply and Demand

Shipments of PV cells and modules by region are a key indicator of market evolution. Shipments attributed to a given region represent PV supplied by that region, as measured at the first point of sale. However, not all shipped cells and modules end up in the market the year they are produced or in the country in which they were first sold.

Figure 2-1 shows the dramatic growth in PV shipments during the past decade: a 53% compound annual growth rate from 2000 through 2010, reaching 17.4 GW in annual shipments in 2010. The United States accounted for 30% of global PV shipments in 2000, but then lost market share over the next decade, first to Japan, then to Germany, and finally to China and Taiwan. In 2010, China and Taiwan accounted for 53% of global PV shipments. The Japanese market surge resulted largely from its residential subsidy program, which began during the mid-1990s. The European surge resulted largely from the German feed-in tariff, which was implemented in 2000, streamlined over the next couple of years, and adopted by a number of other European countries during the past 5 years. During 2006–2010, China and Taiwan invested heavily in PV manufacturing and demonstrated an ability to scale-up production rapidly while reducing manufacturing cost substantially.

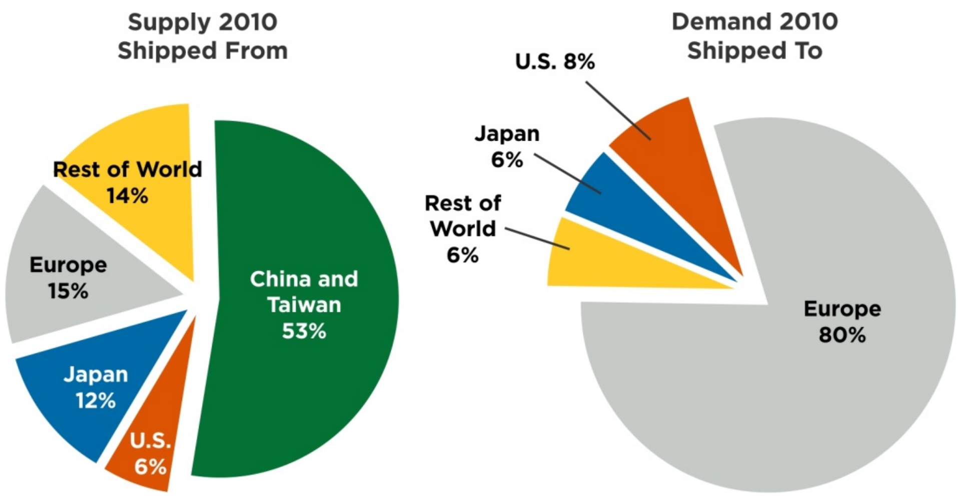
Figure 2-1. Regional PV Cell and Module Shipments, 2000–2010



Source: Mints (2011a)

Figure 2-2, which depicts global PV supply and demand in 2010, clearly shows the dominance of manufacturers in China and Taiwan. The rest of world (ROW) region includes Australia, India, the Philippines, and Malaysia.

Figure 2-2. 2010 Global PV Supply and Demand



Source: Mints (2011a) and Mints (2011b)

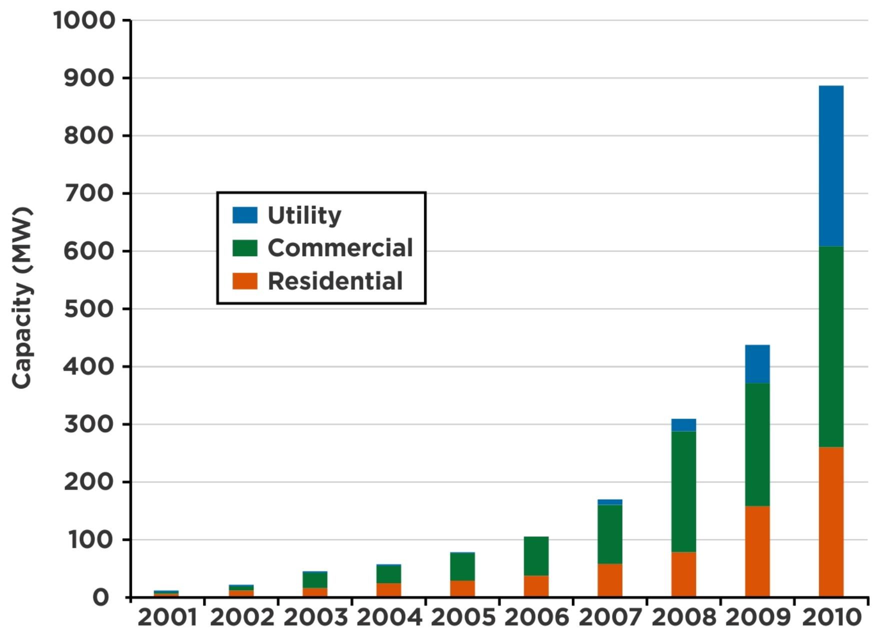
Historically, PV shipments have been dominated by crystalline-silicon technology. In 2003, the market share for crystalline-silicon PV was 95%, compared with 5% for thin-film PV. However, thin-film shipments have grown rapidly in recent years, particularly shipments of cadmium telluride (CdTe) and amorphous silicon (a-Si) technologies. At the same time, newer PV technologies—such as copper indium gallium diselenide (CIGS) and concentrating photovoltaics (CPV)—have been preparing to enter full-scale production. By the end of 2010, thin-film technology accounted for 13% of global PV shipments (3% a-Si, 8% CdTe, and 2% CIGS). The United States was responsible for 18% of global CdTe and 20% of global a-Si shipments in 2010 (Mints 2011a).

U.S. PV Demand

Despite a long history of public and private investments in PV technology, the United States remains a relatively immature PV market. In the 1980s, the U.S. and global PV demand was dominated by off-grid applications, typically very small systems with installed capacities measured in hundreds of watts. During the late 1990s, grid-connected systems—with installed capacities measured initially in kilowatts and later in megawatts—began dominating global demand. As this transition occurred, system cost declined significantly owing to a combination of research and development (R&D) advances as well as economies of scale on the production and installation sides. In the United States, the transition to a market dominated by grid-connected systems occurred slightly later, driven by state and federal incentives.

Figure 2-3 illustrates the annual growth in U.S.-installed grid-connected PV from 2001 to 2010 for residential, commercial, and utility-owned applications.[11] The entire installed PV market has grown substantially over the past decade. The utility market segment made a notable market share increase from 2009–2010, primarily the result of only 34 large (over 1 MW) installations. Off-grid PV installations—not depicted in this figure—accounted for approximately 40–60 MW in 2010 (IREC

Figure 2-3. U.S. Annual Installed Grid-Connected PV Capacity by Market, 2001–2010



Source: IREC (2011)

2011).

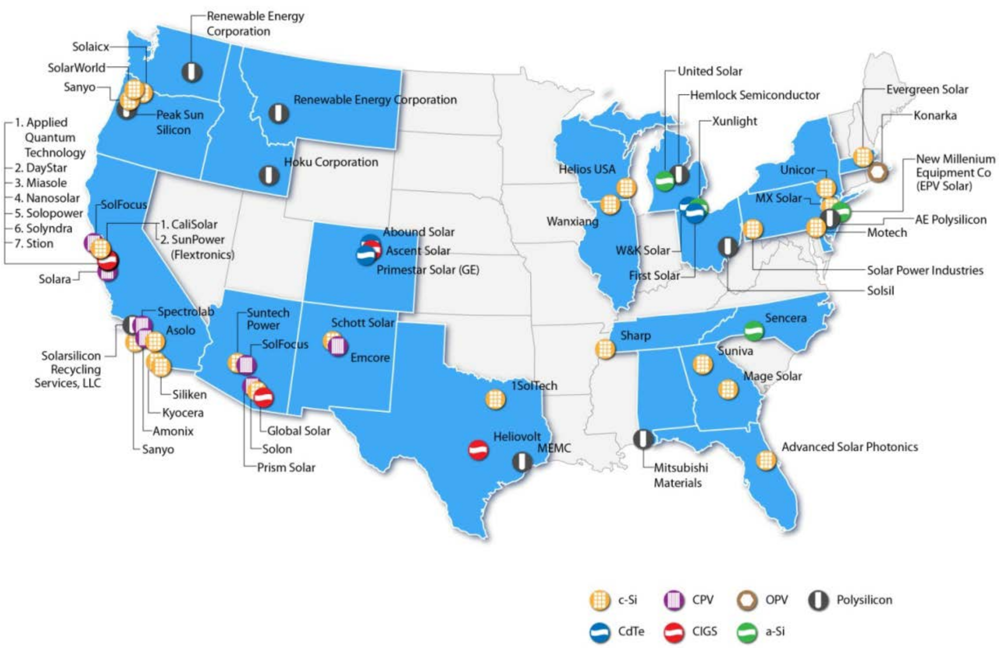
As of 2010, California was by far the strongest U.S. PV market. The California Solar Initiative, enacted in December 2005, provided the long-term market stability critical for encouraging new entrants on the production and installation sides. California continues to encourage solar and other renewable energy technologies through innovative policies, including a strong renewable portfolio standard (RPS), a diverse portfolio of incentives, and utility involvement. Other U.S. markets that have grown significantly during the past few years are Arizona, Colorado, New Mexico, New Jersey, New York, and Nevada.

U.S. PV Manufacturing

Recent federal and state incentives have encouraged manufacturers to expand PV production in the United States. Figure 2-4 shows the location and technology of

[11] The residential and commercial data generally represent installations where electricity is used on-site, whereas the utility data represent installations that generate electricity sent to the bulk grid. Commercial data capture government, non-profit, and other non-residential installations. The owner of the installation for any of the three market segments could be either the site owner or a third party.

Figure 2-4. U.S. PV Cell, Module, Wafer, and Polysilicon Manufacturing Facilities, July 2011



Sources: SEIA and GTM Research (2011a), Mehta (2009), Bradford (2008), BNEF (2009)

U.S. PV manufacturing facilities as of July 2011.[12] The figure shows that 59 PV facilities in 22 states were in operation in mid-2011.

These facilities produce crystalline-silicon, CPV, and thin-film technologies such as a-Si, CdTe, CIGS, and organic photovoltaics (OPV), as well as polysilicon and wafers for use in crystalline-silicon PV. In 2010, U.S. cell production was about 1,100 MW or 5% of global production, and module production was about 1,200 MW or 6% of global production (SEIA and GTM Research 2011b). The United States produced 42,561 metric tons (MT) of polysilicon in 2010, approximately 30% of global supply. The median estimate of total polysilicon produced in 2010 was 148,750 MT, of which about 81% (or 120,400 MT) was produced for the solar industry. In addition to these numbers, scrap polysilicon from the electronics industry has always supplied the solar industry with varying amounts of the material. The total 2010 production of polysilicon represented an estimated 60% increase over 2009 production.

The discrepancy between U.S. polysilicon production versus module production is due in part to polysilicon production being very capital intensive and complex, requiring technological sophistication, whereas module production is labor intensive, benefiting countries with low-cost labor. In addition, shipping costs of

[12] An attempt was made to only include all manufacturing plant locations with at least 5 MW of production capacity as of July 2011. However, the constantly changing landscape for PV component manufacturing and diversity of players in the solar manufacturing industry make it difficult to have a comprehensive list at any point in time. This list is not an exception, and should not be viewed as absolute.

polysilicon are minimal, so plant location near the end customer is not a key factor, whereas modules are more expensive to ship, benefitting countries in Europe where the largest end markets are located.

2.1.2 Concentrating Solar Power

The market for CSP has surged in recent years, especially in Spain and the United States. Trough systems dominate global CSP installations, but other technologies are gaining market share.

Global CSP Installations

Luz, a California-based company, first commercialized CSP in the 1980s with the Solar Energy Generating Systems (SEGS), 354 MW of parabolic trough plants in the Mojave Desert of southern California. The next CSP plant to come online in the United States was the Arizona Public Service (APS) Saguaro 1-MW parabolic trough plant, installed in Red Rock, Arizona, in 2005. Another 64 MW of CSP capacity were added in 2007 when the Nevada Solar One parabolic trough plant was installed in Boulder City, Nevada. At the end of 2008, 430 MW of grid-tied CSP capacity were in commercial operation worldwide, more than 95% of which was in the southwestern United States.

By December 2010, global CSP capacity increased to about 1,300 MW. Most of the capacity additions during 2009–2010 were in Spain, and at the end of 2010, Spain accounted for about 57% of all global CSP capacity. Parabolic trough technology accounted for about 96% of global CSP capacity at the end of 2010; tower technology accounted for 3%. Table 2-1 lists commercial and grid-tied demonstration CSP plants (with capacities of 1 MW or greater) installed worldwide as of December 2010. The Andasol 1 and Andasol 2 plants shown in the table are the first commercial CSP plants to feature thermal storage, using a two-tank molten salt system to store up to 7.5 hours of peak-load energy (Solar Millennium 2010).

Table 2-1. Commercial and Grid-Tied Demonstration CSP Plants ($\geq$ 1 MW_{AC} capacity) Installed Worldwide as of December 2010

Plant Name	Location	Technology Type	Year Installed	Capacity (MW_{AC})
SEGS I – IX	California, U.S.	Trough	1985–1990	354
Inditep	Spain	Trough	2005	1.2*
APS Saguaro	Arizona, U.S.	Trough	2006	1
Nevada Solar One	Nevada, U.S.	Trough	2007	64
PS10	Spain	Tower	2007	11
Kimberlina	California, U.S.	Compact linear Fresnel reflector (CLFR)	2008	7*
Andasol 1	Spain	Trough w/thermal storage	2008	50
Liddell	Australia	CLFR	2008	3
Sierra Sun Tower	California, U.S.	Tower	2009	5*
Holaniku	Hawaii, U.S.	Trough	2009	2*
Stadtwerke Julich	Germany	Tower	2009	1.5*

Plant Name	Location	Technology Type	Year Installed	Capacity (MW_{AC})
Puerto Errado 1	Spain	Linear Fresnel	2009	1.4*
Puertollano Ibersol	Spain	Trough	2009	50
La Risca	Spain	Trough	2009	50
PS20	Spain	Tower	2009	20
Holaniku	Hawaii, U.S.	Trough	2009	2
Maricopa Solar	Arizona, U.S.	Dish	2010	1.5*
IEECAS Badaling	China	Tower	2010	1.5*
Cameo	Colorado, U.S.	Trough	2010	1*
Casa del Ángel Termosolar	Spain	Stirling	2010	1*
Himin Yanqing	China	Tower	2010	1*
Martin	Florida, U.S.	Trough	2010	75
Andasol 2	Spain	Trough w/thermal storage	2010	50
Extresol 1	Spain	Trough w/thermal storage	2010	50
Solnova 1	Spain	Trough	2010	50
Solnova 3	Spain	Trough	2010	50
Solnova 4	Spain	Trough	2010	50
La Florida	Spain	Trough	2010	50
Majadas	Spain	Trough	2010	50
La Dehesa	Spain	Trough w/thermal storage	2010	50
Palma Del Rio II	Spain	Trough	2010	50
Extresol-2	Spain	Trough w/thermal storage	2010	50
Manchasol-1	Spain	Trough w/thermal storage	2010	50
Ain Beni Mathar	Morocco	Trough	2010	20
Al Kuraymat	Egypt	Trough	2010	20
Archimede	Italy	Trough	2010	5

*Denotes grid-tied demonstration plant

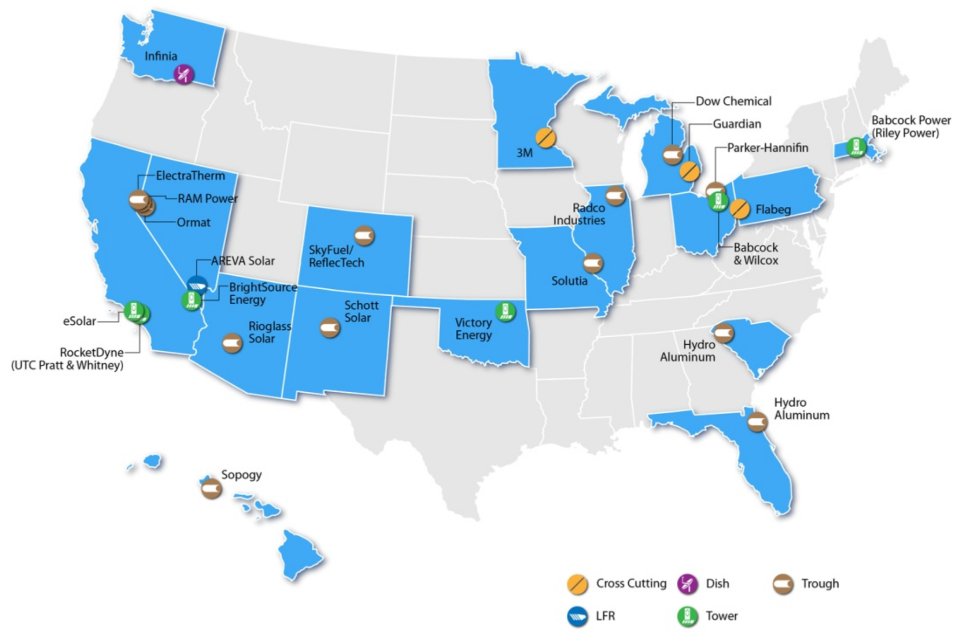
Sources: Abengoa Solar (2011), Acciona Energy (2008), Ausra (2009), BrightSource Energy (2008), Emerson Process Management (2009), eSolar (2009), Grama et al. (2008), Solar Millennium (2010), Sopogy (2009), Tessera Solar (2010), Protermosolar (2011), NREL (2011a), Renovalia Energy (2010), EIA (2010a), SEIA-GTM (2011b), BNEF (2011), NextEra Energy (2011), Areva Solar (2010)

U.S. CSP Manufacturing

Figure 2-5 shows U.S. component manufacturing facilities for CSP technologies including parabolic troughs, power towers, linear Fresnel reflectors, and dish/engine systems. A total of 24 manufacturing facilities that produce CSP components—possibly among other products—were in operation by mid-2011.[13] CSP

[13] An attempt was made to only include all manufacturing plant locations with at least 5 MW of production capacity as of July 2011. However, the constantly changing landscape for CSP component manufacturing and diversity of players in the solar manufacturing industry make it difficult to have a comprehensive list at any point in time. This list is not an exception, and should not be viewed as absolute.

Figure 2-5. U.S. CSP Component Manufacturing Facilities, July 2011



Sources: SEIA and GTM Research (2011a), BNEF (2009), DOE (2010)

components—many of which cut across technologies—include mirrors, reflectors, collector structures, heat-transfer fluids and salts, turbines, and controls. The expectation of strong CSP installation growth has resulted in CSP component production facilities being established by specialized manufacturers and large industrial conglomerates.

2.1.3 Solar Industry Employment

This section discusses the existing types and levels of employment in the solar industry for PV and CSP.

The PV and CSP industries include a variety of jobs across their supply chains and in support roles. In measuring economic impact, jobs can be divided among three categories: direct, indirect, and induced jobs. Direct jobs accomplish final production along the solar industry supply chains, e.g., manufacturing, installation, and R&D. Indirect jobs are in industries that support the solar industry, e.g., glass, steel, and office-equipment industries. Induced jobs result from the economic activity stimulated by the solar industry, e.g., jobs related to people buying more goods and services in a region that hosts a manufacturing plant or project under construction.

It is most feasible to quantify direct and indirect jobs resulting from solar industry growth. The range of direct and indirect solar jobs includes the following:

- *Manufacturing:* Technology research, engineering, raw materials production, assembly line, quality control, shipping, and marketing
- *Project planning:* Mechanical, electrical, and structural engineers, energy transmission engineers, architects, project developers, land brokers, contract personnel, environmental consultants, utility procurement staff, local permitting officials, lenders, and investors
- *Installation:* Construction managers, installers, pipefitters, electricians, plumbers, laborers, and truck drivers
- *Operations, maintenance, and ownership:* System monitors, field technicians, warranty servicing, and accounting
- *Decommissioning and disposal:* Demolition, transportation, and recycling
- *Education and training:* Professors, instructors, and administrators
- *Policy, program administration, research, and advocacy:* Energy officials, utility program administrators, government-relations staff, trade associations, market analysts, non-profits, and media.

There were an estimated 51,000 full-time-equivalent PV- and CSP-related jobs in 2010, about 90% of which were related to PV and 10% to CSP. See Chapter 3 for employment details and projections through 2050.

The distributed energy model afforded by solar technologies is a key factor influencing solar employment characteristics. The multiplicity of small- and mid-sized solar energy systems yields more installation and operations jobs compared to common central station energy technologies, per energy unit [e.g., megawatt-hours (MWh)] produced. These jobs are more widely distributed in communities across the nation, including rural locations. This enables communities to "in-source" energy production, expanding local economies and providing jobs that cannot be moved offshore (Wei et al. 2010).

2.1.4 Hedging Against Energy Price Increases

Solar energy technologies enable users to reduce their exposure to future increases in the cost of energy because these systems do not face variable fuel costs. This is an attractive attribute of solar energy technologies. In particular, the potential impact of increased solar market penetration on natural gas use and pricing is important (this is discussed in more detail in Chapter 3). Natural gas is currently a key determinant of electricity, heating, and cooling costs in the United States. Natural gas accounts for roughly 20% of U.S. electricity generation; however, because natural-gas generation plants are usually the last power source to be activated to meet a given load, it is a key determinant in setting the wholesale market price of electricity throughout much of the country. Solar energy technologies provide potential price-hedging benefits to individual consumers, by substituting a fixed cost in place of a potentially volatile fuel cost, and the broader public, by displacing demand for natural gas.

2.2 Solar Resource Availability and Technical Potential

The U.S. solar resource is enormous. In fact, the amount of solar energy falling on the United States in 1 hour of noontime summer sun is about equal to the annual U.S. electricity demand. Moreover, as shown in Figure 2-6 and discussed below, every region of the contiguous United States has a good solar resource.

The ability to exploit the available solar resource varies by technology. Solar energy contains a direct component, i.e., light from the solar disk that has not been scattered by the atmosphere, and an indirect or diffuse component, i.e., light that has been scattered by the atmosphere. Only the direct solar component can be focused effectively by mirrors or lenses such as those used by CPV and CSP systems. The direct component typically accounts for 60%–80% of surface solar insolation in clear-sky conditions and decreases with increasing relative humidity, cloud cover, and atmospheric aerosols, e.g., due to dust and urban pollution. This section describes the technical potential for PV and CSP market growth in the context of the exploitable U.S. solar resource.

2.2.1 Photovoltaics

Flat-plate PV can take advantage of direct and indirect insolation, so PV modules need not directly face and track incident radiation. This gives PV systems a broad geographical application.

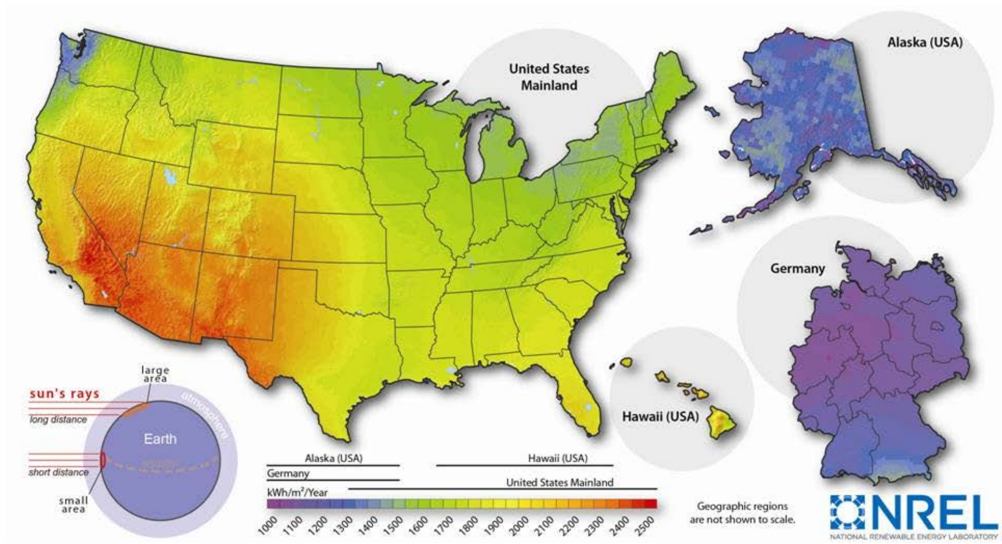
Figure 2-6 illustrates the solar resource in the United States and Germany for a flat-plate PV collector tilted south at latitude. Solar resources across the United States are mostly good to excellent at about 1,000–2,500 kilowatt-hours (kWh)/square meter (m^2)/year. The Southwest is at the top of this range, while only Alaska and part of Washington are at the low end. The range for the 48 contiguous states is about 1,350–2,500 kWh/m^2/year. Nationwide, solar resource levels vary by about a factor of two, which is considered relatively homogeneous compared with other renewable energy resources.

The U.S. solar resource is much higher than Germany's, and the southwestern United States has a better resource than southern Spain. Germany's solar resource has about the same range as Alaska's (1,000–1,500 kWh/m^2/year), but more of Germany's resource is at the lower end of the range. Spain's solar resource ranges from about 1,300–2,000 kWh/m^2/year, among the best in Europe.

The total U.S. land area suitable for PV is significant and will not limit PV deployment. For example, one estimate suggested that the land area required to supply all end-use electricity in the United States using PV is about 5,500,000 hectares (ha) (13,600,000 acres), which is equivalent to 0.6% of the country's land area or about 22% of the "urban area" footprint (Denholm and Margolis 2008a).[14] See Chapter 7 for calculations of PV land use and electricity generation under the SunShot scenario. In addition to siting PV on greenfields, there are many opportunities for installing PV on underused real estate such as parking structures,

[14] This calculation is based on deployment/land in all 50 states.

Figure 2-6. PV Solar Resource: United States and Germany



Source: NREL (2011b)

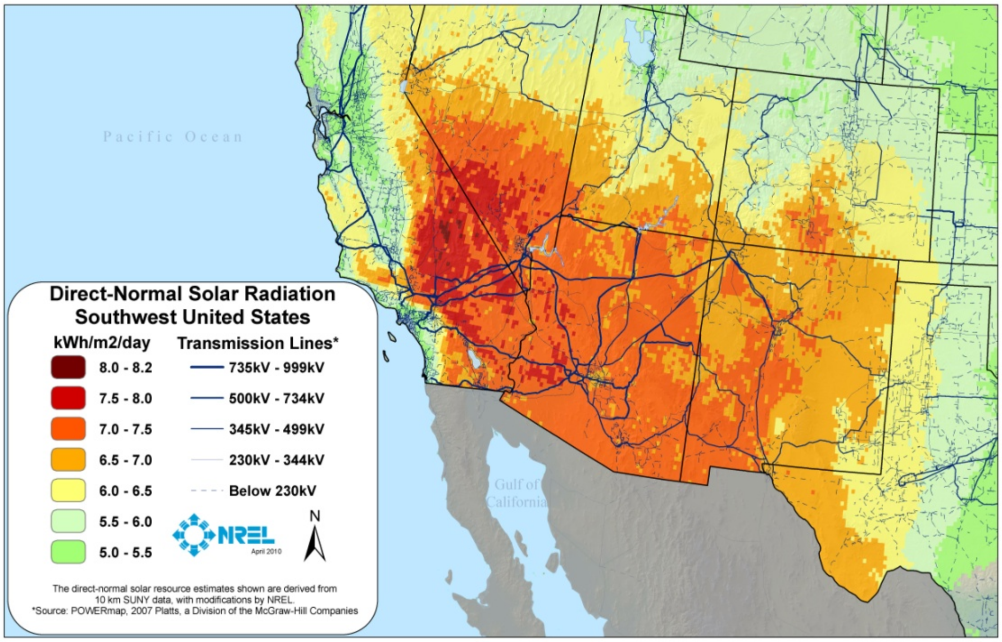
awnings, airports, freeway margins, and farmland set-asides. PV can also be located on rooftops, where it will have essentially no land-use impacts. A recent estimate of the total roof area suitable for PV in the United States is about 6 billion m^2, even after eliminating 35%–80% of roof space to account for panel shading (e.g., by trees) and suboptimal roof orientations; with current PV performance, this area has the potential for more than 600 GW of capacity (Denholm and Margolis 2008b).

2.2.2 Concentrating Solar Power

The geographic area most suitable for CSP is smaller than that for PV because CSP can exploit only direct-normal irradiance (DNI), i.e., light that can be focused effectively by mirrors or lenses. Globally, the most suitable sites for CSP plants are arid lands within 35° north and south of the equator. In the United States, the best location for CSP is the Southwest, which has some of the best solar resources in the world. Figure 2-7 shows the DNI resource in the Southwest; red indicates the most intense solar resource, and green indicates the least intense.

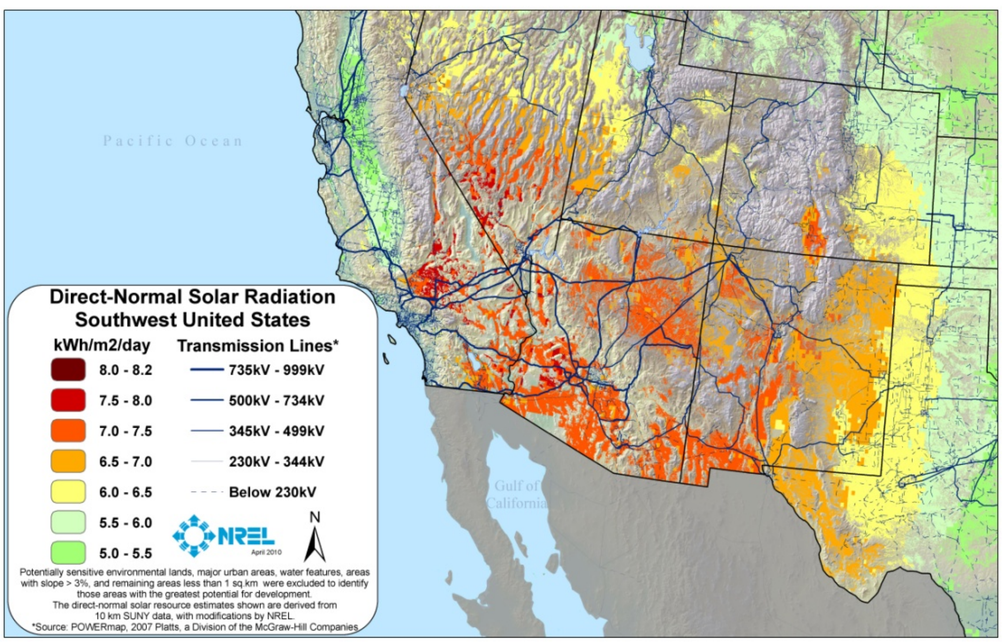
A strong solar resource is only one criterion for the effective deployment of large solar power stations. The land must also be relatively flat, unoccupied, and suitable for development. NREL has performed various assessments of the Southwest to estimate the quantity of land suitable for solar power stations and the amount of energy that might be produced. Figure 2-8 shows locations in the Southwest with characteristics ideal for CSP systems, including DNI greater than 6.0 kWh/m^2/day (2,200 kWh/m^2/year) and a land slope of less than 1°. In addition, land-use filters exclude bodies of water, urban areas, national parks and preserves, wilderness areas, and wildlife refuges. Because the economics of utility-scale solar facilities favor large size, land areas smaller than 1 square kilometer (km^2) are also excluded (Mehos et al. 2009).

Figure 2-7. DNI Resource in the U.S. Southwest



kV: kilovolts
Source: Mehos and Kearney (2007)

Figure 2-8. DNI Resource in the U.S. Southwest, Filtered by Resource, Topography, and Land Use



Sources: Mehos et al. (2009), Turchi (2009)

After implementing the appropriate insolation, slope, and land-use filters, 22,593,000 ha (55,800,000 acres) are available in the seven states considered to be most CSP compatible: Arizona, California, Colorado, Nevada, New Mexico, Texas, and Utah (Table 2-2). This relatively small land area amounts to nearly 7,500 GW of resource potential and more than 17.5 million gigawatt-hours (GWh) of annual generating capacity, assuming a capacity factor of 27% (Mehos et al. 2009, Turchi 2009). The potential generating capacity exceeds the total U.S. electric grid capacity by a factor of more than six, while the potential energy production exceeds U.S. demand by a factor of more than four (EIA 2010b, EIA 2010c).

Table 2-2. Ideal CSP Resource Potential and Land Area in Seven Southwestern States

State	Available Area (ha)	Capacity (GW)	Annual Electricity[a] (GWh)
Arizona	3,525,700	1,162	2,748,000
California	1,626,000	536	1,267,000
Colorado	1,614,100	532	1,258,000
Nevada	2,872,300	946	2,238,000
New Mexico	5,272,200	1,737	4,108,000
Texas	1,650,800	544	1,286,000
Utah	6,031,600	1,987	4,700,000
Total CSP Resource	**22,593,000**	**7,444**	**17,605,000**

[a] Annual electricity production was estimated using an average capacity factor of 27%, although actual values would depend on technology and level of thermal energy storage deployed.

Sources: Mehos et al. (2009), Turchi (2009)

A value of 3 ha/MW (7.5 acres/MW) was used to determine capacity per unit of land area. This value represents an estimated average for different CSP technologies, and actual values will depend on the specific technology used, location, and system efficiency. CSP systems with thermal storage will have a higher land use per unit of capacity due to a larger collector area needed for generating excess thermal energy. However, because the storage also results in a higher capacity factor, these effects offset each other in the calculation of annual energy production. See Chapter 7 for calculations of CSP land use and electricity generation under the SunShot scenario.

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