3

Direct Solar Energy

Coordinating Lead Authors:
Dan Arvizu (USA) and Palani Balaya (Singapore/India)

Lead Authors:
Luisa F. Cabeza (Spain), K.G. Terry Hollands (Canada), Arnulf Jäger-Waldau (Italy/Germany), Michio Kondo (Japan), Charles Konseibo (Burkina Faso), Valentin Meleshko (Russia), Wesley Stein (Australia), Yutaka Tamaura (Japan), Honghua Xu (China), Roberto Zilles (Brazil)

Contributing Authors:
Armin Aberle (Singapore/Germany), Andreas Athienitis (Canada), Shannon Cowlin (USA), Don Gwinner (USA), Garvin Heath (USA), Thomas Huld (Italy/Denmark), Ted James (USA), Lawrence Kazmerski (USA), Margaret Mann (USA), Koji Matsubara (Japan), Anton Meier (Switzerland), Arun Mujumdar (Singapore), Takashi Oozeki (Japan), Oumar Sanogo (Burkina Faso), Matheos Santamouris (Greece), Michael Sterner (Germany), Paul Weyers (Netherlands)

Review Editors:
Eduardo Calvo (Peru) and Jürgen Schmid (Germany)

This chapter should be cited as:

Arvizu, D., P. Balaya, L. Cabeza, T. Hollands, A. Jäger-Waldau, M. Kondo, C. Konseibo, V. Meleshko, W. Stein, Y. Tamaura, H. Xu, R. Zilles, 2011: Direct Solar Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Table of Contents

Executive Summary

Solar energy is abundant and offers significant potential for near-term (2020) and long-term (2050) climate change mitigation. There are a wide variety of solar technologies of varying maturities that can, in most regions of the world, contribute to a suite of energy services. Even though solar energy generation still only represents a small fraction of total energy consumption, markets for solar technologies are growing rapidly. Much of the desirability of solar technology is its inherently smaller environmental burden and the opportunity it offers for positive social impacts. The cost of solar technologies has been reduced significantly over the past 30 years and technical advances and supportive public policies continue to offer the potential for additional cost reductions. Potential deployment scenarios range widely—from a marginal role of direct solar energy in 2050 to one of the major sources of energy supply. The actual deployment achieved will depend on the degree of continued innovation, cost reductions and supportive public policies.

Solar energy is the most abundant of all energy resources. Indeed, the rate at which solar energy is intercepted by the Earth is about 10,000 times greater than the rate at which humankind consumes energy. Although not all countries are equally endowed with solar energy, a significant contribution to the energy mix from direct solar energy is possible for almost every country. Currently, there is no evidence indicating a substantial impact of climate change on regional solar resources.

Solar energy conversion consists of a large family of different technologies capable of meeting a variety of energy service needs. Solar technologies can deliver heat, cooling, natural lighting, electricity, and fuels for a host of applications. Conversion of solar energy to *heat* (i.e., thermal conversion) is comparatively straightforward, because any material object placed in the sun will absorb thermal energy. However, maximizing that absorbed energy and stopping it from escaping to the surroundings can take specialized techniques and devices such as evacuated spaces, optical coatings and mirrors. Which technique is used depends on the application and temperature at which the heat is to be delivered. This can range from 25°C (e.g., for swimming pool heating) to 1,000°C (e.g., for dish/Stirling concentrating solar power), and even up to 3,000°C in solar furnaces.

Passive solar heating is a technique for maintaining comfortable conditions in buildings by exploiting the solar irradiance incident on the buildings through the use of glazing (windows, sun spaces, conservatories) and other transparent materials and managing heat gain and loss in the structure without the dominant use of pumps or fans. Solar *cooling* for buildings can also be achieved, for example, by using solar-derived heat to drive thermodynamic refrigeration absorption or adsorption cycles. Solar energy for lighting actually requires no conversion since solar lighting occurs naturally in buildings through windows. However, maximizing the effect requires specialized engineering and architectural design.

Generation of *electricity* can be achieved in two ways. In the first, solar energy is converted directly into electricity in a device called a photovoltaic (PV) cell. In the second, solar thermal energy is used in a concentrating solar power (CSP) plant to produce high-temperature heat, which is then converted to electricity via a heat engine and generator. Both approaches are currently in use. Furthermore, solar driven systems can deliver process heat and cooling, and other solar technologies are being developed that will deliver energy carriers such as hydrogen or hydrocarbon fuels—known as *solar fuels*.

The various solar technologies have differing maturities, and their applicability depends on local conditions and government policies to support their adoption. Some technologies are already competitive with market prices in certain locations, and in general, the overall viability of solar technologies is improving. Solar thermal can be used for a wide variety of applications, such as for domestic hot water, comfort heating of buildings, and industrial process heat. This is significant, as many countries spend up to one-third of their annual energy usage for heat. Service hot water heating for domestic and commercial buildings is now a mature technology growing at a rate of about 16% per year and employed in most countries of the world. The world installed capacity of solar thermal systems at the end of 2009 has been estimated to be 180 GW_{th}.

Passive solar and daylighting are conserving energy in buildings at a highly significant rate, but the actual amount is difficult to quantify. Well-designed passive solar systems decrease the need for additional comfort heating requirements by about 15% for existing buildings and about 40% for new buildings.

The generation of electricity using PV panels is also a worldwide phenomenon. Assisted by supportive pricing policies, the compound annual growth rate for PV production from 2003 to 2009 was more than 50%—making it one of the fastest-growing energy technologies in percentage terms. As of the end of 2009, the installed capacity for PV power production was about 22 GW. Estimates for 2010 give a consensus value of about 13 GW of newly added capacity. Most of those installations are roof-mounted and grid-connected. The production of electricity from CSP installations has seen a large increase in planned capacity in the last few years, with several countries beginning to experience significant new installations.

Integration of solar energy into broader energy systems involves both challenges and opportunities. Energy provided by PV panels and solar domestic water heaters can be especially valuable because the energy production often occurs at times of peak loads on the grid, as in cases where there is a large summer daytime load associated with air conditioning. PV and solar domestic water heaters also fit well with the needs of many countries because they are modular, quick to install, and can sometimes delay the need for costly construction or expansion of the transmission grid. At the same time, solar energy typically has a variable production profile with some degree of unpredictability that must be managed, and central-station solar electricity plants may require new transmission infrastructure. Because CSP can be readily coupled with thermal storage, the production profile can be controlled to limit production variability and enable dispatch capability.

Solar technologies offer opportunities for positive social impacts, and their environmental burden is small. Solar technologies have low lifecycle greenhouse gas emissions, and quantification of external costs has yielded favourable values compared to fossil fuel-based energy. Potential areas of concern include recycling and use of toxic materials in manufacturing for PV, water usage for CSP, and energy payback and land requirements for both. An important social benefit of solar technologies is their potential to improve the health and livelihood opportunities for many of the world's poorest populations—addressing some of the gap in availability of modern energy services for the roughly 1.4 billion people who do not have access to electricity and the 2.7 billion people who rely on traditional biomass for home cooking and heating needs. On the downside, some solar projects have faced public concerns regarding land requirements for centralized CSP and PV plants, perceptions regarding visual impacts, and for CSP, cooling water requirements. Land use impacts can be minimized by selecting areas with low population density and low environmental sensitivity. Similarly, water usage for CSP could be significantly reduced by using dry cooling approaches. Studies to date suggest that none of these issues presents a barrier against the widespread use of solar technologies.

Over the last 30 years, solar technologies have seen very substantial cost reductions. The current levelized costs of energy (electricity and heat) from solar technologies vary widely depending on the upfront technology cost, available solar irradiation as well as the applied discount rates. The levelized costs for solar thermal energy at a 7% discount rate range between less than USD_{2005} 10 and slightly more than USD_{2005} 20/GJ for solar hot water generation with a high degree of utilization in China to more than USD_{2005} 130/GJ for space heating applications in Organisation for Economic Co-operation and Development (OECD) countries with relative low irradiation levels of 800 kWh/m^2/yr. Electricity generation costs for utility-scale PV in regions of high solar irradiance in Europe and the USA are in the range of approximately 15 to 40 US cents_{2005} /kWh at a 7% discount rate, but may be lower or higher depending on the available resource and on other framework conditions. Current cost data are limited for CSP and are highly dependent on other system factors such as storage. In 2009, the levelized costs of energy for large solar troughs with six hours of thermal storage ranged from below 20 to approximately 30 US cents_{2005} /kWh. Technological improvements and cost reductions are expected, but the learning curves and subsequent cost reductions of solar technologies depend on production volume, research and development (R&D), and other factors such as access to capital, and not on the mere passage of time. Private capital is flowing into all the technologies, but government support and stable political conditions can lessen the risk of private investment and help ensure faster deployment.

Potential deployment scenarios for solar energy range widely—from a marginal role of direct solar energy in 2050 to one of the major sources of global energy supply. Although it is true that direct solar energy provides only a very small fraction of global energy supply today, it has the largest technical potential of all energy sources. In concert with technical improvements and resulting cost reductions, it could see dramatically expanded use in the decades to come. Achieving continued cost reductions is the central challenge that will influence the future deployment of solar energy. Moreover, as with some other forms of renewable energy, issues of variable production profiles and energy market integration as well as the possible need for new transmission infrastructure will influence the magnitude, type and cost of solar energy deployment. Finally, the regulatory and legal framework in place can also foster or hinder the uptake of direct solar energy applications.

3.1 Introduction

The aim of this chapter is to provide a synopsis of the state-of-the-art and possible future scenarios of the full realization of direct solar energy's potential for mitigating climate change. It establishes the resource base, describes the many and varied technologies, appraises current market development, outlines some methods for integrating solar into other energy systems, addresses its environmental and social impacts, and finally, evaluates the prospects for future deployment.

Some of the solar energy absorbed by the Earth appears later in the form of wind, wave, ocean thermal, hydropower and excess biomass energies. The scope of this chapter, however, does not include these other indirect forms. Rather, it deals with the *direct* use of solar energy.

Various books have been written on the history of solar technology (e.g., Butti and Perlin, 1980). This history began when early civilizations discovered that buildings with openings facing the Sun were warmer and brighter, even in cold weather. During the late 1800s, solar collectors for heating water and other fluids were invented and put into practical use for domestic water heating and solar industrial applications, for example, large-scale solar desalination. Later, mirrors were used (e.g., by Augustin Mouchot in 1875) to boost the available fluid temperature, so that heat engines driven by the Sun could develop motive power, and thence, electrical power. Also, the late 1800s brought the discovery of a device for converting sunlight directly into electricity. Called the photovoltaic (PV) cell, this device bypassed the need for a heat engine. The modern silicon solar cell, attributed to Russell Ohl working at American Telephone and Telegraph's (AT&T) Bell Labs, was discovered around 1940.

The modern age of solar research began in the 1950s with the establishment of the International Solar Energy Society (ISES) and increased research and development (R&D) efforts in many industries. For example, advances in the solar hot water heater by companies such as Miromit in Israel and the efforts of Harry Tabor at the National Physical Laboratory in Jerusalem helped to make solar energy the standard method for providing hot water for homes in Israel by the early 1960s. At about the same time, national and international networks of solar irradiance measurements were beginning to be established. With the oil crisis of the 1970s, most countries in the world developed programs for solar energy R&D, and this involved efforts in industry, government labs and universities. These policy support efforts, which have, for the most part, continued up to the present, have borne fruit: now one of the fastest-growing renewable energy (RE) technologies, solar energy is poised to play a much larger role on the world energy stage.

Solar energy is an abundant energy resource. Indeed, in just one hour, the solar energy intercepted by the Earth exceeds the world's energy consumption for the entire year. Solar energy's potential to mitigate climate change is equally impressive. Except for the modest amount of carbon dioxide (CO_2) emissions produced in the manufacture of conversion devices (see Section 3.6.1) the direct use of solar energy produces very little greenhouse gases, and it has the potential to displace large quantities of non-renewable fuels (Tsilingiridis et al., 2004).

Solar energy conversion is manifest in a family of technologies having a broad range of energy service applications: lighting, comfort heating, hot water for buildings and industry, high-temperature solar heat for electric power and industry, photovoltaic conversion for electrical power, and production of solar fuels, for example, hydrogen or synthesis gas (syngas). This chapter will further detail all of these technologies.

Several solar technologies, such as domestic hot water heating and pool heating, are already competitive and used in locales where they offer the least-cost option. And in jurisdictions where governments have taken steps to actively support solar energy, very large solar electricity (both PV and CSP) installations, approaching 100 MW of power, have been realized, in addition to large numbers of rooftop PV installations. Other applications, such as solar fuels, require additional R&D before achieving significant levels of adoption.

In pursuing any of the solar technologies, there is the need to deal with the variability and the cyclic nature of the Sun. One option is to store excess collected energy until it is needed. This is particularly effective for handling the lack of sunshine at night. For example, a 0.1-m thick slab of concrete in the floor of a home will store much of the solar energy absorbed during the day and release it to the room at night. When totalled over a long period of time such as one year, or over a large geographical area such as a continent, solar energy can offer greater service. The use of both these concepts of time and space, together with energy storage, has enabled designers to produce more effective solar systems. But much more work is needed to capture the full value of solar energy's contribution.

Because of its inherent variability, solar energy is most useful when integrated with another energy source, to be used when solar energy is not available. In the past, that source has generally been a non-renewable one. But there is great potential for integrating direct solar energy with other RE technologies.

The rest of this chapter will include the following topics. Section 3.2 summarizes research that characterizes this solar resource and discusses the global and regional technical potential for direct solar energy as well as the possible impacts of climate change on this resource. Section 3.3 describes the five different technologies and their applications: passive solar heating and lighting for buildings (Section 3.3.1), active solar heating and cooling for buildings and industry (Section 3.3.2), PV electricity generation (Section 3.3.3), CSP electricity generation (Section 3.3.4), and solar fuel production (Section 3.3.5). Section 3.4 reviews the current status of market development, including installed capacity and energy currently being generated (Section 3.4.1), and the industry capacity and supply chain (Section 3.4.2). Following this are sections on the integration of solar technologies into other energy systems (Section 3.5), the environmental and social impacts (Section 3.6), and the prospects for future technology innovations (Section 3.7). The two final sections cover cost trends (Section 3.8) and the policies needed to achieve the goals for deployment (Section 3.9). Many of the sections, such as Section 3.3, are segmented into subsections, one for each of the five solar technologies.

3.2 Resource potential

The solar resource is virtually inexhaustible, and it is available and able to be used in all countries and regions of the world. But to plan and design appropriate energy conversion systems, solar energy technologists must know how much irradiation will fall on their collectors.

Iqbal (1984), among others, has described the character of solar irradiance, which is the electromagnetic radiation emitted by the Sun. Outside the Earth's atmosphere, the solar irradiance on a surface perpendicular to the Sun's rays at the mean Earth-Sun distance is practically constant throughout the year. Its value is now accepted to be 1,367 W/m^2 (Bailey et al., 1997). With a clear sky on Earth, this figure becomes roughly 1,000 W/m^2 at the Earth's surface. These rays are actually electromagnetic waves—travelling fluctuations in electric and magnetic fields. With the Sun's surface temperature being close to 5800 Kelvin, solar irradiance is spread over wavelengths ranging from 0.25 to 3 µm. About 40% of solar irradiance is visible light, while another 10% is ultraviolet radiation, and 50% is infrared radiation. However, at the Earth's surface, evaluation of the solar irradiance is more difficult because of its interaction with the atmosphere, which contains clouds, aerosols, water vapour and trace gases that vary both geographically and temporally. Atmospheric conditions typically reduce the solar irradiance by roughly 35% on clear, dry days and by about 90% on days with thick clouds, leading to lower average solar irradiance. On average, solar irradiance on the ground is 198 W/m^2 (Solomon et al., 2007), based on ground surface area (Le Treut et al., 2007).

The solar irradiance reaching the Earth's surface (Figure 3.1) is divided into two primary components: beam solar irradiance on a horizontal surface, which comes directly from the Sun's disk, and diffuse irradiance, which comes from the whole of the sky except the Sun's disk. The term 'global solar irradiance' refers to the sum of the beam and the diffuse components.

There are several ways to assess the global resource potential of solar energy. The *theoretical* potential, which indicates the amount of irradiance at the Earth's surface (land and ocean) that is theoretically available for energy purposes, has been estimated at 3.9×10^6 EJ/yr (Rogner et al., 2000; their Table 5.18). *Technical potential* is the amount of solar irradiance output obtainable by full deployment of demonstrated and likely-to-develop technologies or practices (see Annex I, Glossary).

3.2.1 Global technical potential

The amount of solar energy that could be put to human use depends significantly on local factors such as land availability and meteorological conditions and demands for energy services. The technical potential varies over the different regions of the Earth, as do the assessment methodologies. As described in a comparative literature study (Krewitt et al., 2009) for the German Environment Agency, the solar electricity technical potential of PV and CSP depends on the available solar irradiance, land use exclusion factors and the future development of technology improvements. Note that this study used different assumptions for the land use factors for PV and CSP. For PV, it assumed that 98% of the technical potential comes from centralized PV power plants and that the suitable land area in the world for PV deployment averages 1.67% of total land area. For CSP, all land areas with high direct-normal irradiance (DNI)—a minimum DNI of 2,000 kWh/m^2/yr (7,200 MJ/m^2/yr)—were defined as suitable, and just 20% of that land was excluded for other uses. The

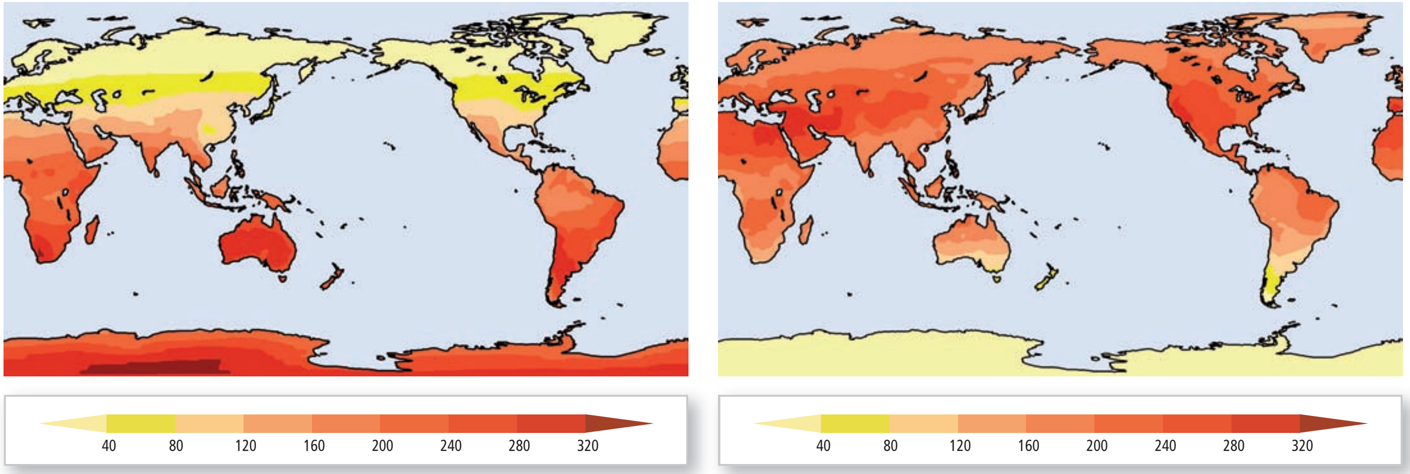


Figure 3.1 | The global solar irradiance (W/m^2) at the Earth's surface obtained from satellite imaging radiometers and averaged over the period 1983 to 2006. Left panel: December, January, February. Right panel: June, July, August (ISCCP Data Products, 2006).

resulting technical potentials for 2050 are 1,689 EJ/yr for PV and 8,043 EJ/yr for CSP.

Analyzing the PV studies (Hofman et al., 2002; Hoogwijk, 2004; de Vries et al., 2007) and the CSP studies (Hofman et al., 2002; Trieb, 2005; Trieb et al., 2009a) assessed by Krewitt et al. (2009), the technical potential varies significantly between these studies, ranging from 1,338 to 14,778 EJ/yr for PV and 248 and 10,791 EJ/yr for CSP. The main difference between the studies arises from the allocated land area availabilities and, to some extent, on differences in the power conversion efficiency used.

The technical potential of solar energy for heating purposes is vast and difficult to assess. The deployment potential is mainly limited by the demand for heat. Because of this, the technical potential is not assessed in the literature except for REN21 (Hoogwijk and Graus, 2008) to which Krewitt et al. (2009) refer. In order to provide a reference, REN21 has made a rough assessment of the technical potential of solar water heating by taking the assumed available rooftop area for solar PV applications from Hoogwijk (2004) and the irradiation for each of the regions. Therefore, the range given by REN21 is a lower bound only.

3.2.2 Regional technical potential

Table 3.1 shows the minimum and maximum estimated range for total solar energy technical potential for different regions, not differentiating the ways in which solar irradiance might be converted to secondary energy forms. For the minimum estimates, minimum annual clear-sky irradiance, sky clearance and available land used for installation of solar collectors are assumed. For the maximum estimates, maximum annual clear-sky irradiance and sky clearance are adopted with an assumption of maximum available land used. As Table 3.1 also indicates, the worldwide solar energy technical potential is considerably larger than the current primary energy consumption.

3.2.3 Sources of solar irradiance data

The calculation and optimization of the energy output and economical feasibility of solar energy systems such as buildings and power plants requires detailed solar irradiance data measured at the site of the solar installation. Therefore, it is essential to know the overall global solar energy available, as well as the relative magnitude of its two primary components: direct-beam irradiation and diffuse irradiation from the sky including clouds. Additionally, sometimes it is necessary to account for irradiation received by reflection from the ground and other surfaces. The details on how solar irradiance is measured and calculated can be found in the *Guide to Meteorological Instruments and Methods of Observation* (WMO, 2008). Also important are the patterns of seasonal availability, variability of irradiation, and daytime temperature onsite. Due to significant interannual variability of regional climate conditions in different parts of the world, such measurements must be generated over several years for many applications to provide sufficient statistical validity.

In regions with a high density of well-maintained ground measurements of solar irradiance, sophisticated gridding of these measurements can be expected to provide accurate information about the local solar irradiance. However, many parts of the world have inadequate ground-based sites (e.g., central Asia, northern Africa, Mexico, Brazil, central South America). In these regions, satellite-based irradiance measurements are

Table 3.1 | Annual total technical potential of solar energy for various regions of the world, not differentiated by conversion technology (Rogner et al., 2000; their Table 5.19).

REGIONS	Range of Estimates	
	Minimum, EJ	Maximum, EJ
North America	181	7,410
Latin America and Caribbean	113	3,385
Western Europe	25	914
Central and Eastern Europe	4	154
Former Soviet Union	199	8,655
Middle East and North Africa	412	11,060
Sub-Saharan Africa	372	9,528
Pacific Asia	41	994
South Asia	39	1,339
Centrally planned Asia	116	4,135
Pacific OECD	73	2,263
TOTAL	**1,575**	**49,837**
Ratio of technical potential to primary energy supply in 2008 (492 EJ)	*3.2*	*101*

Note: Basic assumptions used in assessing minimum and maximum technical potentials of solar energy are given in Rogner et al. (2000):

- Annual minimum clear-sky irradiance relates to horizontal collector plane, and annual maximum clear-sky irradiance relates to two-axis-tracking collector plane; see Table 2.2 in WEC (1994).
- Maximum and minimum annual sky clearance assumed for the relevant latitudes; see Table 2.2 in WEC (1994).

the primary source of information, but their accuracy is inherently lower than that of a well-maintained and calibrated ground measurement. Therefore, satellite radiation products require validation with accurate ground-based measurements (e.g., the Baseline Surface Radiation Network). Presently, the solar irradiance at the Earth's surface is estimated with an accuracy of about 15 W/m^2 on a regional scale (ISCCP Data Products, 2006). The Satellite Application Facility on Climate Monitoring project, under the leadership of the German Meteorological Service and in partnership with the Finnish, Belgian, Dutch, Swedish and Swiss National Meteorological Services, has developed methodologies for irradiance data from satellite measurements.

Various international and national institutions provide information on the solar resource, including the World Radiation Data Centre (Russia), the National Renewable Energy Laboratory (USA), the National Aeronautics and Space Administration (NASA, USA), the Brasilian Spatial Institute (Brazil), the German Aerospace Center (Germany), the Bureau of Meteorology Research Centre (Australia), and the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Spain), National Meteorological Services, and certain commercial companies. Table 3.2 gives references to some international and national projects that are collecting, processing and archiving information on solar irradiance resources at the Earth's surface and subsequently distributing it in easily accessible formats with understandable quality metrics.

3.2.4 Possible impact of climate change on resource potential

Climate change due to an increase of greenhouse gases (GHGs) in the atmosphere may influence atmospheric water vapour content, cloud cover, rainfall and turbidity, and this can impact the resource potential of solar energy in different regions of the globe. Changes in major climate variables, including cloud cover and solar irradiance at the Earth's surface, have been evaluated using climate models and considering anthropogenic forcing for the 21st century (Meehl et al., 2007; Meleshko et al., 2008). These studies found that the pattern of variation of monthly mean global solar irradiance does not exceed 1% over some regions of the globe, and it varies from model to model. Currently, there is no other evidence indicating a substantial impact of global warming on regional solar resources. Although some research on global dimming and global brightening indicates a probable impact on irradiance, no current evidence is available. Uncertainty in pattern changes seems to be rather large, even for large-scale areas of the Earth.

3.3 Technology and applications

This section discusses technical issues for a range of solar technologies, organized under the following categories: passive solar and daylighting,

Table 3.2 | International and national projects that collect, process and archive information on solar irradiance resources at the Earth's surface.

Available Data Sets	Responsible Institution/Agency
Ground-based solar irradiance from 1,280 sites for 1964 to 2009 provided by national meteorological services around the world.	World Radiation Data Centre, Saint Petersburg, Russian Federation (wrdc.mgo.rssi.ru)
National Solar Radiation Database that includes 1,454 ground locations for 1991 to 2005. The satellite-modelled solar data for 1998 to 2005 provided on 10-km grid. The hourly values of solar data can be used to determine solar resources for collectors.	National Renewable Energy Laboratory, USA (www.nrel.gov)
European Solar Radiation Database that includes measured solar radiation complemented with other meteorological data necessary for solar engineering. Satellite images from METEOSAT help in improving accuracy in spatial interpolation. Test Reference Years were also included.	Supported by Commission of the European Communities, National Weather Services and scientific institutions of the European countries
The Solar Radiation Atlas of Africa contains information on surface radiation over Europe, Asia Minor and Africa. Data covering 1985 to 1986 were derived from measurements by METEOSAT 2.	Supported by the Commission of the European Communities
The solar data set for Africa based on images from METEOSAT processed with the Heliosat-2 method covers the period 1985 to 2004 and is supplemented with ground-based solar irradiance.	Ecole des Mines de Paris, France
Typical Meteorological Year (Test Reference Year) data sets of hourly values of solar radiation and meteorological parameters derived from individual weather observations in long-term (up to 30 years) data sets to establish a typical year of hourly data. Used by designers of heating and cooling systems and large-scale solar thermal power plants.	National Renewable Energy Laboratory, USA. National Climatic Data Center, National Oceanic and Atmospheric Administration, USA. (www.ncdc.noaa.gov)
The solar radiation data for solar energy applications. IEA/SHC Task36 provides a wide range of users with information on solar radiation resources at Earth's surface in easily accessible formats with understandable quality metrics. The task focuses on development, validation and access to solar resource information derived from surface- and satellite-based platforms.	International Energy Agency (IEA) Solar Heating and Cooling Programme (SHC). (swera.unep.net)
Solar and Wind Energy Resource Assessment (SWERA) project aimed at developing information tools to simulate RE development. SWERA provides easy access to high-quality RE resource information and data for users. Covered major areas of 13 developing countries in Latin America, the Caribbean, Africa and Asia. SWERA produced a range of solar data sets and maps at better spatial scales of resolution than previously available using satellite- and ground-based observations.	Global Environment Facility-sponsored project. United Nations Environment Programme (swera.unep.net)

active heating and cooling, PV electricity generation, CSP electricity generation and solar fuel production. Each section also describes applications of these technologies.

3.3.1 Passive solar and daylighting technologies

Passive solar energy technologies absorb solar energy, store and distribute it in a natural manner (e.g., natural ventilation), without using mechanical elements (e.g., fans) (Hernandez Gonzalvez, 1996). The term 'passive solar building' is a qualitative term describing a building that makes significant use of solar gain to reduce heating energy consumption based on the natural energy flows of radiation, conduction and convection. The term 'passive building' is often employed to emphasize use of passive energy flows in both heating and cooling, including redistribution of absorbed direct solar gains and night cooling (Athienitis and Santamouris, 2002).

Daylighting technologies are primarily passive, including windows, skylights and shading and reflecting devices. A worldwide trend, particularly in technologically advanced regions, is for an increased mix of passive and active systems, such as a forced-air system that redistributes passive solar gains in a solar house or automatically controlled shades that optimize daylight utilization in an office building (Tzempelikos et al., 2010).

The basic elements of passive solar design are windows, conservatories and other glazed spaces (for solar gain and daylighting), thermal mass, protection elements, and reflectors (Ralegaonkar and Gupta, 2010). With the combination of these basic elements, different systems are obtained: direct-gain systems (e.g., the use of windows in combination with walls able to store energy, solar chimneys, and wind catchers), indirect-gain systems (e.g., Trombe walls), mixed-gain systems (a combination of direct-gain and indirect-gain systems, such as conservatories, sunspaces and greenhouses), and isolated-gain systems. Passive technologies are integrated with the building and may include the following components:

- Windows with high solar transmittance and a high thermal resistance facing towards the Equator as nearly as possible can be employed to maximize the amount of direct solar gains into the living space while reducing heat losses through the windows in the heating season and heat gains in the cooling season. Skylights are also often used for daylighting in office buildings and in solaria/sunspaces.

- Building-integrated thermal storage, commonly referred to as thermal mass, may be sensible thermal storage using concrete or brick materials, or latent thermal storage using phase-change materials (Mehling and Cabeza, 2008). The most common type of thermal storage is the direct-gain system in which thermal mass is adequately distributed in the living space, absorbing the direct solar gains. Storage is particularly important because it performs two essential functions: storing much of the absorbed direct solar energy for slow release, and maintaining satisfactory thermal comfort conditions by limiting the maximum rise in operative (effective) room temperature (ASHRAE, 2009). Alternatively, a collector-storage wall, known as a Trombe wall, may be used, in which the thermal mass is placed directly next to the glazing, with possible air circulation between the cavity of the wall system and the room. However, this system has not gained much acceptance because it limits views to the outdoor environment through the fenestration. Hybrid thermal storage with active charging and passive heat release can also be employed in part of a solar building while direct-gain mass is also used (see, e.g., the EcoTerra demonstration house (Figure 3.2, left panel), which uses solar-heated air from a building-integrated photovoltaic/thermal system to heat a ventilated concrete slab). Isolated thermal storage passively coupled to a fenestration system or solarium/sunspace is another option in passive design.

- Well-insulated opaque envelope appropriate for the climatic conditions can be used to reduce heat transfer to and from the outdoor environment. In most climates, this energy efficiency aspect must be integrated with the passive design. A solar technology that may be used with opaque envelopes is transparent insulation (Hollands et al., 2001) combined with thermal mass to store solar gains in a wall, turning it into an energy-positive element.

- Daylighting technologies and advanced solar control systems, such as automatically controlled shading (internal, external) and fixed shading devices, are particularly suited for daylighting applications in the workplace (Figure 3.2, right panel). These technologies include electrochromic and thermochromic coatings and newer technologies such as transparent photovoltaics, which, in addition to a passive daylight transmission function, also generate electricity. Daylighting is a combination of energy conservation and passive solar design. It aims to make the most of the natural daylight that is available. Traditional techniques include: shallow-plan design, allowing daylight to penetrate all rooms and corridors; light wells in the centre of buildings; roof lights; tall windows, which allow light to penetrate deep inside rooms; task lighting directly over the workplace, rather than lighting the whole building interior; and deep windows that reveal and light room surfaces to cut the risk of glare (Everett, 1996).

- Solariums, also called sunspaces, are a particular case of the direct-gain passive solar system, but with most surfaces transparent, that is, made up of fenestration. Solariums are becoming increasingly attractive both as a retrofit option for existing houses and as an integral part of new buildings (Athienitis and Santamouris, 2002). The major driving force for this growth is the development of new advanced energy-efficient glazing.

Some basic rules for optimizing the use of passive solar heating in buildings are the following: buildings should be well insulated to reduce overall heat losses; they should have a responsive, efficient heating system; they should face towards the Equator, that is, the glazing should

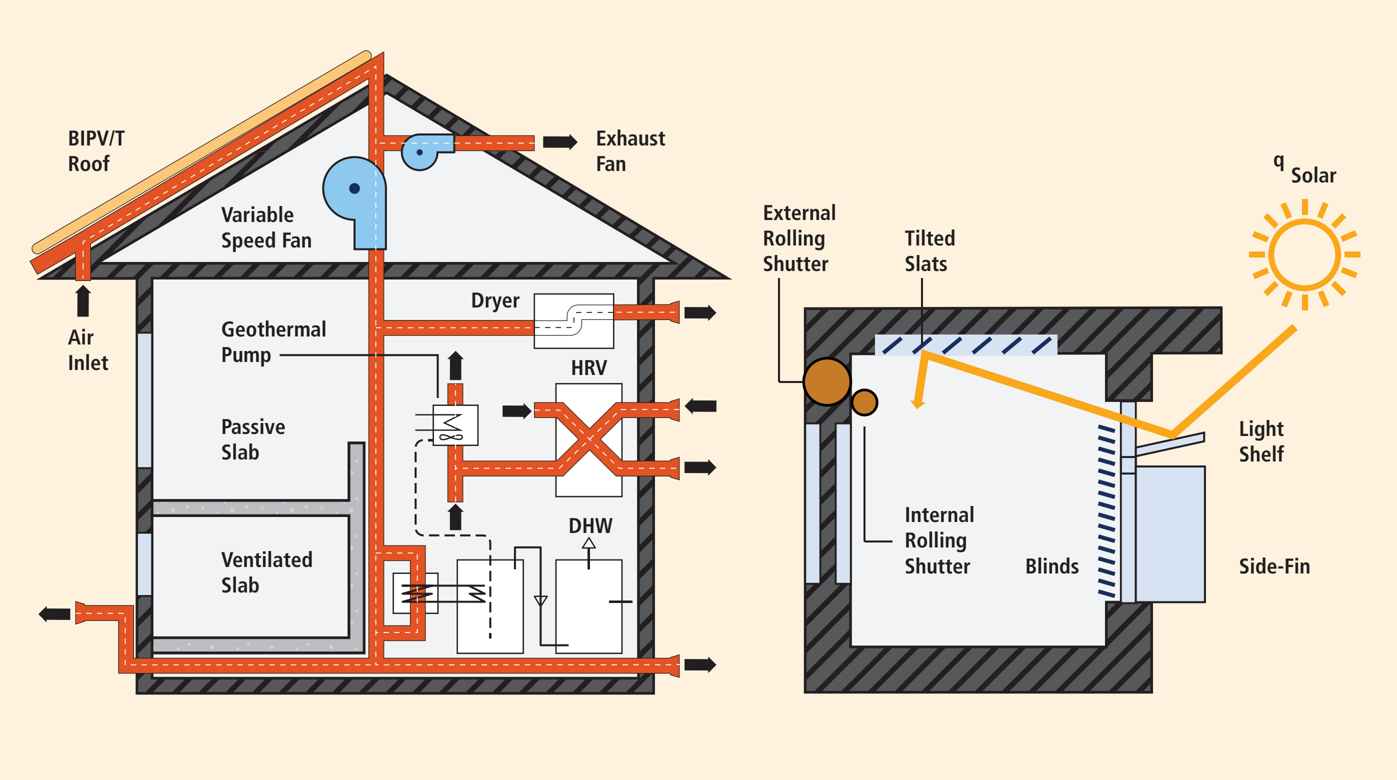


Figure 3.2 | Left: Schematic of thermal mass placement and passive-active systems in a house; solar-heated air from building-integrated photovoltaic/thermal (BIPV/T) roof heats ventilated slab or domestic hot water (DHW) through heat exchanger; HRV is heat recovery ventilator. Right: Schematic of several daylighting concepts designed to redistribute daylight into the office interior space (Athienitis, 2008).

be concentrated on the equatorial side, as should the main living rooms, with rooms such as bathrooms on the opposite side; they should avoid shading by other buildings to benefit from the essential mid-winter sun; and they should be 'thermally massive' to avoid overheating in the summer and on certain sunny days in winter (Everett, 1996).

Clearly, passive technologies cannot be separated from the building itself. Thus, when estimating the contribution of passive solar gains, the following must be distinguished: 1) buildings specifically designed to harness direct solar gains using passive systems, defined here as solar buildings, and 2) buildings that harness solar gains through near-equatorial facing windows; this orientation is more by chance than by design. Few reliable statistics are available on the adoption of passive design in residential buildings. Furthermore, the contribution of passive solar gains is missing in existing national statistics. Passive solar is reducing the demand and is not part of the supply chain, which is what is considered by the energy statistics.

The passive solar design process itself is in a period of rapid change, driven by the new technologies becoming affordable, such as the recently available highly efficient fenestration at the same prices as ordinary glazing. For example, in Canada, double-glazed low-emissivity argon-filled windows are presently the main glazing technology used; but until a few years ago, this glazing was about 20 to 40% more expensive than regular double glazing. These windows are now being used in retrofits of existing homes as well. Many homes also add a solarium during retrofit. The new glazing technologies and solar control systems allow the design of a larger window area than in the recent past.

In most climates, unless effective solar gain control is employed, there may be a need to cool the space during the summer. However, the need for mechanical cooling may often be eliminated by designing for passive cooling. Passive cooling techniques are based on the use of heat and solar protection techniques, heat storage in thermal mass and heat dissipation techniques. The specific contribution of passive solar and energy conservation techniques depends strongly on the climate (UNEP, 2007). Solar-gain control is particularly important during the 'shoulder' seasons when some heating may be required. In adopting larger window areas—enabled by their high thermal resistance—active solar-gain control becomes important in solar buildings for both thermal and visual considerations.

The potential of passive solar cooling in reducing CO_2 emissions has been shown recently (Cabeza et al., 2010; Castell et al., 2010). Experimental work demonstrates that adequate insulation can reduce by up to 50% the cooling energy demand of a building during the hot season. Moreover, including phase-change materials in the already-insulated building envelope can reduce the cooling energy demand in such buildings further by up to 15%—about 1 to 1.5 kg/yr/m^2 of CO_2 emissions would be saved in these buildings due to reducing the energy consumption compared to the insulated building without phase-change material.

Passive solar system applications are mainly of the direct-gain type, but they can be further subdivided into the following main application categories: multi-story residential buildings and two-story detached or semi-detached solar homes (see Figure 3.2, left panel), designed to have a large equatorial-facing façade to provide the potential for a large solar capture area (Athienitis, 2008). Perimeter zones and their fenestration systems in office buildings are designed primarily based on daylighting performance. In this application, the emphasis is usually on reducing cooling loads, but passive heat gains may be desirable as well during the heating season (see Figure 3.2, right panel, for a schematic of shading devices).

In addition, residential or commercial buildings may be designed to use natural or hybrid ventilation systems and techniques for cooling or fresh air supply, in conjunction with designs for using daylight throughout the year and direct solar gains during the heating season. These buildings may profit from low summer night temperatures by using night hybrid ventilation techniques that utilize both mechanical and natural ventilation processes (Santamouris and Asimakopoulos, 1996; Voss et al., 2007).

In 2010, passive technologies played a prominent role in the design of net-zero-energy solar homes—homes that produce as much electrical and thermal energy as they consume in an average year. These houses are primarily demonstration projects in several countries currently collaborating in the International Energy Agency (IEA) Task 40 of the Solar Heating and Cooling (SHC) Programme (IEA, 2009b)—Energy Conservation in Buildings and Community Systems Annex 52—which focuses on net-zero-energy solar buildings. Passive technologies are essential in developing affordable net-zero-energy homes. Passive solar gains in homes based on the Passive House Standard are expected to reduce the heating load by about 40%. By extension, systematic passive solar design of highly insulated buildings at a community scale, with optimal orientation and form of housing, should easily result in a similar energy saving of 40%. In Europe, according to the Energy Performance of Buildings Directive recast, Directive 2010/31/EC (The European Parliament and the Council of the European Union, 2010), all new buildings must be nearly zero-energy buildings by 31 December 2020, while EU member states should set intermediate targets for 2015. New buildings occupied and owned by public authorities have to be nearly zero-energy buildings after 31 December 2018. The nearly zero or very low amount of energy required should to a very significant level be covered by RE sources, including onsite energy production using combined heat and power generation or district heating and cooling, to satisfy most of their demand. Measures should also be taken to stimulate building refurbishments into nearly zero-energy buildings.

Low-energy buildings are known under different names. A survey carried out by Concerted Action Energy Performance of Buildings (EPBD) identified 17 different terms to describe such buildings across Europe, including: low-energy house, high-performance house, passive house ('Passivhaus'), zero-carbon house, zero-energy house, energy-savings house, energy-positive house and 3-litre house. Concepts that take into account more parameters than energy demand again use special terms such as eco-building or green building.

Another IEA Annex—Energy Conservation through Energy Storage Implementing Agreement (ECES IA) Annex 23—was initiated in November 2009 (IEA ECES, 2004). The general objective of the Annex is to ensure that energy storage techniques are properly applied in ultra-low-energy buildings and communities. The proper application of energy storage is expected to increase the likelihood of sustainable building technologies.

Another passive solar application is natural drying. Grains and many other agricultural products have to be dried before being stored so that insects and fungi do not render them unusable. Examples include wheat, rice, coffee, copra (coconut flesh), certain fruits and timber (Twidell and Weir, 2006). Solar energy dryers vary mainly as to the use of the solar heat and the arrangement of their major components. Solar dryers constructed from wood, metal and glass sheets have been evaluated extensively and used quite widely to dry a full range of tropical crops (Imre, 2007).

3.3.2 Active solar heating and cooling

Active solar heating and cooling technologies use the Sun and mechanical elements to provide either heating or cooling; various technologies are discussed here, as well as thermal storage.

3.3.2.1 Solar heating

In a solar heating system, the solar collector transforms solar irradiance into heat and uses a carrier fluid (e.g., water, air) to transfer that heat to a well-insulated storage tank, where it can be used when needed. The two most important factors in choosing the correct type of collector are the following: 1) the service to be provided by the solar collector, and 2) the related desired range of temperature of the heat-carrier fluid. An uncovered absorber, also known as an unglazed collector, is likely to be limited to low-temperature heat production (Duffie and Beckman, 2006).

A solar collector can incorporate many different materials and be manufactured using a variety of techniques. Its design is influenced by the system in which it will operate and by the climatic conditions of the installation location.

Flat-plate collectors are the most widely used solar thermal collectors for residential solar water- and space-heating systems. They are also used in air-heating systems. A typical flat-plate collector consists of an absorber, a header and riser tube arrangement or a single serpentine tube, a transparent cover, a frame and insulation (Figure 3.3a). For low-temperature applications, such as the heating of swimming pools, only a single plate is used as an absorber (Figure 3.3b). Flat-plate collectors demonstrate a good price/performance ratio, as well as a broad range of mounting possibilities (e.g., on the roof, in the roof itself, or unattached).

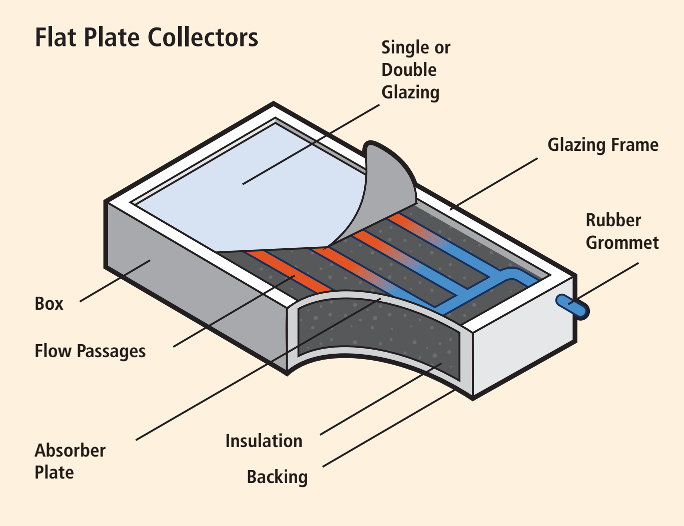


Figure 3.3a | Schematic diagram of thermal solar collectors: Glazed flat-plate.

Evacuated-tube collectors are usually made of parallel rows of transparent glass tubes, in which the absorbers are enclosed, connected to a header pipe (Figure 3.3c). To reduce heat loss within the frame by convection, the air is pumped out of the collector tubes to generate a vacuum. This makes it possible to achieve high temperatures, useful

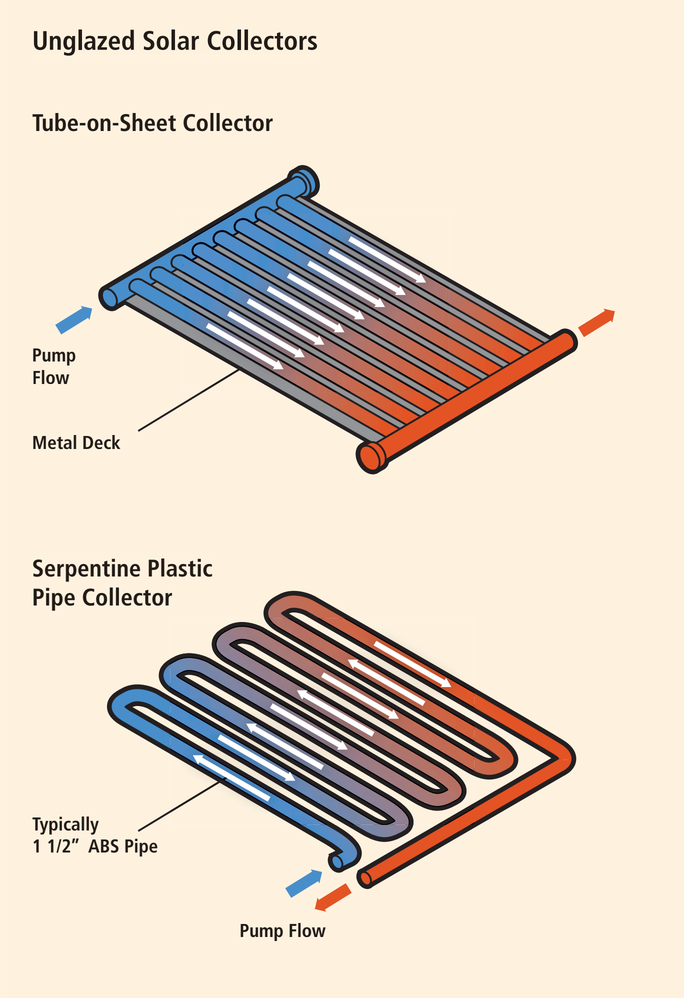


Figure 3.3b | Schematic diagram of thermal solar collectors: Unglazed tube-on-sheet and serpentine plastic pipe.

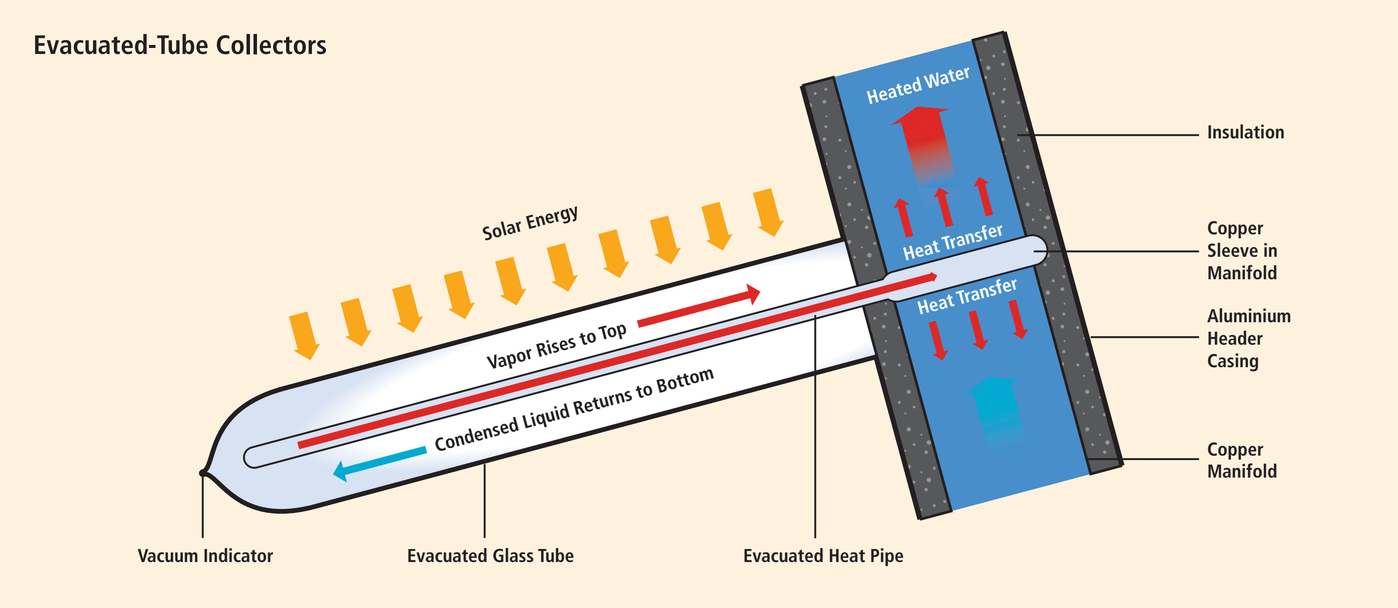


Figure 3.3c | Schematic diagram of thermal solar collectors: Evacuated-tube collectors.

for cooling (see below) or industrial applications. Most vacuum tube collectors use heat pipes for their core instead of passing liquid directly through them. Evacuated heat-pipe tubes are composed of multiple evacuated glass tubes, each containing an absorber plate fused to a heat pipe. The heat from the hot end of the heat pipes is transferred to the transfer fluid of a domestic hot water or hydronic space-heating system.

Solar water-heating systems used to produce hot water can be classified as passive or active solar water heaters (Duffie and Beckman, 2006). Also of interest are active solar cooling systems, which transform the hot water produced by solar energy into cold water.

Passive solar water heaters are of two types (Figure 3.4). Integral collector-storage (ICS) or 'batch' systems include black tanks or tubes in an insulated glazed box. Cold water is preheated as it passes through the solar collector, with the heated water flowing to a standard backup water heater. The heated water is stored inside the collector itself. In thermosyphon (TS) systems, a separate storage tank is directly above the collector. In direct (open-loop) TS systems, the heated water rises from the collector to the tank and cool water from the tank sinks back into the collector. In indirect (closed-loop) TS systems (Figure 3.4, left), heated fluid (usually a glycol-water mixture) rises from the collector to an outer tank that surrounds the water storage tank and acts as a heat exchanger (double-wall heat exchangers) for separation from potable water. In climates where freezing temperatures are unlikely, many collectors include an integrated storage tank at the top of the collector. This design has many cost and user-friendly advantages compared to a system that uses a separate standalone heat-exchanger tank. It is also appropriate in households with significant daytime and evening hot water needs; but it does not work well in households with predominantly morning draws because sometimes the tanks can lose most of the collected energy overnight.

Active solar water heaters rely on electric pumps and controllers to circulate the carrier fluid through the collectors. Three types of active solar water-heating systems are available. Direct circulation systems use pumps to circulate pressurized potable water directly through the collectors. These systems are appropriate in areas that do not freeze for long periods and do not have hard or acidic water. Antifreeze indirect-circulation systems pump heat-transfer fluid, which is usually a glycol-water mixture, through collectors. Heat exchangers transfer the heat from the fluid to the water for use (Figure 3.4, right). Drainback indirect-circulation systems use pumps to circulate water through the collectors. The water in the collector and the piping system drains into a reservoir tank when the pumps stop, eliminating the risk of freezing in cold climates. This system should be carefully designed and installed to ensure that the piping always slopes downward to the reservoir tank. Also, stratification should be carefully considered in the design of the water tank (Hadorn, 2005).

A *solar combisystem* provides both solar space heating and cooling as well as hot water from a common array of solar thermal collectors, usually backed up by an auxiliary non-solar heat source (Weiss, 2003). Solar combisystems may range in size from those installed in individual properties to those serving several in a block heating scheme. A large number of different types of solar combisystems are produced. The systems on the market in a particular country may be more restricted, however, because different systems have tended to evolve in different countries.

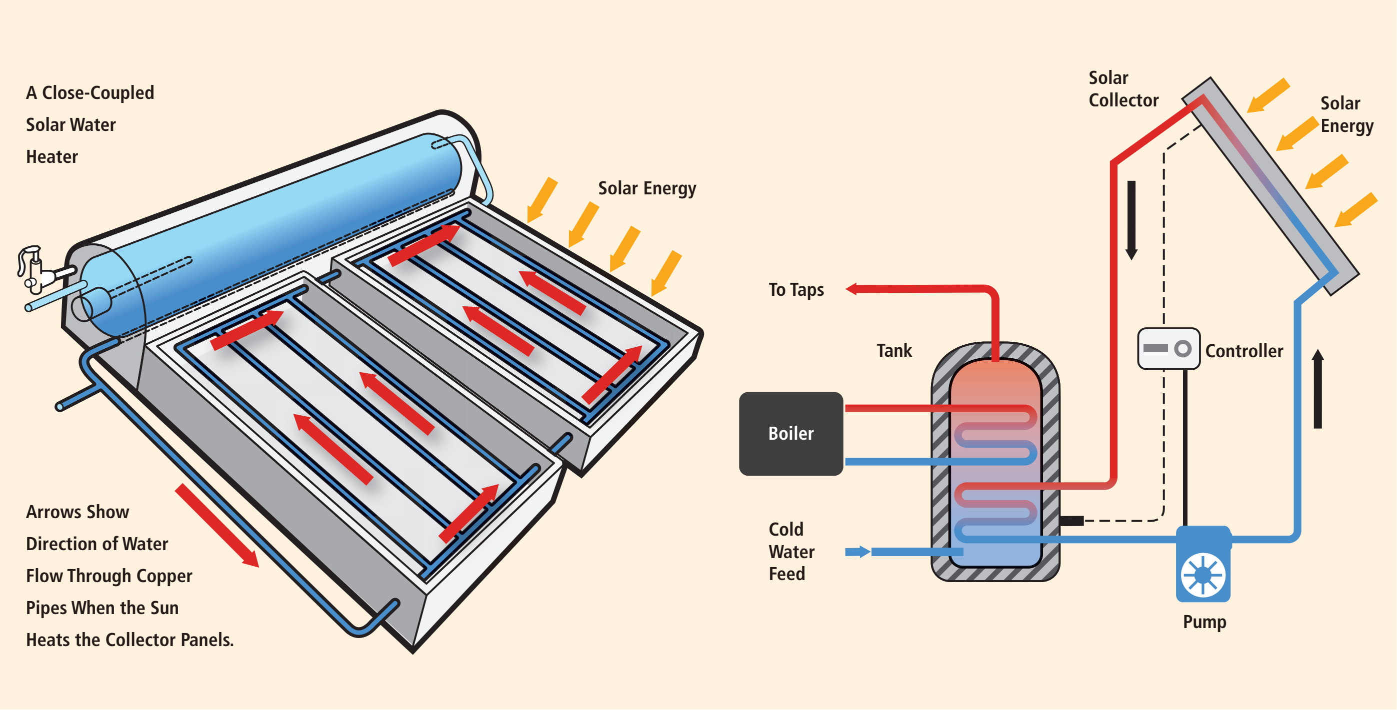


Figure 3.4 | Generic schematics of thermal solar systems. Left: Passive (thermosyphon). Right: Active system.

Depending on the size of the combisystem installed, the annual space heating contribution can range from 10 to 60% or more in ultra-low energy Passivhaus-type buildings, and even up to 100% where a large seasonal thermal store or concentrating solar thermal heat is used.

3.3.2.2 Solar cooling

Solar cooling can be broadly categorized into solar electric refrigeration, solar thermal refrigeration, and solar thermal air-conditioning. In the first category, the solar electric compression refrigeration uses PV panels to power a conventional refrigeration machine (Fong et al., 2010). In the second category, the refrigeration effect can be produced through solar thermal gain; solar mechanical compression refrigeration, solar absorption refrigeration, and solar adsorption refrigeration are the three common options. In the third category, the conditioned air can be directly provided through the solar thermal gain by means of desiccant cooling. Both solid and liquid sorbents are available, such as silica gel and lithium chloride, respectively.

Solar electrical air-conditioning, powered by PV panels, is of minor interest from a systems perspective, unless there is an off-grid application (Henning, 2007). This is because in industrialized countries, which have a well-developed electricity grid, the maximum use of photovoltaics is achieved by feeding the produced electricity into the public grid.

Solar thermal air-conditioning consists of solar heat powering an absorption chiller and it can be used in buildings (Henning, 2007). Deploying such a technology depends heavily on the industrial deployment of low-cost small-power absorption chillers. This technology is being studied within the IEA Task 25 on solar-assisted air-conditioning of buildings, SHC program and IEA Task 38 on solar air-conditioning and refrigeration, SHC program.

Closed heat-driven cooling systems using these cycles have been known for many years and are usually used for large capacities of 100 kW and greater. The physical principle used in most systems is based on the sorption phenomenon. Two technologies are established to produce thermally driven low- and medium-temperature refrigeration: absorption and adsorption.

Open cooling cycle (or desiccant cooling) systems are mainly of interest for the air conditioning of buildings. They can use solid or liquid sorption. The central component of any open solar-assisted cooling system is the dehumidification unit. In most systems using solid sorption, this unit is a desiccant wheel. Various sorption materials can be used, such as silica gel or lithium chloride. All other system components are found in standard air-conditioning applications with an air-handling unit and include the heat recovery units, heat exchangers and humidifiers. Liquid sorption techniques have been demonstrated successfully.

3.3.2.3 Thermal storage

Thermal storage within thermal solar systems is a key component to ensure reliability and efficiency. Four main types of thermal energy storage technologies can be distinguished: sensible, latent, sorption and thermochemical heat storage (Hadorn, 2005; Paksoy, 2007; Mehling and Cabeza, 2008; Dincer and Rosen, 2010).

Sensible heat storage systems use the heat capacity of a material. The vast majority of systems on the market use water for heat storage. Water heat storage covers a broad range of capacities, from several hundred litres to tens of thousands of cubic metres.

Latent heat storage systems store thermal energy during the phase change, either melting or evaporation, of a material. Depending on the temperature range, this type of storage is more compact than heat storage in water. Melting processes have energy densities of the order of 100 kWh/m^3 (360 MJ/m^3), compared to 25 kWh/m^3 (90 MJ/m^3) for sensible heat storage. Most of the current latent heat storage technologies for low temperatures store heat in building structures to improve thermal performance, or in cold storage systems. For medium-temperature storage, the storage materials are nitrate salts. Pilot storage units in the 100-kW range currently operate using solar-produced steam.

Sorption heat storage systems store heat in materials using water vapour taken up by a sorption material. The material can either be a solid (adsorption) or a liquid (absorption). These technologies are still largely in the development phase, but some are on the market. In principle, sorption heat storage densities can be more than four times higher than sensible heat storage in water.

Thermochemical heat storage systems store heat in an endothermic chemical reaction. Some chemicals store heat 20 times more densely than water (at a $\Delta T \approx 100°C$); but more typically, the storage densities are 8 to 10 times higher. Few thermochemical storage systems have been demonstrated. The materials currently being studied are the salts that can exist in anhydrous and hydrated form. Thermochemical systems can compactly store low- and medium-temperature heat. Thermal storage is discussed with specific reference to higher-temperature CSP in Section 3.3.4.

Underground thermal energy storage is used for seasonal storage and includes the various technologies described below. The most frequently used storage technology that makes use of the underground is *aquifer* *thermal energy storage*. This technology uses a natural underground layer (e.g., sand, sandstone or chalk) as a storage medium for the temporary storage of heat or cold. The transfer of thermal energy is realized by extracting groundwater from the layer and by re-injecting it at the modified temperature level at a separate location nearby. Most applications are for the storage of winter cold to be used for the cooling of large office buildings and industrial processes. Aquifer cold storage is gaining interest because savings on electricity bills for chillers are about 75%, and in many cases, the payback time for additional investments is shorter than five years. A major condition for the application of this technology is the availability of a suitable geologic formation.

3.3.2.4 Active solar heating and cooling applications

For active solar heating and cooling applications, the amount of hot water produced depends on the type and size of the system, amount of sun available at the site, seasonal hot-water demand pattern, and installation characteristics of the system (Norton, 2001).

Solar heating for industrial processes is at a very early stage of development in 2010 (POSHIP, 2001). Worldwide, less than 100 operating solar thermal systems for process heat are reported, with a total capacity of about 24 MW_{th} (34,000 m^2 collector area). Most systems are at an experimental stage and relatively small scale. However, significant potential exists for market and technological developments, because 28% of the overall energy demand in the EU27 countries originates in the industrial sector, and much of this demand is for heat below 250°C. Education and knowledge dissemination are needed to deploy this technology.

In the short term, solar heating for industrial processes will mainly be used for low-temperature processes, ranging from 20°C to 100°C. With technological development, an increasing number of medium-temperature applications—up to 250°C—will become feasible within the market. According to Werner (2006), about 30% of the total industrial heat demand is required at temperatures below 100°C, which could theoretically be met with solar heating using current technologies. About 57% of this demand is required at temperatures below 400°C, which could largely be supplied by solar in the foreseeable future.

In several specific industry sectors—such as food, wine and beverages, transport equipment, machinery, textiles, and pulp and paper—the share of heat demand at low and medium temperatures (below 250°C) is around 60% (POSHIP, 2001). Tapping into this low- and medium-temperature heat demand with solar heat could provide a significant opportunity for solar contribution to industrial energy requirements. A substantial opportunity for solar thermal systems also exists in chemical industries and in washing processes.

Among the industrial processes, desalination and water treatment (e.g., sterilization) are particularly promising applications for solar thermal energy, because these processes require large amounts of medium-temperature heat and are often necessary in areas with high solar irradiance and high energy costs.

Some process heat applications can be met with temperatures delivered by ‘ordinary’ low-temperature collectors, namely, from 30°C to 80°C. However, the bulk of the demand for industrial process heat requires temperatures from 80°C to 250°C.

Process heat collectors are another potential application for solar thermal heat collectors. Typically, these systems require a large capacity (hence, large collector areas), low costs, and high reliability and quality. Although low- and high-temperature collectors are offered in a dynamically growing market, process heat collectors are at a very early stage of development and no products are available on an industrial scale. In addition to ‘concentrating’ collectors, improved flat collectors with double and triple glazing are currently being developed, which could meet needs for process heat in the range of up to 120°C. Concentrating-type solar collectors are described in Section 3.3.4.

Solar refrigeration is used, for example, to cool stored vaccines. The need for such systems is greatest in peripheral health centres in rural communities in the developing world, where no electrical grid is available.

Solar cooling is a specific area of application for solar thermal technology. High-efficiency flat plates, evacuated tubes or parabolic troughs can be used to drive absorption cycles to provide cooling. For a greater coefficient of performance (COP), collectors with low concentration levels can provide the temperatures (up to around 250°C) needed for double-effect absorption cycles. There is a natural match between solar energy and the need for cooling.

A number of closed heat-driven cooling systems have been built, using solar thermal energy as the main source of heat. These systems often have large cooling capacities of up to several hundred kW. Since the early 2000s, a number of systems have been developed in the small-capacity range, below 100 kW, and, in particular, below 20 kW and down to 4.5 kW. These small systems are single-effect machines of different types, used mainly for residential buildings and small commercial applications.

Although open-cooling cycles are generally used for air conditioning in buildings, closed heat-driven cooling cycles can be used for both air conditioning and industrial refrigeration.

Other solar applications are listed below. The production of potable water using solar energy has been readily adopted in remote or isolated regions (Narayan et al., 2010). Solar stills are widely used in some parts of the world (e.g., Puerto Rico) to supply water to households of up to 10 people (Khanna et al., 2008). In appropriate isolation conditions, solar detoxification can be an effective low-cost treatment for low-contaminant waste (Gumy et al., 2006). Multiple-effect humidification (MEH) desalination units indirectly use heat from highly efficient solar thermal collectors to induce evaporation and condensation inside a thermally isolated, steam-tight container. These MEH systems are now beginning to appear in the market. Also see the report on water desalination by CSP (DLR, 2007) and the discussion of SolarPACES Task VI (SolarPACES, 2009b).

In solar drying, solar energy is used either as the sole source of the required heat or as a supplemental source, and the air flow can be generated by either forced or free (natural) convection (Fudholi et al., 2010). Solar cooking is one of the most widely used solar applications in developing countries (Lahkar and Samdarshi, 2010) though might still be considered an early stage commercial product due to limited overall deployment in comparison to other cooking methods. A solar cooker uses sunlight as its energy source, so no fuel is needed and operating costs are zero. Also, a reliable solar cooker can be constructed easily and quickly from common materials.

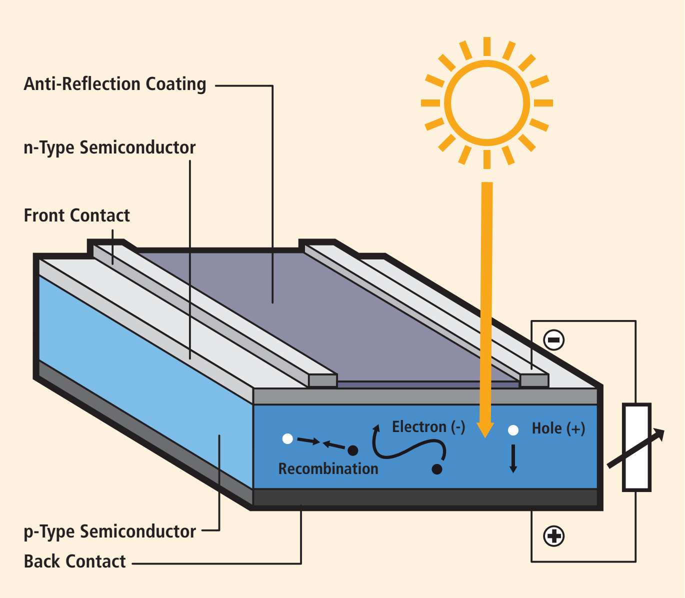


Figure 3.5 | Generic schematic cross-section illustrating the operation of an illuminated solar cell.

3.3.3 Photovoltaic electricity generation

Photovoltaic (PV) solar technologies generate electricity by exploiting the photovoltaic effect. Light shining on a semiconductor such as silicon (Si) generates electron-hole pairs that are separated spatially by an internal electric field created by introducing special impurities into the semiconductor on either side of an interface known as a p-n junction. This creates negative charges on one side of the interface and positive charges are on the other side (Figure 3.5). This resulting charge separation creates a voltage. When the two sides of the illuminated cell are connected to a load, current flows from one side of the device via the load to the other side of the cell. The conversion efficiency of a solar cell is defined as a ratio of output power from the solar cell with unit area (W/cm^2) to the incident solar irradiance. The maximum potential efficiency of a solar cell depends on the absorber material properties and device design. One technique for increasing solar cell efficiency is with a multijunction approach that stacks specially selected absorber materials that can collect more of the solar spectrum since each different material can collect solar photons of different wavelengths.

PV cells consist of organic or inorganic matter. Inorganic cells are based on silicon or non-silicon materials; they are classified as wafer-based cells or thin-film cells. Wafer-based silicon is divided into two different types: monocrystalline and multicrystalline (sometimes called 'polycrystalline').

3.3.3.1 Existing photovoltaic technologies

Existing PV technologies include wafer-based crystalline silicon (c-Si) cells, as well as thin-film cells based on copper indium/gallium disulfide/diselenide ($CuInGaSe_2$; CIGS), cadmium telluride (CdTe), and thin-film silicon (amorphous and microcrystalline silicon). Mono- and multicrystalline silicon wafer PV (including ribbon technologies) are the dominant technologies on the PV market, with a 2009 market share of about 80%; thin-film PV (primarily CdTe and thin-film Si) has the remaining 20% share. Organic PV (OPV) consists of organic absorber materials and is an emerging class of solar cells.

Wafer-based silicon technology includes solar cells made of monocrystalline or multicrystalline wafers with a current thickness of around 200 µm, while the thickness is decreasing down to 150 µm. Single-junction wafer-based c-Si cells have been independently verified to have record energy conversion efficiencies of 25.0% for monocrystalline silicon cells and 20.3% for multicrystalline cells (Green et al., 2010b) under standard test conditions (i.e., irradiance of 1,000 W/m^2, air-mass 1.5, 25°C). The theoretical Shockley-Queisser limit of a single-junction cell with an energy bandgap of crystalline silicon is 31% energy conversion efficiency (Shockley and Queisser, 1961).

Several variations of wafer-based c-Si PV for higher efficiency have been developed, for example, heterojunction solar cells and interdigitated back-contact (IBC) solar cells. Heterojunction solar cells consist of a crystalline silicon wafer base sandwiched by very thin (~5 nm) amorphous silicon layers for passivation and emitter. The highest-efficiency heterojunction solar cell is 23.0% for a 100.4-cm^2 cell (Taguchi et al., 2009). Another advantage is a lower temperature coefficient. The efficiency of conventional c-Si solar cells declines with elevating ambient temperature at a rate of -0.45%/°C, while the heterojunction cells show a lower rate of -0.25%/°C (Taguchi et al., 2009). An IBC solar cell, where both the base and emitter are contacted at the back of the cell, has the advantage of no shading of the front of the cell by a top electrode. The highest efficiency of such a back-contact silicon wafer cell is 24.2% for 155.1 cm^2 (Bunea et al., 2010). Commercial module efficiencies for wafer-based silicon PV range from 12 to 14% for multicrystalline Si and from 14 to 20% for monocrystalline Si.

Commercial thin-film PV technologies include a range of absorber material systems: amorphous silicon (a-Si), amorphous silicon-germanium, microcrystalline silicon, CdTe and CIGS. These thin-film cells have an absorber layer thickness of a few µm or less and are deposited on glass, metal or plastic substrates with areas of up to 5.7 m^2 (Stein et al., 2009).

The a-Si solar cell, introduced in 1976 (Carlson and Wronski, 1976) with initial efficiencies of 1 to 2%, has been the first commercially successful thin-film PV technology. Because a-Si has a higher light absorption coefficient than c-Si, the thickness of an a-Si cell can be less than 1 µm—that is, more than 100 times thinner than a c-Si cell. Developing higher efficiencies for a-Si cells has been limited by inherent material quality and by light-induced degradation identified as the Staebler-Wronski effect (Staebler and Wronski, 1977). However, research efforts have successfully lowered the impact of the Staebler-Wronski effect to around 10% or less by controlling the microstructure of the film. The highest stabilized efficiency—the efficiency after the light-induced degradation—is reported as 10.1% (Benagli et al., 2009).

Higher efficiency has been achieved by using multijunction technologies with alloy materials, e.g., germanium and carbon or with microcrystalline silicon, to form semiconductors with lower or higher bandgaps, respectively, to cover a wider range of the solar spectrum (Yang and Guha, 1992; Yamamoto et al., 1994; Meier et al., 1997). Stabilized efficiencies of 12 to 13% have been measured for various laboratory devices (Green et al., 2010b).

CdTe solar cells using a heterojunction with cadmium sulphide (CdS) have a suitable energy bandgap of 1.45 electron-volt (eV) (0.232 aJ) with a high coefficient of light absorption. The best efficiency of this cell is 16.7% (Green et al., 2010b) and the best commercially available modules have an efficiency of about 10 to 11%.

The toxicity of metallic cadmium and the relative scarcity of tellurium are issues commonly associated with this technology. Although several assessments of the risk (Fthenakis and Kim, 2009; Zayed and Philippe, 2009) and scarcity (Green et al., 2009; Wadia et al., 2009) are available, no consensus exists on these issues. It has been reported that this potential hazard can be mitigated by using a glass-sandwiched module design and by recycling the entire module and any industrial waste (Sinha et al., 2008).

The CIGS material family is the basis of the highest-efficiency thin-film solar cells to date. The copper indium diselenide ($CuInSe_2$)/CdS solar cell was invented in the early 1970s at AT&T Bell Labs (Wagner et al., 1974). Incorporating Ga and/or S to produce $CuInGa(Se,S)_2$ results in the benefit of a widened bandgap depending on the composition (Dimmler and Schock, 1996). CIGS-based solar cells have been validated at an efficiency of 20.1% (Green et al., 2010b). Due to higher efficiencies and lower manufacturing energy consumptions, CIGS cells are currently in the industrialization phase, with best commercial module efficiencies of up to 13.1% (Kushiya, 2009) for $CuInGaSe_2$ and 8.6% for $CuInS_2$ (Meeder et al., 2007). Although it is acknowledged that the scarcity of In might be an issue, Wadia et al. (2009) found that the current known economic indium reserves would allow the installation of more than 10 TW of CIGS-based PV systems.

High-efficiency solar cells based on a multijunction technology using III-V semiconductors (i.e., based on elements from the III and V columns of the periodic chart), for example, gallium arsenide (GaAs) and gallium indium phosphide (GaInP) , can have superior efficiencies. These cells were originally developed for space use and are already commercialized. An economically feasible terrestrial application is the use of these cells in concentrating PV (CPV) systems, where concentrating optics are used to focus sunlight onto high efficiency solar cells (Bosi and Pelosi, 2007). The most commonly used cell is a triple-junction device based on GaInP/GaAs/germanium (Ge), with a record efficiency of 41.6% for a lattice-matched cell (Green et al., 2010b) and 41.1% for a metamorphic or lattice-mismatched device (Bett et al., 2009). Sub-module efficiencies have reached 36.1% (Green et al., 2010b). Another advantage of the concentrator system is that cell efficiencies increase under higher irradiance (Bosi and Pelosi, 2007), and the cell area can be decreased in proportion to the concentration level. Concentrator applications, however, require direct-normal irradiation, and are thus suited for specific climate conditions with low cloud coverage.

3.3.3.2 Emerging photovoltaic technologies

Emerging PV technologies are still under development and in laboratory or (pre-) pilot stage, but could become commercially viable within the next decade. They are based on very low-cost materials and/or processes and include technologies such as dye-sensitized solar cells, organic solar cells and low-cost (printed) versions of existing inorganic thin-film technologies.

Electricity generation by dye-sensitized solar cells (DSSCs) is based on light absorption in dye molecules (the 'sensitizers') attached to the very large surface area of a nanoporous oxide semiconductor electrode (usually titanium dioxide), followed by injection of excited electrons from the dye into the oxide. The dye/oxide interface thus serves as the separator of negative and positive charges, like the p-n junction in other devices. The negatively charged electrons are then transported through the semiconductor electrode and reach the counter electrode through the load, thus generating electricity. The injected electrons from the dye molecules are replenished by electrons supplied through a liquid electrolyte that penetrates the pores of the semiconductor electrode, providing the electrical path from the counter electrode (Graetzel, 2001). State-of-the-art DSSCs have achieved a top conversion efficiency of 10.4% (Chiba et al., 2005). Despite the gradual improvements since its discovery in 1991 (O'Regan and Graetzel, 1991), long-term stability against ultraviolet light irradiation, electrolyte leakage and high ambient temperatures continue to be key issues in commercializing these PV cells.

Organic PV (OPV) cells use stacked solid organic semiconductors, either polymers or small organic molecules. A typical structure of a small-molecule OPV cell consists of a stack of p-type and n-type organic semiconductors forming a planar heterojunction. The short-lived nature of the tightly bound electron-hole pairs (excitons) formed upon light absorption limits the thickness of the semiconductor layers that can be used—and therefore, the efficiency of such devices. Note that excitons need to move to the interface where positive and negative charges can be separated before they recombine. If the travel distance is short, the 'active' thickness of material is small and not all light can be absorbed within that thickness.

The efficiency achieved with single-junction OPV cells is about 5% (Li et al., 2005), although predictions indicate about twice that value or higher can be achieved (Forrest, 2005; Koster et al., 2006). To decouple exciton transport distances from optical thickness (light absorption), so-called bulk-heterojunction devices have been developed. In these devices, the absorption layer is made of a nanoscale mixture of p- and n-type materials to allow excitons to reach the interface within their lifetime, while also enabling a sufficient macroscopic layer thickness. This bulk-heterojunction structure plays a key role in improving the efficiency, to a record value of 7.9% in 2009 (Green et al., 2010a). The developments in cost and processing (Brabec, 2004; Krebs, 2005) of materials have caused OPV research to advance further. Also, the main development challenge is to achieve a sufficiently high stability in combination with a reasonable efficiency.

3.3.3.3 Novel photovoltaic technologies

Novel technologies are potentially disruptive (high-risk, high-potential) approaches based on new materials, devices and conversion concepts. Generally, their practically achievable conversion efficiencies and cost structure are still unclear. Examples of these approaches include intermediate-band semiconductors, hot-carrier devices, spectrum converters, plasmonic solar cells, and various applications of quantum dots (Section 3.7.3). The emerging technologies described in the previous section primarily aim at very low cost, while achieving a sufficiently high efficiency and stability. However, most of the novel technologies aim at reaching very high efficiencies by making better use of the entire solar spectrum from infrared to ultraviolet.

3.3.3.4 Photovoltaic systems

A photovoltaic system is composed of the PV module, as well as the balance of system (BOS) components, which include an inverter, storage devices, charge controller, system structure, and the energy network. The system must be reliable, cost effective, attractive and match with the electric grid in the future (US Photovoltaic Industry Roadmap Steering Committee, 2001; Navigant Consulting Inc., 2006; EU PV European Photovoltaic Technology Platform, 2007; Kroposki et al., 2008; NEDO, 2009).

At the component level, BOS components for grid-connected applications are not yet sufficiently developed to match the lifetime of PV modules. Additionally, BOS component and installation costs need to be reduced. Moreover, devices for storing large amounts of electricity (over 1 MWh or 3,600 MJ) will be adapted to large PV systems in the new energy network. As new module technologies emerge in the future, some of the ideas relating to BOS may need to be revised. Furthermore, the quality of the system needs to be assured and adequately maintained according to defined standards, guidelines and procedures. To ensure system quality, assessing performance is important, including on-line analysis (e.g., early fault detection) and off-line analysis of PV systems. The knowledge gathered can help to validate software for predicting the energy yield of future module and system technology designs.

To increasingly penetrate the energy network, PV systems must use technology that is compatible with the electric grid and energy supply and demand. System designs and operation technologies must also be developed in response to demand patterns by developing technology to forecast the power generation volume and to optimize the storage function. Moreover, inverters must improve the quality of grid electricity by controlling reactive power or filtering harmonics with communication in a new energy network that uses a mixture of inexpensive and effective communications systems and technologies, as well as smart meters (see Section 8.2.1).

3.3.3.5 Photovoltaic applications

Photovoltaic applications include PV power systems classified into two major types: those not connected to the traditional power grid (i.e., off-grid applications) and those that are connected (i.e., grid-connected applications). In addition, there is a much smaller, but stable, market segment for consumer applications.

Off-grid PV systems have a significant opportunity for economic application in the un-electrified areas of developing countries. Figure 3.6 shows the ratio of various off-grid and grid-connected systems in the Photovoltaic Power Systems (PVPS) Programme countries. Of the total capacity installed in these countries during 2009, only about 1.2% was installed in off-grid systems that now make up 4.2% of the cumulative installed PV capacity of the IEA PVPS countries (IEA, 2010e).

Off-grid centralized PV mini-grid systems have become a reliable alternative for village electrification over the last few years. In a PV mini-grid system, energy allocation is possible. For a village located in an isolated area and with houses not separated by too great a distance, the power may flow in the mini-grid without considerable losses. Centralized systems for local power supply have different technical advantages concerning electrical performance, reduction of storage needs, availability

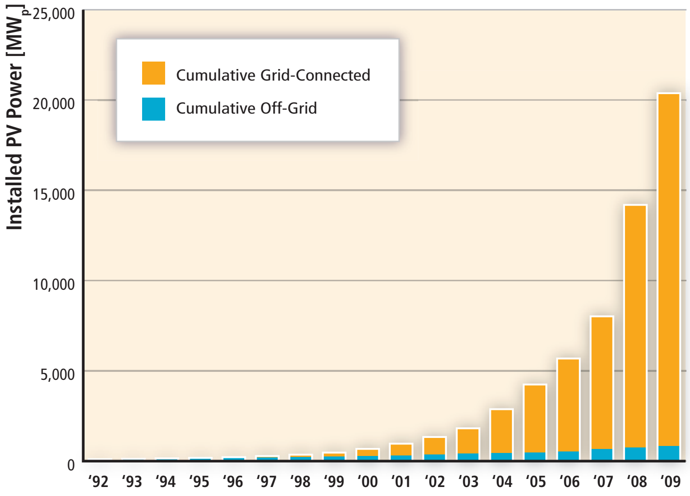


Figure 3.6 | Historical trends in cumulative installed PV power of off-grid and grid-connected systems in the OECD countries (IEA, 2010e). Vertical axis is in peak megawatts.

of energy, and dynamic behaviour. Centralized PV mini-grid systems could be the least-cost options for a given level of service, and they may have a diesel generator set as an optional balancing system or operate as a hybrid PV-wind-diesel system. These kinds of systems are relevant for reducing and avoiding diesel generator use in remote areas (Munoz et al., 2007; Sreeraj et al., 2010).

Grid-connected PV systems use an inverter to convert electricity from direct current (DC)—as produced by the PV array—to alternating current (AC), and then supply the generated electricity to the electricity network. Compared to an off-grid installation, system costs are lower because energy storage is not generally required, since the grid is used as a buffer. The annual output yield ranges from 300 to 2,000 kWh/kW (Clavadetscher and Nordmann, 2007; Gaiddon and Jedliczka, 2007; Kurokawa et al., 2007; Photovoltaic Geographic Information System, 2008) for several installation conditions in the world. The average annual performance ratio—the ratio between average AC system efficiency and standard DC module efficiency—ranges from 0.7 to 0.8 (Clavadetscher and Nordmann, 2007) and gradually increases further to about 0.9 for specific technologies and applications.

Grid-connected PV systems are classified into two types of applications: distributed and centralized. Grid-connected *distributed* PV systems are installed to provide power to a grid-connected customer or directly to the electricity network. Such systems may be: 1) on or integrated into the customer's premises, often on the demand side of the electricity meter; 2) on public and commercial buildings; or 3) simply in the built environment such as on motorway sound barriers. Typical sizes are 1 to 4 kW for residential systems, and 10 kW to several MW for rooftops on public and industrial buildings.

These systems have a number of advantages: distribution losses in the electricity network are reduced because the system is installed at the point of use; extra land is not required for the PV system, and costs for mounting the systems can be reduced if the system is mounted on an existing structure; and the PV array itself can be used as a cladding or roofing material, as in building-integrated PV (Eiffert, 2002; Ecofys Netherlands BV, 2007; Elzinga, 2008).

An often-cited disadvantage is the greater sensitivity to grid interconnection issues, such as overvoltage and unintended islanding (Kobayashi and Takasaki, 2006; Cobben et al., 2008; Ropp et al., 2008). However, much progress has been made to mitigate these effects, and today, by Institute of Electrical and Electronics Engineers (IEEE) and Underwriter Laboratories standards (IEEE 1547 (2008), UL 1741), all inverters must have the function of the anti-islanding effect.

Grid-connected *centralized* PV systems perform the functions of centralized power stations. The power supplied by such a system is not associated with a particular electricity customer, and the system is not located to specifically perform functions on the electricity network other than the supply of bulk power. Typically, centralized systems are mounted on the ground, and they are larger than 1 MW.

The economical advantage of these systems is the optimization of installation and operating cost by bulk buying and the cost effectiveness of the PV components and balance of systems at a large scale. In addition, the reliability of centralized PV systems can be greater than distributed PV systems because they can have maintenance systems with monitoring equipment, which can be a smaller part of the total system cost.

Multi-functional PV, daylighting and solar thermal components involving PV or solar thermal that have already been introduced into the built environment include the following: shading systems made from PV and/or solar thermal collectors; hybrid PV/thermal (PV/T) systems that generate electricity and heat from the same 'panel/collector' area; semi-transparent PV windows that generate electricity and transmit daylight from the same surface; façade collectors; PV roofs; thermal energy roof systems; and solar thermal roof-ridge collectors. Currently, fundamental and applied R&D activities are also underway related to developing other products, such as transparent solar thermal window collectors, as well as façade elements that consist of vacuum-insulation panels, PV panels, heat pump, and a heat-recovery system connected to localized ventilation.

Solar energy can be integrated within the building envelope and with energy conservation methods and smart-building operating strategies. Much work over the last decade or so has gone into this integration, culminating in the 'net-zero' energy building.

Much of the early emphasis was on integrating PV systems with thermal and daylighting systems. Bazilian et al. (2001) and Tripanagnostopoulos (2007) listed methods for doing this and reviewed case studies where the methods had been applied. For example, PV cells can be laid on the absorber plate of a flat-plate solar collector. About 6 to 20% of the solar energy absorbed on the cells is converted to electricity; the remaining roughly 80% is available as low-temperature heat to be transferred to the fluid being heated. The resulting unit produces both heat and electricity and requires only slightly more than half the area used if the two conversion devices had been mounted side by side and worked independently. PV cells have also been developed to be applied to windows to allow daylighting and passive solar gain. Reviews of recent work in this area are provided by Chow (2010) and Arif Hasan and Sumathy (2010).

Considerable work has also been done on architecturally integrating the solar components into the building. Any new solar building should be very well insulated, well sealed, and have highly efficient windows and heat recovery systems. Probst and Roecker (2007), surveying the opinions of more than 170 architects and engineers who examined numerous existing solar buildings, concluded the following: 1) best integration is achieved when the solar component is integrated as a construction element, and 2) appearance—including collector colour, orientation and jointing—must sometimes take precedence over performance in the overall design. In describing 16 case studies of building-integrated photovoltaics, Eiffert and Kiss (2000) identified two main products available on the architectural market: façade systems and roof systems. Façade systems include curtain wall products, spandrel panels and glazings; roofing products include tiles, shingles, standing-seam products and skylights. These can be integrated as components or constitute the entire structure (as in the case of a bus shelter).

The idea of the net-zero-energy solar building has sparked recent interest. Such buildings send as much excess PV-generated electrical energy to the grid as the energy they draw over the year. An IEA Task is considering how to achieve this goal (IEA NZEB, 2009). Recent examples for the Canadian climate are provided by Athienitis (2008). Starting from a building that meets the highest levels of conservation, these homes use hybrid air-heating/PV panels on the roof; the heated air is used for space heating or as a source for a heat pump. Solar water-heating collectors are included, as is fenestration permitting a large passive gain through equatorial-facing windows. A key feature is a ground-source heat pump, which provides a small amount of residual heating in the winter and cooling in the summer.

Smart solar-building control strategies may be used to manage the collection, storage and distribution of locally produced solar electricity and heat to reduce and shift peak electricity demand from the grid. An example of a smart solar-building design is given by Candanedo and Athienitis (2010), where predictive control based on weather forecasts one day ahead and real-time prediction of building response are used to optimize energy performance while reducing peak electricity demand.

3.3.4 Concentrating solar power electricity generation

Concentrating solar power (CSP) technologies produce electricity by concentrating direct-beam solar irradiance to heat a liquid, solid or gas that is then used in a downstream process for electricity generation. The majority of the world's electricity today—whether generated by coal, gas, nuclear, oil or biomass—comes from creating a hot fluid. CSP simply provides an alternative heat source. Therefore, an attraction of this technology is that it builds on much of the current know-how on power generation in the world today. And it will benefit not only from ongoing advances in solar concentrator technology, but also as improvements continue to be made in steam and gas turbine cycles.

Any concentrating solar system depends on direct-beam irradiation as opposed to global horizontal irradiation as for flat-plate systems. Thus, sites must be chosen accordingly, and the best sites for CSP are in near-equatorial cloud-free regions such as the North African desert. The average capacity factor of a solar plant will depend on the quality of the solar resource.

Some of the key advantages of CSP include the following: 1) it can be installed in a range of capacities to suit varying applications and conditions, from tens of kW (dish/Stirling systems) to multiple MWs (tower and trough systems); 2) it can integrate thermal storage for peaking loads (less than one hour) and intermediate loads (three to six hours); 3) it has modular and scalable components; and 4) it does not require exotic materials. This section discusses various types of CSP systems and thermal storage for these systems.

Large-scale CSP plants most commonly concentrate sunlight by reflection, as opposed to refraction with lenses. Concentration is either to a line (linear focus) as in trough or linear Fresnel systems or to a point (point focus) as in central-receiver or dish systems. The major features of each type of CSP system are illustrated in Figure 3.7 and are described below.

In trough concentrators, long rows of parabolic reflectors concentrate the solar irradiance by the order of 70 to 100 times onto a heat collection element (HCE) mounted along the reflector's focal line. The troughs track the Sun around one axis, with the axis typically being oriented north-south. The HCE comprises a steel inner pipe (coated with a solar-selective surface) and a glass outer tube, with an evacuated space in between. Heat-transfer oil is circulated through the steel pipe and heated to about 390°C. The hot oil from numerous rows of troughs is passed through a heat exchanger to generate steam for a conventional steam turbine generator (Rankine cycle). Land requirements are of the order of 2 km^2 for a 100-MW$_e$ plant, depending on the collector technology and assuming no storage. Alternative heat transfer fluids to the synthetic oil commonly used in trough receivers, such as steam and molten salt, are being developed to enable higher temperatures and overall efficiencies, as well as integrated thermal storage in the case of molten salt.

Linear Fresnel reflectors use long lines of flat or nearly flat mirrors, which allow the moving parts to be mounted closer to the ground, thus reducing structural costs. (In contrast, large trough reflectors presently use thermal bending to achieve the curve required in the glass surface.) The receiver is a fixed inverted cavity that can have a simpler construction than evacuated tubes and be more flexible in sizing. The attraction of

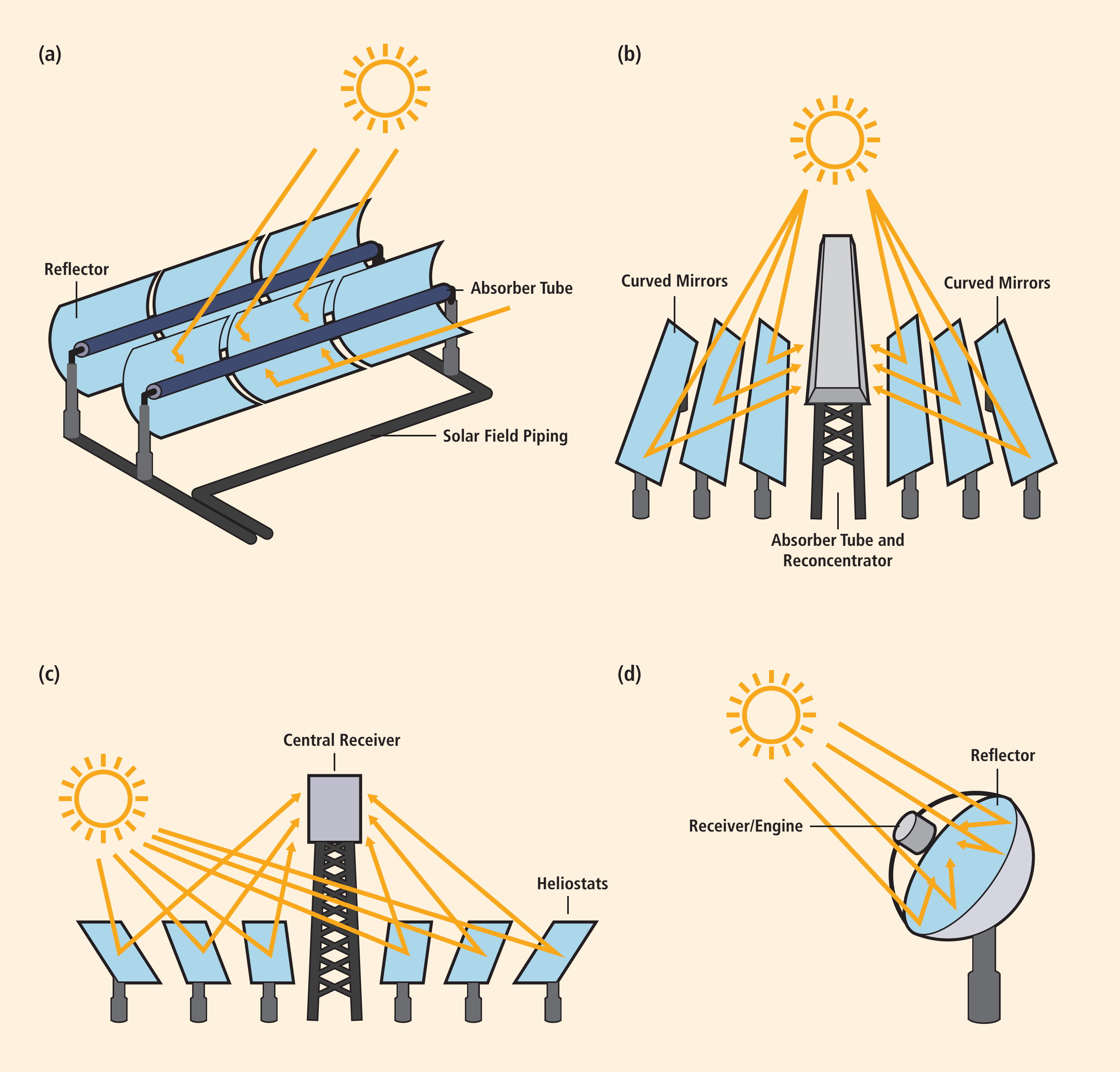


Figure 3.7 | Schematic diagrams showing the underlying principles of four basic CSP configurations: (a) parabolic trough, (b) linear Fresnel reflector, (c) central receiver/power tower, and (d) dish systems (Richter et al., 2009).

linear Fresnel reflectors is that the installed costs on a per square metre basis can be lower than for trough systems. However, the annual optical performance is less than that for a trough.

Central receivers (or power towers), which are one type of point-focus collector, are able to generate much higher temperatures than troughs and linear Fresnel reflectors, although requiring two-axis tracking as the Sun moves through solar azimuth and solar elevation. This higher temperature is a benefit because higher-temperature thermodynamic cycles used for generating electricity are more efficient. This technology uses an array of mirrors (heliostats), with each mirror tracking the Sun and reflecting the light onto a fixed receiver atop a tower. Temperatures of more than 1,000°C can be reached. Central receivers can easily generate the maximum temperatures of advanced steam turbines, can use high-temperature molten salt as the heat transfer fluid, and can be used to power gas turbine (Brayton) cycles.

Dish systems include an ideal optical reflector and therefore are suitable for applications requiring high temperatures. Dish reflectors are paraboloid and concentrate the solar irradiation onto a receiver mounted at the focal point, with the receiver moving with the dish. Dishes have been used to power Stirling engines at 900°C, and also for steam generation. There is now significant operational experience with dish/Stirling engine systems, and commercial rollout is planned. In 2010, the capacity of each Stirling engine is small—on the order of 10 to 25 $\text{kW}_{\text{electric}}$. The largest solar dishes have a 485-m^2 aperture and are in research facilities or demonstration plants.

In *thermal storage*, the heat from the solar field is stored prior to reaching the turbine. Thermal storage takes the form of sensible or latent heat storage (Gil et al., 2010; Medrano et al., 2010). The solar field needs to be oversized so that enough heat can be supplied to both operate the turbine during the day and, in parallel, charge the thermal storage. The term 'solar multiple' refers to the total solar field area installed divided by the solar field area needed to operate the turbine at design point without storage. Thermal storage for CSP systems needs to be at a temperature higher than that needed for the working fluid of the turbine. As such, system temperatures are generally between 400°C and 600°C, with the lower end for troughs and the higher end for towers. Allowable temperatures are also dictated by the limits of the media available. Examples of storage media include molten salt (presently comprising separate hot and cold tanks), steam accumulators (for short-term storage only), solid ceramic particles, high-temperature phase-change materials, graphite, and high-temperature concrete. The heat can then be drawn from the storage to generate steam for a turbine, as and when needed. Another type of storage associated with high-temperature CSP is thermochemical storage, where solar energy is stored chemically. This is discussed more fully in Sections 3.3.5 and 3.7.5.

Thermal energy storage integrated into a system is an important attribute of CSP. Until recently, this has been primarily for operational purposes, providing 30 minutes to 1 hour of full-load storage. This eases the impact of thermal transients such as clouds on the plant, assists start-up and shut-down, and provides benefits to the grid. Trough plants are now designed for 6 to 7.5 hours of storage, which is enough to allow operation well into the evening when peak demand can occur and tariffs are high. Trough plants in Spain are now operating with molten-salt storage. In the USA, Abengoa Solar's 280-MW Solana trough project, planned to be operational by 2013, intends to integrate six hours of thermal storage. Towers, with their higher temperatures, can charge and store molten salt more efficiently. Gemasolar, a 17-MW_e solar tower project under construction in Spain, is designed for 15 hours of storage, giving a 75% annual capacity factor (Arce et al., 2011).

Thermal storage is a means of providing dispatchability. Hybridization with non-renewable fuels is another way in which CSP can be designed to be dispatchable. Although the back-up fuel itself may not be renewable (unless it is biomass-derived), it provides significant operational benefits for the turbine and improves solar yield.

CSP applications range from small distributed systems of tens of kW to large centralized power stations of hundreds of MW.

Stirling and Brayton cycle generation in CSP can be installed in a wide range from small distributed systems to clusters forming medium- to large-capacity power stations. The dish/Stirling technology has been under development for many years, with advances in dish structures, high-temperature receivers, use of hydrogen as the circulating working fluid, as well as some experiments with liquid metals and improvements in Stirling engines—all bringing the technology closer to commercial deployment. Although the individual unit size may only be of the order of tens of kW_e, power stations having a large capacity of up to 800 MW_e have been proposed by aggregating many modules. Because each dish represents a stand-alone electricity generator, from the perspective of distributed generation there is great flexibility in the capacity and rate at which units are installed. However, the dish technology is less likely to integrate thermal storage.

An alternative to the Stirling engine is the Brayton cycle, as used by gas turbines. The attraction of these engines for CSP is that they are already in significant production, being used for distributed generation fired with landfill gas or natural gas. In the solarized version, the air is instead heated by concentrated solar irradiance from a tower or dish reflector. It is also possible to integrate with a biogas or natural gas combustor to back up the solar. Several developments are currently underway based on solar tower and micro-turbine combinations.

Centralized CSP benefits from the economies of scale offered by large-scale plants. Based on conventional steam and gas turbine cycles, much of the technological know-how of large power station design and practice is already in place. However, although larger capacity has significant cost benefits, it has also tended to be an inhibitor until recently because of the much larger investment commitment required from investors. In addition, larger power stations require strong infrastructural support, and new or augmented transmission capacity may be needed.

The earliest commercial CSP plants were the 354 MW of Solar Electric Generating Stations in California—deployed between 1985 and 1991—that continue to operate commercially today. As a result of the positive experiences and lessons learned from these early plants, the trough systems tend to be the technology most often applied today as the CSP industry grows. In Spain, regulations to date have mandated that the largest capacity unit that can be installed is 50 MW_e to help stimulate industry competition. In the USA, this limitation does not exist, and proposals are in place for much larger plants—280 MW_e in the case of troughs and 400-MW_e plants (made up of four modules) based on towers. There are presently two operational solar towers of 10 and 20 MW_e, and all tower developers plan to increase capacity in line with technology development, regulations and investment capital. Multiple dishes have also been proposed as a source of aggregated heat, rather than distributed-generation Stirling or Brayton units.

CSP or PV electricity can also be used to power reverse-osmosis plants for desalination. Dedicated CSP desalination cycles based on pressure and temperature are also being developed for desalination (see Section 3.3.2).

3.3.5 Solar fuel production

Solar fuel technologies convert solar energy into chemical fuels, which can be a desirable method of storing and transporting solar energy. They can be used in a much wider variety of higher-efficiency applications than just electricity generation cycles. Solar fuels can be processed into liquid transportation fuels or used directly to generate electricity in fuel cells; they can be employed as fuels for high-efficiency gas-turbine cycles or internal combustion engines; and they can serve for upgrading fossil fuels, CO_2 synthesis, or for producing industrial or domestic heat. The challenge is to produce large amounts of chemical fuels directly from sunlight in cost-effective ways and to minimize adverse effects on the environment (Steinfeld and Meier, 2004).

Solar fuels that can be produced include synthesis gas (syngas, i.e., mixed gases of carbon monoxide and hydrogen), pure hydrogen (H_2) gas, dimethyl ether (DME) and liquids such as methanol and diesel. The high energy density of H_2 (on a mass basis) and clean conversion give it attractive properties as a future fuel and it is also used as a feedstock for many industrial processes. H_2 has a higher energy density than batteries, although batteries have a higher round-trip efficiency. However, its very low energy density on a volumetric basis poses economic challenges associated with its storage and transport. It will require significant new distribution infrastructure and either new designs of internal combustion engine or a move to fuel cells. Additionally, the synthesis of hydrogen with CO_2 can produce hydrocarbon fuels that are compatible with existing infrastructures. DME gas is similar to liquefied petroleum gas (LPG) and easily stored. Methanol is liquid and can replace gasoline without significant changes to the engine or the fuel distribution infrastructure. Methanol and DME can be used for fuel cells after reforming, and DME can also be used in place of LPG. Fischer-Tropsch processes can produce hydrocarbon fuels and electricity (see Sections 2.6 and 8.2.4).

There are three basic routes, alone or in combination, for producing storable and transportable fuels from solar energy: 1) the electrochemical route uses solar electricity from PV or CSP systems followed by an electrolytic process; 2) the photochemical/photobiological route makes direct use of solar photon energy for photochemical and photobiological processes; and 3) the thermochemical route uses solar heat at moderate and/or high temperatures followed by an endothermic thermochemical process (Steinfeld and Meier, 2004). Note that the electrochemical and thermochemical routes apply to any RE technology, not exclusively to solar technologies.

Figure 3.8 illustrates possible pathways to produce H_2 or syngas from water and/or fossil fuels using concentrated solar energy as the source of high-temperature process heat. Feedstocks include *inorganic* compounds such as water and CO_2, and *organic* sources such as coal, biomass and natural gas (NG). See Chapter 2 for parallels with biomass-derived syngas.

Electrolysis of water can use solar electricity generated by PV or CSP technology in a conventional (alkaline) electrolyzer, considered a benchmark for producing solar hydrogen. With current technologies, the overall solar-to-hydrogen energy conversion efficiency ranges between 10 and 14%, assuming electrolyzers working at 70% efficiency and solar electricity being produced at 15% (PV) and 20% (CSP) annual efficiency. The electricity demand for electrolysis can be significantly reduced if the electrolysis of water proceeds at higher temperatures (800° to 1,000°C) via solid-oxide electrolyzer cells (Jensen et al., 2007). In this case, concentrated solar energy can be applied to provide both the high-temperature process heat and the electricity needed for the high-temperature electrolysis.

Thermolysis and thermochemical cycles are a long-term sustainable and carbon-neutral approach for hydrogen production from water. This route involves energy-consuming (endothermic) reactions that make use of concentrated solar irradiance as the energy source for high-temperature process heat (Abanades et al., 2006). Solar thermolysis requires temperatures above 2,200°C and raises difficult challenges for reactor materials and gas separation. Water-splitting thermochemical cycles allow operation at lower temperature, but require several chemical reaction steps and also raise challenges because of inefficiencies associated with heat transfer and product separation at each step.

Decarbonization of fossil fuels is a near- to mid-term transition pathway to solar hydrogen that encompasses the carbothermal reduction of metal oxides (Epstein et al., 2008) and the decarbonization of fossil fuels via solar cracking (Spath and Amos, 2003; Rodat et al., 2009), reforming (Möller et al., 2006) and gasification (Z'Graggen and Steinfeld, 2008; Piatkowski et al., 2009). These routes are being pursued by European, Australian and US academic and industrial research consortia. Their technical feasibility has been demonstrated in concentrating solar chemical pilot plants at the power level of 100 to 500 kW_{th}. Solar hybrid fuel can be produced by supplying concentrated solar thermal energy to the endothermic processes of methane and biomass reforming—that is, solar heat is used for process energy only, and fossil fuels are still a required input. Some countries having vast solar and natural gas resources, but a relatively small domestic energy market (e.g., the Middle East and Australia) are in a position to produce and export solar energy in the form of liquid fuels.

Solar fuel synthesis from solar hydrogen and CO_2 produces hydrocarbons that are compatible with existing energy infrastructures such as the natural gas network or existing fuel supply structures. The renewable methane process combines solar hydrogen with CO_2 from the

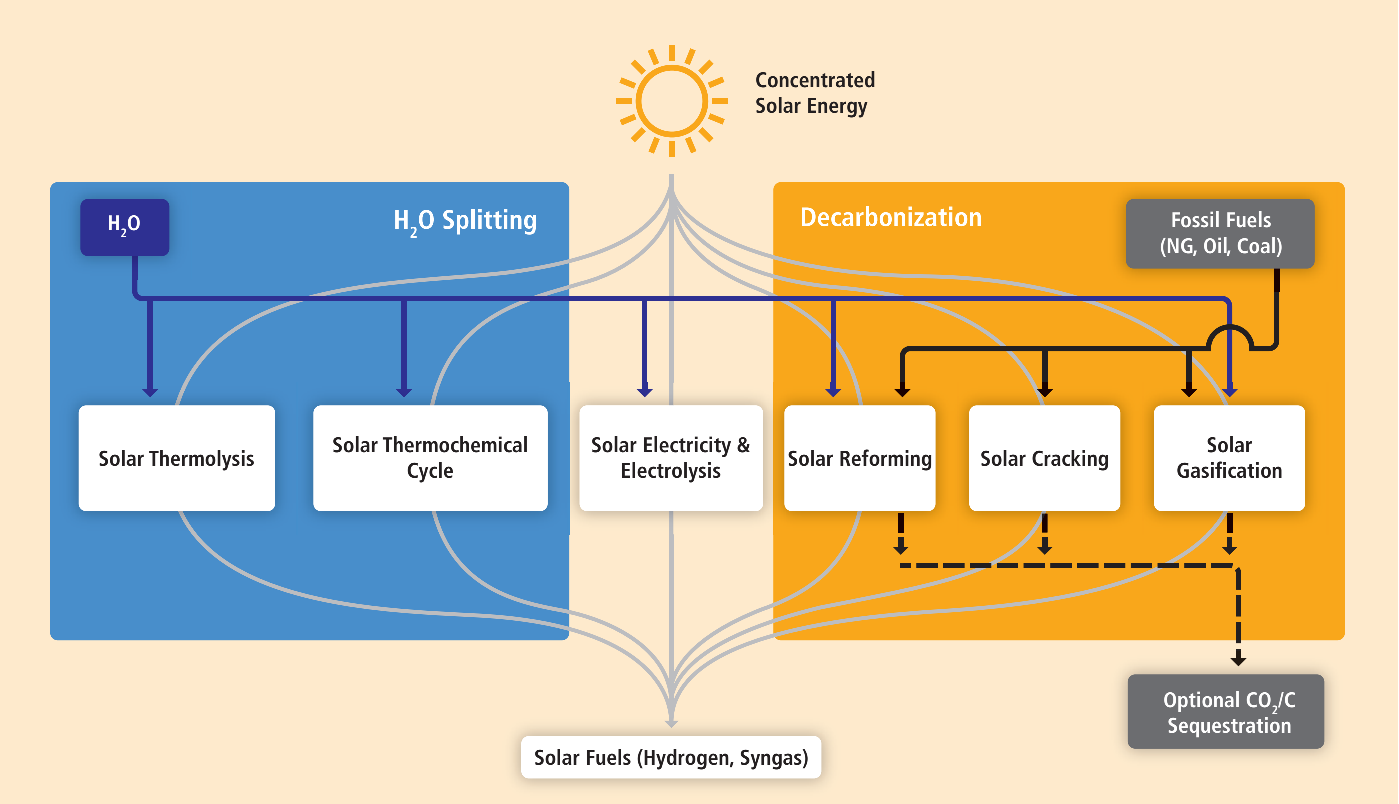


Figure 3.8 | Thermochemical routes for solar fuels production, indicating the chemical source of H_2: water (H_2O) for solar thermolysis and solar thermochemical cycles to produce H_2 only; fossil or biomass fuels as feedstock for solar cracking to produce H_2 and carbon (C); or a combination of fossil/biomass fuels and H_2O/CO_2 for solar reforming and gasification to produce syngas, H_2 and carbon monoxide (CO). For the solar decarbonization processes, sequestration of the CO_2/C may be considered (from Steinfeld and Meier, 2004; Steinfeld, 2005).

atmosphere or other sources in a synthesis reactor with a nickel catalyst. In this way, a substitute for natural gas is produced that can be stored, transported and used in gas power plants, heating systems and gas vehicles (Sterner, 2009).

Solar methane can be produced using water, air, solar energy and a source of CO_2. Possible CO_2 sources are biomass, industry processes or the atmosphere. CO_2 is regarded as the carrier for hydrogen in this energy system. By separating CO_2 from the combustion process of solar methane, CO_2 can be recycled in the energy system or stored permanently. Thus, carbon sink energy systems powered by RE can be created (Sterner, 2009). The first pilot plants at the kW scale with atmospheric CO_2 absorption have been set up in Germany, proving the technical feasibility. Scaling up to the utility MW scale is planned in the next few years (Specht et al., 2010).

In an alternative conversion step, liquid fuels such as Fischer-Tropsch diesel, DME, methanol or solar kerosene (jet fuel) can be produced from solar energy and CO_2/water (H_2O) for long-distance transportation. The main advantages of these solar fuels are the same range as fossil fuels (compared to the generally reduced range of electric vehicles), less competition for land use, and higher per-hectare yields compared to biofuels. Solar energy can be harvested via natural photosynthesis in biofuels with an efficiency of 0.5%, via PV power and solar fuel conversion (technical photosynthesis) with an efficiency of 10% (Sterner, 2009) and via solar-driven thermochemical dissociation of CO_2 and H_2O using metal oxide redox reactions, yielding a syngas mixture of carbon monoxide (CO) and H_2, with a solar-to-fuel efficiency approaching 20% (Chueh et al., 2010). This approach would provide a solution to the issues and controversy surrounding existing biofuels, although the cost of this technology is a possible constraint.

3.4 Global and regional status of market and industry development

This section looks at the five key solar technologies, first focusing on installed capacity and generated energy, then on industry capacity and supply chains, and finally on the impact of policies specific to these technologies.

3.4.1 Installed capacity and generated energy

This subsection discusses the installed capacity and generated energy within the five technology areas of passive solar, active solar heating and cooling, PV electricity generation, CSP electricity generation, and solar fuel production.

For *passive solar technologies*, no estimates are available at this time for the installed capacity of passive solar or the energy generated or saved through this technology.

For *active solar heating*, the total installed capacity worldwide was about 149 GW_{th} in 2008 and 180 GW_{th} in 2009 (Weiss and Mauthner, 2010; REN21, 2010).

In 2008, new capacity of 29.1 GW_{th}, corresponding to 41.5 million m^2 of solar collectors, was installed worldwide (Weiss and Mauthner, 2010). In 2008, China accounted for about 79% of the installations of glazed collectors, followed by the EU with 14.5%.

The overall new installations grew by 34.9% compared to 2007. The growth rate in 2006/2007 was 18.8%. The main reasons for this growth were the high growth rates of glazed water collectors in China, Europe and the USA.

In 2008, the global market had high growth rates for evacuated-tube collectors and flat-plate collectors, compared to 2007. The market for unglazed air collectors also increased significantly, mainly due to the installation of 23.9 MW_{th} of new systems in Canada.

Compared to 2007, the 2008 installation rates for new unglazed, glazed flat-plate, and evacuated-tube collectors were significantly up in Jordan, Cyprus, Canada, Ireland, Germany, Slovenia, Macedonia (FYROM), Tunisia, Poland, Belgium and South Africa.

New installations in China, the world's largest market, again increased significantly in 2008 compared to 2007, reaching 21.7 GW_{th}. After a market decline in Japan in 2007, the growth rate was once again positive in 2008.

Market decreases compared to 2007 were reported for Israel, the Slovak Republic and the Chinese province of Taiwan.

The main markets for unglazed water collectors are still found in the USA (0.8 GW_{th}), Australia (0.4 GW_{th}), and Brazil (0.08 GW_{th}). Notable markets are also in Austria, Canada, Mexico, The Netherlands, South Africa, Spain, Sweden and Switzerland, with values between 0.07 and 0.01 GW_{th} of new installed unglazed water collectors in 2008.

Comparison of markets in different countries is difficult due to the wide range of designs used for different climates and different demand requirements. In Scandinavia and Germany, a solar heating system will typically be a combined water-heating and space-heating system, known as a solar combisystem, with a collector area of 10 to 20 m^2. In Japan, the number of solar domestic water-heating systems is large, but most installations are simple integral preheating systems. The market in Israel is large due to a favourable climate, as well as regulations mandating installation of solar water heaters. The largest market is in China, where there is widespread adoption of advanced evacuated-tube solar collectors. In terms of per capita use, Cyprus is the leading country in the world, with an installed capacity of 527 kW_{th} per 1,000 inhabitants.

The type of application of solar thermal energy varies greatly in different countries (Weiss and Mauthner, 2010). In China (88.7 GW_{th}), Europe (20.9 GW_{th}) and Japan (4.4 GW_{th}), flat-plate and evacuated-tube collectors mainly prepare hot water and provide space heating. However, in the USA and Canada, swimming pool heating is still the dominant application, with an installed capacity of 12.9 GW_{th} of unglazed plastic collectors.

The biggest reported solar thermal system for industrial process heat was installed in China in 2007. The 9 MW_{th} plant produces heat for a textile company. About 150 large-scale plants (>500 m^2; 350 kW_{th})[1] with a total capacity of 160 MW_{th} are in operation in Europe. The largest plants for solar-assisted district heating are located in Denmark (13 MW_{th}) and Sweden (7 MW_{th}).

In Europe, the market size more than tripled between 2002 and 2008. However, even in the leading European solar thermal markets of Austria, Greece, and Germany, only a minor portion of residential homes use solar thermal. For example, in Germany, only about 5% of one- and two-family homes are using solar thermal energy.

The European market has the largest variety of different solar thermal applications, including systems for hot-water preparation, plants for space heating of single- and multi-family houses and hotels, large-scale plants for district heating, and a growing number of systems for air-conditioning, cooling and industrial applications.

Advanced applications such as solar cooling and air conditioning (Henning, 2004, 2007), industrial applications (POSHIP, 2001) and desalination/water treatment are in the early stages of development. Only a few hundred first-generation systems are in operation.

For *PV electricity generation*, newly installed capacity in 2009 was about 7.5 GW, with shipments to first point in the market at 7.9 GW (Jäger-Waldau, 2010a; Mints, 2010). This addition brought the cumulative installed PV capacity worldwide to about 22 GW—a capacity able to generate up to 26 TWh (93,600 TJ) per year. More than 90% of this capacity is installed in three leading markets: the EU27 with 16 GW (73%), Japan with 2.6 GW (12%), and the USA with 1.7 GW (8%) (Jäger-Waldau, 2010b). These markets are dominated by grid-connected PV systems, and growth within PV markets has been stimulated by various government programmes around the world. Examples of such programmes include feed-in tariffs in Germany and Spain, and various mechanisms in the USA, such as buy-down incentives, investment tax credits, performance-based incentives and RE quota systems. For 2010,

---

[1] To enable comparison, the IEA's Solar Heating and Cooling Programme, together with the European Solar Thermal Industry Federation and other major solar thermal trade associations, publish statistics in kW_{th} (kilowatt thermal) and use a factor of 0.7 kW_{th}/m^2 to convert square metres of collector area into installed thermal capacity (kW_{th}).

the market is estimated between 9 and 24 GW of additional installed PV systems, with a consensus value in the 13 GW range (Jäger-Waldau, 2010a).

Figure 3.9 illustrates the cumulative installed capacity for the top eight PV markets through 2009, including Germany (9,800 MW), Spain (3,500 MW), Japan (2,630 MW), the USA (1,650 MW), Italy (1,140 MW), Korea (460 MW), France (370 MW) and the People's Republic of China (300 MW). By far, Spain and Germany have seen the largest amounts of growth in installed PV capacity in recent years, with Spain seeing a huge surge in 2008 and Germany having experienced steady growth over the last five years.

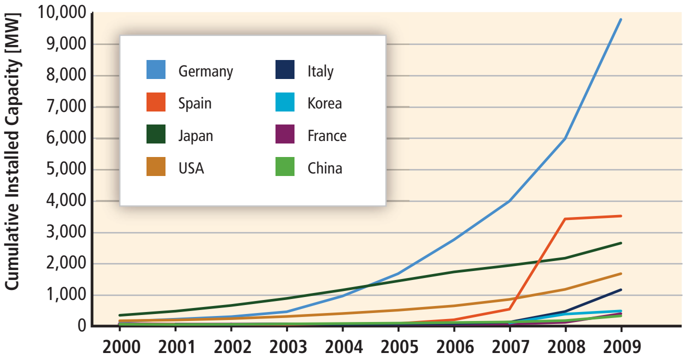


Figure 3.9 | Installed PV capacity in eight markets. Data sources: EurObserv'ER (2009); IEA (2009c); REN21 (2009); and Jäger-Waldau (2010b).

Concentrating photovoltaics (CPV) is an emerging market with about 17 MW of cumulative installed capacity at the end of 2008. The two main tracks are high-concentration PV (>300 times or 300 suns) and low- to medium-concentration PV with a concentration factor of 2 to about 300 (2 to ~300 suns). To maximize the benefits of CPV, the technology requires high direct-beam irradiance, and these areas have a limited geographical range—the 'Sun Belt' of the Earth. The market share of CPV is still small, but an increasing number of companies are focusing on CPV. In 2008, about 10 MW of CPV were installed, and market estimates for 2009 are in the 20 to 30 MW range; for 2010, about 100 MW are expected.

Regarding CSP *electricity generation*, at the beginning of 2009, more than 700 MW$_e$ of grid-connected CSP plants were installed worldwide, with another 1,500 MW$_e$ under construction (Torres et al., 2010). The majority of installed plants use parabolic trough technology. Central-receiver technology comprises a growing share of plants under construction and those announced. The bulk of the operating capacity is installed in Spain and the south-western United States.

In 2007, after a hiatus of more than 15 years, the first major CSP plants came on line with Nevada Solar One (64 MW$_e$, USA) and PS10 (11 MW$_e$, Spain). In Spain, successive Royal Decrees have been in place since 2004 and have stimulated the CSP industry in that country. Royal Decree 661/2007 has been a major driving force for CSP plant construction and expansion plans. As of November 2009, 2,340 MW$_e$ of CSP projects had been preregistered for the tariff provisions of the Royal Decree. In the USA, more than 4,500 MW$_e$ of CSP are currently under power purchase agreement contracts. The different contracts specify when the projects must start delivering electricity between 2010 and 2015 (Bloem et al., 2010). More than 10,000 MW$_e$ of new CSP plants have been proposed in the USA. More than 50 CSP electricity projects are currently in the planning phase, mainly in North Africa, Spain and the USA. In Australia, the federal government has called for 1,000 MW$_e$ of new solar plants, covering both CSP and PV, under the Solar Flagships programme. Figure 3.10 shows the current and planned deployment to add more CSP capacity in the near future.

Hybrid solar/fossil plants have received increasing attention in recent years, and several integrated solar combined-cycle (ISCC) projects have been either commissioned or are under construction in the Mediterranean region and the USA. The first plant in Morocco (Ain Beni Mathar: 470 MW total, 22 MW solar) began operating in June 2010, and two additional plants in Algeria (Hassi R'Mel: 150 MW total, 30 MW solar) and Egypt (Al Kuraymat: 140 MW total, 20 MW solar) are under construction. In Italy, another example of an ISCC project is Archimede; however, the plant's 31,000-m^2 parabolic trough solar field will be the first to use molten salt as the heat transfer fluid (SolarPACES, 2009a).

Solar fuel production technologies are in an earlier stage of development. The high-temperature solar reactor technology is typically being developed at a laboratory scale of 1 to 10 kW$_{th}$ solar power input.

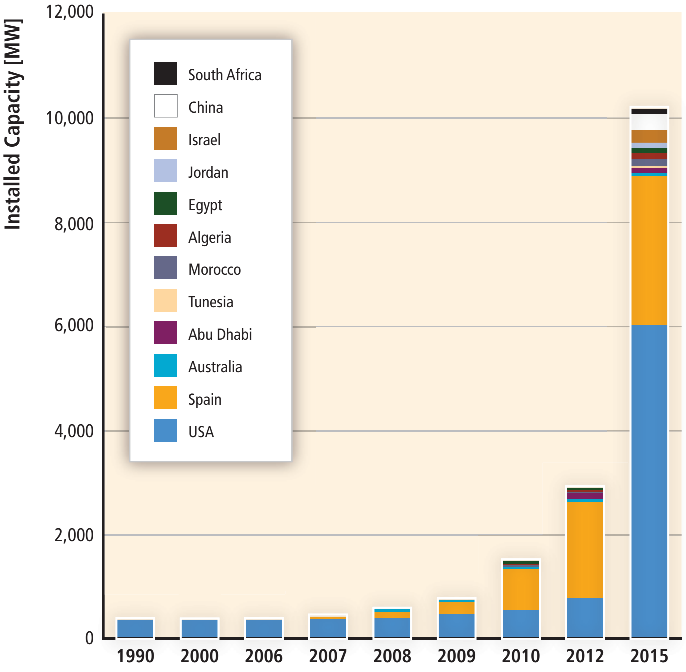


Figure 3.10 | Installed and planned concentrated solar power plants by country (Bloem et al., 2010).

Scaling up thermochemical processes for hydrogen production to the 100-kW$_{th}$ power level is reported for a medium-temperature mixed iron oxide cycle (800°C to 1,200°C) (Roeb et al., 2006, 2009) and for the high-temperature zinc oxide (ZnO) dissociation reaction at above 1,700°C (Schunk et al., 2008, 2009). Pilot plants in the power range of 300 to 500 kW$_{th}$ have been built for the carbothermic reduction of ZnO (Epstein et al., 2008), the steam reforming of methane (Möller et al., 2006), and the steam gasification of petcoke (Z'Graggen and Steinfeld, 2008). Solar-to-gas has been demonstrated at a 30-kW scale to drive a commercial natural gas vehicle, applying a nickel catalyst (Specht et al., 2010). Demonstration at the MW scale should be warranted before erecting commercial solar chemical plants for fuels production, which are expected to be available only after 2020 (Pregger et al., 2009).

Direct conversion of solar energy to fuel is not yet widely demonstrated or commercialized. But two options appear commercially feasible in the near to medium term: 1) the solar hybrid fuel production system (including solar methane reforming and solar biomass reforming), and 2) solar PV or CSP electrolysis.

Australia's Commonwealth Scientific and Industrial Research Organisation is running a 250-kW$_{th}$ reactor and plans to build a MW-scale demonstration plant using solar steam-reforming technology, with an eventual move to CO_2 reforming for higher performance and less water usage. With such a system, liquid solar fuels can be produced in sunbelts such as Australia and solar energy shipped on a commercial basis to Asia and beyond.

Oxygen gas produced by solar (PV or CSP) electrolysis can be used for coal gasification and partial oxidation of natural gas. With the combined process of solar electrolysis and partial oxidation of coal or methane, theoretically 10 to 15% of solar energy is incorporated into the methanol or DME. Also, the production cost of the solar hybrid fuel can be lower than the solar hydrogen produced by the solar electrolysis process only.

3.4.2 Industry capacity and supply chain

This subsection discusses the industry capacity and supply chain within the five technology areas of passive solar, active solar heating and cooling, PV electricity generation, CSP electricity generation and solar fuel production.

In passive solar technologies, people make up part of the industry capacity and the supply chain: namely, the engineers and architects who collaborate to produce passively heated buildings. Close collaboration between the two disciplines has often been missing in the past, but the dissemination of systematic design methodologies issued by different countries has improved the design capabilities (Athienitis and Santamouris, 2002).

The integration of passive solar systems with the active heating/cooling air-conditioning systems both in the design and operation stages of the building is essential to achieve good comfort conditions while saving energy. However, this is often overlooked because of inadequate collaboration for integrating building design between architects and engineers. Thus, the architect often designs the building envelope based solely on qualitative passive solar design principles, and the engineer often designs the heating-ventilation-air-conditioning system based on extreme design conditions without factoring in the benefits due to solar gains and natural cooling. The result may be an oversized system and inappropriate controls incompatible with the passive system and that can cause overheating and discomfort (Athienitis and Santamouris, 2002). Collaboration between the disciplines involved in building design is now improving with the adoption of computer tools for integrated analysis and design.

The design of high-mass buildings with significant near-equatorial-facing window areas is common in some areas of the world such as Southern Europe. However, a systematic approach to designing such buildings is still not widely employed. This is changing with the introduction of the passive house standard in Germany and other countries (PHPP, 2004), the deployment of the European Directives, and new national laws such as China's standard based on the German one.

Glazing and window technologies have made substantial progress in the last 20 years (Hollands et al., 2001). New-generation windows result in low energy losses, high daylight efficiency, solar shading, and noise reduction. New technologies such as transparent PV and electrochromic and thermochromic windows provide many possibilities for designing solar houses and offices with abundant daylight. The change from regular double-glazed to double-glazed low-emissivity argon windows is presently occurring in Canada and is accelerated by the rapid drop in prices of these windows.

The primary materials for low-temperature thermal storage in passive solar systems are concrete, bricks and water. A review of thermal storage materials is given by Hadorn (2008) under IEA SHC Task 32, focusing on a comparison of the different technologies. Phase-change material (PCM) thermal storage (Mehling and Cabeza, 2008) is particularly promising in the design, control and load management of solar buildings because it reduces the need for structural reinforcement required for heavier traditional sensible storage in concrete-type construction. Recent developments facilitating integration include microencapsulated PCM that can be mixed with plaster and applied to interior surfaces (Schossig et al., 2005). PCM in microencapsulated polymers is now on the market and can be added to plaster, gypsum or concrete to enhance the thermal capacity of a room. For renovation, this provides a good alternative to new heavy walls, which would require additional structural support (Hadorn, 2008).

In spite of the advances in PCM, concrete has certain advantages for thermal storage when a massive building design approach is used, as in many of the Mediterranean countries. In this approach, the concrete also serves as the structure of the building and is thus likely more cost effective than thermal storage without this added function.

For active solar heating and cooling, a number of different collector technologies and system approaches have been developed due to different applications—including domestic hot water, heating, preheating and combined systems—and varying climatic conditions.

In some parts of the production process, such as selective coatings, large-scale industrial production levels have been attained. A number of different materials, including copper, aluminium and stainless steel, are applied and combined with different welding technologies to achieve a highly efficient heat-exchange process in the collector. The materials used for the cover glass are structured or flat, low-iron glass. The first antireflection coatings are coming onto the market on an industrial scale, leading to efficiency improvements of about 5%.

In general, vacuum-tube collectors are well-suited for higher-temperature applications. The production of vacuum-tube collectors is currently dominated by the Chinese Dewar tubes, where a metallic heat exchanger is integrated to connect them with the conventional hot-water systems. In addition, some standard vacuum-tube collectors, with metallic heat absorbers, are on the market.

The largest exporters of solar water-heating systems are Australia, Greece and the USA. The majority of exports from Greece are to Cyprus and the near-Mediterranean area. France also sends a substantial number of systems to its overseas territories. The majority of US exports are to the Caribbean region. Australian companies export about 50% of production (mainly thermosyphon systems with external horizontal tanks) to most of the areas of the world that do not have hard-freeze conditions.

PV electricity generation is discussed under the areas of overall solar cell production, thin-film module production and polysilicon production. The development characteristic of the PV sector is much different than the traditional power sector, more closely resembling the semiconductor market, with annual growth rates between 40 to 50% and a high learning rate. Therefore, scientific and peer-reviewed papers can be several years behind the actual market developments due to the nature of statistical time delays and data consolidation. The only way to keep track of such a dynamic market is to use commercial market data. Global PV cell production[2] reached more than 11.5 GW in 2009. Figure 3.11 plots the increase in production from 2000 through 2009, showing regional contributions (Jäger-Waldau, 2010a). The compound annual growth rate in production from 2003 to 2009 was more than 50%.

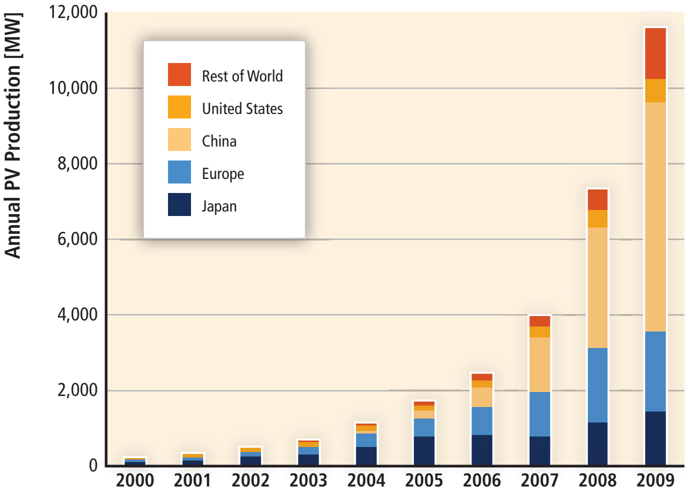


Figure 3.11 | Worldwide PV production from 2000 to 2009 (Jäger-Waldau, 2010b).

The announced production capacities—based on a survey of more than 300 companies worldwide—increased despite very difficult economic conditions in 2009 (Figure 3.12) (Jäger-Waldau, 2010b). Only published announcements from the respective companies, not third-party information, were used. April 2010 was the cut-off date for the information included. This method has the drawback that not all companies announce their capacity increases in advance; also, in times of financial tightening, announcements of scale-backs in expansion plans are often delayed to prevent upsetting financial markets. Therefore, the capacity figures provide a trend, but do not represent final numbers.

In 2008 and 2009, Chinese production capacity increased overproportionally. In actual production, China surpassed all other countries,

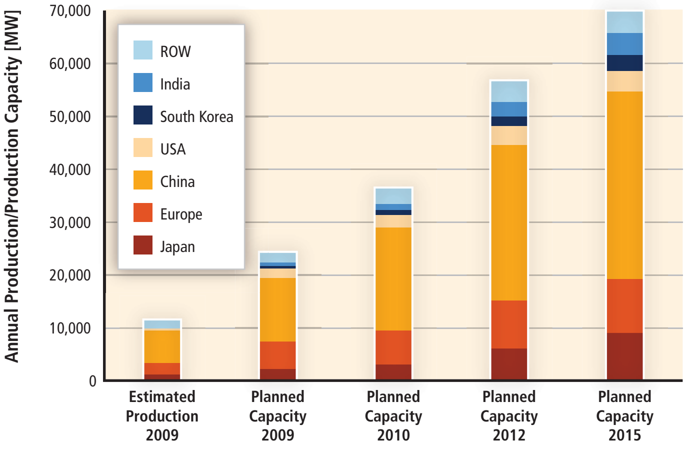


Figure 3.12 | Worldwide annual PV production in 2009 compared to the announced production capacities (Jäger-Waldau, 2010a).

---

[2] Solar cell production capacities mean the following: for wafer-silicon-based solar cells, only the cells; for thin films, the complete integrated module. Only those companies that actually produce the active circuit (solar cell) are counted; companies that purchase these circuits and then make modules are not counted.

estimated in 2009 at between 5.4 and 6.1 GW (including 1.5 to 1.7 GW production in the Chinese province of Taiwan), Europe had 2.0 to 2.2 GW, and was followed by Japan, with 1.5 to 1.7 GW (Jäger-Waldau, 2010b). In terms of production, First Solar (USA/Germany/France/Malaysia) was number one (1,082 MW), followed by Suntech (China) estimated at 750 MW and Sharp (Japan) estimated at 580 MW.

If all these ambitious plans can be realized by 2015, then China will have about 51% (including 16% in the Chinese province of Taiwan) of the worldwide production capacity of 70 GW, followed by Europe (15%) and Japan (13%).

Worldwide, more than 300 companies produce solar cells. In 2009, *silicon-based solar cells and modules* represented about 80% of the worldwide market (Figure 3.13). In addition to a massive increase in production capacities, the current development predicts that thin-film-based solar cells will increase their market share to over 30% by 2012.

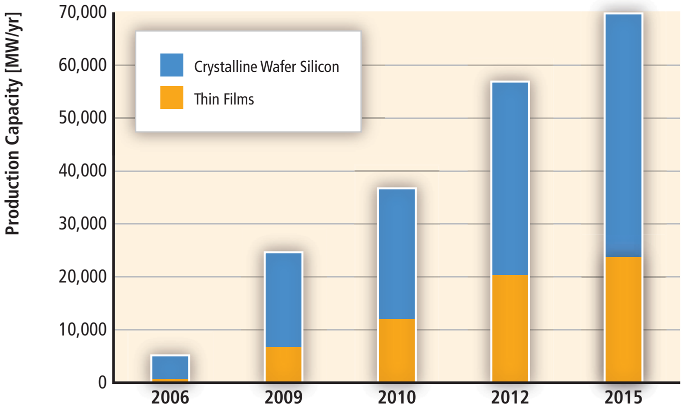


Figure 3.13 | Actual (2006) and announced (2009 to 2015) production capacities of thin-film and crystalline silicon-based solar modules (Jäger-Waldau, 2010b).

In 2005, production of *thin-film PV modules* grew to more than 100 MW per year. Since then, the compound annual growth rate of thin-film PV module production was higher than that of the industry—thus increasing the market share of thin-film products from 6% in 2005 to about 20% in 2009. Most of this thin-film share comes from the largest PV company.

More than 150 companies are involved in the thin-film solar cell production process, ranging from R&D activities to major manufacturing plants. The first 100-MW thin-film factories became operational in 2007, and the announcements of new production capacities accelerated again in 2008. If all expansion plans are realized in time, thin-film production capacity could be 20.0 GW, or 35% of the total 56.7 GW in 2012, and 23.5 GW, or 34% of a total of 70 GW in 2015 (Jäger-Waldau, 2009, 2010b). The first thin-film factories with GW production capacity are already under construction for various thin-film technologies.

The rapid growth of the PV industry since 2000 led to the situation between 2004 and early 2008 where the demand for polysilicon outstripped the supply from the semiconductor industry. This led to a silicon shortage, which resulted in silicon spot-market prices as high as USD_{2005} 450/kg (USD_{2005}, assumed 2008 base) in 2008 compared to USD_{2005} 25.5/kg in 2003 and consequently higher prices for PV modules. This extreme price hike triggered the massive capacity expansion, not only of established companies, but of many new entrants as well.

The six companies that reported shipment figures delivered together about 43,900 tonnes of polysilicon in 2008, as reported by Semiconductor Equipment and Materials International (SEMI, 2009a). In 2008, these companies had a production capacity of 48,200 tonnes of polysilicon (Service, 2009). However, all polysilicon producers, including new entrants with current and alternative technologies, had a production capacity of more than 90,000 tonnes of polysilicon in 2008. Considering that not all new capacity actually produced polysilicon at nameplate capacity in 2008, it was estimated that 62,000 tonnes of polysilicon could be produced. Subtracting the needs of the semiconductor industry and adding recycling and excess production, the available amount of silicon for the PV industry was estimated at 46,000 tonnes of polysilicon. With an average material need of 8.7 g/W_p (p = peak), this would have been sufficient for the production of 5.3 GW of crystalline silicon PV cells.

The drive to reduce costs and secure key markets has led to the emergence of two interesting trends. One is the move to large original design manufacturing units, similar to the developments in the semiconductor industry. A second is that an increasing number of solar manufacturers move part of their module production close to the final market to demonstrate the local job creation potential and ensure the current policy support. This may also be a move to manufacture in low-cost or subsidized markets.

The regional distribution of polysilicon production capacities is as follows: China 20,000 tonnes, Europe 17,500 tonnes, Japan 12,000 tonnes, and USA 37,000 tonnes (Service, 2009).

In 2009, solar-grade silicon production of about 88,000 tonnes was reported, sufficient for about 11 GW of PV assuming an average materials need of 8 g/W_p (Displaybank, 2010). China produced about 18,000 tonnes or 20% of world demand, fulfilling about half of its domestic demand (Baoshan, 2010).

Projections of silicon production capacities for solar applications in 2012 span a range between 140,000 tonnes from established polysilicon producers, up to 250,000 tonnes including new producers (e.g., Bernreuther and Haugwitz, 2010; Ruhl et al., 2010). The possible solar cell production will also depend on the material use per W_p. Material consumption could decrease from the current 8 g/W_p to 7 g/W_p or even 6 g/W_p (which could increase delivered PV capacity from 31 to 36 to 42 GW, respectively), but this may not be achieved by all manufacturers.

Forecasts of the future costs of vital materials have a high-profile history, and there is ongoing public debate about possible material shortages and competition regarding some (semi-)metals (e.g., In and Te) used in thin-film cell production. In a recent study, Wadia et al. (2009) explored material limits for PV expansion by examining the dual constraints of material supply and least cost per watt for the most promising semiconductors as active photo-generating materials. Contrary to the commonly assumed scarcity of indium and tellurium, the study concluded that the currently known economic reserves of these materials would allow about 10 TW of CdTe or $CuInS_2$ solar cells to be installed.

In CSP electricity generation, the solar collector field is readily scalable, and the power block is based on adapted knowledge from the existing power industry such as steam and gas turbines. The collectors themselves benefit from a range of existing skill sets such as mechanical, structural and control engineers, and metallurgists. Often, the materials or components used in the collectors are already mass-produced, such as glass mirrors.

By the end of 2010, strong competition had emerged and an increasing number of companies had developed industry-level capability to supply materials such as high-reflectivity glass mirrors and manufactured components. Nonetheless, the large evacuated tubes designed specifically for use in trough/oil systems for power generation remain a specialized component, and only two companies (Schott and Solel) have been capable of supplying large orders of tubes, with a third company (Archimedes) now emerging. The trough concentrator itself comprises know-how in both structures and thermally sagged glass mirrors. Although more companies are now offering new trough designs and considering alternatives to conventional rear-silvered glass (e.g., polymer-based reflective films), the essential technology of concentration remains unchanged. Direct steam generation in troughs is under demonstration, as is direct heating of molten salt, but these designs are not yet commercially available. As a result of its successful operational history, the trough/oil technology comprised most of the CSP installed capacity in 2010.

Linear Fresnel and central-receiver systems comprise a high level of know-how, but the essential technology is such that there is the potential for a greater variety of new industry participants. Although only a couple of companies have historically been involved with central receivers, new players have entered the market over the last few years. There are also technology developers and projects at the demonstration level (China, USA, Israel, Australia, Spain). Central-receiver developers are aiming for higher temperatures, and, in some cases, alternative heat transfer fluids such as molten salts. The accepted standard to date has been to use large heliostats, but many of the new entrants are pursuing much smaller heliostats to gain potential cost reductions through high-volume mass production. The companies now interested in heliostat development range from optics companies to the automotive industry looking to diversify. High-temperature steam receivers will benefit from existing knowledge in the boiler industry. Similarly, with linear Fresnel, a range of new developments are occurring, although not yet as developed as the central-receiver technology.

Dish technology is much more specialized, and most effort presently has been towards developing the dish/Stirling concept as a commercial product. Again, the technology can be developed as specialized components through specific industry know-how such as the Stirling engine mass-produced through the automotive industry.

Within less than 10 years prior to 2010, the CSP industry has gone from negligible activity to over 2,400 MW_e either commissioned or under construction. A list of new CSP plants and their characteristics can be found at the IEA SolarPACES web site.[3] More than ten different companies are now active in building or preparing for commercial-scale plants, compared to perhaps only two or three who were in a position to build a commercial-scale plant three years ago. These companies range from large organizations with international construction and project management expertise who have acquired rights to specific technologies, to start-ups based on their own technology developed in-house. In addition, major independent power producers and energy utilities are playing a role in the CSP market.

The supply chain does not tend to be limited by raw materials, because the majority of required materials are bulk commodities such as glass, steel/aluminium, and concrete. The sudden new demand for the specific solar salt mixture material for molten-salt storage is claimed to have impacted supply. At present, evacuated tubes for trough plants can be produced at a sufficient rate to service several hundred MW per year. However, expanded capacity can be introduced readily through new factories with an 18-month lead time.

Solar fuel technology is still at an emerging stage—thus, there is no supply chain in place at present for commercial applications. However, solar fuels will comprise much of the same solar-field technology being deployed for other high-temperature CSP systems, with solar fuels requiring a different receiver/reactor at the focus and different downstream processing and control. Much of the downstream technology, such as Fischer-Tropsch liquid fuel plants, would come from existing expertise in the petrochemical industry. The scale of solar fuel demonstration plants is being ramped up to build confidence for industry, which will eventually expand operations.

---

[3] See: www.solarpaces.org.

Hydrogen has been touted as a future transportation fuel due to its versatility, pollutant-free end use and storage capability. The key is a sustainable, CO_2-free source of hydrogen such as solar, cost-effective storage and appropriate distribution infrastructure. The production of solar hydrogen, in and of itself, does not produce a hydrogen economy because many factors are needed in the chain. The suggested path to solar hydrogen is to begin with solar enhancement of existing steam reforming processes, with a second generation involving solar electricity and advanced electrolysis, and a third generation using thermolysis or advanced thermochemical cycles, with many researchers aiming for the production of fuels from concentrated solar energy, water, and CO_2. In terms of making a transition, solar hydrogen can be mixed with natural gas and transported together in existing pipelines and distribution networks to customers, thus enhancing the solar portion of the global energy mix.

Steam reforming of natural gas for hydrogen production is a conventional industrial-scale process that produces most of the world's hydrogen today, with the heat for the process derived from burning a significant proportion of the fossil fuel feedstock. Using concentrated solar power, instead, as the source of the heat embodies solar energy in the fuel. The solar steam-reforming of natural gas and other hydrocarbons, and the solar steam-gasification of coal and other carbonaceous materials yields a high-quality syngas, which is the building block for a wide variety of synthetic fuels including Fischer-Tropsch-type chemicals, hydrogen, ammonia and methanol (Steinfeld and Meier, 2004).

The solar cracking route refers to the thermal decomposition of natural gas and other hydrocarbons. Besides H_2 and carbon, other compounds may also be formed, depending on the reaction kinetics and on the presence of impurities in the raw materials. The thermal decomposition yields a carbon-rich condensed phase and a hydrogen-rich gas phase. The carbonaceous solid product can either be sequestered without CO_2 release or used as material commodity (carbon black) under less severe CO_2 restraints. It can also be applied as reducing agent in metallurgical processes. The hydrogen-rich gas mixture can be further processed to high-purity hydrogen that is not contaminated with oxides of carbon; thus, it can be used in proton-exchange-membrane fuel cells without inhibiting platinum electrodes. From the perspective of carbon sequestration, it is easier to separate, handle, transport and store solid carbon than gaseous CO_2. Further, thermal cracking removes and separates carbon in a single step. The major drawback of thermal cracking is the energy loss associated with the sequestration of carbon. Thus, solar cracking may be the preferred option for natural gas and other hydrocarbons with a high H_2/C ratio (Steinfeld and Meier, 2004).

3.4.3 Impact of policies[4]

Direct solar energy technologies support a broad range of applications, and their deployment is confronted by many of the barriers outlined in Chapter 1. Solar technologies differ in levels of maturity, and although some applications are already competitive in localized markets, they generally face one common barrier: the need to achieve cost reductions (see Section 3.8). Utility-scale CSP and PV systems face different barriers than distributed PV and solar heating and cooling technologies. Important barriers include: 1) siting, permitting and financing challenges to develop land with favourable solar resources for utility-scale projects; 2) lack of access to transmission lines for large projects far from electric load centres; 3) complex access laws, permitting procedures and fees for smaller-scale projects; 4) lack of consistent interconnection standards and time-varying utility rate structures that capture the value of distributed generated electricity; 5) inconsistent standards and certifications and enforcement of these issues; and 6) lack of regulatory structures that capture environmental and risk mitigation benefits across technologies (Denholm et al., 2009).

Through appropriate policy designs (see Chapter 11), governments have shown that they can support solar technologies by funding R&D and by providing incentives to overcome economic barriers. Price-driven instruments (see Section 11.5.2), for example, were popularized after feed-in tariff (FIT) policies boosted levels of PV deployment in Germany and Spain. In 2009, various forms of FIT policies were implemented in more than 50 countries (REN21, 2010) and some designs offer premiums for building-integrated PV. Quota-driven frameworks such as renewable portfolio standards (RPS) and government bidding are common in the USA and China, respectively (IEA, 2009a). Traditional RPS frameworks are designed to be technology-neutral, and this puts at a disadvantage many solar applications that are more costly than alternatives such as wind power. In response, features of RPS frameworks (set-asides and credits) increasingly are including solar-specific policies, and such programs have led to increasing levels of solar installations (Wiser et al., 2010). In addition to these regulatory frameworks, fiscal policies and financing mechanisms (e.g., tax credits, soft loans and grants) are often employed to support the manufacturing of solar goods and to increase consumer demand (Rickerson et al., 2009). The challenge for solar projects to secure financing is a critical barrier, especially for developing technologies in market structures dominated by short-term transactions and planning.

Most successful solar policies are tailored to the barriers posed by specific applications. Across technologies, there is a need to offset relatively high upfront investment costs (Denholm et al., 2009). Yet, in the case of utility-scale CSP and PV projects, substantial and long-term investments are required at levels that exceed solar applications in distributed markets. Solar heating and cooling technologies are included in many policies, yet the characteristics of their applications differ from electricity-generating technologies. Policies based on energy yield rather than collector surface area are generally preferred for various types of solar thermal collectors (IEA, 2007). See Section 1.5 for further discussion.

Similar to other renewable sources, there is ongoing discussion about the merits of existing solar policies to spur innovation and accelerate deployment using cost-effective measures. Generally—and as discussed

---

[4] Non-technology-specific policy issues are covered in Chapter 11 of this report.

in Chapter 11—the most successful policies are those that send clear, long-term and consistent signals to the market. In addition to targeted economic policies, government action through educationally based schemes (e.g., workshops, workforce training programs and seminars) and engagement of regulatory organizations are helping to overcome many of the barriers listed in this section.

3.5 Integration into the broader energy system[5]

This section discusses how direct solar energy technologies are part of the broader energy framework, focusing specifically on the following: low-capacity energy demand; district heating and other thermal loads; PV generation characteristics and the smoothing effect; and CSP generation characteristics and grid stabilization. Chapter 8 addresses the broader technical and institutional options for managing the unique characteristics, production variability, limited predictability and locational dependence of some RE technologies, including solar, as well as existing experience with and studies associated with the costs of that integration.

3.5.1 Low-capacity electricity demand

There can be comparative advantages for using solar energy rather than non-renewable fuels in many developing countries. Within a country, the advantages can be higher in un-electrified rural areas compared to urban areas. Indeed, solar energy has the advantage, due to being modular, of being able to provide small and decentralized supplies, as well as large centralized ones. For more on integrated buildings and households, see Section 8.3.2.

In a wide range of countries, particularly those that are not oil producers, solar energy and other forms of RE can be the most appropriate energy source. If electricity demand exceeds supply, the lack of electricity can prevent development of many economic sectors. Even in countries with high solar energy sustainable development potential, RE is often only considered to satisfy high-power requirements such as the industrial sector. However, large-scale technologies such as CSP are often not available to them due, for example, to resource conditions or suitable land area availability. In such cases, it is reasonable to keep the electricity generated near the source to provide high amounts of power to cover industrial needs.

Applications that have low power consumption, such as lighting in rural areas, can primarily be satisfied using onsite PV—even if the business plan for electrification of the area indicates that a grid connection would be more profitable. Furthermore, the criteria to determine the most suitable technological option for electrifying a rural area should include benefits such as local economic development, exploiting natural resources, creating jobs, reducing the country's dependence on imports, and protecting the environment.

3.5.2 District heating and other thermal loads

Highly insulated buildings can be heated easily with relatively low-temperature district-heating systems, where solar energy is ideal, or quite small quantities of renewable-generated electricity (Boyle, 1996). A district cooling and heating system (DCS) can provide both cooling and heating for blocks of buildings. Since the district heating system already makes the outdoor pipe network available, a district cooling system becomes a viable solution to the cooling demand of buildings. There are already many DCS installations in the USA, Europe, Japan and other Asian countries because this system has many advantages compared to a decentralized cooling system. For example, it takes full advantage of economy of scale and diversity of cooling demand of different buildings, reduces noise and structure load, and saves considerable equipment area. It also allows greater flexibility in designing the building by removing the cooling tower on the roof and chiller plant in the building or on the roof, and it can provide more reliable and flexible services through a specialized professional team in cold-climate areas (Shu et al., 2010). For more on RE integration in district heating and cooling networks, see Section 8.2.2.3.

In China, Greece, Cyprus and Israel, solar water heaters make a significant contribution to supplying residential energy demand. In addition, solar water heating is widely used for pool heating in Australia and the USA. In countries where electricity is a major resource for water heating (e.g., Australia, Canada and the USA), the impact of numerous solar domestic water heaters on the operation of the power grid depends on the utility's load management strategy. For a utility that uses centralized load switching to manage electric water heater load, the impact is limited to fuel savings. Without load switching, the installation of many solar water heaters may have the additional benefit of reducing peak demand on the grid. For a utility that has a summer peak, the time of maximum solar water heater output corresponds with peak electrical demand, and there is a capacity benefit from load displacement of electric water heaters. Large-scale deployment of solar water heating can benefit both the customer and the utility. Another benefit to utilities is emissions reduction, because solar water heating can displace the marginal and polluting generating plant used to produce peak-load power.

Combining biomass and low-temperature solar thermal energy could provide zero emissions and high capacity factors to areas with less frequent direct-beam solar irradiance. In the short term, local tradeoffs exist for areas that have high biomass availability due to increased cloud cover and rainfall. However, solar technology is more land-efficient for energy production and greatly reduces the need for biomass growing area and biomass transport cost. Some optimum ratio of CSP and biomass supply is likely to exist at each site. Research is being conducted on tower and dish systems to develop technologies—such as solar-driven gasification of biomass—that optimally combine both these renewable resources. In the longer term, greater interconnectedness across different climate regimes may provide more stability of supply as a total grid system; this situation could reduce the need for occasional fuel supply for each individual CSP system.

---

[5] Non-technology-specific issues related to integration of RE sources in current and future energy systems are covered in Chapter 8 of this report.

3.5.3 Photovoltaic generation characteristics and the smoothing effect

At a specific location, the generation of electricity by a PV system varies systematically during a day and a year, but also randomly according to weather conditions. The variation of PV generation can, in some instances, have a large impact on voltage and power flow of the local transmission/distribution system from the early penetration stage, and on supply-demand balance in a total power system operation in the high-penetration stage (see also Section 8.2.1 for a further discussion of solar electricity characteristics, and the implications of those characteristics for electricity market planning, operations, and infrastructure).

Various studies have been published on the impact of supply-demand balance for a power system with a critical constraint of PV systems integration (Lee and Yamayee, 1981; Chalmers et al., 1985; Chowdhury and Rahman, 1988; Jewell and Unruh, 1990; Bouzguenda and Rahman, 1993; Asano et al., 1996). These studies generally conclude that the economic value of PV systems is significantly reduced at increasing levels of system penetration due to the high variability of PV. Today's base-load generation has a limited ramp rate—the rate at which a generator can change its output—which limits the feasible penetration of PV systems. However, these studies generally lack high-time-resolution PV system output data from multiple sites. The total electricity generation of numerous PV systems in a broad area should have less random and fast variation—because the generation output variations of numerous PV systems have low correlation and cancel each other in a 'smoothing effect'. The critical impact on supply-demand balance of power comes from the total generation of the PV systems within a power system (Piwko et al., 2007, 2010; Ogimoto et al., 2010).

Some approaches for analyzing the smoothing effect use modelling and measured data from around the world. Cloud models have been developed to estimate the smoothing effect of geographic diversity by considering regions ranging in size from 10 to 100,000 km^2 (Jewell and Ramakumar, 1987) and down to 0.2 km^2 (Kern and Russell, 1988). Using measured data, Kitamura (1999) proposed a set of specifications for describing fluctuations, considering three parameters: magnitude, duration of a transition between clear and cloudy, and speed of the transition, defined as the ratio of magnitude and duration; he evaluated the smoothing effect in a small area (0.1 km by 0.1 km). A similar approach, 'ramp analysis', was proposed by Beyer et al. (1991) and Scheffler (2002).

In a statistical approach, Otani et al. (1997) characterized irradiance data by the fluctuation factor using a high-pass filtered time series of solar irradiance. Woyte et al. (2001, 2007) analyzed the fluctuations of the instantaneous clearness index by means of a wavelet transform. To demonstrate the smoothing effect, Otani et al. (1998) demonstrated that the variability of sub-hourly irradiance even within a small area of 4 km by 4 km can be reduced due to geographic diversity. They analyzed the non-correlational irradiation/generation characteristics of several PV systems/sites that are dispersed spatially.

Wiemken et al. (2001) used data from actual PV systems in Germany to demonstrate that five-minute ramps in normalized PV power output at one site may exceed ±50%, but that five-minute ramps in the normalized PV power output from 100 PV systems spread throughout the country never exceed ±5%. Ramachandran et al. (2004) analyzed the reduction in power output fluctuation for spatially dispersed PV systems and for different time periods, and they proposed a cluster model to represent very large numbers of small, geographically dispersed PV systems. Results from Curtright and Apt (2008) based on three PV systems in Arizona indicate that 10-minute step changes in output can exceed 60% of PV capacity at individual sites, but that the maximum of the aggregate of three sites is reduced. Kawasaki et al. (2006) similarly analyzed the smoothing effect within a small (4 km by 4 km) network of irradiance sensors and concluded that the smoothing effect is most effective during times when the irradiance variability is most severe—particularly days characterized as partly cloudy.

Murata et al. (2009) developed and validated a method for estimating the variability of power output from PV plants dispersed over a wide area that is very similar to the methods used for wind by Ilex Energy Consulting Ltd et al. (2004) and Holttinen (2005). Mills and Wiser (2010) measured one-minute solar insolation for 23 sites in the USA and characterized the variability of PV with different degrees of geographic diversity, comparing the variability of PV to the variability of similarly sited wind. They determined that the relative aggregate variability of PV plants sited in a dense ten by ten array with 20-km spacing is six times less than the variability of a single site for variability on time scales of less than 15 minutes. They also found that for PV and wind plants similarly sited in a five by five grid with 50-km spacing, the variability of PV is only slightly more than the variability of wind on time scales of 5 to 15 minutes.

Oozeki et al. (2010) quantitatively evaluated the smoothing effect in a load-dispatch control area in Japan to determine the importance of data accumulation and analysis. The study also proposed a methodology to calculate the total PV output from a limited number of measurement data using Voronoi Tessellation. Marcos et al. (2010) analyzed one-second data collected throughout a year from six PV systems in Spain, ranging from 1 to 9.5 MW$_p$, totalling 18 MW. These studies concluded that over shorter and longer time scales, the level of variability is nearly identical because the aggregate fluctuation of PV systems spread over the large area depends on the correlation of the fluctuation between PV systems. The correlation of fluctuation, in turn, is a function both of the time scale and distance between PV systems. Variability is less correlated for PV systems that are further apart and for variability over shorter time scales.

Currently, however, not enough data on generation characteristics exist to evaluate the smoothing effect. Data collection from a sufficiently large number of sites (more than 1,000 sites and at distances of 2 to 200 km), periods and time resolution (one minute or less) had just begun in mid-2010 in several areas in the world. The smoothed generation characteristics of PV penetration considering area and multiple sites will be analyzed precisely after collecting reliable measurement data with sufficient time resolution and time synchronization. The results will contribute to the economic and reliable integration of PV into the energy system.

3.5.4 Concentrating solar power generation characteristics and grid stabilization

In a CSP plant, even without integrated storage, the inherent thermal mass in the collector system and spinning mass in the turbine tend to significantly reduce the impact of rapid solar transients on electrical output, and thus, lead to less impact on the grid (also see Section 8.2.1). By including integrated thermal storage systems, base-load capacity factors can be achieved (IEA, 2010b). This and the ability to dispatch power on demand during peak periods are key characteristics that have motivated regulators in the Mediterranean region, starting with Spain, to support large-scale deployment of this technology with tailored FITs. CSP is suitable for large-scale 10- to 300-MW_e plants replacing non-renewable thermal power capacity. With thermal storage or onsite thermal backup (e.g., fossil or biogas), CSP plants can also produce power at night or when irradiation is low. CSP plants can reliably deliver firm, scheduled power while the grid remains stable.

CSP plants may also be integrated with fossil fuel-fired plants such as displacing coal in a coal-fired power station or contributing to gas-fired integrated solar combined-cycle (ISCC) systems. In ISCC power plants, a solar parabolic trough field is integrated in a modern gas and steam power plant; the waste heat boiler is modified and the steam turbine is oversized to provide additional steam from a solar steam generator. Better fuel efficiency and extended operating hours make combined solar/fossil power generation much more cost-effective than separate CSP and combined-cycle plants. However, without including thermal storage, solar steam could only be supplied for some 2,000 of the 6,000 to 8,000 combined-cycle operating hours of a plant in a year. Furthermore, because the solar steam is only feeding the combined-cycle turbine—which supplies only one-third of its power—the maximum solar share obtainable is under 10%. Nonetheless, this concept is of special interest for oil- and gas-producing sunbelt countries, where solar power technologies can be introduced to their fossil-based power market (SolarPACES, 2008).

3.6 Environmental and social impacts[6]

This section first discusses the environmental impacts of direct solar technologies, and then describes potential social impacts. However, an overall issue identified at the start is the small number of peer-reviewed studies on impacts, indicating the need for much more work in this area.

3.6.1 Environmental impacts

No consensus exists on the premium, if any, that society should pay for cleaner energy. However, in recent years, there has been progress in analyzing environmental damage costs, thanks to several major projects to evaluate the externalities of energy in the USA and Europe (Gordon, 2001; Bickel and Friedrich, 2005; NEEDS, 2009; NRC, 2010). Solar energy has been considered desirable because it poses a much smaller environmental burden than non-renewable sources of energy. This argument has almost always been justified by qualitative appeals, although this is changing.

Results for damage costs per kilogram of pollutant and per kWh were presented by the International Solar Energy Society in Gordon (2001). The results of studies such as NEEDS (2009), summarized in Table 3.3 for PV and in Table 3.4 for CSP, confirm that RE is usually comparatively beneficial, though impacts still exist. In comparison to the figures presented for PV and CSP here, the external costs associated with fossil generation options, as summarized in Chapter 10.6, are considerably higher, especially for coal-fired generation.

Considering passive solar technology, higher insulation levels provide many benefits, in addition to reducing heating loads and associated costs (Harvey, 2006). The small rate of heat loss associated with high levels of insulation, combined with large internal thermal mass, creates a more comfortable dwelling because temperatures are more uniform. This can indirectly lead to higher efficiency in the equipment supplying the heat. It also permits alternative heating systems that would not

Table 3.3 | Quantifiable external costs for photovoltaic, tilted-roof, single-crystalline silicon, retrofit, average European conditions; in US_{2005} cents/kWh (NEEDS, 2009).

	2005	2025	2050
Health Impacts	0.17	0.14	0.10
Biodiversity	0.01	0.01	0.01
Crop Yield Losses	0.00	0.00	0.00
Material Damage	0.00	0.00	0.00
Land Use	N/A	0.01	0.01
Total	**0.18**	**0.17**	**0.12**

Table 3.4 | Quantifiable external costs for concentrating solar power; in US_{2005} cents/kWh (NEEDS, 2009).

	2005	2025	2050
Health Impacts	0.65	0.10	0.06
Biodiversity	0.03	0.00	0.00
Crop Yield Losses	0.00	0.00	0.00
Material Damage	0.01	0.00	0.00
Land Use	N/A	N/A	N/A
Total	**0.69**	**0.10**	**0.06**

---

[6] A comprehensive assessment of social and environmental impacts of all RE sources covered in this report can be found in Chapter 9.

otherwise be viable, but which are superior to conventional heating systems in many respects. Better-insulated houses eliminate moisture problems associated, for example, with thermal bridges and damp basements. Increased roof insulation also increases the attenuation of outside sounds such as from aircraft.

For active solar heating and cooling, the environmental impact of solar water-heating schemes in the UK would be very small according to Boyle (1996). For example, in the UK, the materials used are those of everyday building and plumbing. Solar collectors are installed to be almost indistinguishable visually from normal roof lights. In Mediterranean countries, the use of free-standing thermosyphon systems on flat roofs can be visually intrusive. However, the collector is not the problem, but rather, the storage tank above it. A study of the lifecycle environmental impact of a thermosyphon domestic solar hot water system in comparison with electrical and gas water heating shows that these systems have improved LCA indices over electrical heaters, but the net gain is reduced by a factor of four when the primary energy source is natural gas instead of electricity (Tsilingiridis et al., 2004).

With regard to complete solar domestic hot water systems, the energy payback time requires accounting for any difference in the size of the hot water storage tank compared to the non-solar system and the energy used to manufacture the tank (Harvey, 2006). It is reported that the energy payback time for a solar/gas system in southern Australia is 2 to 2.5 years, despite the embodied energy being 12 times that of a tankless system. For an integrated thermosyphon flat-plate solar collector and storage device operating in Palermo (Italy), a payback time of 1.3 to 4.0 years is reported (Harvey, 2006).

PV systems do not generate any type of solid, liquid or gaseous byproducts when producing electricity. Also, they do not emit noise or use non-renewable resources during operation. However, two topics are often considered: 1) the emission of pollutants and the use of energy during the full lifecycle of PV manufacturing, installation, operation and maintenance (O&M) and disposal; and 2) the possibility of recycling the PV module materials when the systems are decommissioned.

Starting with the latter concern, the PV industry uses some toxic, explosive gases, GHGs, as well as corrosive liquids, in its production lines. The presence and amount of those materials depend strongly on the cell type (see Section 3.3.3). However, the intrinsic needs of the production process of the PV industry force the use of quite rigorous control methods that minimize the emission of potentially hazardous elements during module production.

Recycling the material in PV modules is already economically viable, mainly for concentrated and large-scale applications. Projections are that between 80 and 96% of the glass, ethylene vinyl acetate, and metals (Te, selenium and lead) will be recycled. Other metals, such as Cd, Te, tin, nickel, aluminium and Cu, should be saved or they can be recycled by other methods. For discussions of Cd, for example, see Sinha et al. (2008), Zayed and Philippe (2009) and Wadia et al. (2009).

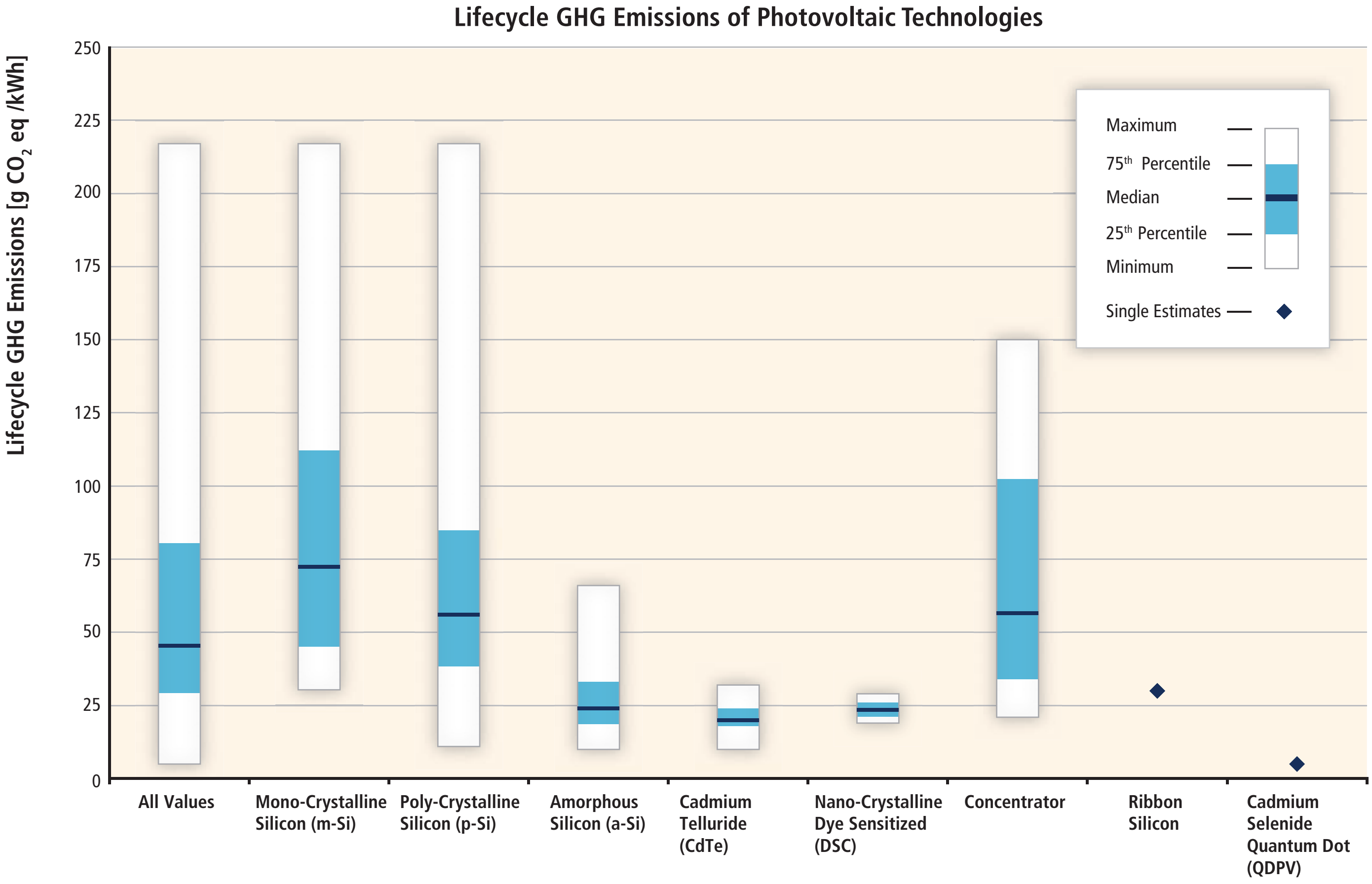
It is noted that, in certain locations, periodic cleaning of the PV panels may be necessary to maintain performance, resulting in non-negligible water requirements.

With respect to lifecycle GHG emissions, Figure 3.14 shows the result of a comprehensive literature review of PV-related lifecycle assessment (LCA) studies published since 1980 conducted by the National Renewable Energy Laboratory. The majority of lifecycle GHG emission estimates cluster between about 30 and 80 g CO_2eq/kWh, with potentially important outliers at greater values (Figure 3.14). Note that the distributions shown in Figure 3.14 do not represent an assessment of likelihood; the figure simply reports the distribution of currently published literature estimates passing screens for quality and relevance. Refer to Annex II for a description of literature search methods and complete reference list, and Section 9.3.4.1 for further details on interpretation of LCA data. Variability in estimates stems from differences in study context (e.g., solar resource, technological vintage), technological performance (e.g., efficiency, silicon thickness) and methods (e.g., LCA system boundaries). Efforts to harmonize the methods and assumptions of these studies are recommended such that more robust estimates of central tendency and variability can be realized, as well as a better understanding of the upper-quartile estimates. Further LCA studies are also needed to increase the number of estimates for some technologies (e.g., CdTe).

As for the energy payback of PV (see also Box 9.3), Perpinan et al. (2009) report paybacks of 2.0 and 2.5 years for microcrystalline silicon and monocrystalline silicon PV, respectively, taking into account use in locations with moderate solar irradiation levels of around 1,700 kWh/m^2/yr (6,120 MJ/m^2/yr). Fthenakis and Kim (2010) show payback times of grid-connected PV systems that range from 2 to 5 years for locations with global irradiation ranges from 1,900 to 1,400 kWh/m^2/yr (6,840 MJ/m^2/yr).

For CSP plants, the environmental consequences vary depending on the technology. In general, GHG emissions and other pollutants are reduced without incurring additional environmental risks. Each square metre of CSP concentrator surface is enough to avoid the annual production of 0.25 to 0.4 t of CO_2. The energy payback time of CSP systems can be as low as five months, which compares very favourably with their lifespan of about 25 to 30 years (see Box 9.3 for further discussion). Most CSP solar field materials can be recycled and reused in new plants (SolarPACES, 2008).

Land consumption and impacts on local flora and wildlife during the build-up of the heliostat field and other facilities are the main environmental issues for CSP systems (Pregger et al., 2009). Other impacts are associated with the construction of the steel-intensive infrastructure for solar energy collection due to mineral and fossil resource consumption,



	All Values	Mono-Crystalline Silicon (m-Si)	Poly-Crystalline Silicon (p-Si)	Amorphous Silicon (a-Si)	Cadmium Telluride (CdTe)	Nano-Crystalline Dye Sensitized (DSC)	Concentrator	Ribbon Silicon	Cadmium Selenide Quantum Dot (QDPV)
Estimates:	124	30	56	12	13	4	6	2*	1
References:	26	9	15	3	3	1	2	2	1

*same value

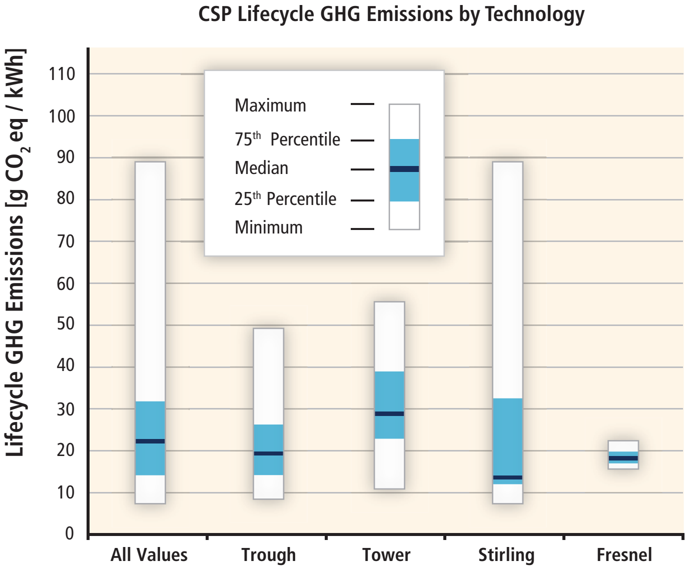
Figure 3.14 | Lifecycle GHG emissions of PV technologies (unmodified literature values, after quality screen). See Annex II for details of the literature search and citations of literature contributing to the estimates displayed.

as well as discharge of pollutants related to today's steel production technology (Felder and Meier, 2008).

The cost of land generally represents a very minor cost proportion of the whole plant. A 100-MW CSP plant with a solar multiple of one (see Section 3.3.4) would require 2 km^2 of land. However, the land does need to be relatively flat (particularly for linear trough and Fresnel systems), ideally near transmission lines and roads for construction traffic, and not on environmentally sensitive land. Although the mirror area itself is typically only about 25 to 35% of the land area occupied, the site of a solar plant will usually be arid. Thus, it is generally not suitable for other agricultural pursuits, but may still have protected or sensitive species. For this kind of system, sunny deserts close to electricity infrastructure are ideal. As CSP plant capacity is increased, however, the economics of longer electricity transmission distances improves. So, more distant siting might be expected with according increases in transmission infrastructure needs. Attractive sites exist in many regions of the world, including southern Europe, northern and southern African countries, the Middle East, Central Asian countries, China (Tibet, Xinjan), India (Rajasthan and Gujarat states), Australia, Chile, Peru, Mexico and south-western USA.

In the near term, water availability may be important to minimize the cost of Rankine cycle-based CSP systems. Water is also needed for steam-cycle make-up and mirror cleaning, although these two uses represent only a few percent of that needed if wet cooling is used. However, there will be otherwise highly favourable sites where water is not available for cooling. In these instances, water use can be substantially reduced if dry or hybrid cooling is used, although at an additional cost. The additional cost of electricity from a dry-cooled plant is 2 to 10% (US DOE, 2009), although it depends on many factors such as ambient conditions and technology, for example, tower plants operating at higher temperatures require less cooling per MWh than troughs. Tower and dish Brayton and Stirling systems are being developed for their ability to operate efficiently without cooling water.

In a manner similar to that for PV, NREL conducted an analogous search for CSP lifecycle assessments. Figure 3.15 displays distributions



	All Values	Trough	Tower	Stirling	Fresnel
Estimates:	42	20	14	4	4
References:	13	7	5	3	1

Figure 3.15 | Lifecycle GHG emissions of CSP technologies (unmodified literature values, after quality screen). See Annex II for details of literature search and citations of literature contributing to the estimates displayed.

of as-published estimates of lifecycle GHG emissions. The majority of estimates fall between 14 and 32 g CO_2eq/kWh for trough, tower, Stirling and Fresnel systems, and no great difference between technologies emerges from the available literature. Less literature is available to evaluate CSP systems than for some PV designs; however, the current state of knowledge of lifecycle GHG emissions for these technologies appears fairly consistent, although augmentation with additional LCAs is recommended.

In *solar fuel production*, solar thermal processes use concentrated solar irradiance as the main or sole source of high-temperature process heat. Such a plant consists of a central-receiver system comprising a heliostat field focusing direct solar irradiance on a receiver mounted on a tower. The receiver comprises a chemical reactor or a heat-exchanging device. Direct CO_2 emissions released by the thermochemical processes are negligible or significantly lower than from current processes (Pregger et al., 2009). All other possible effects are comparable to the conventional processes or can be prevented by safety measures and equipment that are common practice in the chemical industry.

3.6.2 Social impacts

Solar energy has the potential to meet rising energy demands and decrease GHG emissions, but solar technologies have faced resistance due to public concerns among some groups. The land area requirements for centralized CSP and PV plants raise concerns about visual impacts, which can be minimized during the siting phase by choosing locations in areas with low population density, although this will usually be the case for suitable solar sites anyway. Visual concerns also exist for distributed solar systems in built-up areas, which may find greater resistance for applications on historical or cultural buildings versus modern construction. By avoiding conservation areas and incorporating solar technologies into building design, these conflicts can be minimized. Noise impacts may be of concern in the construction phase, but impacts can be mitigated in the site-selection phase and by adopting good work practices (Tsoutsos et al., 2005). Community engagement throughout the planning process of renewable projects can also significantly increase public acceptance of projects (Zoellner et al., 2008).

Increased deployment of consumer-purchased systems still faces barriers with respect to costs, subsidy structures that may be confusing, and misunderstandings about reliability and maintenance requirements (Faiers and Neame, 2006). Effective marketing of solar technologies—including publicizing impacts relative to traditional power generation facilities, environmental benefits and contribution to a secure energy supply—have helped to accelerate social acceptance and increase willingness to pay (Batley et al., 2001). Government spending on solar technologies through fiscal incentives and R&D could garner increased public support through increased quantification and dissemination of the economic impacts associated with those programs. A recent study comparing job impacts across energy technologies showed that solar PV had the greatest job-generating potential at an average of 0.87 job-years per GWh, whereas CSP yielded an average of 0.23 job-years per GWh, both of which exceeded estimated job creation for fossil technologies (Wei et al., 2010). Section 9.3.1 discusses qualifications and limitations of assessing the job market impact of RE.

Solar technologies can also improve the health and livelihood opportunities for many of the world's poorest populations. Solar technologies have the potential to address some of the gap in availability of modern energy services for the roughly 1.4 billion people who do not have access to electricity and the more than 2.7 billion people who rely on traditional biomass for home cooking and heating needs (IEA, 2010d; see Section 9.3.2).

Solar home systems and PV-powered community grids can provide economically favourable electricity to many areas for which connection to a main grid is impractical, such as in remote, mountainous and delta regions. Electric lights are the most frequently owned and operated household appliance in electrified households, and access to electric lighting is widely accepted as the principal benefit of electrification programs (Barnes, 1988). Electric lighting may replace light supplied by kerosene lanterns, which are generally associated with poor-quality light and high household fuel expenditures, and which pose fire and poisoning risks. The improved quality of light allows for increased reading by household members, study by children, and home-based enterprise activities after dark, resulting in increased education and income opportunities for the household. Higher-quality light can also be provided through solar lanterns, which can afford the same benefits achieved through solar home system-generated lighting. Solar lantern models can be stand-alone or can require central-station charging, and programs of manufacture, distribution and maintenance can provide micro-enterprise opportunities. Use of solar lighting can represent a significant cost savings to households over the lifetime of the technology compared to kerosene, and it can reduce the 190 Mt of estimated annual CO_2 emissions attributed to fuel-based lighting (Mills, 2005). Solar-powered street lights and lights for community buildings can increase security and safety and provide night-time gathering locations for classes or community meetings. PV systems have been effectively deployed in disaster situations to provide safety, care and comfort to victims in the USA and Caribbean and could be similarly deployed worldwide for crisis relief (Young, 1996).

Solar home systems can also power televisions, radios and cellular telephones, resulting in increased access to news, information and distance education opportunities. A study of Bangladesh's Rural Electrification Program revealed that in electrified households all members are more knowledgeable about public health issues, women have greater knowledge of family planning and gender equality issues, the income and gender discrepancies in adult literacy rates are lower, and immunization guidelines for children are adhered to more regularly when compared with non-electrified households (Barkat et al., 2002). Electrified households may also buy appliances such as fans, irons, grinders, washing machines and refrigerators to increase comfort and reduce the drudgery associated with domestic tasks (ESMAP, 2004).

Indoor smoke from solid fuels is responsible for more than 1.6 million deaths annually and 3.6% of the global burden of disease. This mortality rate is similar in scale to the 1.7 million annual deaths associated with unsafe sanitation and more than twice the estimated 0.8 million yearly deaths from exposure to urban air pollution (Ezzati et al., 2002; see Sections 9.3.2 and 9.3.4.3). In areas where solar cookers can satisfactorily produce meals, these cookers can reduce unhealthy exposure to high levels of particulate matter from traditional use of solid fuels for cooking and heating and the associated morbidity and mortality from respiratory and other diseases. Decreased consumption of firewood will correspondingly reduce the time women spend collecting firewood. Studies in India and Africa have collected data showing that this time can total 2 to 15 hours per week, and this is increasing in areas of diminishing fuelwood supply (Brouwer et al., 1997; ESMAP, 2004). Risks to women collecting fuel include injury, snake bites, landmines and sexual violence (Manuel, 2003; Patrick, 2007); when children are enlisted to help with this activity, they may do so at the expense of educational opportunities (Nankhuni and Findeis, 2004). Well-being may be acutely at risk in refugee situations, as are strains on the natural resource systems where fuel is collected (Lynch, 2002). Solar cookers do not generally fulfil all household cooking needs due to technology requirements or their inability to cook some traditional foods; however, even partial use of solar cookers can realize fuelwood savings and reductions in exposure to indoor air pollution (Wentzel and Pouris, 2007).

Solar technologies also have the potential to combat other prevalent causes of morbidity and mortality in poor, rural areas. Solar desalination and water purification technologies can help combat the high prevalence of diarrhoeal disease brought about by lack of access to potable water supplies. PV systems for health clinics can provide refrigeration for vaccines and lights for performing medical procedures and seeing patients at all hours. Improved working conditions for rural health-care workers can also lead to decreased attrition of talented staff to urban centres.

Solar technologies can improve the economic opportunities and working conditions for poor rural populations. Solar dryers can be used to preserve foods and herbs for consumption year round and produce export-quality products for income generation. Solar water pumping can minimize the need for carrying water long distances to irrigate crops, which can be particularly important and impactful in the dry seasons and in drought years. Burdens and risks from water collection parallel those of fuel collection, and decreased time spent on this activity can also increase the health and well-being of women, who are largely responsible for these tasks.

3.7 Prospects for technology improvements and innovation[7]

This section considers technical innovations that are possible in the future for a range of solar technologies, under the following headings: passive solar and daylighting technologies; active solar heat and cooling; PV electricity generation; CSP electricity generation; solar fuel production; and other possible applications.

3.7.1 Passive solar and daylighting technologies

Passive solar technologies, particularly the direct-gain system, are intrinsically highly efficient because no energy is needed to move collected energy to storage and then to a load. The collection, storage and use are all integrated. Through technological advances such as low-emissivity coatings and the use of gases such as argon in glazings, near-equatorial-facing windows have reached a high level of performance at increasingly affordable cost. Nevertheless, in heating-dominated climates, further advances are possible, such as the following: 1) reduced thermal conductance by using dynamic exterior night insulation (night shutters); 2) use of evacuated glazing units; and 3) translucent glazing systems, which may include materials that change solar/visible transmittance with temperature (including a

---

[7] Section 10.5 offers a complementary perspective on drivers and trends of technological progress across RE technologies.

possible phase change) while providing increased thermal resistance in the opaque state.

Increasingly larger window areas become possible and affordable with the drop in prices of highly efficient double-glazed and triple-glazed low-emissivity argon-filled windows (see Sections 3.4.1 and 3.4.2). These increased window areas make systematic solar gain control essential in mild and moderate climatic conditions, but also in continental areas that tend to be cold in winter and hot in summer. Solar gain control techniques may increasingly rely on active systems such as automatically controlled blinds/shades or electrochromic, thermochromic and gasochromic coatings to admit the solar gains when they are desirable or keep them out when overheating in the living space is detected or anticipated. Solar gain control, thermal storage design and heating/cooling system control are three strongly linked aspects of passive solar design and control.

Advances in thermal storage integrated in the interior of direct-gain zones are still possible, such as phase-change materials integrated in gypsum board, bricks, or tiles and concrete. The target is to maximize energy storage per unit volume/mass of material so that such materials can be integrated in lightweight wood-framed homes common in cold-climate areas. The challenge for such materials is to ensure that they continue to store and release heat effectively after 10,000 cycles or more while meeting other performance requirements such as fire resistance. Phase-change materials may also be used systematically in plasters to reduce high indoor temperatures in summer.

Considering cooling-load reduction in solar buildings, advances are possible in areas such as the following: 1) cool-roof technologies involving materials with high solar reflectivity and emissivity; 2) more systematic use of heat-dissipation techniques such as using the ground and water as a heat sink; 3) advanced pavements and outdoor structures to improve the microclimate around the buildings and decrease urban ambient temperatures; and 4) advanced solar control devices allowing penetration of daylight, but not thermal energy.

In any solar building, there are normally some direct-gain zones that receive high solar gains and other zones behind that are generally colder in winter. Therefore, it is beneficial to circulate air between the direct-gain zones and back zones in a solar home, even when heating is not required. With forced-air systems commonly used in North America, this is increasingly possible and the system fan may be run at a low flow rate when heating is not required, thus helping to redistribute absorbed direct solar gains to the whole house (Athienitis, 2008).

During the summer period, hybrid ventilation systems and techniques may be used to provide fresh air and reduce indoor temperatures (Heiselberg, 2002). Various types of hybrid ventilation systems have been designed, tested and applied in many types of buildings. Performance tests have found that although natural ventilation cannot maintain appropriate summer comfort conditions, the use of a hybrid system is the best choice—using at least 20% less energy than any purely mechanical system.

Finally, design tools are expected to be developed that will facilitate the simultaneous consideration of passive design, daylighting, active solar gain control, heating, ventilation and air-conditioning (HVAC) system control, and hybrid ventilation at different stages of the design of a solar building. Indeed, systematically adopting these technologies and their optimal integration is essential to move towards the goal of cost-effective solar buildings with net-zero annual energy consumption (IEA, 2009b). Optimal integration of passive with active technologies requires smart buildings with optimized energy generation and use (Candanedo and Athienitis, 2010). A smart solar house would rely on predictions of the weather to optimally control solar gains and their storage, ensure good thermal comfort, and optimize its interaction with the electricity grid, applying a mixture of inexpensive and effective communications systems and technologies (see Section 8.2.1).

3.7.2 Active solar heating and cooling

Improved designs for solar heating and cooling systems are expected to address longer lifetimes, lower installed costs and increased temperatures. The following are some design options: 1) the use of plastics in residential solar water-heating systems; 2) powering air-conditioning systems using solar energy systems, especially focusing on compound parabolic concentrating collectors; 3) the use of flat-plate collectors for residential and commercial hot water; and 4) concentrating and evacuated-tube collectors for industrial-grade hot water and thermally activated cooling (see Section 3.3.4).

Heat storage represents a key technological challenge, because the wide deployment of active solar buildings, covering 100% of their demand for heating (and cooling, if any) with solar energy, largely depends on developing cost-effective and practical solutions for seasonal heat storage (Hadorn, 2005; Dincer and Rosen, 2010). The European Solar Thermal Technology Platform vision assumes that by 2030, heat storage systems will be available that allow for seasonal heat storage with an energy density eight times higher than water (ESTTP, 2006).

In the future, active solar systems—such as thermal collectors, PV panels, and PV-thermal systems—will be the obvious components of roof and façades, and will be integrated into the construction process at the earliest stages of building planning. The walls will function as a component of the active heating and cooling systems, supporting thermal energy storage by applying advanced materials (e.g., phase-change materials). One central control system will lead to optimal regulation of the whole HVAC system, maximizing the use of solar energy within the comfort parameters set by users. Heat- and cold-storage systems will play an increasingly important role in reaching maximum solar thermal contributions to cover the thermal requirements in buildings.

Solar-assisted air-conditioning technology is still in an early stage of development (Henning, 2007). However, increased efforts in technological development will help to increase the competitiveness of this technology in the future. The major trends are as follows:

- Research in providing thermally driven cooling equipment in the low cooling power range (less than 20 kW);
- Developing single-effect cycles with increased COP values at low driving temperatures;
- Studying new approaches to enhance heat transfer in compartments containing sorption material to improve the power density and thermal performance of adsorption chillers;
- Developing new schemes and new working fluids for steam jet cycles and promising candidates for closed cycles to produce chilled water; and
- Research activities on cooled open sorption cycles for solid and liquid sorbents.

3.7.3 Photovoltaic electricity generation

This subsection discusses photovoltaic technology improvements and innovation within the areas of solar PV cells and the entire PV system. Photovoltaic modules are the basic building blocks of flat-plate PV systems. Further technological efforts will likely lead to reduced costs, enhanced performance and improved environmental profiles. It is useful to distinguish between technology categories that require specific R&D approaches.

Funding of PV R&D over the past four decades has supported innovation and gains in PV cell quality, efficiencies and price. In 2008, public budgets for R&D programs in the IEA Photovoltaic Power Systems Programme countries collectively reached about USD_{2005} 390 million (assumed 2008 base), a 30% increase compared to 2007, but stagnated in 2009 (IEA, 2009c, 2010e).

For wafer-based crystalline silicon, existing thin-film technologies, and emerging and novel technologies (including ‘boosters’ to the first two categories), the following paragraphs list R&D topics that have highest priority. Further details can be found in the various PV roadmaps, for example, the Strategic Research Agenda for Photovoltaic Solar Energy Technology (US Photovoltaic Industry Roadmap Steering Committee, 2001; European Commission, 2007; NEDO, 2009).

- **Efficiency, energy yield, stability and lifetime.** Research often aims at optimizing rather than maximizing these parameters, which means that additional costs and gains are critically compared. Because research is primarily aimed at reducing the cost of electricity generation, it is important not to focus only on initial costs (USD/W_p), but also on lifecycle gains, that is, actual energy yield (kWh/W_p or kJ/W_p over the economic or technical lifetime).
- **High-productivity manufacturing, including in-process monitoring and control.** Throughput and yield are important parameters in low-cost manufacturing and essential to achieve the cost targets. In-process monitoring and control are crucial tools to increase product quality and yield. Focused effort is needed to bring PV manufacturing to maturity.
- **Environmental sustainability.** The energy and materials requirements in manufacturing, as well as the possibilities for recycling, are important parameters in the overall environmental quality of the product. Further shortening of the energy payback time, design for recycling and, ideally, avoiding the use of materials that are not abundant on Earth are the most important issues to be addressed.
- **Applicability.** As discussed in more detail in the paragraphs on BOS and systems, standardization and harmonization are important to bring down the investment costs of PV. Some related aspects are addressed on a module level. In addition, improved ease of installation is partially related to module features. Finally, aesthetic quality of modules (and systems) is an important aspect for large-scale use in the built environment.

Advanced technologies include those that have passed some proof-of-concept phase or can be considered as 10- to 20-year development options for the PV approaches discussed in Section 3.3.3 (Green, 2001, 2003; Nelson, 2003). These emerging PV concepts are medium to high risk and are based on extremely low-cost materials and processes with high performance. Examples are four- to six-junction concentrators (Marti and Luque, 2004; Dimroth et al., 2005), multiple-junction polycrystalline thin films (Coutts et al., 2003), crystalline silicon in the sub-100-µm-thick regime (Brendel, 2003), multiple-junction organic PV (Yakimov and Forrest, 2002; Sun and Sariciftci, 2005) and hybrid solar cells (Günes and Sariciftci, 2008).

Even further out on the timeline are concepts that offer exceptional performance and/or very low cost but are yet to be demonstrated beyond some preliminary stages. These technologies are truly high risk, but have extraordinary technical potential involving new materials, new device architectures and even new conversion concepts (Green, 2001, 2003; Nelson, 2003). They go beyond the normal Shockley-Queisser limits (Shockley and Queisser, 1961) and may include biomimetic devices (Bar-Cohen, 2006), quantum dots (Conibeer et al., 2010), multiple-exciton generation (Schaller and Klimov, 2004; Ellingson et al., 2005) and plasmonic solar cells (Catchpole and Polman, 2008).

PV concentrator systems are considered a separate category, because the R&D issues are fundamentally different compared to flat-plate technologies. As mentioned in Section 3.3.3, CPV offers a variety of technical solutions that are provided at the system level. Research issues can be divided into the following activities: 1) concentrator solar cell manufacturing; 2) optical system; 3) module assembly and fabrication method of concentrator modules and systems; and 4) system aspects, such as tracking, inverter and installation issues.

However, it should be clearly stated once more: CPV is a system approach. The whole system is optimized only if all the interconnections between the components are considered. A corollary is that an optimized component is not necessarily the best choice for the optimal CPV system. Thus, strong interactions are required among the various research groups.

A photovoltaic system is composed of the PV module, as well as the *balance-of-system components and system*, which can include an inverter, storage, charge controller, system structure and the energy network. Users meet PV technology at the system level, and their interest is in a reliable, cost-effective and attractive solution to their energy supply needs. This research agenda concentrates on topics that will achieve one or more of the following: 1) reduce costs at the component and/or system level; 2) increase the overall performance of the system, including increased and harmonized component lifetimes, reduced performance losses and maintenance of performance levels throughout system life; and 3) improve the functionality of and services provided by the system, thus adding value to the electricity produced (US Photovoltaic Industry Roadmap Steering Committee, 2001; Navigant Consulting Inc., 2006; EU PV European Photovoltaic Technology Platform, 2007; Kroposki et al., 2008; NEDO, 2009).

At the component level, a major objective of BOS development is to extend the lifetime of BOS components for grid-connected applications to that of the modules, typically 20 to 30 years.

For off-grid systems, component lifetime should be increased to around 10 years, and components for these systems need to be designed so that they require little or no maintenance. Storage devices are necessary for off-grid PV systems and will require innovative approaches to the short-term storage of small amounts of electricity (1 to 10 kWh, or 3,600 to 36,000 kJ), and for providing a single streamlined product (such as integrating the storage component into the module) that is easy to use in off-grid and remote applications.

For on-grid systems, high penetration of distributed PV may raise concerns about potential impacts on the stability and operation of the grid, and these concerns may create barriers to future expansion (see also Section 8.2.1). An often-cited disadvantage is the greater sensitivity to grid interconnection issues such as overvoltage and unintended islanding in the low- or middle-voltage network (Kobayashi and Takasaki, 2006; Cobben et al., 2008; Ropp et al., 2008). Moreover, imbalance between demand and supply is often discussed with respect to the variation of PV system output (Braun et al., 2008; NEDO, 2009; Piwko et al., 2010). PV system designs and operation technologies can address these issues to a degree through technical solutions and through more accurate solar energy forecasting. Moreover, PV inverters can help to improve the quality of grid electricity by controlling reactive power or filtering harmonics with communication in a new energy network that applies a mixture of inexpensive and effective communications systems and technologies, including smart meters (see Section 8.2.1).

As new module technologies emerge in the future, some ideas relating to BOS, such as micro-converters, may need to be revised. Furthermore, the quality of the system needs to be assured and adequately maintained according to defined standards, guidelines and procedures. To assure system quality, assessing performance is important, including on-line analysis (e.g., early fault detection) and off-line analysis of PV systems. The gathered knowledge can help to validate software for predicting the energy yield of future module and system technology designs.

Furthermore, very-large-scale PV systems with capacities ranging from several MW to GW are beginning to be planned for deployment (Komoto et al., 2009). In the long term, these systems may play an important role in the worldwide energy network (DESERTEC Foundation, 2007), but may demand new transmission infrastructure and new technical and institutional solutions for electricity system interconnection and operational management.

Standards, quality assurance, and safety and environmental aspects are other important issues. National and especially local authorities and utilities require that PV systems meet agreed-upon standards (such as building standards, including fire and electrical safety requirements). In a number of cases, the development of the PV market is being hindered by either: 1) existing standards, 2) differences in local standards (e.g., inverter requirements/settings) or 3) the lack of standards (e.g., PV modules/PV elements not being certified as a building element because of the lack of an appropriate standard). Standards and/or guidelines are required for the whole value chain. In many cases, developing new and adapted standards and guidelines implies that dedicated R&D is required.

Quality assurance is an important tool that assures the effective functioning of individual components in a PV system, as well as the PV system as a whole. Standards and guidelines are an important basis for quality assurance. In-line production control procedures and guidelines must also be developed. At the system level, monitoring techniques must be developed for early fault detection.

Recycling is an important building block to ensure a sustainable PV industry. Through 2010, most attention has focused on recycling crystalline silicon and CdTe solar modules. Methods for recycling other thin-film modules and BOS components (where no recycling procedures exist) must be addressed in the future. LCA studies are an important tool for evaluating the environmental profile of the various RE sources. Reliable LCA data are required to assure the position of PV with respect to other sources. From these data, properties such as the CO_2 emission per kWh or kJ of electricity produced and the energy payback time can be calculated. In addition, the results of LCA analyses can be used in the design phase of new processes and equipment for cell and module production lines.

3.7.4 Concentrating solar power electricity generation

CSP is a proven technology at the utility scale. The longevity of components has been established over two decades, O&M aspects are understood, and there is enough operational experience to have enabled O&M cost-reduction studies not only to recommend, but also to test, those improvements. In addition, field experience has been fed back to industry and research institutes and has led to improved components and more advanced processes. Importantly, there is now substantial experience that allows researchers and developers to better understand the limits of performance, the likely potential for cost reduction, or both. Studies (Sargent and Lundy LLC Consulting Group, 2003) have concluded that cost reductions will come from technology improvement, economies of scale and mass production. Other innovations related to power cycles and collectors are discussed below.

CSP is a technology driven largely by thermodynamics. Thus, the *thermal energy conversion cycle* plays a critical role in determining overall performance and cost. In general, thermodynamic cycles with higher temperatures will perform more efficiently. Of course, the solar collectors that provide the higher-temperature thermal energy to the process must be able to perform efficiently at these higher temperatures, and today, considerable R&D attention is on increasing the operating temperature of CSP systems. Although CSP works with turbine cycles used by the fossil-fuel industry, there are opportunities to refine turbines such that they can better accommodate the duties associated with thermal cycling invoked by solar inputs.

Considerable development is taking place to optimize the linkage between solar collectors and higher-temperature thermodynamic cycles. The most commonly used power block to date is the steam turbine (Rankine cycle). The steam turbine is most efficient and most cost effective in large capacities. Present trough plants using oil as the heat transfer fluid limit steam turbine temperatures to 370°C and turbine cycle efficiencies to around 37%, leading to design-point solar-to-electric efficiencies of the order of 18% and annual average efficiency of 14%. To increase efficiency, alternatives to the use of oil as the heat transfer fluid—such as producing steam directly in the receiver or using molten salts—are being developed for troughs.

These fluids and others are already preferred for central receivers. Central receivers and dishes are capable of reaching the upper temperature limits of these fluids (around 600°C for present molten salts) for advanced steam turbine cycles, whether subcritical or supercritical, and they can also provide the temperatures needed for higher-efficiency cycles such as gas turbines (Brayton cycle) and Stirling engines. Such high-temperature cycles have the capacity to boost design-point solar-to-electricity efficiency to 35% and annual average efficiency to 25%. The penalty for dry cooling is also reduced, and at higher temperatures thermal storage is more efficient.

The *collector* is the single largest area for potential cost reduction in CSP plants. For CSP collectors, the objective is to lower their cost while achieving the higher optical efficiency necessary for powering higher-temperature cycles. Trough technology will benefit from continuing advances in solar-selective surfaces, and central receivers and dishes will benefit from improved receiver/absorber design that allows collection of very high solar fluxes. Linear Fresnel is attractive in part because the inverted-cavity design can reduce some of the issues associated with the heat collection elements of troughs, although with reduced annual optical performance.

Improved overall efficiency yields a corresponding decrease in the area of mirrors needed in the field, and thus, lower collector cost and lower O&M cost. Investment cost reduction is expected to come primarily from the benefits of mass production of key components that are specific to the solar industry, and from economies of scale as the fixed price associated with manufacturing tooling and installation is spread over larger and larger capacities. In addition, the benefits of 'learning by doing' cannot be overestimated. A more detailed assessment of future technology improvements that would benefit CSP can be found in ECOSTAR (2005), a European project report edited by the German Aerospace Center.

3.7.5 Solar fuel production

The ability to store solar energy in the form of a fuel may be desirable not only for the transportation industry, but also for high-efficiency electricity generation using today's combined cycles, improved combined cycles using advances in gas turbines, and fuel cells. In addition, solar fuels offer a form of storage for solar electricity generation.

Future solar fuel processes will benefit from the continuing development of high-temperature solar collectors, but also from other fields of science such as electrochemistry and biochemistry. Many researchers consider hydrogen to offer the most attraction for the future, although intermediate and transitional approaches are also being developed. Hydrogen is considered in this section, with other solar fuels having been covered in previous sections.

Future technology innovation for solar electrolysis is the photoelectrochemical (PEC) cell, which converts solar irradiance into chemical energy such as H_2. A PEC cell is fabricated using an electrode that absorbs the solar light, two catalytic films, and a membrane separating H_2 and oxygen (O_2). Semiconductor material can be used as a solar light-absorbing anode in PEC cells (Bolton, 1996; Park and Holt, 2010).

Promising *thermochemical* processes for future 'clean' hydrogen mass production encompass the hybrid-sulphur cycle and metal oxide-based cycles. The hybrid-sulphur cycle is a two-step water-splitting process using an electrochemical, instead of thermochemical, reaction for one of the two steps. In this process, sulphur dioxide depolarizes the anode of the electrolyzer, which results in a significant decrease in the reversible cell potential—and, therefore, the electric power requirement for the electrochemical reaction step. A number of solar reactors applicable to solar thermochemical metal oxide-based cycles have been developed, including a 100-kW_{th} monolithic dual-chamber solar reactor for a mixed-iron-oxide cycle, demonstrated within the European R&D project *HYDROSOL-2* (Roeb et al., 2009); a rotary solar reactor for the ZnO/Zn process being scaled up to 100 kW_{th} (Schunk et al., 2009); the Tokyo Tech rotary-type solar reactor (Kaneko et al., 2007); and the Counter-Rotating-Ring Receiver/Reactor/Recuperator, a device using recuperation of sensible heat to efficiently produce H_2 in a two-step thermochemical process (Miller et al., 2008).

High temperatures demanded by the thermodynamics of the thermochemical processes pose considerable material challenges and also increase re-radiation losses from the reactor, thereby lowering the absorption efficiency (Steinfeld and Meier, 2004). The overall energy conversion efficiency is improved by reducing thermal losses at high temperatures through improved mirror optics and cavity-receiver design, and by recovering part of the sensible heat from the thermochemical processes.

High-temperature thermochemical processes require thermally and chemically stable reactor-wall materials that can withstand the extreme operating conditions of the various solar fuel production processes. For many lower-temperature processes (e.g., sulphur-based thermochemical cycles), the major issue is corrosion. For very high-temperature metal-oxide cycles, the challenge is the thermal shock resistance of the ceramic wall materials. Near-term solutions include surface modification of thermally compatible refractory materials such as graphite and silicon carbide. Longer-term solutions include modifications of bulk materials. Novel reactor designs may prevent wall reactions.

A key aspect is integrating the chemical process into the solar concentrating system. The concentrating optics—consisting of heliostats and secondary concentrators (compound parabolic concentrator)—need to be further developed and specifically optimized to obtain high solar-flux intensities and high temperatures in solar chemical reactors for producing fuels.

Photochemical and photobiological processes are other strong candidates for solar fuel conversion. Innovative technologies are being developed for producing biofuels from modified photosynthetic microorganisms and photocatalytic cells for fuel production. Both approaches have the potential to provide fuels with solar energy conversion efficiencies far greater than those based on field crops (Turner et al., 2008). Solar-driven fuel production requires biomimetic nanotechnology, where scientists must develop a series of fundamental and technologically advanced multi-electron redox catalysts coupled to photochemical elements. Hydrogen production by these methods at scale has vast technical potential and promising avenues are being vigorously pursued.

A combination of all three forms is found in the *synthesis of biogas*, a mixture of methane and CO_2, with solar-derived hydrogen. Solar hydrogen is added by electrochemical water-splitting. Bio-CO_2 reacts with hydrogen in a thermochemical process to generate hydrocarbons such as synthetic natural gas or liquid solar fuels (Sterner, 2009). These approaches are still nascent, but could become viable in the future as energy market prices increase and solar power generation costs continue to decrease.

3.7.6 Other potential future applications

There are also methods for producing electricity from solar thermal energy without the need for an intermediate thermodynamic cycle. This direct solar thermal power generation includes such concepts as thermoelectric, thermionic, magnetohydrodynamic and alkali-metal methods. The thermoelectric concept is the most investigated to date, and all have the attraction that the absence of a heat engine should mean a quieter and theoretically more efficient method of producing electricity, with suitability for distributed generation. Specialized applications include military and space power.

Space-based solar power (SSP) is the concept of collecting vast quantities of solar power in space using large satellites in Earth orbit, then sending that power to receiving antennae (rectennae) on Earth via microwave power beaming. The concept was first introduced in 1968 by Peter Glaser. NASA and the US Department of Energy (US DOE) studied SSP extensively in the 1970s as a possible solution to the energy crisis of that time. Scientists studied system concepts for satellites large enough to send GW of power to Earth and concluded that the concept seemed technically feasible and environmentally safe, but the state of enabling technologies was insufficient to make SSP economically competitive. Since the 1970s, however, great advances have been made in these technologies, such as high-efficiency PV cells, highly efficient solid-state microwave power electronics, and lower-cost space launch vehicles (Mankins, 1997, 2002, 2009; Kaya et al., 2001; Hoffert et al., 2002). Still, significant breakthroughs will be required to achieve cost-competitive terrestrial base-load power (NAS, 2004).

3.8 Cost trends[8]

3.8.1 Passive solar and daylighting technologies

High-performance building envelopes entail greater upfront construction costs, but lower energy-related costs during the lifetime of the building (Harvey, 2006). The total investment cost of the building may or may not be higher, depending on the extent to which heating and cooling systems can be downsized, simplified or eliminated altogether as a result of the high-performance envelope. Any additional investment cost will be compensated for, to some extent, by reduced energy costs over the lifetime of the building.

---

[8] Discussion of costs in this section is largely limited to the perspective of private investors. Chapters 1 and 8 to 11 offer complementary perspectives on cost issues covering, for example, costs of integration, external costs and benefits, economy-wide costs and costs of policies.

The reduction in the cost of furnaces or boilers due to substantially better thermal envelopes is normally only a small fraction of the additional cost of the better thermal envelope. However, potentially larger cost savings can occur through downsizing or eliminating other components of the heating system, such as ducts to deliver warm air or radiators (Harvey, 2006). High-performance windows eliminate the need for perimeter heating. A very high-performance envelope can reduce the heating load to that which can be met by ventilation airflow alone. High-performance envelopes also lead to a reduction in peak cooling requirements, and hence, in cooling equipment sizing costs, and they permit use of a variety of passive and low-energy cooling techniques.

If a fully integrated design takes advantage of all opportunities facilitated by a high-performance envelope, savings in the cost of mechanical systems may offset all or much of the additional cost of the high-performance envelope.

In considering daylighting, the economic benefit for most commercial buildings is enhanced when sunlight is plentiful because daylighting reduces electricity demand for artificial lighting. This is also when the daily peak in electricity demand tends to occur (Harvey, 2006). Several authors report measurements and simulations with annual electricity savings from 50 to 80%, depending on the hours and the location. Daylighting can lead to reduced cooling loads if solar heat gain is managed and an integrated thermal-daylighting design of the building is followed (Tzempelikos et al., 2010). This means that replacing artificial light with just the amount of natural light needed reduces internal heating. Savings in lighting plus cooling energy use of 22 to 86%, respectively, have been reported (Duffie and Beckman, 2006).

Daylighting and passive solar features in buildings can have significant financial benefits not easily addressed in standard lifecycle and payback analysis. They generally add value to the building, and in the case of office buildings, can contribute to enhanced productivity (Nicol et al., 2006).

3.8.2 Active solar heating and cooling

Solar drying of crops and timber is common worldwide, either by using natural processes or by concentrating the heat in specially designed storage buildings. However, market data are not available.

Advanced applications—such as solar cooling and air conditioning, industrial applications and desalination/water treatment—are in the early stages of development, with only a few hundred first-generation systems in operation. Considerable cost reductions are expected if R&D efforts are increased over the next few years.

Solar water heating is characterized by a higher first cost investment and low operation and maintenance (O&M) costs. Some solar heating applications require an auxiliary energy source, and then annual loads are met by a combination of different energy sources. Solar thermal hot water systems are generally more competitive in sunny regions but this picture changes for space heating due to its usually higher overall heating load. In colder regions, capital costs can be spread over a longer heating season and solar thermal can then become more competitive (IEA, 2007).

The investment costs for solar water heating depend on the complexity of the technology used as well as the market conditions in the country of operation (IEA, 2007; Chang et al., 2009; Han et al., 2010). The costs for an installed solar hot-water system vary from as low as USD$_{2005}$ 83/m^2 to more than USD$_{2005}$ 1,200/m^2, which is equivalent to the USD$_{2005}$ 120 to 1,800/kW$_p$[9] used in Annex III and the resulting levelized cost of heat (LCOH) calculations presented here as well as in Chapters 1 and 10. For the costs of the delivered heat, there is an additional geographic variable related to the available solar irradiation and the number of heating degree days (Mills and Schleich, 2009).

Based on the data and assumptions provided in Annex III, and the methods specified in Annex II, the plot in Figure 3.16 shows the sensitivity of the LCOH with respect to investment cost as a function of capacity factor.

Research to decrease the cost of solar water-heating systems is mainly oriented towards developing the next generation of low-cost, polymer-based systems for mild climates. The focus includes testing the durability of materials. The work to date includes unpressurized polymer integral collector-storage systems that use a load-side immersed heat exchanger and direct thermosyphon systems.

Over the last decade, for each 50% increase in the installed capacity of solar water heaters, investment costs have fallen by around 20% in Europe (ESTTP, 2008). According to the IEA (2010a), cost reductions in OECD countries will come from the use of cheaper materials, improved manufacturing processes, mass production, and the direct integration into buildings of collectors as multi-functional building components and modular, easy to install systems. Delivered energy costs are anticipated by the IEA to eventually decline by around 70 to 75%. One measure suggested by the IEA to realize those cost reductions are more research, development and demonstration (RD&D) investments. Priority areas for attention include new flat-plate collectors that can be more easily integrated into building façades and roofs, especially as multi-functional building components.

Energy costs should fall with ongoing decreases in the costs of individual system components and with better optimization and design. For example, Furbo et al. (2005) show that better design of solar domestic hot-water storage tanks when combined with an auxiliary energy source can improve the utilization of solar energy by 5 to 35%, thereby permitting a smaller collector area for the same solar yield.

---

[9] 1 m^2 of collector area is converted into 0.7 kW$_{th}$ of installed capacity (see Section 3.4.1).

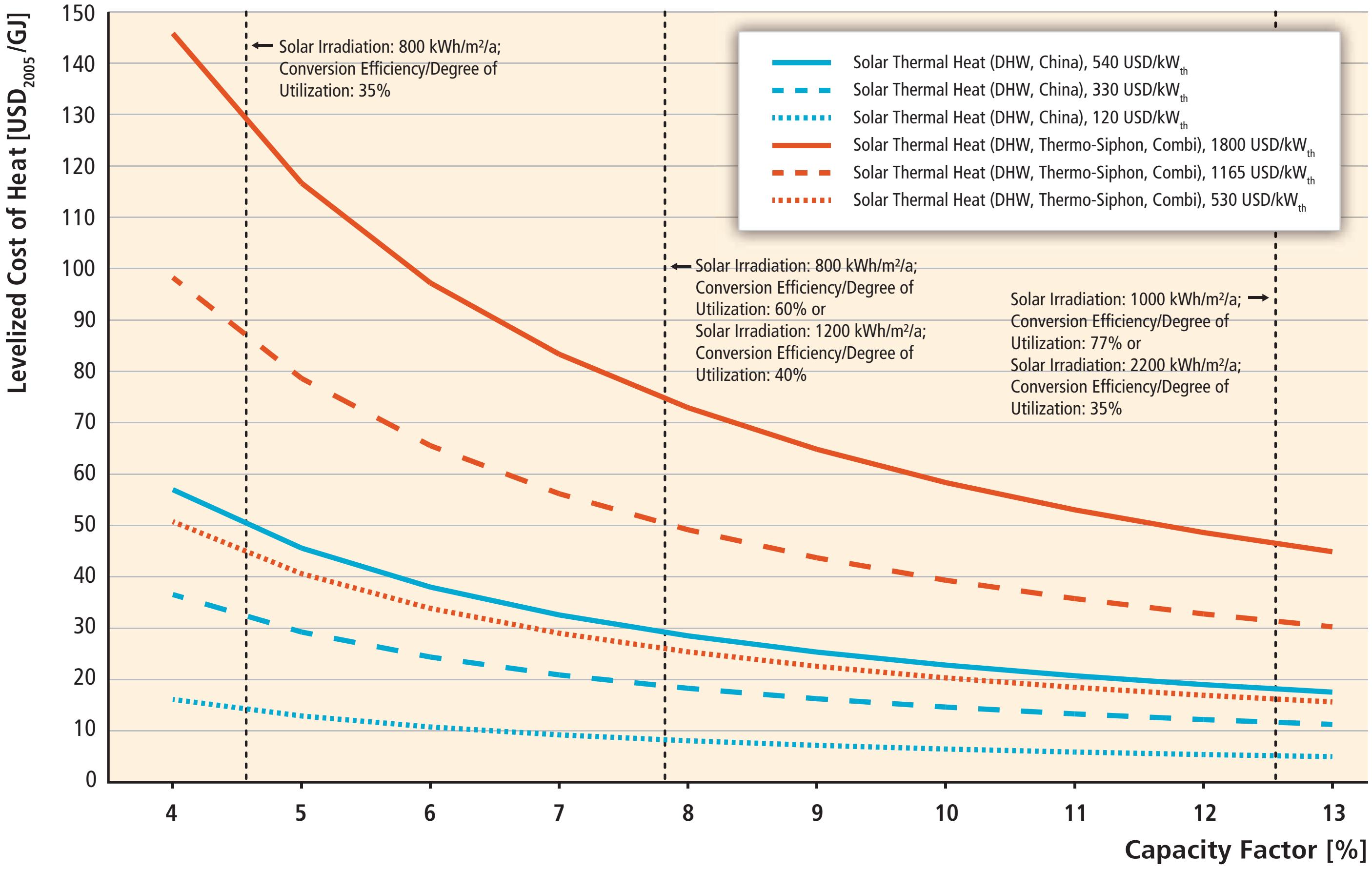


Figure 3.16 | Sensitivity of LCOH with respect to investment cost as a function of capacity factor (Source: Annex III).

3.8.3 Photovoltaic electricity generation

PV prices have decreased by more than a factor of 10 over the last 30 years; however, the current levelized cost of electricity (LCOE) from solar PV is generally still higher than wholesale market prices for electricity.[10] The competitiveness in other markets depends on a variety of local conditions.

The LCOE of PV systems is generally highly dependent on the cost of individual system components as well as on location and other factors affecting the overall system performance. The largest component of the investment cost of PV systems is the cost of the PV module. Other cost factors that affect the LCOE include—but are not limited to—BOS components, labour cost of installation and O&M costs. Due to the dynamic development of the cost of PV systems, this section focuses on cost trends rather than current cost. Nonetheless, recent costs are presented in the discussion of individual cost factors and resulting LCOE below.

Average global PV module factory prices dropped from about USD_{2005} 22/W in 1980 to less than USD_{2005} 1.5/W in 2010 (Bloomberg, 2010). Most studies about learning curve experience in photovoltaics focus on PV modules because they represent the single-largest cost item of a PV system (Yang, 2010). The PV module historical learning experience ranges between 11 and 26% (Maycock, 2002; Parente et al., 2002; Neij, 2008; IEA, 2010c) with a median progress ratio of 80%, and consequently, a median historical learning rate (price experience factor) of 20%, which means that the price was reduced by 20% for each doubling of cumulative sales (Hoffmann, 2009; Hoffmann et al., 2009). Figure 3.17 depicts the price developments for crystalline silicon modules over the last 35 years. The huge growth of demand after 2003 led to an increase in prices due to the supply-constrained market, which then changed into a demand-driven market leading to a significant price reduction due to module overcapacities in the market (Jäger-Waldau, 2010a).

The second-largest technical-related costs are the BOS components, and therein, the single largest item is the inverter. While the overall BOS experience curve was between 78 and 81%, or a 19 to 22% learning rate, quite similar to the module rates, learning rates for inverters were just in the range of 10% (Schaeffer et al., 2004). A similar trend was found in the USA for cost reduction for labour costs attributed to installed PV systems (Hoff et al., 2010).

The average investment cost of PV systems, that, the sum of the costs of the PV module, BOS components and labour cost of installation, has also

---

[10] LCOE is not the sole determinant of its value or economic competitiveness (relative environmental and social impacts must be considered, as well as the contribution that the technology provides to meeting specific energy services, for example, peak electricity demands, or integration costs).

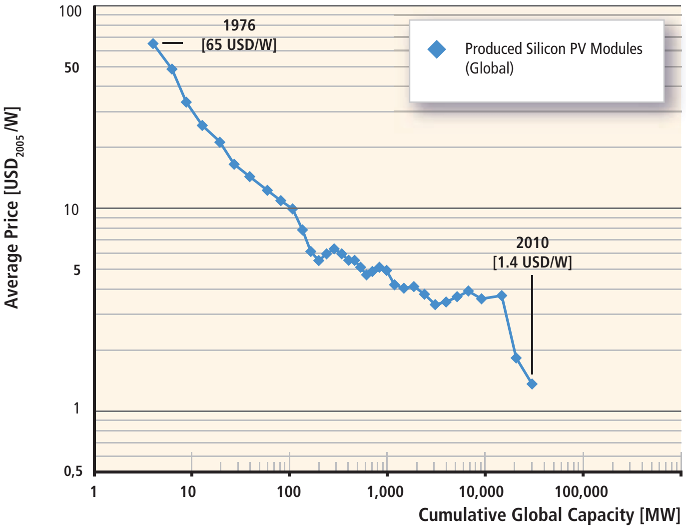


Figure 3.17 | Solar price experience or learning curve for silicon PV modules. Data displayed follow the supply and demand fluctuations. Data source: Maycock (1976-2003); Bloomberg (2010).

decreased significantly over the past couple of decades and is projected to continue decreasing rapidly as PV technology and markets mature. However, the system price decrease[11] varies significantly from region to region and depends strongly on the implemented support schemes and maturity of markets (Wiser et al., 2009). Figure 3.18 shows the system price developments in Europe, Japan, and the USA.

The capacity-weighted average investment costs of PV systems installed in the USA declined from USD$_{2005}$ 9.7/W in 1998 to USD$_{2005}$ 6.8/W in 2008. This decline was attributed primarily to a drop in non-module (BOS) costs. Figure 3.18 also shows that PV system prices continued to decrease considerably since the second half of 2008. This decrease is considered to be due to huge increases in production capacity and production overcapacities and, as a result, increased competition between PV companies (LBBW, 2009; Barbose et al., 2010; Mints, 2011). More generally, Figure 3.18 shows that the gap between PV system prices or investment cost between and within different world regions narrowed until 2005. In the period from 2006 to 2008, however, the cost spread widened at least temporarily. The first-quarter 2010 average PV system price in Germany dropped to € 2,864/kW$_p$ (USD$_{2005}$ 3,315/kW$_p$) for systems below 100 kW$_p$ (Bundesverband Solarwirtschaft e.V., 2010). In 2009, thin-film projects at utility scale were realized at costs as low as USD$_{2005}$ 2.72/W$_p$ (Bloomberg, 2010).

O&M costs of PV electricity generation systems are low and are found to be in a range between 0.5 and 1.5% annually of the initial investment costs (Breyer et al., 2009; IEA, 2010c).

The main parameter that influences the capacity factor of a PV system is the actual annual solar irradiation at a given location given in kWh/m^2/yr. Capacity factors for PV installations are found to be between 11 and 24% (Sharma, 2011), which is in line with earlier findings of the IEA Implementing Agreement PVPS (IEA, 2007), which found that most of the residential PV systems had capacity factors in the range of 11 to 19%. Utility-scale systems currently under construction or in the planning phase are projected to have 20 to 30% capacity factors (Sharma, 2011).

Based on recent data representative of the global range of investment cost around 2008 as discussed above, assumptions provided in Annex III of this report, and the methods specified in Annex II, the following two plots show the sensitivity of the LCOE of various types of PV systems with respect to investment cost (Figure 3.19a) and discount rates (Figure 3.19b) as a function of the capacity factor.

Note that 1-axis tracking for utility-scale PV systems range from 15-20% increase in investment cost over fixed utility-scale PV systems. Modeling studies for c-Si indicate 16% increase for 1-axis tracking over fixed utility-scale PV systems (Goodrich et al., 2011). In 2008 and 2009, commercial rooftop PV systems of 20 to 500 kW were reported to be roughly 5% lower in investment cost than residential rooftop PV systems of 4 to 10 kW (NREL, 2011).

These figures highlight that the LCOE of individual projects depends strongly on the particular combination of investment costs, discount rates and capacity factors as well as on the type of project (residential, commercial, utility-scale).

Several studies have published LCOEs for PV electricity generation based on different assumptions and methodologies. Based on investment cost for thin-film projects of USD$_{2005}$ 2.72/W$_p$ in 2009 and further assumptions, Bloomberg (2010) finds LCOEs in the range of 14.5 and 36.3 US cent$_{2005}$/kWh. Breyer et al. (2009) find LCOEs in the range of 19.2 to 22.6 US cent$_{2005}$/kWh in regions of high solar irradiance (>1,800 kWh/m^2/yr) in Europe and the USA in 2009. All of these ranges can be considered to be reasonably achievable according to the LCOE ranges shown in Figure 3.19 and included in Annex III.

Assuming the PV market will continue to grow at more than 35% per year, the cost is expected to drop more than 50% to about 7.3 US cent$_{2005}$/kWh by 2020 (Breyer et al., 2009). Table 3.5 shows the 2010 IEA PV roadmap projections, which are somewhat less ambitious, but still show significant reductions (IEA, 2010c). The underlying deployment scenario assumes 3,155 GW of cumulative installed PV capacity by 2050.

The goal of the US DOE Solar Program's Technology Plan is to make PV-generated electricity cost-competitive with market prices in the USA by 2015. Their ambitious energy cost targets for various market sectors are 8 to 10 US cents$_{2005}$/kWh for residential, 6 to 8 US cents$_{2005}$/kWh for commercial

---

[11] System prices determine the investment cost for independent project developers. Since, prices can contain profit mark-ups, the investment cost may be higher for independent project developers than for vertically integrated companies that are engaged in the production of PV systems or components thereof.

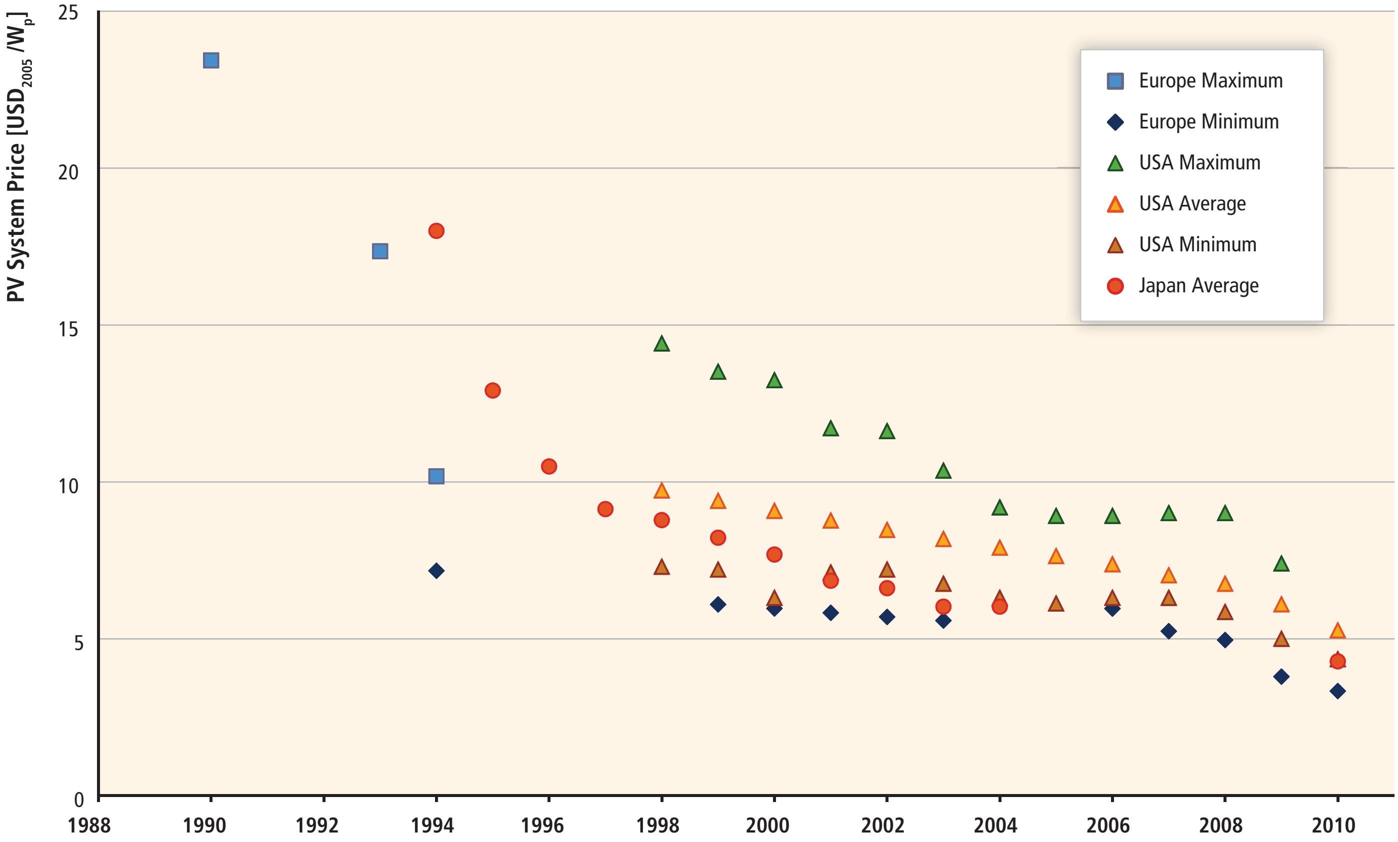


Figure 3.18 | Installed cost of PV systems smaller than 100 kW_p in Europe, Japan and the USA. Data sources: Urbschat et al. (2002); Jäger-Waldau (2005); Wiser et al. (2009); Bundesverband Solarwirtschaft e.V. (2010); SEIA (2010a,b).

and 5 to 7 US $cents_{2005}$/kWh for utilities (US DOE, 2008). All of these cost targets are just below what seems to be possible to achieve for projects of similar type realized around 2008 even under very optimistic conditions (see Figure 3.19 as well as Annex III). Given continued cost reductions in the near term, these cost targets appear to be well within reach for projects that can be realized under favourable conditions. Relatively more progress will be required, however, to allow achieving such costs on a broader scale.

3.8.4 Concentrating solar power electricity generation

Concentrating solar power electricity systems are a complex technology operating in a complex resource and financial environment, so many factors affect the LCOE (Gordon, 2001). A study for the World Bank (World Bank Global Environment Facility Program, 2006) suggested four phases of cost reduction for CSP technology and forecast that cost competitiveness with non-renewable fuel could be reached by 2025. Figure 3.20 shows that cost reductions for CSP technologies are expected to come from plant economies of scale, reducing costs of components through material improvements and mass production, and implementing higher-efficiency processes and technologies.

The total investment for the nine plants comprising the Solar Electric Generating Station (SEGS) in California was USD_{2005} 1.18 billion, and construction and associated costs for the Nevada Solar One plant amounted to 245 million (USD_{2005}, assumed 2007 base).

The publicized investment costs of CSP plants are often confused when compared with other renewable sources, because varying levels of integrated thermal storage increase the investment, but also improve the annual output and capacity factor of the plant.

The two main parameters that influence the solar capacity factor of a CSP plant are the solar irradiation and the amount of storage or the availability of a gas-fired boiler as an auxiliary heater, for example, the SEGS plants in California (Fernández-García et al., 2010). In case of solar-only CSP plants, the capacity factor is directly related to the available solar irradiation. With storage, the capacity factor could in theory be increased to 100%; however, this is not an economic option and trough plants are now designed for 6 to 7.5 hours of storage and a capacity factor of 36 to 41% (see Section 3.3.4). Tower plants, with their higher temperatures, can charge and store molten salt more efficiently, and projects designed for up to

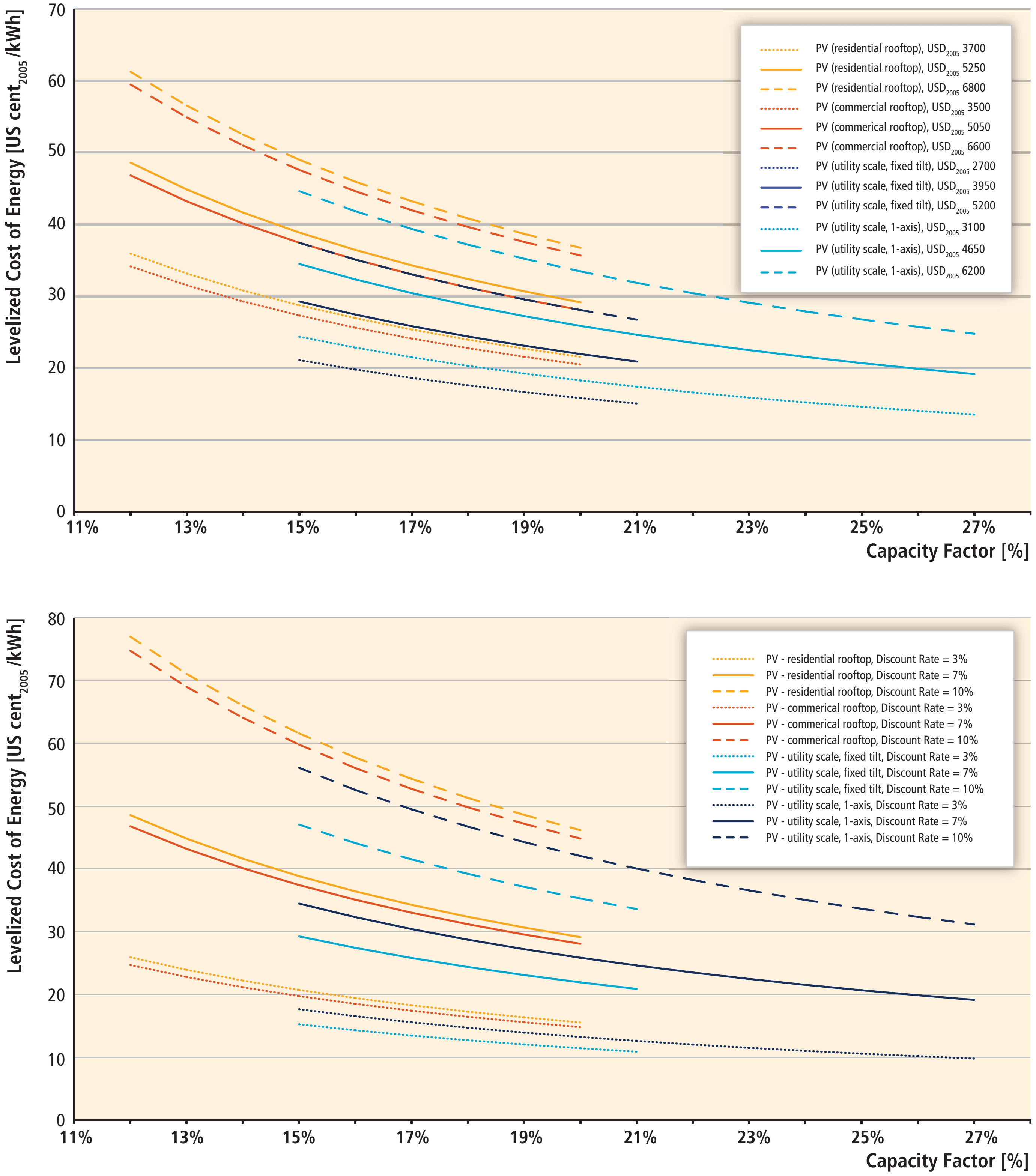


Figure 3.19 | Levelized cost of PV electricity generation, 2009. Upper panel: Cost of PV electricity generation as a function of capacity factor and investment cost[1,3]. Lower panel: Cost of PV electricity generation as a function of capacity factor and discount rate[2,3]. Source: (Annex III).

Notes: 1. Discount rate assumed to equal 7%. 2. Investment cost for residential rooftop systems assumed at USD$_{2005}$ 5,250/kW, for commercial rooftop systems at USD$_{2005}$ 5,050/kW, for utility-scale fixed tilt projects at USD$_{2005}$ 3,950/kW and for utility-scale one-axis projects at USD$_{2005}$ 4,650/kW. 3. Annual O&M cost assumed at USD$_{2005}$ 41 to 64/kW, lifetime at 25 years.

Table 3.5 | IEA price forecasts for 2020 and 2050. The ranges are given for 2,000 kWh/kW$_p$ and 1,000 kWh/kW$_p$ (IEA, 2010c).

	2020 (US cents$_{2005}$)		2050 (US cents$_{2005}$)	
Energy yields (kWh/kW$_p$)	*2000*	*1000*	*2000*	*1000*
Equivalent Capacity Factor	*22.8%*	*11.4%*	*22.8%*	*11.4%*
Residential PV	14.5	28.6	5.9	12.2
Utility-scale PV	9.5	19.0	4.1	8.2

15 hours of storage, giving a 75% annual capacity factor, are under construction.

Because, other than the SEGS plants, new CSP plants only became operational from 2007 onwards, few actual performance data are available. For the SEGS plants, capacity factors of between 12.5 and 28% are reported (Sharma, 2011). The predicted yearly average capacity factor of a number of European CSP plants in operation or close to completion of construction is given as 22 to 29% without thermal storage and 27 to 75% with thermal storage (Arce et al., 2011). These numbers are well in line with the capacity figures given in the IEA CSP Roadmap (IEA, 2010b) and the US Solar Vision Study (US DOE, 2011). However, the limited available performance data for the thermal storage state should be noted.

For large, state-of-the-art trough plants, current investment costs are reported as USD$_{2005}$ 3.82/W (without storage) to USD$_{2005}$ 7.65/W (with storage) depending on labour and land costs, technologies, the amount and distribution of direct-normal irradiance and, above all, the amount of storage and the size of the solar field (IEA, 2010b). Storage increases the investment costs due to the storage itself, as well as the additional collector area needed to charge the storage. But it also improves the ability to dispatch electricity at times of peak tariffs in the market or when balancing power is needed. Thus, a strategic approach to storage can improve a project's internal rate of return.

The IEA (2010b) estimates LCOEs for large solar troughs in 2009 to range from USD$_{2005}$ 0.18 to 0.27/kWh for systems with different amounts of thermal storage and for different levels of solar irradiation. This is broadly in line with the range of LCOEs derived for a system with six hours of storage at a 10% discount rate (as applied by the IEA), although the full range of values derived for different discount rates is broader (see Annex III). Based on the data and assumptions provided in Annex III of this report, and the methods specified in Annex II, the following two

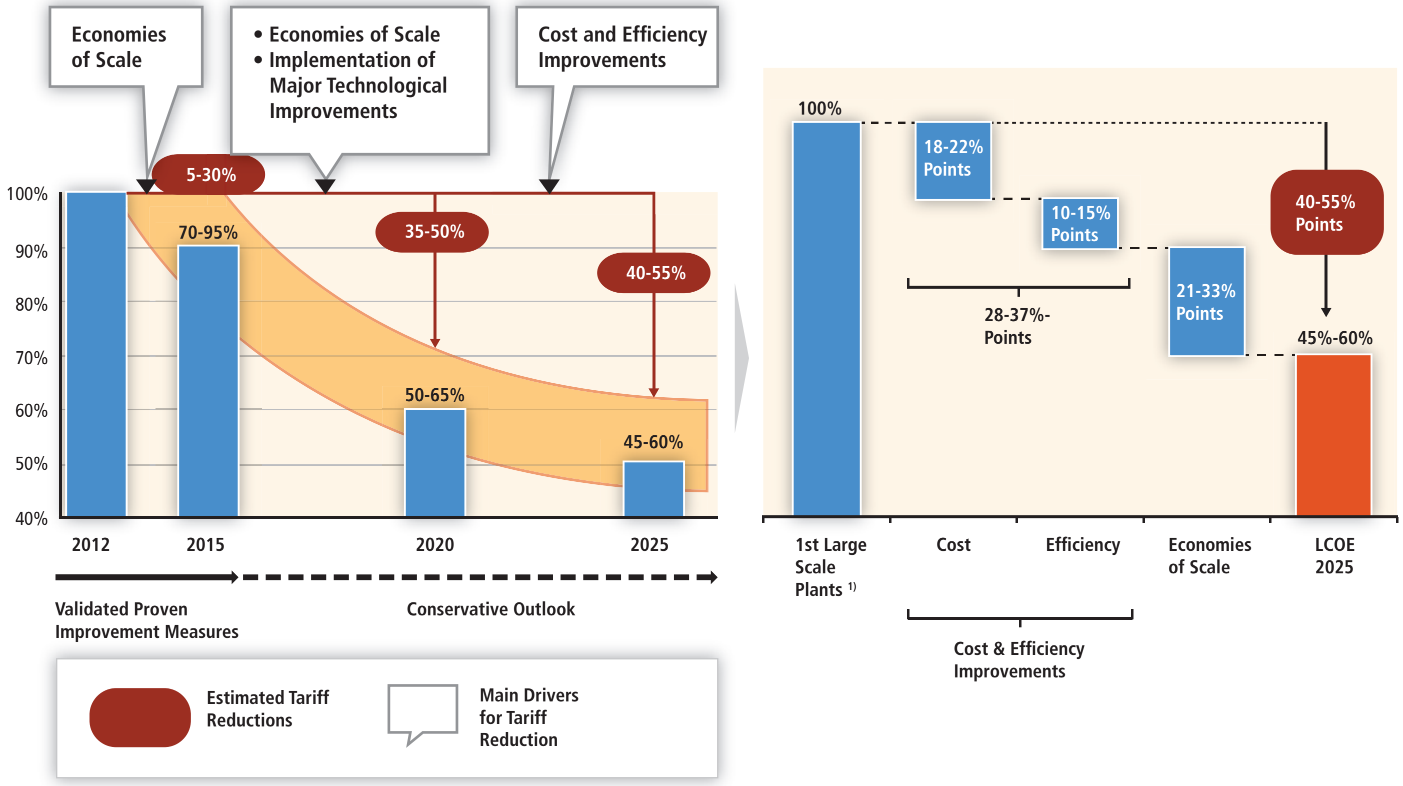


Figure 3.20 | Expected cost decline for CSP plants from 2012 to 2025. The cost number includes the cost of the plant plus financing (A.T. Kearney, 2010). As reduction ranges for cost, efficiency and economies of scale in the right panel overlap, their total contribution in 2025 amounts to less than their overall total.

Note: General. Tariffs equal the minimum required tariff, and are compared to 2012 tariffs. 1. Referring to 2010 to 2013 according to planned commercialization date of each technology (reference plant).

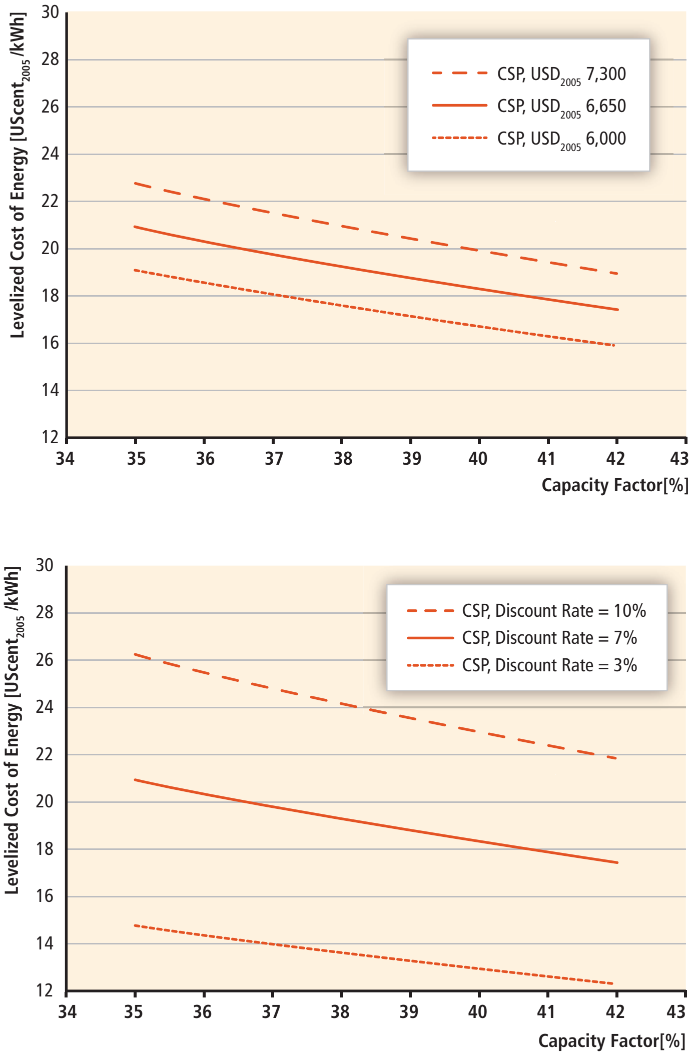


Figure 3.21 | Levelized cost of CSP electricity generation, 2009. Upper panel: Cost of CSP electricity generation as a function of capacity factor and investment cost[1,3]. Lower panel: Cost of CSP electricity generation as a function of capacity factor and discount rate[2,3]. Source: Annex III.

Notes: 1. Discount rate assumed to equal 7%. 2. Investment cost for CSP plant with six hours of thermal storage assumed at USD$_{2005}$ 6,650/kW. 3. Annual O&M cost assumed at USD$_{2005}$ 71/kW, lifetime at 25 years.

plots show the sensitivity of the LCOE of CSP plants with six hours of thermal storage with respect to investment cost (Figure 3.21, upper) and discount rates (Figure 3.21, lower) as a function of capacity factor.

The learning ratio for CSP, excluding the power block, is given as 10 ±5% by Neij (2008; IEA, 2010b). Other studies provide learning rates according to CSP components: Trieb et al. (2009b) give 10% for the solar field, 8% for storage, and 2% for the power block, whereas NEEDS (2009) and Viebahn et al. (2010) state 12% for the solar field, 12% for storage, and 5% for the power block.

Cost reductions for trough plants of the order of 30 to 40% within the next decade are considered achievable. Central-receiver technology is less commercially mature than troughs and thus presents slightly higher investment costs than troughs at the present time; however, cost reductions of 40 to 75% are predicted for central-receiver technology (IEA, 2010b).

The US DOE (2011) states its CSP goals for the USA in terms of USD/kWh, rather than USD/W, because the Solar Energy Technologies Program is designed to affect the LCOE and includes significant storage. The specific CSP goals are the following: 9 to 11 US cents$_{2005}$/kWh by 2010; 6 to 8 US cents$_{2005}$/kWh (with 6 hours of thermal storage) by 2015; and 5 to 6 US cents$_{2005}$/kWh (with 12 to 17 hours of thermal storage) by 2020 (USD$_{2005}$, assumed 2009 base). The EU is pursuing similar goals through a comprehensive RD&D program.

3.8.5 Solar fuel production

Direct conversion of solar energy to fuel is not yet widely demonstrated or commercialized. Thermochemical cycles along with electrolysis of water are the most promising processes for 'clean' hydrogen production in the future. In a comparison study, both the hybrid-sulphur cycle and a metal-oxide-based cycle were operated by solar tower technology for multi-stage water splitting (Graf et al., 2008). The electricity required for the alkaline electrolysis was produced by a parabolic trough power plant. For each process, the investment, operating and hydrogen production costs were calculated on a 50-MW$_{th}$ scale. The study points out the market potential of sustainable hydrogen production using solar energy and thermochemical cycles compared to commercial electrolysis. A sensitivity analysis was done for three different cost scenarios: conservative, standard and optimistic (Table 3.6).

As a result, variation of the chosen parameters has the least impact on the hydrogen production costs of the hybrid-sulphur process, ranging from USD$_{2005}$ 4.4 to 6.4/kg (Graf et al., 2008). The main cost factor for electrolysis is the electricity: just the variation of electricity costs leads to hydrogen costs of between USD$_{2005}$ 2.4 to 7.7/kg. The highest range of hydrogen costs is obtained with the metal oxide-based process: USD$_{2005}$ 4.0 to 14.5/kg. The redox system has the largest impact on the costs for the metal oxide-based cycle. The high electrical energy demand for nitrogen recycling influences the result significantly.

A substitute natural gas can be produced by the combination of solar hydrogen and CO_2 in a thermochemical synthesis at cost ranges from 12 to 14 US cents$_{2005}$/kWh$_{th}$ with renewable power costs of 2 to 6 US cents$_{2005}$/kWh$_e$ (Sterner, 2009). These costs depend highly on the operation mode of the plant and can be reduced by improving efficiency and reducing electricity costs.

The weakness of current economic assessments is primarily related to the uncertainties in the viable efficiencies and investment costs of the various solar components due to their early stage of development and their economy of scale as well as the limited amount of available literature data.

Table 3.6 | Overview of parameters for sensitivity (Graf et al., 2008).

	Cost scenario		
	Conservative	Standard	Optimistic
Heliostat costs (USD_{2005}/m^2)	159	136	114
Lifetime (years)	20	25	30
Redox system costs (USD_{2005}/kg)	1,700	170	17
Electricity costs (USD_{2005}/kWh_e)	0.14	0.11	0.05
Electrolyzer (decrease in %)	0	-10	-20
Chemical application (decrease in %)	0	-10	-20
Recycling of nitrogen (decrease in %)	0	-20	-40

3.9 Potential deployment[12]

Forecasts for the future deployment of direct solar energy may be underestimated, because direct solar energy covers a wide range of technologies and applications, not all of which are adequately captured in the energy scenarios literature. Nonetheless, this section presents near-term (2020) and long-term (2030 to 2050) forecasts for solar energy deployment. It then comments on the prospects and barriers to solar energy deployment in the longer-term scenarios, and the role of the deployment of solar energy in reaching different GHG concentration stabilization levels. This discussion is based on energy-market forecasts and carbon and energy scenarios published in recent literature.

3.9.1 Near-term forecasts

In 2010, the main market drivers are the various national support programs for solar-powered electricity systems or low-temperature solar heat installations. These programs either support the installation of the systems or the generated electricity. The market support for the different solar technologies varies significantly between the technologies, and also varies regionally for the same technology. This leads to very different thresholds and barriers for becoming competitive with existing technologies. Regardless, the future deployment of solar technologies depends strongly on public support to develop markets, which can then drive down costs due to learning. It is important to remember that learning-related cost reductions depend, in part at least, on actual production and deployment volumes, not just on the passage of time, though other factors such as R&D also act to drive costs down (see Section 10.5).

Table 3.7 presents the results of a selection of scenarios for the growth in solar deployment capacities in the near term, until 2020. It should be highlighted that passive solar gains are not included in these statistics, because this technology reduces demand and is therefore not part of the supply chain considered in energy statistics. The same PV technology can be applied for stand-alone, mini-grid, or hybrid systems in remote areas without grid connection, as well as for distributed and centralized grid-connected systems. The deployment of CSP technology is limited by regional availability of good-quality direct-normal irradiance of 2,000 kWh/m^2 (7,200 MJ/m^2) or more in the Earth's sunbelt. As shown in Table 3.7, solar capacity is expected to expand even in reference or baseline scenarios, but that growth is anticipated to accelerate dramatically in alternative scenarios that seek a more dramatic transformation of the global energy sector towards lower carbon emissions.

Photovoltaic market projections at the end of 2009 for the short term until 2013 indicate a steady increase, with annual growth rates ranging between 10 and more than 50% (UBS, 2009; EPIA, 2010; Fawer and Magyar, 2010). Several countries are discussing and proposing ambitious targets for the accelerated deployment of solar technologies. If fully implemented, the following policies could drive global markets in the period up to 2020:

- The National Development and Reform Commission (NDRC) expects non-fossil energy to supply 15% of China's total energy demand by 2020. Specifically for installed solar capacity, the NDRC's 2007 'Medium and Long-Term Development Plan for Renewable Energy in China' set a target of 1,800 MW by 2020. However, these goals have been discussed as being too low, and the possibility of reaching 20 GW or more seems more likely.

- The 2009 European Directive on the Promotion of Renewable Energy set a target of 20% RE in 2020 (The European Parliament and the Council of the European Union, 2010), and the Strategic Energy Technology plan is calling for electricity from PV in Europe of up to 12% in 2020 (European Commission, 2007).

- The 2009 Indian Solar Plan ('India Solar Mission') calls for a goal of 20 GW of solar power in 2022: 12 GW are to come specifically from ground-mounted PV and CSP plants; 3 GW from rooftop PV systems; another 3 GW from off-grid PV arrays in villages; and 2 GW from other PV projects, such as on telecommunications towers (Ministry of New and Renewable Energy, 2009).

- Relating to US cumulative installed capacity by 2030, the USDOE-sponsored Solar Vision Study (US DOE, 2011) is exploring the following two scenarios: a 10% solar target of 180 GW PV (120 GW central, 60 GW distributed); and a 20% solar target of 300 GW PV (200 GW central, 100 GW distributed).

3.9.2 Long-term deployment in the context of carbon mitigation

The IPCC Fourth Assessment Report estimated the available (technical) solar energy resource as 1,600 EJ/yr for PV and 50 EJ/yr for CSP; however, this estimate was given as very uncertain, with sources reporting values orders of magnitude higher (Sims et al., 2007). On the other hand, the projected deployment of direct solar in the IPCC Fourth Assessment Report gives an economic potential contribution of

---

[12] Complementary perspectives on potential deployment based on a comprehensive assessment of numerous model-based scenarios of the energy system are presented in Sections 10.2 and 10.3.

Table 3.7 | Evolution of cumulative solar capacities based on different scenarios reported in EREC-Greenpeace (Teske et al., 2010) and IEA Roadmaps (IEA, 2010b,c).

Cumulative installed capacity	Low-Temperature Solar Heat (GW_{th})			Solar PV Electricity (GW)			CSP Electricity (GW)		
	2009	2015	2020	2009	2015	2020	2009	2015	2020
Current value	180			22			0.7		
EREC – Greenpeace (reference scenario)		180	230		44	80		5	12
EREC – Greenpeace ([r]evolution scenario)		715	1,875		98	335		25	105
EREC – Greenpeace (advanced scenario)		780	2,210		108	439		30	225
IEA Roadmaps		N/A			95[1]	210		N/A	148

Note: 1. Extrapolated from average 2010 to 2020 growth rate.

direct solar to the world electricity supply by 2030 of 633 TWh (2.3 EJ/yr) (Sims et al., 2007).

Chapter 10 provides a summary of the literature on the possible future contribution of RE supplies in meeting global energy needs under a range of GHG concentration stabilization scenarios. Focusing specifically on solar energy, Figure 3.22(a) presents modelling results for the global supply of solar energy. Figure 3.22(b) shows solar thermal heat generation, and Figures 3.22(c) and (d) present solar PV and CSP electricity generation respectively, all at the global scale. Depending on the quantity shown, between 44 and about 156 different long-term scenarios underlie these figures derived from a diversity of modelling teams and spanning a wide range of assumptions about—among other variables—energy demand growth, cost and availability of competing low-carbon technologies, and cost and availability of RE technologies (including solar energy). Chapter 10 discusses how changes in some of these variables impact RE deployment outcomes, with Section 10.2.2 describing the literature from which the scenarios have been taken. Figures 3.22(a) to 3.22(d) present the solar energy deployment results under these scenarios for 2020, 2030 and 2050 for three GHG concentration stabilization ranges, based on the IPCC's Fourth Assessment Report: >600 ppm CO_2 (Baselines), 440 to 600 ppm (Categories III and IV) and <440 ppm (Categories I and II), all by 2100. Results are presented for the median scenario, the 25th to 75th percentile range among the scenarios, and the minimum and maximum scenario results.[13]

In the baseline scenarios, that is, without any climate policies assumed, the median deployment levels for solar energy remain very low, in the range of today's solar primary energy supply of below 1 EJ/yr, until 2050. It is worthwhile noting that the much smaller set of scenarios that reports solar thermal heat generation (44 compared to the full set of 156 that report solar primary energy) shows substantially higher median deployment levels of solar thermal heat of up to about 12 EJ/yr by 2050 even in the baseline cases. In contrast, electricity generation from solar PV and CSP is projected to stay at very low levels.

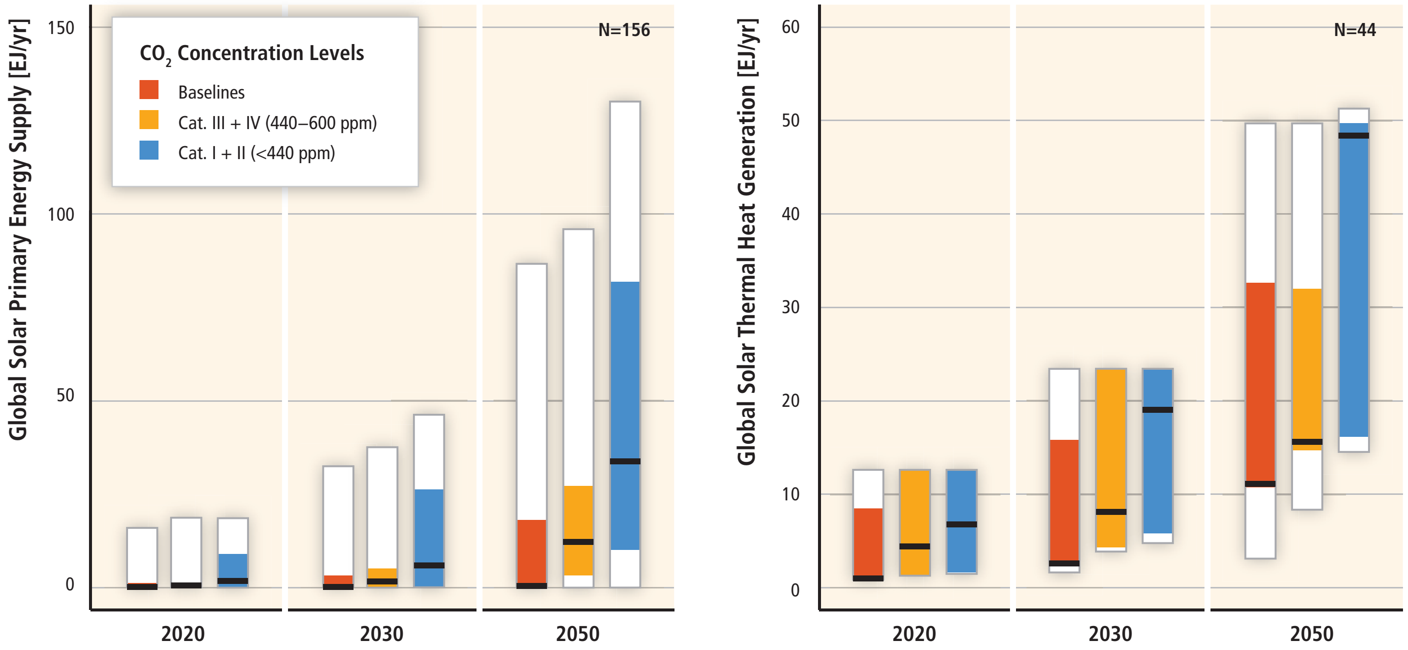
The picture changes with increasingly low GHG concentration stabilization levels that exhibit significantly higher median contributions from solar energy than the baseline scenarios. By 2030 and 2050, the median deployment levels of solar energy reach 1.6 and 12.2 EJ/yr, respectively, in the intermediate stabilization categories III and IV that result in atmospheric CO_2 concentrations of 440-600 ppm by 2100. In the most ambitious stabilization scenario category, where CO_2 concentrations remain below 440 ppm by 2100, the median contribution of solar energy to primary energy supply reaches 5.9 and 39 EJ/yr by 2030 and 2050, respectively.

The scenario results suggest a strong dependence of the deployment of solar energy on the climate stabilization level, with significant growth expected in the median cases until 2030 and in particular until 2050 in the most ambitious climate stabilization scenarios. Breaking down the development by individual technology, it appears that solar PV deployment is most dependent on climate policies to reach significant deployment levels while CSP and even more so solar thermal heat deployment show a lower dependence on climate policies. However, this interpretation should be applied with care, because CSP electricity and solar thermal heat generation were reported by significantly fewer scenarios than solar PV electricity generation.

The ranges of solar energy deployment at the global level are extremely large, also compared to other RE sources (see Section 10.2.2.5), indicating

---

[13] In scenario ensemble analyses such as the review underlying the figures, there is a constant tension between the fact that the scenarios are not truly a random sample and the sense that the variation in the scenarios does still provide real and often clear insights into collective knowledge or lack of knowledge about the future (see Section 10.2.1.2 for a more detailed discussion).



(a) Global Solar Primary Energy Supply

(b) Global Solar Thermal Heat Generation

(c) Global Solar PV Electricity Generation

(d) Global CSP Electricity Generation

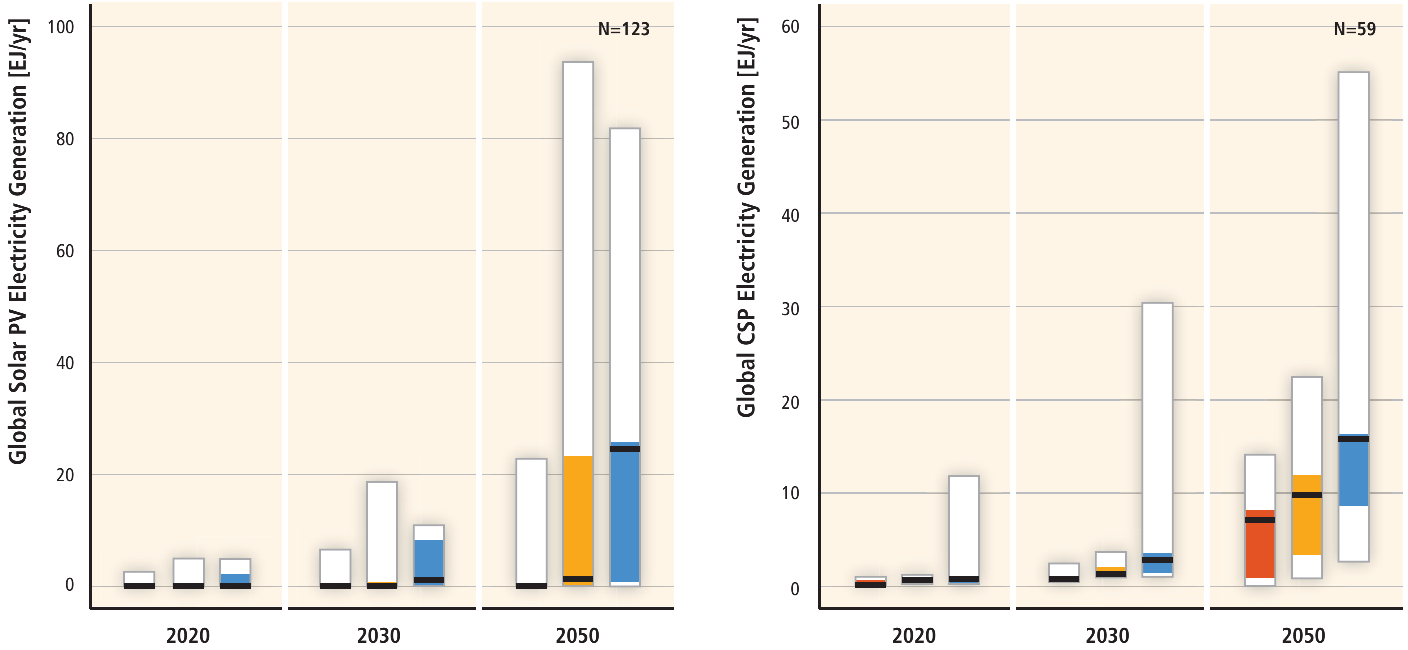


Figure 3.22 | Global solar energy supply and generation in long-term scenarios (median, 25th to 75th percentile range, and full range of scenario results; colour coding is based on categories of atmospheric CO$_2$ concentration level in 2100; the specific number of scenarios underlying the figure is indicated in the right upper corner): (a) Global solar primary energy supply; (b) global solar thermal heat generation; (c) global PV electricity generation; and (d) Global CSP electricity generation (adapted from Krey and Clarke, 2011; see also Chapter 10).

a very wide range of assumptions about the future development of solar technologies in the reviewed scenarios. In the majority of baseline scenarios the solar deployment remains low until 2030, with the 75th percentile reaching some 3 EJ/yr and only very few scenarios showing significantly higher levels. By 2050, this relatively narrow deployment range in the baselines disappears; the 75th percentile shows roughly a 30-fold increase compared to the median baseline case, reaching about 15 EJ/yr and even much higher levels in the uppermost quartile. A combination of increasing relative prices of fossil fuels with more optimistic assumptions about cost declines for solar technologies is likely to be responsible for the higher baseline deployment levels.

In the most ambitious climate stabilization scenarios, the 75th percentiles of the solar primary energy supply by 2030 reach up to 26 EJ/yr, a five-fold increase compared to the median of the same category and the highest estimates even reach up to 50 EJ/yr. For 2050 the equivalent numbers are 82 EJ/yr (75th percentile) and 130 EJ/yr (maximum level), which can be attributed to a large extent to solar PV electricity generation, which reaches deployment levels of more than 80 EJ/yr by 2050, but CSP electricity and solar thermal heat also contribute significantly under these very high solar deployment levels. The share of solar PV in global electricity generation in the most extreme scenarios reaches up to about 12% by 2030 and up to one-third by 2050, but in the vast majority of scenarios remains in the single digit percentage range.

To achieve the higher levels of deployment envisioned by some of these scenarios, policies to reduce GHG emissions and/or increase RE supplies are likely to be necessary, and those policies would need to be of adequate economic attractiveness *and* predictability to motivate substantial private investment (see Chapter 11). A variety of other possible challenges to rapid solar energy growth also deserve discussion, as do factors that can contribute to it.

Resource potential. The solar resource is virtually inexhaustible, and it is available and able to be used in most countries and regions of the world. The worldwide technical potential of solar energy is considerably larger than the current primary energy consumption (IEA, 2008), and will not serve as a primary barrier to even the most ambitious deployment paths included in the scenarios literature summarized above.

Regional deployment. Industry-driven scenarios with regional visions for up to 100% of RE supply by 2050 have been developed in various parts of the world, often with substantial levels of solar energy deployment.

The Semiconductor Equipment and Materials International Association developed PV roadmaps for China and India that go far beyond the targets of the national governments (SEMI, 2009b,c). These targets are about 20 GW by 2020 and 100 GW by 2050 for electricity generation in China and 20 GW and 200 GW in India (both PV and CSP) (Ministry of New and Renewable Energy, 2009; Zhang et al., 2010).

In Europe, the European Renewable Energy Council developed a 100% Renewable Energy vision based on the inputs of the various European industrial associations (Zervos et al., 2010). Assumptions for 2020 about final electricity, heating and cooling, as well as transport demand are based on the European Commission's New Energy Policy (NEP) scenario with both a moderate and high price environment as outlined in the Second Strategic Energy Review (European Commission, 2008). The scenarios for 2030 and 2050 assume a massive improvement in energy efficiency to realize the 100% RE goals. For Europe, this scenario assumes that solar can contribute about 557 TWh (2,005 PJ) and 1415 TWh (5,094 PJ) heating and cooling in 2030 and 2050, respectively. For electricity generation, about 556 TWh (2,002 PJ) from PV and 141 TWh (508 PJ) from CSP are anticipated for 2030 and 1,347 TWh (4,849 PJ) and 385 TWh (1,386 PJ) for 2050, respectively.

In Japan, the New Energy Development Organisation, the Ministry for Economy, Trade and Industry, the Photovoltaic Power Generation Technology Research Association and the Japan Photovoltaic Energy Association drafted the 'PV Roadmap Towards 2030' in 2004 (Kurokawa and Aratani, 2004). In 2009, the roadmap was revised: the target year was extended from 2030 to 2050, and a goal was set to cover between 5 and 10% of domestic primary energy demand with PV power generation in 2050. The targets for electricity from PV systems range between 35 TWh (126 PJ) for the reference scenario and 89 TWh (320 PJ) for the advanced scenario in 2050 (Komiyama et al., 2009).

In the USA, the industry associations—the Solar Electric Power Association and the Solar Energy Industry Association—are working together with the USDOE and other stakeholders to develop scenarios for electricity from solar resources (PV and CSP) of 10 and 20% in 2030. The results of the Solar Vision Study (USDOE, 2011) are expected in 2011.

Achieving the higher *global* scenario results for solar energy would clearly require substantial solar deployment in every region of the world. The *regional* scenarios presented here suggest that regional deployment paths may exist to support such a global result. Nonetheless, enabling this growth in regions new to solar energy may present cost and institutional challenges that would require active management; institutional and technical knowledge transfer from those regions that are already witnessing substantial solar energy activity may be required.

Supply chain issues. Passive solar energy markets and industries have largely developed locally to this point because the building market itself is local. Enabling high-penetration solar energy futures may require a globalization of at least knowledge on passive solar technologies to enable broader market penetration. Low-temperature solar thermal is implemented all over the world within local markets, with local suppliers, but a global market is starting to be developed. The PV industry is already global in scope, with a global supply chain, while CSP is starting to develop a global supply chain—in 2010, the CSP market was driven by Spain and the USA, but other countries such as Germany and India are also helping to expand the market. In general, supply chain and materials constraints may impact the speed and scope of solar energy deployment in certain regions and at certain times, but such factors are unlikely to restrict the ability of solar energy technologies to meet the higher penetrations envisioned by the more aggressive scenarios presented earlier. In fact, the modular nature of many of the solar technologies, both in manufacturing and use, as well as the diverse applications for solar energy suggest that supply chain issues are unlikely to constrain growth.

Technology and economics. The technical maturity and economic competitiveness of solar technologies vary. Passive solar consists of well-established technologies, though with room for improvement;

however, the awareness of the building sector is not always available. The economics are understood, but they depend on local solar resources and local support and building regulations. Low-temperature solar thermal is also a well-established technology, with economics that depend on the solar resource, the applications, and the cost of competing technologies—some regions may need support programs to create markets and enable growth, whereas in other regions solar thermal is already competitive.

PV is already an established technology, but substantial further technological advances are possible with the prospect for continued cost reduction. To this point, however, the deployment of PV technology has strongly depended on local support programs in most markets. Similarly, CSP technology has substantial room for additional improvement, but CSP costs have to this point exceeded market energy prices.

Continued cost reductions are therefore likely to be needed if solar energy is to meet the higher global scenario results presented earlier. Support programs to encourage solar deployment and R&D may both play an important role in seeking to achieve the necessary reductions.

Integration and transmission. Integration and transmission are not a central concern for passive solar applications. Integration issues in low-temperature solar, on the other hand, are especially important for larger systems where integration into local district heating systems is needed, and where the temporal variability of solar output needs to be matched with other supply sources to meet customer demands (see Chapter 8). Due to the availability of the resource only during the day and the short-time-period variability associated with passing clouds, proactive technical and institutional solutions to operational integration concerns will need to be implemented to enable large-scale PV penetration; CSP, if implemented with thermal storage, would not impose similar requirements. Moreover, high-penetration PV and CSP scenarios that involve larger-scale developments are likely to require additional transmission infrastructure in order to access the highest-quality solar sites. Section 8.2.1 identifies a variety of the technical and institutional challenges associated with increased deployment of variable generation sources, and also highlights the variety of solutions for managing those challenges. Though Chapter 8 finds no insurmountable technical barriers to increased variable renewable energy supply, as solar deployment increases, transmission expansion and operational integration costs are also expected to rise, potentially constraining growth on economic terms. Proactively managing these challenges is likely to be central to achieving the high-penetration solar energy scenarios described earlier.

Social and environmental concerns. Direct solar energy appears to have relatively few social and environmental concerns. Rather, the main benefit of passive solar is in reducing the energy demand of buildings. Similarly, low-temperature solar thermal applications are comparatively benign from an environmental perspective. One concern for some PV technologies is that the PV industry uses some toxic materials and corrosive liquids in its production lines. The presence and amount of those materials depend strongly on the cell type, however, and rigorous control methods are used to minimize the risk of accidental releases. Recycling of PV materials may also become more common as deployment continues. Water availability and consumption is the main environmental concern for CSP, though dry cooling technology can substantially reduce water usage. Finally, especially for central-station PV and CSP installations, the ecological, social and visual impacts associated with plant infrastructure may be of concern. Efforts to better understand the nature and magnitude of these impacts, together with efforts to minimize and mitigate them, may need to be pursued in concert with increasing solar energy deployment.

3.9.3 Conclusions regarding deployment

Potential deployment scenarios range widely—from a marginal role of direct solar energy in 2050 to one of the major sources of energy supply. Although direct solar energy provides only a very small fraction of global energy supply in 2011, it has the largest technical potential of all energy sources and, in concert with technical improvements and resulting cost reductions, could see dramatically expanded use in the decades to come.

Achieving continued cost reductions is the central challenge that will influence the future deployment of solar energy. Reducing cost, meanwhile, can only be achieved if the solar technologies decrease their costs along their learning curves, which depends in part on the level of solar energy deployment. In addition, continuous R&D efforts are required to ensure that the slopes of the learning curves do not flatten before solar is widely cost competitive with other energy sources.

The true costs of and potential for deploying solar energy are still unknown because the main deployment scenarios that exist today often consider only a single solar technology: PV. In addition, scenarios often do not account for the co-benefits of a renewable/sustainable energy supply (but see Section 9.4 for some research in this area). At the same time, as with some other forms of RE, issues of variable production profiles and energy market integration as well as the possible need for new transmission infrastructure will influence the magnitude, type and cost of solar energy deployment.

Finally, the regulatory and legal framework in place can also foster or hinder the uptake of direct solar energy applications. For example, minimum building standards with respect to building orientation and insulation can reduce the energy demand of buildings significantly, increasing the share of RE supply without increasing the overall demand, while building and technical standards can also support or hinder the installation of rooftop solar systems. Transparent, streamlined administrative procedures to site, permit, install and connect solar power sources can further support the deployment of direct solar energy.

References

A.T. Kearney (2010). *Solar Thermal Electricity 2025--Clean Electricity On Demand: Attractive STE Cost Stabilize Energy Production.* A.T. Kearney GmbH, Duesseldorf, Germany, 52 pp.

Abanades, S., P. Charvin, G. Flamant, and P. Neveu (2006). Screening of water-splitting thermochemical cycles potentially attractive for hydrogen production by concentrated solar energy. *Energy*, **31**(14), pp. 2805-2822.

Arce, P., M. Medrano, A. Gil, E. Oró, and L.F. Cabeza (2011). Overview of thermal energy storage (TES) potential energy savings and climate change mitigation in Spain and Europe. *Applied Energy*. **88**(8), pp. 2764-2774.

Arif Hasan, M., and K. Sumathy (2010). Photovoltaic thermal module concepts and their performance analysis: A review. *Renewable and Sustainable Energy Reviews*, **14**, pp. 1845-1859.

Asano, H., K. Yajima, and Y. Kaya (1996). Influence of photovoltaic power generation on required capacity for load frequency control. *IEEE Transactions on Energy Conversion*, **11**(1), pp. 188-193.

ASHRAE (2009). *ASHRAE Handbook – Fundamentals*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, USA.

Athienitis, A.K. (2008). Design of advanced solar homes aimed at net-zero annual energy consumption in Canada. In: *ISES-AP – 3rd International Solar Energy Society Conference – Asia Pacific Region. Incorporating the 46th ANZSES Conference*, Sydney, Australia, 25-28 Nov. 2008, pp. 14.

Athienitis, A.K., and M. Santamouris (2002). *Thermal Analysis and Design of Passive Solar Buildings*. James & James, London, UK, 288 pp.

Bailey, S., D. Brinker, H. Curtis, P. Jenkins, and D. Scheiman (1997). *NASA Technical Memorandum 113155 – Solar Cell Calibration and Measurement Techniques*. IECEC-97534, NASA, Cleveland, OH, USA.

Baoshan, L. (2010). Research on the progress of silicon materials in China. In: *6th China SoG Silicon and PV Conference (CSPV) 2010*, Shanghai, PR China, 16-18 March 2010.

Bar-Cohen, Y. (ed.) (2006). *Biomimetics: Biologically Inspired Technologies.* Taylor & Francis, Boca Raton, FL, USA.

Barbose, G., N. Darghouth, and R. Wiser (2010). *The Installed Cost of Photovoltaics in the U.S. from 1998-2009.* Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Barkat, A., S.H. Khan, M. Rahman, S. Zaman, A. Poddar, S. Halim, N.N. Ratna, M. Majid, A.K.M. Maksud, A. Karim, and S. Islam (2002). Economic and social impact evaluation study of the rural electrification program in Bangladesh. In: *Electric Cooperatives in Bangladesh.* National Rural Electric Cooperative Association (NRECA) International, Dhaka, Bangladesh, pp. 41.

Barnes, D.F. (1988). *Electric Power for Rural Growth: How Electricity Affects Rural Life in Developing Countries.* Westview Press, Boulder, CO, USA, 236 pp.

Batley, S.L., D. Colbourne, P.D. Fleming, and P. Urwin (2001). Citizen versus consumer: challenges in the UK green power market. *Energy Policy*, **29**, pp. 479-487.

Bazilian, M.D., F. Leenders, B.G.C. Van der Ree, and D. Prasad (2001). Photovoltaic cogeneration in the built environment. *Solar Energy*, **71**(1), pp. 57-69.

Benagli, S., D. Borrello, E. Vallat-Sauvain, J. Meier, U. Kroll, J. Hoetzel, J. Bailat, J. Steinhauser, M. Marmelo, and L. Castens (2009). High-efficiency amorphous silicon devices on LPCVD-ZnO-TCO prepared in industrial KaiTM-M R&D reactor. In: *Proceedings of the 24th European Photovoltaic Solar Energy Conference*, Hamburg, Germany, 21-25 September 2009, pp. 2293-2298.

Bernreuther, J., and F. Haugwitz (2010). *The Who's Who of Silicon Production.* Bernreuther Consulting, Wuerzburg, Germany.

Bett, A.W., F. Dimroth, W. Gulter, R. Hoheisel, E. Oliva, S.P. Philips, J. Schone, G. Siefer, M. Steiner, A. Wekkeli, E. Welser, M. Meusel, W. Kostler, and G. Strobl (2009). Highest efficiency multi-junction solar cell for terrestrial and space applications. In: *Proceedings of the 24th European Photovoltaic Solar Energy Conference*, Hamburg, Germany, 21-25 September 2009, pp. 1-6.

Beyer, H.G., B. Decker, J. Luther, and R. Steinberger-Willms (1991). Spatial and temporal characteristics of short term fluctuations in solar radiation for PV-plant applications. In: *Proceedings of the 10th E.C. Photovoltaic Solar Energy Conference*, Lisbon, Portugal, 8-12 Apr 1991, pp. 453–456.

Bickel, P., and R. Friedrich (eds.) (2005). *ExternE--Externalities of Energy: Methodology 2005 Update.* Office for Official Publications of the European Communities, Luxembourg, 270 pp.

Bloem, H., F. Monforti-Ferrario, M. Szabo, and A. Jäger-Waldau (2010). *Renewable Energy Snapshots 2010.* EUR 24440 EN, European Commission, Joint Research Centre, Institute for Energy, Ispra, Italy, 52 pp.

Bloomberg (2010). *Bloomberg New Energy Finance – Renewable Energy Data.* Subscriber info at: bnef.com/bnef/markets/renewable-energy/solar/.

Bolton, J.R. (1996). Solar photoproduction of hydrogen: A review. *Solar Energy*, **57**(1), pp. 37-50.

Bosi, M., and C. Pelosi (2007). The potential of III-V semiconductors as terrestrial photovoltaic devices. *Progress in Photovoltaics: Research and Applications*, **15**(1), pp. 51-68.

Bouzguenda, M., and S. Rahman (1993). Value analysis of intermittent generation sources from the system operations perspective. *IEEE Transactions on Energy Conversion*, **8**(3), pp. 484-490.

Boyle, G. (1996). *Renewable Energy: Power for a Sustainable Future.* Oxford University Press in association with the Open University, Oxford, UK, 479 pp.

Brabec, C.J. (2004). Organic photovoltaics: technology and market. *Solar Energy Materials and Solar Cells*, **83**(2-3), pp. 273-292.

Braun, M., Y.-M. Saint-Drenan, T. Glotzbach, T. Degner, and S. Bofinger (2008). Value of PV energy in Germany – Benefit from the substitution of conventional power plants and local power generation. In: *Proceedings of the 23rd European Photovoltaic Solar Energy Conference*, Valencia, Spain, 1-5 September 2008, pp. 3645-3652.

Brendel, R. (2003). *Thin Film Crystalline Silicon Solar Cells.* Wiley-VCH, Weinheim, Germany.

Breyer, C., A. Gerlach, J. Mueller, H. Behacker, and A. Milner (2009). Grid-parity analysis for EU and US regions and market segments – Dynamics of grid-parity and dependence on solar irradiance, local electricity prices and PV progress ratio. In: *Proceedings of the 24th European Photovoltaic Solar Energy Conference*, Hamburg, Germany, 21-25 September 2009, pp. 4492-4500 (ISBN: 3-936338-25-6).

Brouwer, I.D., J.C. Hoorweg, and M.J. van Liere (1997). When households run out of fuel: responses of rural households to decreasing fuelwood availability, Ntcheu District, Malawi. *World Development*, **25**(2), pp. 255-266.

Bundesverband Solarwirtschaft e.V. (2010). *Statistische Zahlen der deutschen Solarstrombranche (photovoltaik).* Bundesverband Solarwirtschaft e.V. (BSW Solar), Berlin, Germany, 4 pp.

Bunea, M.M., K. Johnston, C.M. Bonner, P. Cousins, D.D. Smith, D.H. Rose, W.P. Mulligan, and R.M. Swanson (2010). Simulation and characterization of high efficiency back contact solar cells for low concentration photovoltaics. In: *Proceedings of the 35th Institute of Electrical and Electronics Engineers (IEEE) Photovoltaic Specialists Conference*, Honolulu, Hawaii, 20-25 June 2010, pp. 823-826 (ISSN: 0160-8371).

Butti, K., and J. Perlin (1980). *A Golden Thread: 2500 Years of Solar Architecture and Technology.* Cheshire Books, Frodsham, UK, 289 pp.

Cabeza, L., A. Castell, M. Medrano, I. Martorell, G. Pérez, and I. Fernández (2010). Experimental study on the performance of insulation materials in Mediterranean construction. *Energy and Buildings*, **42**(5), pp. 630-636.

Candanedo, J., and A.K. Athienitis (2010). A simulation study of anticipatory control strategies in a net zero energy solar-optimized house. *ASHRAE Transactions*, **116**(1), pp. 246-260.

Carlson, D.E., and C.R. Wronski (1976). Amorphous silicon solar cell. *Applied Physics Letters*, **28**(11), pp. 671-673.

Castell, A., I. Martorell, M. Medrano, G. Peréz, and L.F. Cabeza (2010). Experimental study using PCM in brick constructive solutions for passive cooling. *Energy and Buildings*, **42**(4), pp. 534-540.

Catchpole, K.R., and A. Polman (2008). Plasmonic solar cells. *Optics Express*, **16**(26), pp. 21793-21800.

Chalmers, S., M. Hitt, J. Underhill, P. Anderson, P. Vogt, and R. Ingersoll (1985). The effect of photovoltaic power generation on utility operation. *IEEE Transactions on Power Apparatus and Systems*, **104**(3), pp. 524-530.

Chang, K.C., W.M. Lin, T.S. Lee, and K.M. Chung (2009). Local market of solar water heaters in Taiwan: Review and perspectives. *Renewable and Sustainable Energy Reviews*, **13**(9), pp. 2605-2612.

Chiba, Y., A. Islam, K. Kakutani, R. Komiya, N. Koide, and L. Han (2005). High efficiency dye sensitized solar cells. In: *Technical Digest, 15th International Photovoltaic Science and Engineering Conference*, Shanghai, China, 10-15 October 2005, pp. 665-666.

Chow, T.T. (2010). A review on photovoltaic/thermal hybrid solar technology. *Applied Energy*, **87**, pp. 365-379.

Chowdhury, B., and S. Rahman (1988). Is central station photovoltaic power dispatchable? *IEEE Transactions on Energy Conversion*, **3**(4), pp. 747-754.

Chueh, W.C., C. Falter, M. Abbott, D. Scipio, P. Furler, S.M. Haile, and A. Steinfeld (2010). High-flux solar-driven thermochemical dissociation of CO_2 and H_2O using nonstoichiometric ceria. *Science*, **330**, pp. 1797-1801.

Clavadetscher, L., and T. Nordmann (2007). *Cost and Performance Trends in Grid-Connected Photovoltaic System and Case Studies.* IEA Photovoltaic Power Systems Program (PVPS). Task 2, Report IEA-PVPS T2-06:2007, IEA PVPS Pool Switzerland for the IEA Photovoltaic Power Systems Program, 54 pp. Available at: www.iea-pvps-task2.org/public/download/T2_Cost_and_Performance.pdf.

Cobben, S., B. Gaiddon, and H. Laukamp (2008). *Impact of Photovoltaic Generation on Power Quality in Urban areas with High PV Population: Results from Monitoring Campaigns.* PVupscale, WP4 - Deliverable 4.3, Contract EIE/05/171/SI2.420208, Intelligent Energy Europe, PVupscale project, 53 pp. Available at: www.pvupscale.org/IMG/pdf/WP4_D4-3_public_v1c.pdf

Conibeer, G., M.A. Green, D. König, I. Perez-Wurfl, S. Huang, X. Hao, D. Di, L. Shi, S. Shrestha, B. Puthen-Veetil, Y. So, B. Zhang, and Z. Wan (2010). Silicon quantum dot based solar cells: addressing the issues of doping, voltage and current transport. *Progress in Photovoltaics: Research and Applications*, doi:10.1002/pip.1045.

Coutts, T.J., J.S. Ward, D.L. Young, K.A. Emery, T.A. Gessert, and R. Noufi (2003). Critical issues in the design of polycrystalline, thin-film tandem solar cells. *Progress in Photovoltaics: Research and Applications*, **11**(6), pp. 359-375.

Curtright, A., and J. Apt (2008). The character of power output from utility-scale photovoltaic systems. *Progress in Photovoltaics: Research and Applications*, **16**(3), pp. 241-247.

de Vries, B., D. van Vuuren, and M.M. Hoogwijk (2007). Renewable energy sources: Their global potential for the first half of the 21st century at a global level: An integrated approach. *Energy Policy*, **35**(4), pp. 2590-2610.

Denholm, P., E. Drury, R. Margolis, and M. Mehos (2009). *Solar Energy: The Largest Energy Resource, Generating Electricity in a Carbon Constrained World.* Elsevier, Paris, France.

DESERTEC Foundation (2007). *Clean Power from Deserts - The DESERTEC Concept for Energy, Water and Climate Security.* 4th ed. WhiteBook, Protext Verlag, Bonn, Germany.

Dimmler, B., and H.W. Schock (1996). Scaling-up of CIS technology for thin-film solar modules. *Progress in Photovoltaics: Research and Applications*, **4**(6), pp. 425-433.

Dimroth, F., C. Baur, A.W. Bett, M. Meusel, and G. Strobl (2005). 3-6 junction photovoltaic cells for space and terrestrial concentrator. In: *31st Institute of Electrical and Electronics Engineers (IEEE) Photovoltaic Specialists Conference*, Lake Buena Vista, Florida, 3-7 January 2005, pp. 525-529.

Dincer, I., and M. Rosen (2010). *Thermal Energy Storage. Systems and Applications.* 2nd ed. Wiley-Blackwell, Bogner Regis, UK.

Displaybank (2010). *Displaybank Briefing.* January 28, 2010. Displaybank Consulting and Research, San Jose, CA, USA. Available for subscribers at: www.displaybank.com/eng/info/sread.php?id=5724.

DLR (2007). *AQUA-CSP. Concentrating Solar Power for Seawater Desalination. Final Report.* Institute of Technical Thermodynamics, Section Systems Analysis and Technology Assessment, German Aerospace Center (DLR), Stuttgart, Germany, 279 pp.

Duffie, J.A., and W.A. Beckman (2006). *Solar Engineering of Thermal Processes.* 3rd ed. Wiley, New York, NY, USA, 928 pp.

Ecofys Netherlands BV (2007). *Current State-of-the-Art and Best Practices of BIPV. D6.1.1. European Commission Sixth Framework Programme.* Contract No. 019718, Ecofys Netherlands BV, Utrecht, The Netherlands.

ECOSTAR (2005). *European Concentrated Solar Thermal Road-Mapping.* German Aerospace Centre (DLR), Stuttgart, Germany.

Eiffert, P. (2002). *Guidelines for Economic Evaluation of Building Integrated Photovoltaic Power Systems.* IEA Photovoltaic Power Systems Program (PVPS), Task 7, NREL/TP-550-31977, National Renewable Energy Laboratory, Golden, CO, USA, 52 pp. Available at: www.nrel.gov/docs/fy03osti/31977.pdf.

Eiffert, P., and G.K. Kiss (2000). *Building-Integrated Photovoltaic Designs for Commercial and Institutional Structures: A Source Book for Architects.* National Renewable Energy Laboratory, Golden, CO, USA, 90 pp.

Ellingson, R.J., M.C. Beard, J.C. Johnson, P. Yu, O.I. Micic, A.J. Nozik, A. Shabaev, and A.L. Efros (2005). Highly efficient multiple exciton generation in colloidal PbSe and PbS quantum dots. *Nano Letters*, **5**(5), pp. 865-871.

Elzinga, D. (2008). *Urban BIPV in the New Residential Construction Industry.* IEA Photovoltaic Power Systems Program (PVPS), Task 10, Activity 3.1, Report IEA-PVPS-T10-03:2008, Natural Resources Canada for the International Energy Agency Photovoltaic Power Systems Program, Ottawa, Canada, 58 pp. Available at: www.iea-pvps-task10.org/IMG/pdf/IEA-PVPS_T10-03-2006__Urban_BIPV_in_the_New_Residential_Construction_Industry.pdf.

EPIA (2010). *Global Market Outlook for Photovoltaics until 2014.* European Photovoltaic Industry Association (EPIA), Brussels, Belgium, 28 pp.

Epstein, M., G. Olalde, S. Santen, A. Steinfeld, and C. Wieckert (2008). Towards the industrial solar carbothermic production of zinc. *Journal of Solar Energy Engineering*, **130**(1), 014505.

ESMAP (2004). *The Impact of Energy on Women's Lives in Rural India.* Energy Sector Management Assistance Programme (ESMAP) Paper No. ESM276, Joint UNDP/World Bank ESMAP, Washington, DC, 96 pp.

ESTTP (2006). *Solar Thermal Vision 2030. Vision of the Usage and Status of Solar Thermal Energy Technology in Europe and the Corresponding Research Topics to Make the Vision a Reality.* European Solar Thermal Technology Platform (ESTTP) Secretariat, Brussels, Belgium, 123 pp.

ESTTP (2008). *Solar Heating and Cooling for a Sustainable Energy Future in Europe – Strategic Research Agenda.* European Solar Thermal Technology Platform (ESTTP) Secretariat, Brussels, Belgium, 123 pp.

EU PV European Photovoltaic Technology Platform (2007). *A Strategic Research Agenda for Photovoltaic Solar Energy Technology.* European Communities, Sixth European Framework Programme for Research and Technological Development, Luxembourg, 76 pp.

EurObserv'ER (2009). *Photovoltaic Energy Barometer.* EurObserv'ER, Observatoire des Energies Renouvelables, Paris, France.

European Commission (2007). *A European Strategic Energy Technology Plan (SET-Plan) - Technology Map.* European Commission, Brussels, Belgium.

European Commission (2008). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Second Strategic Energy Review. An EU Energy Security and Solidarity Action Plan.* European Commission, Brussels, Belgium, 781 pp.

Everett, B. (1996). Solar Thermal Energy. In: *Renewable Energy: Power for a Sustainable Future.* G. Boyle (ed.), Oxford University Press, Oxford, UK, pp. 41-88.

Ezzati, M., A.D. Lopez, A. Rodgers, S. Vander Hoorn, and C.J.L. Murray (2002). Selected major risk factors and global and regional burden of disease. *Lancet*, **360**(9343), pp. 1347-1360.

Faiers, A., and C. Neame (2006). Consumer attitudes towards domestic solar power systems. *Energy Policy*, **34**, pp. 1797-1806.

Fawer, M., and B. Magyar (2010). *Solar Industry – Entering New Dimensions: Comparison of Technologies, Markets and Industries. Solar Energy 2010.* Sustainable Investment Division, Bank Sarasin, Basel, Switzerland, 56 pp. Available at: www.esocialsciences.com/data/articles/Document110122010400.3811609.pdf.

Felder, R., and A. Meier (2008). Well-to-wheel analysis of solar hydrogen production and utilization for passenger car transportation. *Journal of Solar Energy Engineering*, **130**(1), 011017.

Fernández-García, A., E. Zarza, L. Valenzuela, and M. Pérez (2010). Parabolic-trough solar collectors and their applications. *Renewable and Sustainable Energy Reviews*, **14**, pp. 1695-1721.

Fong, K.F., T.T. Chow, C.K. Lee, Z. Lin, and L.S. Chan (2010). Comparative study of different solar cooling systems for buildings in subtropical city. *Solar Energy*, **84**, pp. 227-244.

Forrest, S.R. (2005). The limits to organic photovoltaic cell efficiency. *Materials Research Society (MRS) Bulletin*, **30**(1), pp. 28-32.

Fthenakis, V., and H.C. Kim (2009). Land use and electricity generation: A life-cycle analysis. *Renew. Renewable and Sustainable Energy Reviews*, **13**(6-7), pp. 1465-1474.

Fthenakis, V.M., and H.C. Kim (2010). Photovoltaics: Life-cycle analyses. *Solar Energy*, doi:10.1016/j.solener.2009.10.002.

Fudholi, A., K. Sopian, M.H. Ruslan, M.A. Alghoul, and M.Y. Sulaiman (2010). Review of solar dryers for agricultural and marine products. *Renewable and Sustainable Energy Reviews*, **14**(1), pp. 1-30.

Furbo, S., E. Andersen, S. Knudsen, N.K. Vejen, and L.J. Shah (2005). Smart solar tanks for small solar domestic hot water systems. *Solar Energy*, **78**(2), pp. 269-279.

Gaiddon, B., and M. Jedliczka (2007). *Compared Assessment of Selected Environmental Indicators of Photovoltaic Electricity in OECD Cities.* IEA Photovoltaic Power Systems Program (PVPS), Task 10, Activity 4.4, Report IEA-PVPS-T10-01:2006, French Agency for Environment and Energy Management for the International Energy Agency, Hespu, Villeurbanne, France, 44 pp. Available at: www2.epia.org/documents/NL_0606_002.pdf.

Gil, A., M. Medrano, I. Martorell, A. Lazaro, P. Dolado, B. Zalba, and L.F. Cabeza (2010). State of the art on high temperature thermal energy storage for power generation. Part 1-Concepts, materials and modellization. *Renewable and Sustainable Energy Reviews*, **14**(1), pp. 31-55.

Goodrich, A. C., M. Woodhouse, and T. James (2011). Solar PV manufacturing cost model group: Installed solar PV system prices. Presentation to SEGIS_ADEPT *Power Electronic in Photovoltaic Systems Workshop*, Arlington, Virginia, 8 February 2001. NREL/PR-6A20-50955. Available at: arpa-e.energy.gov/LinkClick.aspx?fileticket=2WF9d-ukumA%3D&tabid=408.

Gordon, J.M. (ed.) (2001). *Solar Energy: The State of the Art. ISES Position Papers.* James & James London, UK, 706 pp.

Graf, D., N. Monnerie, M. Roeb, M. Schmitz, and C. Sattler (2008). Economic comparison of solar hydrogen generation by means of thermochemical cycles and electrolysis. *International Journal of Hydrogen Energy*, **33**(17), pp. 4511-4519.

Graetzel, M. (2001). Photoelectrochemical cells. *Nature*, **414**(6861), pp. 338-344.

Green, M.A. (2001). Third generation photovoltaics: Ultra-high conversion efficiency at low cost. *Progress in Photovoltaics: Research and Applications*, **9**(2), pp. 123-135.

Green, M.A. (2003). *Third Generation Photovoltaics: Advanced Solar Energy Conversion.* Springer, Berlin, Germany.

Green, M.A., K. Emery, Y. Hishikawa, and W. Warta (2009). Solar cell efficiency tables (version 34). *Progress in Photovoltaics: Research and Applications*, **17**(5), pp. 320-326.

Green, M.A., K. Emery, Y. Hishikawa, and W. Warta (2010a). Solar cell efficiency tables (version 35). *Progress in Photovoltaics: Research and Applications*, **18**(2), pp. 144-150.

Green, M.A., K. Emery, Y. Hishikawa, and W. Warta (2010b). Solar efficiency tables (version 36). *Progress in Photovoltaics: Research and Applications*, **18**(5), pp. 346-352.

Gumy, D., A.G. Rincon, R. Hajdu, and C. Pulgarin (2006). Solar photocatalysis for detoxification and disinfection of water: Different types of suspended and fixed TiO_2 catalysts study. *Solar Energy*, **80**, pp. 1376-1381.

Günes, S., and N.S. Sariciftci (2008). Hybrid solar cells. *Inorganica Chimica Acta*, **361**, pp. 581-588.

Hadorn, J.C. (ed.) (2005). *Thermal Energy Storage for Solar and Low Energy Buildings: State of the Art.* IEA Solar Heating and Cooling Task 32, International Energy Agency, Solar Heating and Cooling Programme, Servei de Publicacions Universidad Lleida, Lleida, Spain, 170 pp.

Hadorn, J.C. (2008). Thermal energy storage – Overview of technologies and status for solar heat. In: *EuroSun 2008, 1st International Conference on Solar Heating, Cooling and Buildings*, International Solar Energy Society, Lisbon, Portugal, 7-10 October 2008, pp.1-8.

Han, J., A.P.J. Mol, and Y. Lu (2010). Solar water heaters in China: A new day dawning. *Energy Policy*, **38**(1), pp. 383-391.

Harvey, L.D.D. (2006). *A Handbook on Low-Energy Buildings and District-Energy Systems: Fundamentals, Techniques and Examples.* Earthscan, Sterling, VA, USA, 701 pp.

Heiselberg, P. (ed.) (2002). *Principles of Hybrid Ventilation.* IEA Energy Conservation in Buildings and Community Systems Programme, Annex 35, Hybrid Ventilation and New and Retrofitted Office Buildings, IEA Energy Conservation in Buildings and Community Systems Programme, Birmingham, UK, 73 pp.

Henning, H.-M. (2004). *Solar-Assisted Air-Conditioning in Buildings: A Handbook for Planners.* Springer, New York, NY, USA, 136 pp.

Henning, H.-M. (2007). Solar assisted air conditioning of buildings – an overview. *Applied Thermal Engineering*, **27**, pp. 1734-1749.

Hernandez Gonzalvez, C. (1996). *Manual de Energía Solar Térmica.* Instituto para la Diversificación de la Energía (IDAE), Madrid, Spain, 123 pp.

Hoff, T.E., B.J. Pasquier, and J.M. Peterson (2010). Market transformation benefits of a PV incentive program. In: *SOLAR 2010 Conference Proceedings*, American Solar Energy Society, Phoenix, Arizona, 17-22 May 2010.

Hoffert, M.I., K. Caldeira, G. Benford, D.R. Criswell, C. Green, H. Herzog, A.K. Jain, H.S. Kheshgi, K.S. Lackner, J.S. Lewis, H.D. Lightfoot, W. Manheimer, J.C. Mankins, M.E. Mauel, L.J. Perkins, M.E. Schlesinger, T. Volk, and T.M.L. Wigley (2002). Advanced technology paths to global climate stability: Energy for a greenhouse planet. *Science*, **298**, pp. 981-987.

Hoffmann, W. (2009). The role of PV solar electricity to power the 21st century's global prime energy demand. *IOP Conference Series: Earth and Environmental Sciences*, **8**, 012007.

Hoffmann, W., S. Wieder, and T. Pellkofer (2009). Differentiated price experience curves as evaluation tool for judging the further development of crystalline silicon and thin film PV solar electricity products. In: *Proceedings of the 24th European Photovoltaic Solar Energy Conference*, Hamburg, Germany, 21-25 September 2009, pp. 4387-4394 (ISBN: 3-936338-25-6).

Hofman, Y., D. de Jager, E. Molenbroek, F. Schilig, and M. Voogt (2002). *The Potential of Solar Electricity to reduce CO_2 Emissions.* Ecofys, Utrecht, The Netherlands, 106 pp.

Hollands, K.G.T., J.L. Wright, and C.G. Granqvist (2001). Glazing and coatings. In: *Solar Energy: The State of the Art. ISES Position Papers.* J.M. Gordon (ed.), James & James, London, UK, pp. 24-107.

Holttinen, H. (2005). Hourly wind power variations in the Nordic countries. *Wind Energy*, **8**(2), pp. 173-195.

Hoogwijk, M. (2004). *On the Global and Regional Potential of Renewable Energy Sources.* Department of Science, Technology and Society, Utrecht University, Utrecht, the Netherlands.

Hoogwijk, M., and W. Graus (2008). *Global Potential of Renewable Energy Sources: A Literature Assessment.* Ecofys, Utrecht, The Netherlands, 45 pp.

IEA (2007). *Renewables for Heating and Cooling – Untapped Potential.* International Energy Agency, Paris, 205 pp.

IEA (2008). *World Energy Outlook 2008.* International Energy Agency, Paris, France, 578 pp.

IEA (2009a). *Global Renewable Energy Policies and Measures Database.* International Energy Agency, Paris, France. Available at: www.iea.org/textbase/pm/?mode=re.

IEA (2009b). *Towards Net Zero Energy Solar Buildings.* IEA Energy Conservation in Buildings and Community Systems (ECBCS) Programme, Solar Heating and Cooling Programme, SHC Task 40, ECBCS Annex 52, International Energy Agency, Paris, France. Available at: www.iea-shc.org/task40/.

IEA (2009c). *Trends in Photovoltaic Applications: Survey Report of Selected IEA Countries between 1992 and 2008.* IEA Photovoltaic Power Systems Program (PVPS), Task 1, Report IEA-PVPS T1-18:2009, International Energy Agency, Paris, France, 44 pp. Available at: www.iea-pvps.org/index.php?id=32.

IEA (2010a). *Energy Technology Perspectives 2010. Scenarios & Strategies to 2050.* International Energy Agency, Paris, France, 708 pp.

IEA (2010b). *Technology Roadmap, Concentrating Solar Power.* International Energy Agency, Paris, France, 48 pp.

IEA (2010c). *Technology Roadmap, Solar Photovoltaic Energy.* International Energy Agency, Paris, France, 48 pp.

IEA (2010d). *World Energy Outlook 2010.* International Energy Agency, Paris, France, 736 pp.

IEA (2010e). *Trends in Photovoltaic Applications: Survey Report of Selected IEA Countries between 1992 and 2009.* IEA Photovoltaic Power Systems Program (PVPS), Task 1, Report IEA-PVPS T1-10-2010, International Energy Agency, Paris, France, 44 pp. Available at: www.iea-pvps.org/index.php?id=32.

IEA ECES (2004). *Energy Conservation through Energy Storage (ECES) Implementing Agreement*, International Energy Agency, Paris, France, 24 pp. Available at: www.iea-eces.org/files/iaeces_2004.pdf.

IEA NZEB (2009). *IEA Joint Project: Towards Net Zero Energy Solar Buildings (NZEBs).* SHC Task 40, ECBCS Annex 52, Revised 25 February 2009, IEA Solar Heating and Cooling Programme. Available at: www.iea-shc.org/publications/downloads/task40-Net_Zero_Energy_Solar_Buildings.pdf.

Weiss, W., and F. Mauthner (2010). *Solar Heat Worldwide – Markets and Contribution to the Energy Supply 2008.* AEE - Institute for Sustainable Technologies, Gleisdorf, Austria for the International Energy Agency Solar Heating and Cooling Programme, 52 pp. Available at: www.iea-shc.org/publications/downloads/Solar_Heat_Worldwide-2010.pdf.

Ilex Energy Consulting Ltd., Electricity Research Centre, Electric Power and Energy Systems Research Group, and Manchester Centre for Electrical Energy (2004). *Operating Reserve Requirements as Wind Power Penetration Increases in the Irish Electricity System.* Report No. 04-RERDD-011-R-01, Sustainable Energy Ireland, Dublin, Ireland. Available at: www.seai.ie/uploadedfiles/InfoCentre/IlexWindReserrev2FSFinal.pdf.

Imre, L. (2007). Solar drying. In: *Handbook of Industrial Drying.* 3rd ed. A.S. Mujumdar (ed.), Taylor & Francis, Philadelphia, PA, USA, pp. 307-361.

Iqbal, M. (1984). *An Introduction to Solar Radiation.* Academic Press, New York, 390 pp.

ISCCP Data Products (2006). International Satellite Cloud Climatology Project (ISCCP). Available at: isccp.giss.nasa.gov/projects/flux.html.

Jäger-Waldau, A. (2005). *Photovoltaics Status Report 2005: Research, Solar Cell Production and Market Implementation of Photovoltaics.* Euro-Report EUR 21836 EN, European Commission, Joint Research Centre, Renewable Energies Unit, Luxembourg.

Jäger-Waldau, A. (2009). *Photovoltaics Status Report 2009: Research, Solar Cell Production and Market Implementation of Photovoltaics.* Euro-Report EUR 24027 EN. Office for Official Publications of the European Union, Luxembourg.

Jäger-Waldau, A. (2010a). *Photovoltaics Status Report 2010: Research, Solar Cell Production and Market Implementation of Photovoltaics.* Office for Official Publications of the European Union, Luxembourg.

Jäger-Waldau, A. (2010b). Status and perspectives of thin film photovoltaics. In: *Thin Film Solar Cells: Current Status and Future Trends.* A. Bosio and A. Romeo (eds.), Nova Publishers, New York, NY, USA, pp. 1-24.

Jensen, S.H., P.H. Larsen, and M. Mogensen (2007). Hydrogen and synthetic fuel production from renewable energy sources. *International Journal of Hydrogen Energy*, **32**(15), pp. 3253-3257.

Jewell, W., and R. Ramakumar (1987). The effect of moving clouds on electric utilities with dispersed photovoltaic generation. *IEEE Transactions on Energy Conversion*, **2**(4), pp. 570-576.

Jewell, W., and T. Unruh (1990). Limits on cloud-induced fluctuation in photovoltaic generation. *IEEE Transaction on Energy Conversion*, **5**(1), pp. 8-14.

Kaneko, H., T. Miura, A. Fuse, H. Ishihara, S. Taku, H. Fukuzumi, Y. Naganuma, and Y. Tamaura (2007). Rotary-type solar reactor for solar hydrogen production with two-step water splitting process. *Energy Fuels*, **21**(4), pp. 2287-2293.

Kawasaki, N., T. Oozeki, K. Otani, and K. Kurokawa (2006). An evaluation method of the fluctuation characteristics of photovoltaic systems by using frequency analysis. *Solar Energy Materials and Solar Cells*, **90**(18-19), pp. 3356-3363.

Kaya, N., J.C. Mankins, B. Erb, D. Vassaux, G. Pignolet, D. Kassing, and P. Collins (2001). Report of workshop on clean and inexhaustible space solar power at Unispace III Conference. *Acta Astronautica*, **49**(11), pp. 627-630.

Kern, E.J., and M. Russell (1988). Spatial and temporal irradiance variations over large array fields. In: *Conference Record of the 20th IEEE Photovoltaic Specialists Conference*, Las Vegas, NV, 26-30 September 2008, 2, pp. 1043-1050.

Khanna, R.K., R.S. Rathore, and C. Sharma (2008). Solar still an appropriate technology for potable water need of remote villages of desert state of India - Rajasthan. *Desalination*, **220**, pp. 645-653.

Kitamura, A. (1999). *Demonstration Test Results for Grid Interconnected Photovoltaic Power Systems.* Report IEA-PVPS T5-02:1999, International Energy Agency, Paris, France.

Kobayashi, H., and M. Takasaki (2006). Demonstration study of autonomous demand area power system. In: *Transmission and Distribution Conference and Exhibition 2005/2006*, Institute of Electrical and Electronics Engineers (IEEE) Power Engineering Society, Dallas, TX, 21-24 May 2006, pp. 548-555.

Komiyama, R., C. Marnay, M. Stadler, J. Lai, S. Borgeson, B. Coffey, and I. Lima Azevedo (2009). *Japan's Long-term Energy Demand and Supply Scenario to 2050 – Estimation for the Potential of Massive CO$_2$ Mitigation.* The Institute for Energy Economics, Tokyo, Japan.

Komoto, K., M. Ito, P. van der Vleuten, D. Faiman, and K. Kurokawa (eds.) (2009). *Energy from the Desert: Very Large Scale Photovoltaic Systems: Socio-economic, Financial, Technical and Environmental Aspects.* Earthscan Publishers, London, UK.

Koster, L.J.A., V.D. Mihailetchi, and P.W.M. Blom (2006). Ultimate efficiency of polymer/fullerene bulk heterojunction solar cells. *Applied Physics Letters*, **88**(9), 093511, doi:10.1063/1.2181635.

Krebs, F.C. (2005). Alternative PV: Large scale organic photovoltaics. *REfocus*, **6**(3), pp. 38-39.

Krewitt, W., K. Nienhaus, C. Kleßmann, C. Capone, E. Stricker, W. Graus, M. Hoogwijk, N. Supersberger, U. von Winterfeld, and S. Samadi (2009). *Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply.* Climate Change 18/2009, ISSN 1862-4359, Federal Environment Agency, Dessau-Roßlau, Germany, 336 pp.

Krey, V., and L. Clarke (2011). Role of renewable energy in climate change mitigation: a synthesis of recent scenarios. *Climate Policy*, in press.

Kroposki, B., R. Margolis, G. Kuswa, J. Torres, W. Bower, T. Key, and D. Ton (2008). *Renewable Systems Interconnection.* National Renewable Energy Laboratory, Golden, CO, USA, 23 pp.

Kurokawa, K., and F. Aratani (2004). Perceived technical issues accompanying large PV development and Japanese "PV2030". In: *19th European Photovoltaic Solar Energy Conference and Exhibition*, Paris, France, 7-11 June 2004.

Kurokawa, K., K. Komoto, P. van der Vleuten, and D. Faiman (eds.) (2007). *Energy from the Desert: Practical Proposals for Very Large Scale Photovoltaic Systems.* Earthscan, London, UK.

Kushiya, K. (2009). Key near-term R&D issues for continuous improvement in CIS-based thin-film PV modules. *Solar Energy Materials & Solar Cells*, **93**, pp. 1037-1041.

Lahkar, P.J., and S.K. Samdarshi (2010). A review of the thermal performance parameters of box type solar cookers and identification of their correlations. *Renewable and Sustainable Energy Reviews*, **14**, pp. 1615-1621.

LBBW (2009). *Branchenanalyse Photovoltaik.* Landesbank Baden-Württemberg (LBBW), Stuttgart, Germany.

Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson, and M. Prather (2007). Historical overview of climate change science. In: *Climate Change 2007: The Physical Science Basis. Working Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Cambridge University Press, pp. 93-127.

Lee, S., and Z. Yamayee (1981). Load-following and spinning-reserve penalties for intermittent generation. *IEEE Transactions on Power Apparatus and Systems*, **100**(3), pp. 1203-1211.

Li, G., V. Shrotriya, J.S. Huang, Y. Yao, T. Moriarty, K. Emery, and Y. Yang (2005). High-efficiency solution processable polymer photovoltaic cells by self-organization of polymer blends. *Nature Materials*, **4**(11), pp. 864-868.

Lynch, M. (2002). Reducing environmental damage caused by the collection of cooking fuel by refugees. *Refuge*, **21**(1), pp. 18-27.

Mankins, J.C. (1997). A fresh look at space solar power: New architectures, concepts, and technologies. *Acta Astronautica*, **41**(4-10), pp. 347-359.

Mankins, J.C. (2002). A technical overview of the "Suntower" solar power satellite concept. *Acta Astronautica*, **50**(6), pp. 369-377.

Mankins, J.C. (2009). New directions for space solar power. *Acta Astronautica*, **65**, pp. 146-156.

Manuel, J. (2003). The quest for fire: Hazards of a daily struggle. *Environmental Health Perspectives*, **111**(1), pp. A28-A33.

Marcos, J., L. Marroyo, E. Lorenzo, D. Alvira, and E. Izco (2010). Power output fluctuations in large scale PV plants: One year observations with one second resolution and a derived analytic model. *Progress in Photovoltaics: Research and Applications*, doi:10.1002/pip.1016.

Marti, A., and A. Luque (eds.) (2004). *Next Generation Photovoltaics: High Efficiency through Full Spectrum Utilization.* Institute of Physics Publishing, Bristol, UK and Philadelphia, PA, USA, 332 pp.

Maycock, P.D. (1976-2003). *PV News.* PV Energy Systems 1982 (vol 1) through 2003 (vol 22). PV Energy Systems, Williamsburg, VA, USA.

Maycock, P.D. (2002). *The World Photovoltaic Market – Report* (January). PV Energy Systems, Williamsburg, VA, USA.

Medrano, M., A. Gil, I. Martorell, X. Potau, and L.F. Cabeza (2010). State of the art on high-temperature thermal energy storage for power generation. Part 2-Case studies. *Renewable and Sustainable Energy Reviews*, **14**(1), pp. 56-72.

Meeder, A., A. Neisser, U. Rühle, and N. Mayer (2007). Manufacturing the first MW of large-area $CuInS_2$-based solar modules – Recent experiences and progress. In: *Proceedings of the 22nd European Photovoltaic Solar Energy Conference*, Milan, Italy, 3-7 September 2007, pp. 2115.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver, and Z.-C. Zhao (2007). Global climate projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.), Cambridge University Press, pp. 747-846.

Mehling, H., and L.F. Cabeza (2008). *Heat and Cold Storage with PCM : An Up to Date Introduction into Basics and Applications.* Springer, Berlin, Germany and London, UK, 308 pp.

Meier, J., S. Dubail, R. Platz, P. Torres, U. Kroll, J.A. Selvan, N. Pellaton Vaucher, C. Hof, D. Fischer, H. Keppner, R. Flückiger, A. Shah, S. Shklover, and K.-D. Ufert (1997). Towards high-efficiency thin-film silicon solar cells with the "micromorph" concept. *Solar Energy Materials and Solar Cells*, **49**(1-4), pp. 35-44.

Meleshko, V.P., V.M. Kattsov, B.A. Govorkova, P.V. Sporyshev, I.M. Skolnik, and B.E. Sneerov (2008). Climate of Russia in the 21st century. Part 3. Future climate change calculated with an ensemble of coupled atmosphere-ocean general circulation CMIP3 models. *Meteorology and Hydrology*, **33**(9), pp. 541-552. Original Russian text published in Meteorologiya i Gidrologiya, no. 9, 2008.

Miller, J.E., M.D. Allendorf, R.B. Diver, L.R. Evans, N.P. Siegel, and J.N. Stuecker (2008). Metal oxide composites and structures for ultra-high temperature solar thermochemical cycles. *Journal of Materials Science*, **43**(14), pp. 4714-4728.

Mills, A., and R. Wiser (2010). *Implications of Wide-Area Geographic Diversity for Short-Term Variability of Solar Power.* DE-AC02-05CH11231, LBNL-3884E, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Mills, B.F., and J. Schleich (2009). Profits or preferences? Assessing the adoption of residential solar thermal technologies. *Energy Policy*, **37**(10), pp. 4145-4154.

Mills, E. (2005). The specter of fuel-based lighting. *Science*, **308**(5726), pp. 1263-1264.

Ministry of New and Renewable Energy (2009). *Jawaharlal Nehru National Solar Mission Towards Building SOLAR INDIA.* Ministry of New and Renewable Energy, New Delhi, India, 15 pp.

Mints, P. (2010). The PV industry's black swan. *Photovoltaics World*, 18 March 2010.

Mints, P. (2011). PV sector market forecast – Thin-film in the era of cheap crystalline PV. *Renewable Energy World Magazine.* 11 February 2011.

Möller, S., D. Kaucic, and C. Sattler (2006). Hydrogen production by solar reforming of natural gas: A comparison study of two possible process configurations. *Journal of Solar Energy Engineering*, **128**(1), pp. 16-23.

Munoz, J., L. Narvarte, and E. Lorenzo (2007). Experience with PV-diesel hybrid village power systems in southern Morocco. *Progress in Photovoltaics: Research and Applications*, **15**, pp. 529-539.

Murata, A., H. Yamaguchi, and K. Otani (2009). A method of estimating the output fluctuation of many photovoltaic power generation systems dispersed in a wide area. *Electrical Engineering in Japan*, **166**(4), pp. 9-19.

Nankhuni, F.J., and J.L. Findeis (2004). Natural resource-collection work and children's schooling in Malawi. *Agricultural Economics*, **31**(2-3), pp. 123-134.

Narayan, G.P., M.H. Sharqawy, E.K. Summers, J.H. Lienhard, S.M. Zubair, and M.A. Antar (2010). The potential of solar-driven humidification-dehumidification desalination for small-scale decentralized water production. *Renewable and Sustainable Energy Reviews*, **14**, pp. 1187-1201.

NAS (2004). *Laying the Foundation for Space Solar Power – An Assessment of NASA's Space Solar Power Investment Strategy.* National Academy of Sciences (NAS), Washington, DC, USA.

NRC (2010). *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use.* National Research Council (NRC), The National Academies Press, Washington, DC, USA, 506 pp.

Navigant Consulting Inc. (2006). *A Review of PV Inverter Technology Cost and Performance Projections.* NREL/SR-620-38771, National Renewable Energy Laboratory, Golden, CO, USA, 100 pp.

NEDO (2009). *The Roadmap PV2030+*. New Energy and Industrial Technology Organization (NEDO), Kawasaki, Japan.

NEEDS (2009). *New Energy Externalities Development for Sustainability (NEEDS). Final Report and Database.* New Energy Externalities Development for Sustainability, Rome, Italy.

Neij, L. (2008). Cost development of future technologies for power generation – A study based on experience curves and complementary bottom-up assessments. *Energy Policy*, **36**, pp. 2200-2211.

Nelson, J. (2003). Over the limit: Strategies for high efficiency. In: *The Physics of Solar Cells.* Imperial College Press, London, England, pp. 289-323.

Nicol, F., M. Wilson, and C. Chiancarella (2006). Using field measurements of desktop illuminance in European offices to investigate its dependence on outdoor conditions and its effect on occupant satisfaction, and the use of lights and blinds. *Energy and Buildings*, **38**(7), pp. 802-813.

Norton, B. (2001). Solar process heat: Distillation, drying, agricultural and industrial uses. In: *Solar Energy: The State of the Art. ISES Position Papers.* J.M. Gordon (ed.), James & James, London, UK, pp. 477-496.

NREL (2011). *The Open PV Project* (online database). National Renewable Energy Laboratory (NREL), Golden, CO, USA. Available at: openpv.nrel.gov.

O'Regan, B., and M. Graetzel (1991). A low-cost, high-efficiency solar-cell based on dye-sensitized colloidal TiO_2 films. *Nature*, **353**(6346), pp. 737-740.

Ogimoto, K., T. Oozeki, and Y. Ueda (2010). Long-range power demand and supply planning analysis including photovoltaic generation penetration. *The Institute of Electrical Engineers of Japan (IEEJ) Transactions on Power and Energy, Tokyo*, **130-B**(6), pp. 575-583.

Oozeki, T., T. Takashima, K. Otani, Y. Hishikawa, G. Koshimizu, Y. Uchida, and K. Ogimoto (2010). Statistical analysis of the smoothing effect for photovoltaic systems in a large area. *The Institute of Energy Economics, Japan (IEEJ) Transactions on Power and Energy, Tokyo*, **130-B**(5), pp. 491-500.

Otani, K., J. Minowa, and K. Kurokawa (1997). Study on areal solar irradiance for analyzing areally-totalized PV systems. *Solar Energy Materials and Solar Cells*, **47**(1-4), pp. 281-288.

Otani, K., A. Murata, K. Sakuta, J. Minowa, and K. Kurokawa (1998). Statistical smoothing of power delivered to utilities by distributed PV systems. In: *2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion. Proceedings of the International Conference*, Vienna, Austria, 6-10 July 1998.

Paksoy, H. (2007). *Thermal Energy Storage for Sustainable Energy Consumption: Fundamentals, Case Studies and Design.* Springer, London, UK and Berlin, Germany.

Parente, V., J. Goldemberg, and R. Zilles (2002). Comments on experience curves for PV modules. *Progress in Photovoltaics: Research and Applications*, **10**, pp. 571-574.

Park, H.G., and J.K. Holt (2010). Recent advances in nanoelectrode architecture for photochemical hydrogen production. *Energy & Environmental Science*, **3**(8), pp. 1028-1036.

Patrick, E. (2007). Sexual violence and fuelwood collection in Darfur. *Forced Migration Review*, **27**, pp. 40-41.

Perpinan, O., E. Lorenzo, M.A. Castro, and R. Eyras (2009). Energy payback time of grid connected PV systems: Comparison between tracking and fixed systems. *Progress in Photovoltaics: Research and Applications*, **17**(2), pp. 137-147.

Photovoltaic Geographic Information System (2008). *Solar Radiation and Photovoltaic Electricity Potential Country and Regional Maps for Europe (Africa).* Institute for Energy, Renewable Energy Unit, European Commission, Joint Research Centre, Ispra, Italy.

PHPP (2004). *PassivHaus Planning Package (PHPP). Technical Information PHI-2004/1(E) - Specifications for Quality Approved Passive Houses.* PassiveHause Institute, Darmstadt, Germany.

Piatkowski, N., C. Wieckert, and A. Steinfeld (2009). Experimental investigation of a packed-bed solar reactor for the steam-gasification of carbonaceous feedstocks. *Fuel Processing Technology*, **90**(3), pp. 360-366.

Piwko, R.J., X. Bai, K. Clark, G.A. Jordan, and N.W. Miller (2007). *Intermittency Analysis Project: Appendix B: Impact of Intermittent Generation on Operation of California Power Grid.* California Energy Commission, PIER Research Development & Demonstration Program, Sacramento, CA, USA.

Piwko, R., K. Clark, L. Freeman, G. Jordan, and N. Miller (2010). *Western Wind and Solar Integration Study.* National Renewable Energy Laboratory, Golden, CO, USA.

POSHIP (2001). *Calor Solar Para Provesos Industriales: Proyecto POSHIP (Potential of Solar Heat for Industrial Processes).* Instituto Para Lad Diversificacion y Ahorro de Energia (IDAE), Madrid, Spain.

Pregger, T., D. Graf, W. Krewitt, C. Sattler, M. Roeb, and S. Moeller (2009). Prospects of solar thermal hydrogen production processes. *International Journal of Hydrogen Energy*, **34**(10), pp. 4256-4267.

Probst, M.M., and C. Roecker (2007). Towards an improved architectural quality of building integrated solar thermal systems (BIST). *Solar Energy*, **81**(9), pp. 1104-1116.

Ralegaonkar, R.V., and R. Gupta (2010). Review of intelligent building construction: A passive solar architecture approach. *Renewable and Sustainable Energy Reviews*, **14**, pp. 2238-2242.

Ramachandran, J., N.M. Pearsall, and G.A. Putrus (2004). Reduction in solar radiation fluctuation by spatial smoothing effect. In: *19th European Photovoltaic Solar Energy Conference. Proceedings of the International Conference*, WIP-Renewable Energies, Paris, France, 7-11 July 2004, pp. 2900-2903.

REN21 (2009). *Renewables Global Status Report. 2009 Update.* Renewable Energy Policy Network for the 21st Century Secretariat, Paris, France, 32 pp.

REN21 (2010). *Renewables 2010 Global Status Report.* Renewable Energy Policy Network for the 21st Century Secretariat, Paris, France, 80 pp.

Richter, C., S. Teske, and R. Short (2009). *Concentrating Solar Power: Global Outlook 2009 – Why Renewable Energy is Hot.* Greenpeace International, SolarPACES (Solar Power and Chemical Energy Storage), and ESTELA (European Solar Thermal Electricity Association), 88 pp. Available at: www.greenpeace.org/raw/content/international/press/reports/concentrating-solar-power-2009.pdf.

Rickerson, W., T. Halfpenny, and S. Cohan (2009). The emergence of renewable heating and cooling policy in the United States. *Policy and Society*, **27**(4), pp. 365-377.

Rodat, S., S. Abanades, and G. Flamant (2009). High-temperature solar methane dissociation in a multitubular cavity-type reactor in the temperature range 1823-2073 K. *Energy & Fuels*, **23**, pp. 2666-2674.

Roeb, M., C. Sattler, R. Kluser, N. Monnerie, L. de Oliveira, A.G. Konstandopoulos, C. Agrafiotis, V.T. Zaspalis, L. Nalbandian, A. Steele, and P. Stobbe (2006). Solar hydrogen production by a two-step cycle based on mixed iron oxides. *Journal of Solar Energy Engineering*, **128**(2), pp. 125-133.

Roeb, M., M. Neises, J.P. Sack, P. Rietbrock, N. Monnerie, J. Dersch, M. Schmitz, and C. Sattler (2009). Operational strategy of a two-step thermochemical process for solar hydrogen production. *International Journal of Hydrogen Energy*, **34**(10), pp. 4537-4545.

Rogner, H.-H., F. Barthel, M. Cabrera, A. Faaij, M. Giroux, D. Hall, V. Kagramanian, S. Kononov, T. Lefevre, R. Moreira, R. Nötstaller, P. Odell, and M. Taylor (2000). Energy resources. In: *World Energy Assessment. Energy and the Challenge of Sustainability.* United Nations Development Programme, United Nations Department of Economic and Social Affairs, World Energy Council, New York, USA, 508 pp.

Ropp, M., J. Newmiller, C. Whitaker, and B. Norris (2008). Review of potential problems and utility concerns arising from high penetration levels of photovoltaics in distribution systems. In: *Proceedings of the 33rd Institute of Electrical and Electronics Engineers (IEEE) Photovoltaic Specialists Conference*, IEEE, San Diego, CA, 11-16 May, 2008, pp. 518-523.

Ruhl, V., F. Luetter, C. Schmidt, J. Wackerbauer, U. Triebswetter (2008). *Standortgutachten Photovoltaik in Deutschland.* EuPD Research and IFO Institut fur Wirtschaftforschung, Universitat Munchen, Bonn, Germany and München, Germany, 28 pp.

Santamouris, M., and D. Asimakopoulos (eds.) (1996). *Passive Cooling of Buildings.* James & James, London, 472 pp.

Sargent and Lundy LLC Consulting Group (2003). *Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts.* National Renewable Energy Laboratory, Golden, CO, USA, 344 pp.

Schaeffer, G.J., A.J. Seebregts, L.W.M. Beurskens, H.H.C. Moor, E.A. Alsema, W. Sark, M. Durstewicz, M. Perrin, P. Boulanger, H. Laukamp, and C. Zuccaro (2004). *Learning from the Sun: Analysis of the Use of Experience Curves for Energy Policy Purposes – The Case of Photovoltaic Power. Final Report of the Photex Project.* DEGO: ECN-C-04-035, Energy Research Centre of the Netherlands, Petten, The Netherlands.

Schaller, R., and V. Klimov (2004). High efficiency carrier multiplication in PbSe nanocrystals: Implications for solar energy conversion. *Physical Review Letters*, **92**(18), 186601.

Scheffler, J. (2002). *Bestimmung der maximal zulässigen Netzanschlussleistung photovoltaischer Energiewandlungsanlagen in Wohnsiedlungsgebieten.* Fakultät Elektrotechnik und Informatik, Technische Universität Chemnitz, Chemnitz, Germany.

Schossig, P., H.-M. Henning, S. Gschwander, and T. Haussmann (2005). Micro-encapsulated phase-change materials integrated into construction materials. *Solar Energy Materials & Solar Cells*, **89**, pp. 297-306.

Schunk, L.O., P. Haeberling, S. Wepf, D. Wuillemin, A. Meier, and A. Steinfeld (2008). A receiver-reactor for the solar thermal dissociation of zinc oxide. *Journal of Solar Energy Engineering*, **130**(2), 021009.

Schunk, L.O., W. Lipinski, and A. Steinfeld (2009). Heat transfer model of a solar receiver-reactor for the thermal dissociation of ZnO - Experimental validation at 10 kW and scale-up to 1 MW. *Chemical Engineering Journal*, **150**(2-3), pp. 502-508.

SEIA (2010a). *US Solar Industry – Year in Review 2009.* US Solar Energy Industries Association (SEIA), Washington, DC, USA.

SEIA (2010b). *US Solar Market Insight, 2nd Quarter 2010 Executive Summary.* US Solar Energy Industries Association (SEIA), Washington, DC, USA.

SEMI (2009a). *Polysilicon shipments reach 43,901 Mt in 2008*. Press Release, 10 March 2009, Semiconductor Equipment and Materials International (SEMI), San Jose, CA, USA. Available at: www.semi.org/en/Press/CTR_028736.

SEMI (2009b). *China's Solar Future (SEMI China White Paper).* Semiconductor Equipment and Materials International (SEMI), San Jose, CA, USA.

SEMI (2009c). *The Solar PV Landscape in India – An Industry Perspective (SEMI India White Paper).* Semiconductor Equipment and Materials International (SEMI), San Jose, CA, USA.

Service, R.F. (2009). Sunlight in your tank. *Science*, **326**(5959), pp. 1471-1475.

Sharma, A. (2011). A comprehensive study of solar power in India and World. *Renewable and Sustainable Energy Reviews*, **15**, pp. 1767–1776.

Shockley, W., and H.J. Queisser (1961). Detailed balance limit of efficiency of p-n junction solar cells. *Journal of Applied Physics*, **32**(3), pp. 510-519.

Shu, H., L. Duanmu, C. Zhang, and Y. Zhu (2010). Study on the decision-making of district cooling and heating systems by means of value engineering. *Renewable Energy*, **35**, pp. 1929-1939.

Sims, R.E.H., R.N. Schock, A. Adegbululgbe, J. Fenhann, I. Konstantinaviciute, W. Moomaw, H.B. Nimir, B. Schlamadinger, J. Torres-Martínez, C. Turner, Y. Uchiyama, S.J.V. Vuori, N. Wamukonya, and X. Zhang (2007). Energy supply. In: *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave and L.A. Meyer (eds.), Cambridge University Press, pp. 251-322.

Sinha, P., C.J. Kriegner, W.A. Schew, S.W. Kaczmar, M. Traister, and D.J. Wilson (2008). Regulatory policy governing cadmium-telluride photovoltaics: A case study contrasting life-cycle management with the precautionary principle. *Energy Policy*, **36**, pp. 381-387.

SolarPACES (2008). *SolarPACES Annual Report 2007.* International Energy Agency, Paris, France, 204 pp.

SolarPACES (2009a). *SolarPACES Annual Report 2008. Task I: Solar Thermal Electric Systems.* International Energy Agency, Paris, France, pp. 3.1-3.14.

SolarPACES (2009b). *SolarPACES Annual Report 2008. Task VI: Solar Energy & Water Processes and Applications.* International Energy Agency, Paris, France, pp. 8.1-12.

Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood, and D. Wratt (2007). Technical summary. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.), Cambridge University Press, pp.19-91.

Spath, P.L., and W.A. Amos (2003). Using a concentrating solar reactor to produce hydrogen and carbon black via thermal decomposition of natural gas: Feasibility and economics. *Journal of Solar Energy Engineering*, **125**(2), pp. 159-164.

Specht, M., F. Baumgart, B. Feigl, V. Frick, B. Stuermer, U. Zuberbuehler, M. Sterner, and G. Waldstein (2010). Speicherung von Bioenergie und erneuerbarem Strom im Erdgasnetz (Storage of bioenergy and renewable power in the natural gas network). In: *FVEE Annual Meeting 2009. Forschen für globale Märkte erneuerbarer Energien*, Berlin, Germany.

Sreeraj, E.S., K. Chatterjee, and S. Bandyopadhyay (2010). Design of isolated renewable hybrid power systems. *Solar Energy*, **84**(7), pp. 1124-1136.

Staebler, D.L., and C.R. Wronski (1977). Reversible conductivity changes in discharge-produced amorphous Si. *Applied Physics Letters*, **31**(4), pp. 292-294.

Stein, W., B. Antonioli, S. Bönisch, M. Hausotte, A. Hofmann, R. Joziak, H. Krautz, P. Minton, B. Mone, J.-C. Müller, J. Pantförder, A Schuster, G. Springer, J. Springer, and S. Klein (2009). Status of thin-film Si high-efficiency tandem junction module fabrication on ultra-large substrates of 2.20 x 2060 m^2 at Sunfilm. In: *Proceedings of the 24th EU PV Solar Energy Conference, 6th European PV Industry Forum*, Hamburg, Germany, 23 September 2009.

Steinfeld, A. (2005). Solar thermochemical production of hydrogen - a review. *Solar Energy*, **78**(5), pp. 603-615.

Steinfeld, A., and A. Meier (2004). Solar Fuels and Materials. In: *Encyclopedia of Energy.* Vol. 5. Elsevier, Amsterdam, The Netherlands, pp. 623-637.

Sterner, M. (2009). *Bioenergy and Renewable Power Methane in Integrated 100% Renewable Energy Systems. Limiting Global Warming by Transforming Energy Systems.* Dissertation, Kassel University, Kassel, Germany.

Sun, S.-S., and N.S. Sariciftci (eds.) (2005). *Organic Photovoltaics: Mechanisms, Materials, and Devices.* CRC Press, Taylor & Francis, Boca Raton, FL, USA.

Taguchi, M., Y. Tsunomura, H. Inoue, S. Taira, T. Nakashima, T. Baba, H. Sakata, and E. Maruyama (2009). High-efficiency HIT solar cell on thin (< 100 µm) silicon wafer. In: *Proceedings of the 24th European Photovoltaic Solar Energy Conference*, Hamburg, Germany, 21-25 September 2009, pp. 1690.

Teske, S., T. Pregger, S. Simon, T. Naegler, W. Graus, and C. Lins (2010). Energy [R]evolution 2010—a sustainable world energy outlook. *Energy Efficiency*, doi:10.1007/s12053-010-9098-y.

The European Parliament and the Council of the European Union (2010). *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings.* 2010/31/EU. Official Journal of the European Union, pp. 23.

Torres, J.M.M., N.G. López, and C. Márquez (2010). *The Global Concentrator Solar Power Industry Report 2010-2011.* First Conferences Ltd., London, UK.

Trieb, F. (2005). *Concentrating Solar Power for the Mediterranean Region, Final Report,* German Aerospace Centre (DLR), Stuttgart, 285 pp.

Trieb, F., M. O'Sullivan, T. Pregger, C. Schillings, and W. Krewitt (2009a). *Characterisation of Solar Electricity Import Corridors from MENA to Europe - Potential, Infrastructure and Cost.* German Aerospace Centre (DLR), Stuttgart, Germany, 172 pp.

Trieb, F., C. Schillings, M. O'Sullivan, T. Pregger, and C. Hoyer-Klick (2009b). Global potential of concentrating solar power. In: *SolarPACES Conference*, Berlin, Germany, 15-18 September 2009.

Tripanagnostopoulos, Y. (2007). Aspects and improvements of hybrid photovoltaic/thermal solar energy systems. *Solar Energy*, **81**(9), pp. 1117-1131.

Tsilingiridis, G., G. Martinopoulos, and N. Kyriakis (2004). Life cycle environmental impact of a thermosyphonic domestic solar hot water system in comparison with electrical and gas water heating. *Renewable Energy*, **29**, pp. 1277-1288.

Tsoutsos, T., N. Fratezeskaki, and V. Gekas (2005). Environmental impacts from the solar energy technologies. *Energy Policy*, **33**, pp. 289-296.

Turner, J., G. Sverdrup, M.K. Mann, P.-C. Maness, B. Kroposki, M. Ghirardi, R.J. Evans, and D. Blake (2008). *Renewable hydrogen production. International Journal of Energy Research,* **32**, pp. 379-407.

Twidell, J. and A.D. Weir (2006). *Renewable Energy Resources.* Taylor & Francis, Oxon, UK.

Tzempelikos, A., A.K. Athienitis, and A. Nazos (2010). Integrated design of perimeter zones with glass facades. *ASHRAE Transactions*, **116**(1), pp. 461-478.

UBS (2009). *UBS Wealth Management Research (5 March 2009). Solar Energy.* Union Bank of Switzerland, 37 pp. Available at: http://www.cleantechsandiego.org/reports/UBS_Solar_Energy_Report_3-5-09.pdf.

UNEP (2007). *Buildings and Climate Change – Status, Challenges and Opportunities.* United Nations Environment Programme, Nairobi, Kenya.

Urbschat, C., F. Barban, B. Baumgartner, M. Beste, M. Herr, A. Schmid-Kieninger, F. Rossani, G. Stry-Hipp, and M. Welke (2002). *Sunrise 2002 – The Solar Thermal and Photovoltaic Markets in Europe. Market Survey.* eclareon GmbH, Berlin, Germany.

US Photovoltaic Industry Roadmap Steering Committee (2001). *Solar-Electric Power: The U.S. Photovoltaic Industry Roadmap.* Sandia National Laboratories, Albuquerque, NM, USA, 36 pp.

US DOE (2008). *Solar Energy Technologies Programme, Multi Year Program Plan 2008-2012.* U.S. Department of Energy (US DOE), Washington, DC, USA.

US DOE (2009). *Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation. Report to Congress.* U.S. Department of Energy (US DOE), Washington, DC, USA, 35 pp.

US DOE (2011). *Solar Vision Study (draft).* U.S. Department of Energy (US DOE), Washington DC, USA, final publication currently postponed.

Viebahn, P., Y. Lechon, and F. Trieb (2010). The potential role of concentrated solar power (CSP) in Africa and Europe: A dynamic assessment of technology development, cost development and life cycle inventories until 2050. *Energy Policy*, doi:10.1016/j.enpol.210.09.026.

Voss, K., S. Herkel, J. Pfafferott, G. Löhnert, and A. Wagner (2007). Energy efficient office buildings with passive cooling – Results and experiences from a research and demonstration programme. *Solar Energy*, **81**, pp. 424-434.

Wadia, C., A.P. Alivisatos, and D.M. Kammen (2009). Materials availability expands the opportunity for large-scale photovoltaic deployment. *Environmental Science & Technology*, **43**(6), pp. 2072-2077.

Wagner, S., J.L. Shay, P. Migliorato, and H.M. Kasper (1974). CuInSe$_2$/CdS heterojunction photovoltaic detectors. *Applied Physics Letters*, **25**, pp. 434.

WEC (1994). *New Energy Resources.* World Energy Council (WEC), London, UK.

Wei, M., S. Patadia, and D. Kammen (2010). Putting renewables to work: How many jobs can the clean energy industry generate in the US? *Energy Policy*, **38**, pp. 919-931.

Weiss, W. (2003). *Solar Heating Systems for Houses. A Design Handbook for Solar Combisystems.* Earthscan, London, UK.

Weiss, W., and F. Mauthner (2010). *Solar Heat Worldwide – Markets and Contribution to the Energy Supply 2008.* AEE - Institute for Sustainable Technologies, Gleisdorf, Austria for the International Energy Agency Solar Heating and Cooling Programme, 52 pp. Available at: www.iea-shc.org/publications/downloads/Solar_Heat_Worldwide-2010.pdf.

Wentzel, M., and A. Pouris (2007). The development impact of solar cookers: A review of solar cooking impact research in South Africa. *Energy Policy*, **35**(3), pp. 1909-1919.

Werner, S. (2006). Ecoheatcool. WP1: The European Heat Market 2003, WP4: District Heating Possibilities, WP2: The European Cooling Market. In: *Nordic Energy Perspectives Conference*, Helsinki, Finland, 24 January 2006. Available at: www.nordicenergyperspectives.org/doc24jan06.asp.

Wiemken, E., H.G. Beyer, W. Heydenreich, and K. Kiefer (2001). Power characteristics of PV ensembles: Experiences from the combined power production of 100 grid connected PV systems distributed over the area of Germany. *Solar Energy*, **70**(6), pp. 513-518.

Wiser, R., G. Barbose, and C. Peterman (2009). *Tracking the Sun: The Installed Cost of Photovoltaics in the U.S. from 1998-2007.* Lawrence Berkeley National Laboratory, Berkeley, CA, USA, 42 pp.

Wiser, R., G. Barbose, and E. Holt (2010). *Supporting Solar Power in Renewable Portfolio Standards: Experience from the United States.* LBNL- 3984E, Lawrence Berkeley National Laboratory, Berkeley, CA, USA, 38 pp.

WMO (2008). *Guide to Meteorological Instruments and Methods of Observation.* WMO-No. 8, World Meteorological Organization (WMO), Geneva, Switzerland, 681 pp.

World Bank Global Environment Facility Program (2006). *Assessment of the World Bank/GEF Strategy for the Market Development of Concentrating Solar Thermal Power.* The International Bank for Reconstruction and Development, The World Bank, Washington, DC, USA, 149 pp.

Woyte, A., R. Belmans, and J. Nijs (2001). Power flow fluctuations in distribution grids with high PV penetration. In: *Proceedings of the 17th EC PV Solar Energy Conference*, Munich, Germany, 22-26 October 2001, pp. 2414-2417.

Woyte, A., R. Belmans, and J. Nijs (2007). Fluctuations in instantaneous clearness index: Analysis and statistics. *Solar Energy*, **81**(2), pp. 195-206.

Yakimov, A., and S.R. Forrest (2002). High photovoltaics multiple-heterojunction organic solar cells incorporating interfacial metallic nanoclusters. *Applied Physics Letters*, **80**(9), pp. 1667-1669.

Yamamoto, K., A. Nakashima, T. Suzuki, M. Yoshimi, H. Nishio, and M. Izumina (1994). Thin-film polycrystalline Si solar cell on glass substrate fabricated by a novel low temperature process. *Japanese Journal of Applied Physics*, **33**, pp. L1751-L1754.

Yang, C.J. (2010). Reconsidering solar grid parity. *Energy Policy*, **38**, pp. 3270-3273.

Yang, J., and S. Guha (1992). Double-junction amorphous silicon-based solar cells with 11-percent stable efficiency. *Applied Physics Letters*, **61**(24), pp. 2917-2919.

Young, W.R. (1996). *History of Applying Photovoltaics to Disaster Relief.* Florida Solar Energy Center, Cocoa, FL, USA, 16 pp.

Z'Graggen, A., and A. Steinfeld (2008). Hydrogen production by steam-gasification of carbonaceous materials using concentrated solar energy – V. Reactor modeling, optimization, and scale-up. *International Journal of Hydrogen Energy*, **33**(20), pp. 5484-5492.

Zayed, J., and S. Philippe (2009). Acute oral and inhalation toxicities in rats with cadmium telluride. *International Journal of Toxicology*, **28**(4), pp. 259-265.

Zervos, A., C. Lins, and J. Muth (2010). *RE-thinking 2050 – A 100% Renewable Energy Vision for the European Union.* European Renewable Energy Council, Brussels, Belgium.

Zhang, X., W. Ruoshui, H. Molin, and E. Martinot (2010). A study of the role played by renewable energies in China's sustainable energy supply. *Energy*, **35**(11), pp.4392-4399, doi:10.1016/j.energy.2009.05.030.

Zoellner, J., P. Schweizer-Ries, and C. Wemheuer (2008). Public acceptance of renewable energies: Results from case studies in Germany. *Energy Policy*, **26**, pp. 4136-4141.