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Chapter 3

Direct Solar Energy

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Chapter 3 has been allocated a total of 68 pages in the SRREN. The actual chapter length (excluding references & cover page) is 102 pages: a total of 34 pages over target.

Expert reviewers are kindly asked to indicate where the Chapter could be shortened in terms of text and/or figures and tables.

References of figures/tables are often missing; references from the text that are found missing in the reference list have been highlighted in yellow. In the same manner, references found in the reference list but missing from the text have also been highlighted.

In addition, all monetary values provided in this document will need to be adjusted for inflation/deflation and then converted to USD for the base year 2005.

Chapter 3: Direct Solar Energy

CONTENTS

EXECUTIVE SUMMARY

This Chapter summarizes the current status of the direct use of solar energy as an agent for mitigating climate change. Drawing on references from the most recent literature, we review solar energy's resource potential, describe the technology and its current status, look at the current trends in its adaptation, and provide predictions of its future role. We summarize here the important findings of the Chapter.

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 all energy is used on this planet. In a more practical example, the world's energy requirements could be met by operating solar power stations on only about 4% of the surface area of the Sahara Desert. Although not all countries are equally blessed with solar energy, every country receives enough to contribute significantly to its energy mix.

Solar technology embraces a family of technologies capable of being integrated amongst themselves, as well as with other renewable energy technologies. The solar technologies can deliver heat, cooling, electricity, lighting, 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 and maintaining that absorbed energy can take specialized techniques and devices such as vacuums, phase-change materials, optical coatings, and mirrors. Which technique will be used depends on the application and temperature at which the heat is to be delivered, and this can range from 25°C (e.g., for swimming pool heating) to 1000°C (e.g., for dish/Stirling solar thermal electrical power). Production of *electricity* can be achieved in either of two ways. The first (concentrating solar power or CSP) uses solar thermal conversion to produce high-temperature heat, which is then converted to electricity via a heat engine and generator. In the second, solar energy is converted directly into electricity in a solid-state semiconductor device called a photovoltaic (PV) cell. Both approaches are currently in use. The use of solar energy for *lighting* requires no conversion per se; solar lighting occurs naturally in buildings through windows, but maximizing the effect requires careful engineering and architectural design. In addition to these applications, passive solar *heating* is a technique for maintaining buildings at comfortable conditions by exploiting the solar rays incident on the buildings' exterior, without using pumps and fans. Solar *cooling* for buildings can also be achieved, for example, by using solar-derived heat to drive a special thermodynamic cycle called absorption refrigeration. In addition, solar devices can deliver process heat and cooling, and other devices are being developed that will deliver *fuels* such as hydrogen.

The various solar technologies have differing maturities, and their viability depends on local conditions and government policies to support their adoption. Some technologies are already viable in certain locations, but the overall viability of solar technologies in general 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. It is significant that many countries spend up to one-third of their energy budget as heat. Service hot-water heating for domestic and commercial buildings is now a mature technology growing at a rate of about 20% per annum and employed by about 50 countries around the world. The time-average combined production of thermal power of the existing devices is estimated to be 20 GW. The production of electricity from PV panels is also a worldwide phenomenon. Assisted by supportive pricing policies, PV production is growing at a rate of about 40% per annum—making it one of the fastest-growing energy technologies. Currently, it claims a time-averaged power production of about 2 GW, with most installations being roof-mounted and grid-connected. Energy from PV panels and solar domestic water heaters can be especially valuable because the energy production can occur at times of peak loads on the grid. For example, a cost savings can be incurred by photovoltaics when it offsets the expensive peak-load electricity generated by conventional technologies. PV and solar domestic water heaters also fit well with the needs of developing countries because they are modular, quick to install, and can forestall the need for a large national grid. The production of electricity from CSP installations has seen a huge increase in just the last few years and has now reached a cumulative installed capacity within a few countries of about 0.5 GW. At the same time, passive solar and solar daylighting are conserving energy in buildings at a highly significant rate, but the actual amount is difficult to quantify. (The use of passive solar has been found to decrease the comfort heating requirements by about 15% for existing buildings and about 40% for well-designed new buildings.) The remaining solar technologies, such as fuel production and the provision of industrial process heat, are still being developed and/or are waiting for higher conventional energy prices and for market barriers to be removed before they can be deployed in a significant way. In total, it is estimated that direct solar technologies are currently preventing about 6000 tonnes of CO_2 per year from entering our atmosphere.

Looking to the future, we can expect that further technological improvements will be achieved. For example, much work is under way to improve the efficiency and reduce the materials requirements of PV cells. And judging from the past track record of improvements in solar semiconductor devices, one may expect the steep learning curve to continue into the future. However, these learning curves will only continue if market volumes for the respective technologies increase in parallel, because these curves depend on production volume, not on the mere passage of time. Without rapidly increasing production volumes, the learning curves with respect to time will slow and increase the total cost of the application of solar technologies in the future. Private capital is flowing into all the technologies, but government support and stable political conditions are needed to lessen the risk of private investment and to boost the assurance of faster development.

3.1 Introduction

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—the direct use of solar energy produces essentially no greenhouse gases (except the modest amount produced in the manufacture of conversion devices), and it has the potential to displace large quantities of fossil fuels.

Some of the solar energy absorbed by the Earth appears later in the form of wind, wave, ocean thermal, 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—a subject with a long and significant impact on human history.

3.1.1 Brief History

That history started 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. Later, attempts were made to use mirrors 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. But these devices could not compete with fossil fuels, which were highly abundant in the years leading up to the mid 1900s.

The modern age of solar research began in the 1950s, with the establishment of the International Solar Energy Society. The Society's founders recognized that the age of fossil fuels was limited, and that a sustainable replacement was needed for coal, oil, and natural gas. Sometime later, it also became clear that the mitigation of adverse climate change was an equally important incentive for developing renewable sources of energy. At about the same time, national and international networks of solar radiation measurements were developed. And, in concert with recommendations of the World Meteorological Organization, these networks have been expanding steadily ever since.

With the oil crisis of the 1970s, most countries in the world developed programs for solar energy research and development (R&D). These efforts, which have, for the most part, continued up to the present, have borne fruit: one of the fastest-growing renewable energy technologies, solar energy is now poised to play a vital and environmentally friendly role on the world energy stage.

3.1.2 Theoretical Potential

A nuclear fusion reactor in the sun's core drives an enormous release of energy at its surface. In fact, the energy release at the sun's surface is so great that even the small fraction intercepted by the Earth—5.5×10^6 exajoules (EJ) per year—dwarfs the rate at which the world's population consumes energy, which is 500 EJ/year.

Every material body emits heat rays, called thermal radiation, and solar radiation is that thermal radiation emitted by the sun. Above the Earth's atmosphere, solar radiation's energy rate equals 1368 watts (W) per every square meter of surface facing the sun. Beneath this atmosphere with clear skies on Earth, this figure becomes roughly 1000 W/m^2. 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 radiation is spread over short wavelengths ranging from 0.25 to 3 micrometers (µm).

The sun's high temperature, unequalled on Earth, makes solar radiation very special. For example it embraces daylight: about 40% of solar radiation is visible light, while another 10% is ultraviolet radiation, and 50% is infrared radiation. Solar radiation can also be viewed as a flux of electromagnet particles or photons. Photons from the sun are highly energetic. They range in energy from about 2.2×10^{-19} to 2.6×10^{-18} joules (J)—or from 1.4 to 16 electron-volts (eV). This means that many have energies larger than those associated with electrons in their shells, and consequently, can promote chemical reactions such as photosynthesis and generate conduction electrons in semiconductors, thereby enabling the PV conversion of sunlight into electricity.

3.1.3 Various Conversion Technologies and Applications

Solar energy is 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, e.g., direct water-splitting with a semiconductor solar device without electricity production. Later sections will deal with all of these technologies in detail.

Several solar technologies, such as domestic hot-water heating and pool heating, are already competitive and used in locales where it offers the least-cost option. But more often, market barriers and the lack of a pricing scheme that values the attributes of clean energy have forestalled wide scale use of these solar technologies. Thus, part of the effort to increase solar energy's contribution in mitigating climate change entails creating the market conditions for adopting solar energy technologies, as some countries have done. In these jurisdictions, very large solar-electricity (both PV and solar-thermal) installations approaching 1000 megawatts of power have been realized.

Another part of the effort is the R&D needed to bring well-positioned solar technologies to the final stage of market readiness, through pilot plants and system trials to accelerate the technology and manufacturability development. Particularly important are ways to integrate solar energy with conservation methods and other renewable energy so as to maximize the role it can play. Solar energy has reached this stage of readiness through R&D expenditures that are very modest compared to other energy sources such as nuclear. A larger expenditure in basic solar research will undoubtedly bring forth new solar technologies that will play an important role in the more distant future.

3.1.4 Context Summary

In pursuing any of the solar technologies, there is the need to deal with the sun's variability. One option is to store excess collected energy until it is needed. This is particularly effective for handling the lack of sun at night, which is the least-challenging aspect of solar variability. For example, a 0.1-meter-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 a year, or over a large geographical area such as a continent, solar energy becomes much more reliable. Using both of these concepts has enabled designers to produce more reliable solar systems.

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 renewable energies. When properly integrated, renewable energy can meet a large portion of the world's energy demands.

The rest of this Chapter will include the following topics. The next section summarizes the research that has gone into characterizing this solar resource. It shows that, in principle, only a relatively small part of the Earth's solar resource is required to meet the energy needs of the entire world's population. We find that the energy flux of 1000 W/m^2 mentioned above is only a rough upper bound for solar radiation: the actual radiation depends on the orientation of the surface, date and time of day, latitude, haziness, and cloud cover, and the following section deals with this variability.

Later sections highlight the different technologies: passive solar heating and lighting for buildings, active solar heating and cooling for buildings and industry, solar PV electricity generation, concentrating solar power electricity generation, and solar fuels conversion. These sections will describe each technology and give its applications. Later sections will review the current status of market development, the integration of solar into other energy systems, the environmental and social impacts, and finally, the prospects for future developments. The two final sections cover cost trends and the potential for deployment of these solar technologies.

3.2 Resource Potential

3.2.1 Resource Characteristics

The solar resource is 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 to know how much radiation will fall on their collectors.

The solar energy flux at the top of the atmosphere can be evaluated with high precision because it depends essentially on astronomical parameters. At the Earth's surface, however, evaluation of the solar flux is more difficult because of its interaction with the atmosphere, which contains amounts of aerosols, water vapor, and clouds that vary both geographically and temporally. Atmospheric conditions reduce direct-beam solar radiation by about 10% on clear, dry days and by 100% on days with thick clouds, leading to lower average solar flux.

The solar radiation reaching the Earth's surface is divided into two components: beam radiation, which comes directly from the sun's disk, and diffuse radiation, which comes from the whole of the sky except the sun's disk. The term "global" solar radiation refers to the sum of the beam and diffuse components. Figure 3.1 shows the average global solar flux as it varies across the Earth for two different three-month time periods.

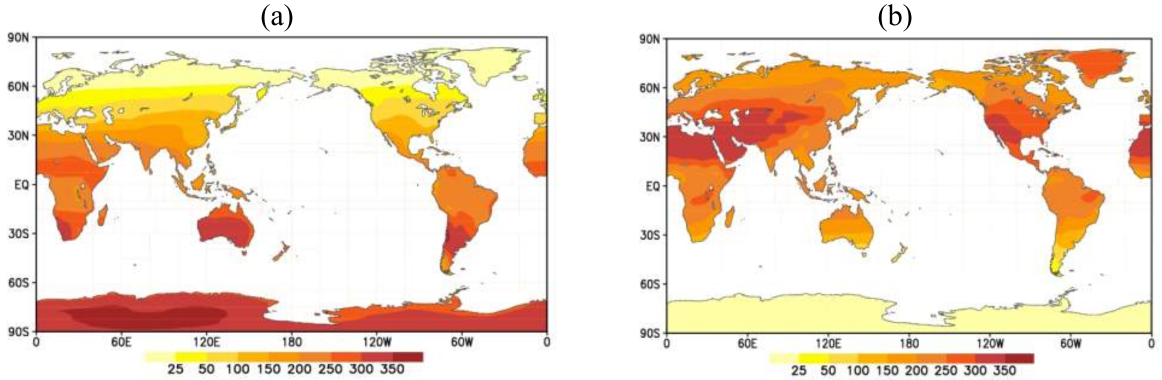

(a) (b)

Figure 3.1: The global solar flux (in W m^{-2}) at the Earth's surface—derived from the European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA)—averaged over two 3-month periods: (a) December-January-February and (b) June-July-August.

There are many different ways to assess the global potential of solar energy. The *theoretical* potential indicates the amount of radiation at the Earth's surface that is theoretically available for energy purposes. It has been estimated as 10.8×10^{11} gigawatt- hours (GWh) per year (World Energy Assessment, 2001). The large-scale generation of solar energy requires land availability and significant area for installation of solar energy collectors. The *technical* potential is a more practical estimate of how much solar radiation could be put to human use by considering the conversion efficiency of available technologies and local factors such as land availability and meteorological conditions. According to some assessments (FAO, 1999), the land area suitable for installation of solar collectors is about 27% of the entire land area, or about 4×10^7 km^2. Assuming that 1% of the world's unused land surface is used for solar power, the technical potential will be about 4.4×10^8 GWh per year. This amount is about three times the world energy consumption from all sources in 2008. On the other hand, the current use of solar energy is estimated as 0.5% for solar heat and 0.04% for solar photovoltaics relative to world total energy consumption (IEA, 2007).

The technical potential varies over the different regions of the Earth. In Table 3.1, the column marked “Minimum” shows a breakdown of the global technical potential for different regions. (A more optimistic assessment of the solar energy resource is also given in the table under the “Maximum” column.) In addition, in the bottom three panels, the table shows the ratio of the global technical potential to the current and projected primary energy consumptions out to 2100. From these last three panels, solar energy’s potential is projected to extend well beyond the current century. Thus, the contribution of solar energy to global energy supplies will not be limited by resource availability. Rather, technological, social, and economic factors will determine the extent to which solar energy is used in the longer term.

Table 3.1: Annual technical potential of solar energy for various regions of the world (modified from Nakićenović et al., 1998).

Region	Minimum, 10^5 GWh	Maximum, 10^5 GWh
North America	500	20000
Latin America and Caribbean	300	9000
Western Europe	70	2500
Central and Eastern Europe	12	400
Former Soviet Union	550	24000
Middle East and North Africa	1100	31000
Sub-Saharan Africa	1000	26000
Pacific Asia	100	2800
South Asia	100	4000
Central Asia	300	11000
Pacific OECD	200	6000
TOTAL	4000	140000
Ratio to current primary energy consumption (1117×10^5 GWh)	3.6	125
Ratio to projected primary energy consumption in 2050 (1639×10^5 – 2917×10^5 GWh)	2.4–1.4	85–48
Ratio to the projected primary energy consumption in 2100 (2444×10^5 – 5275×10^5 GWh)	1.6–0.8	57–27

As Table 3.1 also indicates, the worldwide technical potential of solar energy is considerably larger than the current primary energy consumption. However, the *economic* potential for applying solar energy depends on a variety of factors, namely, theoretical availability of solar energy in a particular region, environmental constraints (e.g., topography, climate condition), resource availability (e.g., land, water), conversion efficiency of the available technology, competition with alternative energy sources, national and local support policies for renewable power generation, coverage and structure of the electricity grid, capability of the power system to deal with power output intermittency, and last but not least, energy consumption demand and patterns in various sectors of the economy and social life. The range of technologies using solar energy is wide and the respective markets have quite different growth rates, ranging between 10% and 50% per year. Therefore, determining the resource potentials is a moving target. Whenever the cost of a specific solar technology is reduced or the cost of conventional energy increases, a new market opens up and the assessment of economic potential changes dramatically.

In determining the amount of solar energy reaching the Earth's surface, one should keep in mind that because of absorption by the atmosphere, its maximum value does not exceed 1000 W/m^2 at a perpendicular surface and for clear-sky conditions. However, the daily mean value of solar flux per unit area is at least three times less due to change of day and night and inclination of the sun above the horizon. During winter, the magnitude of solar flux in the middle latitudes is further reduced; thus, the available amount of energy per unit area at the Earth's surface determines the potential of solar resources. Currently, solar energy is widely used in regions where there are physical limitations in using other energy sources, in off-grid applications, and where the use of solar energy is justified economically.

Regarding the national and local policies on which the application potential also substantially depends, it is important to note that currently at least 60 countries (37 developed and transition countries and 23 developing countries) have some type of policy to promote renewable power generation, including solar energy. The most common policy is the feed-in law, which has been enacted in many countries and regions in recent years, but there are many other forms of policy support (REN21, 2009).

3.2.2 Sources of Solar Radiation Data

3.2.2.1 User Needs

Technologists studying the solar impact on energy systems such as buildings and power plants require data measured at the place of the application, i.e., directly at the site of the solar installation. Knowledge of solar energy resource available at different locations strongly influences the assessment of the economics of solar investments. Therefore, it is very important to know the overall global solar energy available, as well as the relative magnitude of its three components: direct-beam irradiation, diffuse irradiation from the sky including clouds, and irradiation received by reflection from the ground surface. Also important are the patterns of seasonal availability, variability of irradiation, and daytime temperature on site. Due to significant inter-annual 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 the case of solar PV, panels mounted on roofs of buildings located in tropical regions easily reach temperatures over 70°C (158°F), thereby reducing power output by up to 20%. This is attributed to the temperature sensitivity of solar PV modules.

Solar radiation data can be used to do the following: (1) select optimum sites for large solar energy applications such as power plants, (2) estimate the performance of any solar energy system at any location, (3) design optimum solar energy systems for specific sites, and (4) estimate probable returns on investments.

Numerous empirical schemes have been developed to estimate the global radiation mainly using conventional ground-based observation of bright sunshine duration and clear sky solar flux for particular location. The performance of different empirical relations has been studied in large number of publications. None of the available empirical relations reproduces the actual measurements within limit up to ±30 W/m^2 on a monthly basis. This figure equals roughly 3% of maximum clear-sky flux.

Members of the solar energy community require radiation data so they can choose the most suitable locations where appropriate collectors and storage systems must be installed and operated successfully to meet the national and local needs of end-users. Such data can be provided by the world solar radiation network supported by national meteorological services. The World Radiation Data Centre (WRDC, Saint Petersburg, Russia) collects and disseminates daily measurements of global and diffuse radiation, radiation balance and sunshine duration at the Earth's surface submitted by national meteorological services all over the world (Tsvetkov *et al.*, 1995). The data are available from about 1280 sites, and nearly 900 sites have periods of observation of more than 10 years (Figure 3.2: The ground-based solar radiation measuring sites from which solar data are available at the WRDC for period 1964-2007.). The distribution of measuring sites across the globe is rather non-uniform. Because of the scarcity of measuring sites in some parts of the world, the use of representative sites has been a common practice for engineering calculations. The simple method of estimating radiation at a given point is interpolation from neighbouring ground measuring site. It is also the only ground-based method available when the density of ground stations is low.

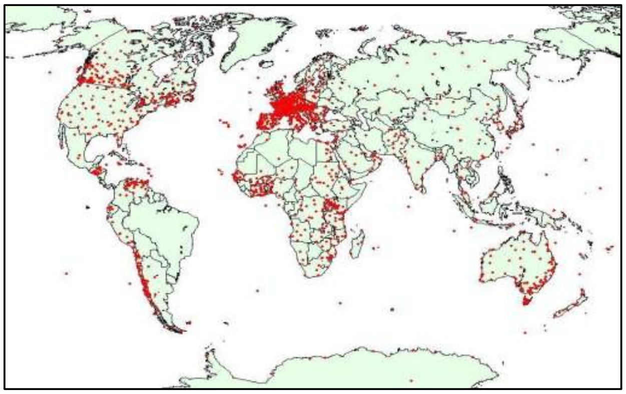


Figure 3.2: The ground-based solar radiation measuring sites from which solar data are available at the WRDC for period 1964-2007.

A complementary source of radiation data can be provided by remote sensing from geostationary satellites. Although such data are inherently less accurate than the ground-based measurements, they may be more suitable for generating specific data at arbitrary locations and times. The images from the satellite provide an estimate of global solar radiation on the horizontal surface with spatial resolution up to about 10 km × 10 km. However, calibration of satellite data from ground measuring stations is also needed.

It is important to note that satellites measure only the upward reflected and scattered solar radiation. Therefore, satellite conversion algorithms are generally based on semi-empirical assumptions. Information contained in these data on the atmospheric composition is then used to compute the amounts of global and diffuse radiation reaching the ground. In the case of variable conditions, satellite-estimated irradiance is representative of the ground-measured irradiance at least in some locations for a time within an hour.

3.2.2.2 Solar Databases

Various national institutions also provide information on the solar resource: National Renewable Energy Laboratory (NREL), National Aeronautics and Space Administration (NASA), Brasilian Spatial Institute (INPE), German Aerospace Center (DLR), Bureau of Meteorology Research Center (Australia), CIEMAT (Spain) and certain commercial companies.

For projects in the USA, NREL has recently released an updated version of the National Solar Radiation Database (NSRDB) that now has 1454 ground locations for 1991 to 2005 (Arvizu, 2008).

The gridded data include hourly satellite-modelled solar data for 1998 to 2005 on a 10-km grid. The data can be combined with hourly meteorological data for photovoltaic (PV) and concentrating solar power (CSP) simulation. These hourly values of the solar resource components (direct beam, global horizontal, and diffuse) can be used by designers to determine the solar resource for any orientation of solar collector.

Another valuable source of solar energy data is the European Solar Radiation Atlas (ESRA) prepared under the auspices of the Commission of the European Communities (ESRA, 2000a, 2000b). The Atlas comprises observed daily global radiation and monthly sums of sunshine duration provided from many National Weather Services and scientific institutions of the European countries. Satellite images from METEOSAT were supplied by GKSS Research Centre (Geesthacht, Germany), Deutscher Wetterdienst (Offenbach, Germany), and NASA Langley Research Center (USA).

The long-term monthly average data of ESRA were taken as the basis for developing PVGIS (Šúri et al., 2005, 2007). In this, the ESRA data are enhanced by 3D spatial interpolation and the use of a higher-resolution (1-km) digital elevation model. The effect of shadows from terrain is also taken into account.

The Solar Radiation Atlas of Africa was prepared with support from the Non-Nuclear Energy R&D programme (SUNSAT project) of the Commission of the European Communities. It contains information on the surface radiation with a temporal detail of one month and a spatial resolution of 30 to 50 km, over all regions of Europe, Asia Minor, Africa, and most parts of the Atlantic Ocean. The data covering 1985 and 1986 were derived from measurements of upward solar radiation, which is reflected from the Earth’s surface to space and was regularly measured by the geostationary satellite METEOSAT 2.

Another data set representing Africa has been developed at the Ecole des Mines de Paris, France. The data are based on images from the METEOSAT geostationary satellites that were processed with the Heliosat-2 method (Rigollier et al., 2004) and covers the period 1985 to 2004. Long-term average solar radiation data from this database can be accessed using the Photovoltaic Geographical Information System (PVGIS, 2008) interface. To control the accuracy of this information for potential users, thorough comparisons were performed with collocated and simultaneously measured data. The ground-based measurements were made at sites in countries that were seen from METEOSAT’s position. These comparisons confirmed that data on a monthly basis showed a 10% uncertainty range. Comparison between monthly averages of global radiation data derived from METEOSAT 2 data (resolution about 30 to 50 km) and collocated at the ground shows that bias could vary from 17 to 68 Wh/m^2 and the unbiased standard deviation could vary from 433 to 474 Wh/m^2. All databases primarily prepared for solar energy applications are available to potential users on request from the Institute of Physics of the GKSS Research Centre.

3.2.2.3 Impact of Climate Change on Potential Solar Resources

On a long timescale, climate warming due to increase of greenhouse gases in the atmosphere may influence cloud cover and turbidity, and it can impact the potential of the solar energy resource in different regions of the globe. Changes of major climate variables, including cloud cover and solar flux at the Earth’s surface, have been evaluated using climate models for the 21st century (Meehl *et al.,* 2007; Meleshko *et al.,* 2008). It was found that the pattern variation of monthly mean global solar flux does not exceed 1% over some regions of the globe, and it varies from model to model. Validity of the pattern changes seems to be rather low, 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, active heating and cooling, photovoltaic (PV) electricity generation, concentrating solar power (CSP) electricity generation, and solar fuel conversion. Each section also describes applications of these technologies.

3.3.1 Passive Solar

This subsection discusses passive solar technologies and applications.

3.3.1.1 Passive Solar Technologies

Passive solar energy technologies absorb solar energy, store and distribute it in a natural manner without using mechanical elements, and also use natural ventilation (Energía Solar Térmica, 1996). Basic principles are based on the characteristics and location of the materials used in construction, being part of the building's structure. One main advantage is durability, because the materials are associated with the building.

The term "passive solar building" is a qualitative term describing a building that makes significant use of solar gain to reduce heating and possibly cooling energy consumption based on the natural energy flows of radiation, conduction, and natural convection. Forced convection based on mechanical means such as pumps and fans is not considered to play a major role in the heat-transfer processes. 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).

The basic elements of passive solar architecture are windows, thermal mass, protection elements, and reflectors. 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), indirect-gain systems (e.g., Trombe walls), mixed-gain systems (a combination of direct-gain and indirect-gain systems, such as greenhouses), and isolated-gain systems. Passive technologies are integrated with the building and may include the following components:

1. Near-equatorial facing **windows** with high solar transmittance and a high thermal resistance 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.
2. Building-integrated **thermal storage**, commonly referred to as thermal mass, may be sensible, such as concrete or brick, or phase-change materials (Mehling and Cabeza, 2008). The most common type of thermal storage is the **direct gain** system in which thermal storage is distributed in the living space, absorbing the direct solar gains (see Figure 3.3.1). Storage is particularly important because it performs two essential functions: storing much of the absorbed direct gains 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 (Figure 3.3.1), 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. **Isolated thermal storage** passively coupled to a fenestration system or solarium/sunspace is another option in passive design.

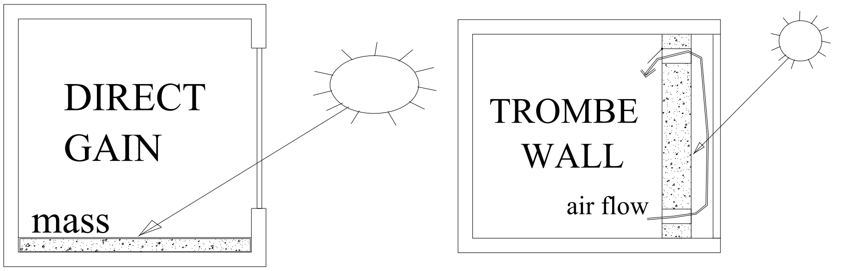


Figure 3.3: The two most-common types of passive systems: direct gain (left) and collector-storage wall or Trombe wall (right).

3. **Airtight insulated opaque envelope** appropriate for the climatic conditions to reduce heat transfer to and from the outdoor environment. In most climates, this energy-efficiency aspect is an essential part of 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.
4. **Daylighting technologies and advanced solar control systems,** such as motorized shading (internal, external) and fixed shading devices, particularly for daylighting applications in the workplace. 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 the following: shallow-plan design, allowing daylight to penetrate all rooms and corridors; light wells in the centre of the buildings; roof lights; tall windows, which allow light to penetrate deep inside rooms; the use of 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).

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 toward the Equator—the glazing should be concentrated on the equatorial side, as should the main living rooms, with little-used rooms such as bathrooms on the opposite-equatorial 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 (Everett, 1996).

Clearly, passive technologies cannot be separated from the building itself. Thus, when estimating the contribution of passive solar gains, we need to distinguish between the following: (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 European project SOLGAIN has evaluated the effect of passive solar gain utilization in the existing residential buildings in Europe. The estimated CO_2 emission savings due to solar gains are 345 kg/person/year or 9 kg/m^2/year. Table 3.2 summarizes the available data.

Table 3.2: Impact of passive solar gain utilization in existing residential buildings in terms of energy and emission savings (Eurec, 2001).

Country	Solar Fraction (%)	Total Solar Gains (TWh)	Total CO2 Reduction (Mt)
Norway	10	4.4	0.4
Finland	18	8.6	2.4
UK	15	57	22.5
Ireland	11	2.0	1.2
Germany	13	76	26
Belgium	12	13	4.4
Greece	18	8.9	3.3

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 glazings. 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.

Assuming random and equal window distribution, one can estimate that about 25% of the window area on existing buildings is within ±45 degrees of facing the Equator. However, these window areas are typically only about 5% (Swan *et al.,* 2009) of the heated floor area in existing Canadian houses, as compared to 9% or more in the case of solar homes such as the Athienitis house (Athienitis, 2008). Solar homes receive significant useful passive solar gains and have the potential to reduce heating loads by about 20% to 30% (Balcomb, 1992)—and up to 40% in well-insulated houses according to the Passive House Standard (PHPP, 2004). However, occupants often leave curtains or blinds closed while away, which potentially reduces the useful passive solar gains by 30% to 50%.

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. Progress on passive cooling techniques is important, and applying such techniques may decrease the cooling load of buildings up to 80%, (Santamouris and Asimakopoulos, 1996). 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, and it can be fully satisfied by part of the solar gains through the direct-gain windows; controls such as motorized shading or electrochromic coatings may be used to optimally control the amount of solar radiation entering a space. 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 in two recent publications (Cabeza *et al.,* 2010; Castell *et al.,* 2010). Experimental work shows 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 building envelop can reduce the cooling energy demand in such buildings by up to 15%—about 1 to 1.5 kg/year/m^2 of CO_2 emissions would be saved in these buildings due to reducing the energy consumption.

3.3.1.2 Solar Passive Applications

Passive solar system applications are mainly of the direct-gain type, but they can be further subdivided into the following main application categories:

Multistory residential buildings designed to have a large equatorial-facing façade so as to provide the potential for a large solar capture area. Figure 3.4 illustrates an example demonstration project with row houses in Sweden (Hastings and Wall, 2009). The space-heating demand is estimated to be about 15 kWh/m^{2}a.

Two-story detached or semi-detached solar homes designed to have a large equatorial-facing façade so to provide the potential for a large solar capture area (see Figure 3.5a).

Perimeter zones and their fenestration systems in office buildings designed primarily based on daylighting performance. In this application, there is usually an emphasis on reducing cooling loads, but passive heat gains may be desirable, as well, in the heating season (see Figure 3.5b 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 design for using daylight throughout the year and direct solar gains during the heating season. These buildings may profit from low summer night temperatures using night hybrid ventilation techniques (Santamouris and Asimakopoulos, 1996).

Figure 3.5a illustrates the passive-hybrid solar design concept in the EcoTerra EQuilibrium demonstration solar home in Canada (Athienitis, 2008). It has a 15-cm concrete slab in the family room and a 13-cm ventilated concrete slab (VCS) in the basement that stores heat from the building-integrated photovoltaic/thermal system in the roof, but with passive discharge of the heat. The basement slab also acts as a direct-gain system, storing solar gains from the south-facing windows in the basement. The VCS is also used for night cooling in the summer by passing outdoor air though the hollow cores because night temperatures are usually lower than 20ºC. This example illustrates a possible trend in the design of both residential and commercial buildings, where thermal mass is used in a hybrid mode for heating and cooling purposes.

Figure 3.4: Lindas demonstration project (Sweden)—passive row houses (Hastings and Wall, 2009).

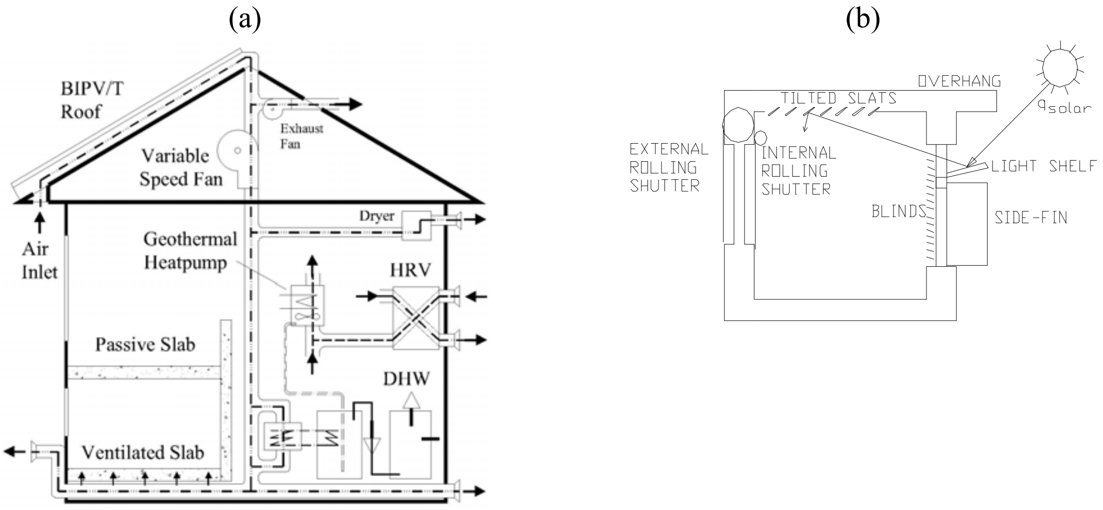


Figure 3.5: (a) Schematic of thermal mass placement and passive-active systems in EcoTerra house; (b) schematic of several daylighting concepts designed to redistribute daylight into the office interior space.

Figure 3.5a illustrates several commonly used fixed shading and daylight redirection systems. Fixed shading devices such as overhangs and side fins work during specific times of the year that depend on solar altitude and azimuth. However, with increasing window areas—both in residential and office buildings—there is increasingly a need for active control of solar gains. Therefore, motorized venetian blinds or louvers are one option that is becoming more popular. Some companies such as Pella Windows and Unicel Architectural integrate the controlled shading device between the glazings, which significantly reduces the amount of solar radiation that is absorbed by the shades/louvers and reemitted as heat into the room interior.

Recent trends include the use of photovoltaic panels as overhangs that can be partly transparent, thus providing some shading while producing electricity, as well. Figure 3.6 shows two examples combining a daylighting and direct solar-gain function with photovoltaics and shading: (a) Queen’s University in Ontario, Canada and (b) the Mataro Library in Barcelona, Spain (Lloret *et al.*, 1995). The Mataro library includes a 53-kW grid-connected semitransparent PV/thermal system. The semitransparent PV façade has a daylighting function, acting like a side luminaire to distribute the daylight.

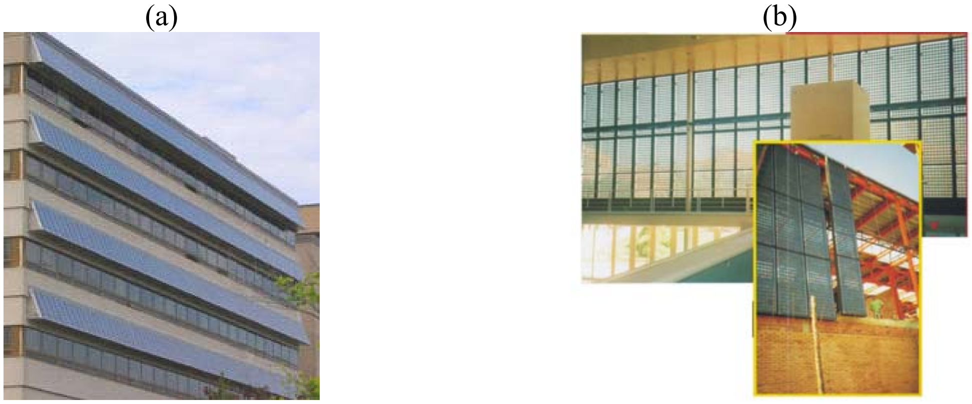


Figure 3.6: PV panels as overhangs, Queen’s University, Ontario); (b) semitransparent PV/thermal modules integrated in curtain wall, Mataro Library, Spain (the facade is also used for fresh-air preheating) (Lloret et al., 1995).

3.3.2 Active Solar Heating and Cooling

This subsection discusses active solar heating and cooling technologies and applications.

3.3.2.1 Active Solar Heating and Cooling Technologies

This subsection describes various technologies that use the sun to provide either heating or cooling. Also discussed is thermal storage and research directions in the area of solar heating and cooling.

3.3.2.1.1 Solar heating systems

A solar heating system is composed of a solar collector and storage tank. The solar collector transforms solar radiation into heat and uses a carrier fluid (e.g., water, solar fluid, or 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 evacuated-tube collector (described below) is likely to be the most suitable option for producing heat for industry. An uncovered absorber is likely to be limited for low-temperature heat production. Figure 3.7 illustrates the relationship of temperature difference between the collector and ambient versus the efficiency of a collector.

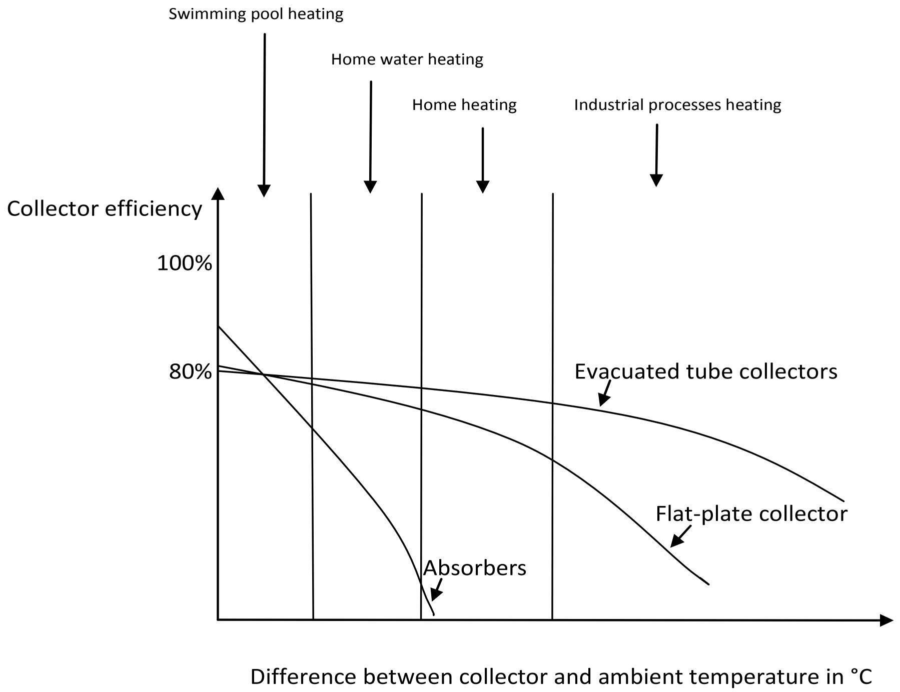


Figure 3.7: Selection of the most suitable solar collector for different applications. The x-axis indicates the difference in temperature between the collector and ambient, and the y-axis indicates the relative efficiency of the collector.

3.3.2.1.1.1 Solar collectors

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 region. It consists primarily of an absorber, which is usually made of several narrow metal strips using a wide range of materials such as copper, stainless steel, mild steel, aluminum, and plastics. Absorbers are usually black, because dark surfaces demonstrate a particularly high absorptance. The absorptance indicates the fraction of short-wavelength solar radiation falling on the surface that is being absorbed and transformed into heat. Matte-black paints mechanically applied to the absorber have been widely used for many years because they are relatively inexpensive and easy to apply with brushes or sprays.

Flat-plate collectors are the most widely used solar thermal collectors for residential solar water-heating and space-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 3.8a). For low-temperature applications, such as the heating of swimming pools, only a single plate is used as an absorber, with the fluid trickling over its surface. Flat 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).

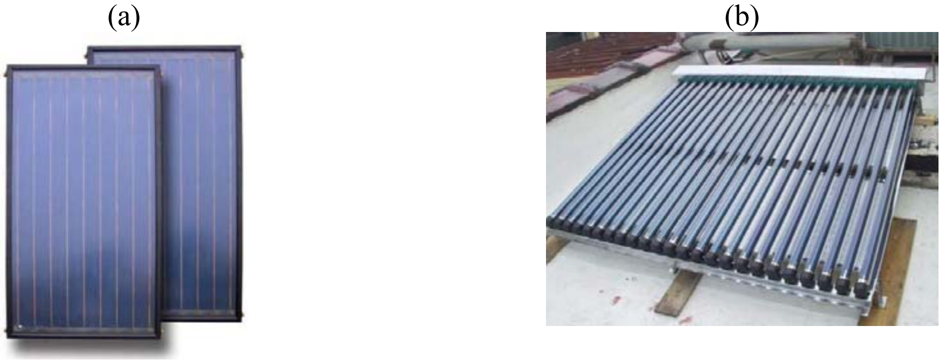


Figure 3.8: Thermal solar collectors: flat-plate (a) and evacuated-tube (b) collectors.

Evacuated-tube collectors are usually made of parallel rows of transparent glass tubes connected to a header pipe (Figure 3.8b). To reduce heat loss within the frame by convection, the air can be pumped out of the collector tubes. These evacuated-tube collectors must be re-evacuated every one to three years. This makes it possible to achieve very high temperatures (more than 150°C), useful for cooling (see below) or industrial applications.

Two main types of evacuated tubes are in use in the solar industry: the direct-flow tube and heat-pipe tube. The *direct-flow evacuated-tube collector* has two pipes running down and back, inside the tube, and the heat-transfer fluid circulates in the pipes. In the case of concentric fluid inlet and outlet pipes, the rotational symmetry allows the absorber to have the desired tilt angle even if there is no flexibility in the collector mounting (e.g., when the collector is mounted in the roof itself). The most common type of direct-flow tube is where the two pipes are at the two extremities of the absorber. To increase the radiation received by the absorbers, some direct-flow evacuated-tube collectors include reflectors mounted behind the collector or inside the glass tube.

In *heat-pipe evacuated-tube collectors*, the heat-transfer fluid exchanges both sensible and latent heat. This type of collector generally contains copper heat pipes attached to an absorber plate, inside a vacuum-sealed solar tube. The heat pipe is hollow and the space inside is evacuated. In this case, the purpose is not insulation, but rather, to lower the vapourization temperature of the small quantity of liquid inside. This liquid is usually alcohol or purified water and some special additives. Due to the vacuum of the tube, the liquid boils at a lower temperature, typically 30ºC. When solar radiation strikes the surface of the absorber, the liquid in the heat tube is heated above 30ºC and quickly turns to hot vapour that rises rapidly to the top of the heat pipe and transfers its sensible and latent heat to the carrier fluid that flows through a manifold and absorbs the heat. As the heat is extracted at the condenser, the vapour condenses to form a liquid and it flows back down to the bottom of the heat pipe while the carrier fluid in the main pipe is heated and the process starts again.

Evacuated tubes offer the advantage that they work efficiently with high absorber temperatures and with low radiation. Higher temperatures also may be obtained for applications such as hot-water heating, steam production, and air conditioning. Conventional evacuated-tube collectors are more expensive than flat-plate collectors, with unit area costs about twice that of flat-plate collectors. However, a new evacuated-tube design has the potential to become cost-competitive with flat plates. This design features two concentric glass tubes separated by a vacuum, and an absorber made of the inside tube with a selective coating. Water is typically allowed to thermosyphon down and back out of the inner cavity to transfer the heat to the storage tank.

3.3.2.1.1.2 Types of solar water heaters

Thermal solar systems used to produce hot water can be classified as passive solar water heaters and active solar water heaters. Also of interest are active solar cooling systems, which transform the hot water produced by solar energy into cold water.

Passive solar water heaters can be either integral collector-storage systems or thermosyphon systems (Figure 3.9). Integral collector-storage systems, also known as ICS or "batch" systems, are made of one or more black tanks or tubes in an insulated glazed box. Cold water first passes through the solar collector, which preheats the water, and then continues to the conventional backup water heater. In climates where freezing temperatures are unlikely, many evacuated-tube 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 they do not work well in households with predominantly morning draws because they lose most of the collected energy overnight.

Thermosyphon systems are an economical and reliable option, especially in new homes. The design is based on the natural convection of warm water, leading to water circulation through the collectors and to the tank located above the collector. As water in the solar collector heats, it becomes lighter and rises naturally into the tank above. Meanwhile, the cooler water flows down the pipes to the bottom of the collector, enhancing the circulation.

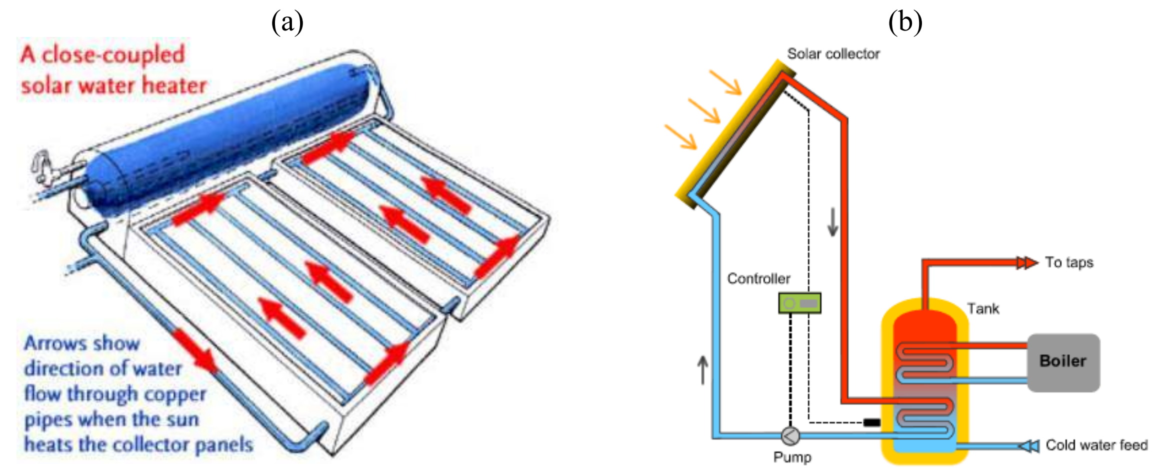


Figure 3.9: Thermal solar system: passive (a) and active (b) system.

Active solar water heaters rely on electric pumps and controllers to circulate the carrier fluid through the collectors (Figure 3.9). 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. *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 climate. This system should be carefully designed and installed to ensure that the piping always slopes downward to the reservoir tank.

3.3.2.1.2 Active solar cooling

Solar cooling is used when solar heat powers an absorption heat pump. This system can be used as an air-conditioning system in any building. Deploying such a technology depends heavily on the industrial deployment of small-power absorption heat pumps.

3.3.2.1.2.1 Open cooling cycles (or desiccant cooling systems)

These 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, which is available from several suppliers for different air volume flows. 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.

The heat required for the regeneration of the sorption wheel can be provided at low temperatures (45° to 90°C), which suits many solar collectors on the market. Other types of desiccant dehumidifiers exist that use solid sorption. These have some thermodynamic advantages and can lead to higher efficiency, but place higher demands on the material and equipment.

3.3.2.1.2.2 Closed heat-driven cooling cycles

Systems using these cycles have been known for many years and are usually used for large capacities, from 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.

Absorption technologies cover the majority of the global thermally driven cooling market. The main advantage of absorption cycles is their higher coefficient of performance (COP) values, which range from 0.6 to 0.8 for single-stage machines, and from 0.9 to 1.3 for double-stage technologies. Typical heat-supply temperatures are 80° to 95°C and 130° to 160°C, respectively. The absorption pair used is either lithium bromide and water, or ammonia and water.

Adsorption refrigeration cycles using silica gel and water, for instance, as the adsorption pair can be driven by low-temperature heat sources down to 55°C, producing temperatures down to 5°C. This kind of system achieves COP values of 0.6 to 0.7. Today, the financial viability of adsorption systems is limited, due to the far higher production costs compared to absorption systems.

3.3.2.1.3 Thermal storage

Within thermal solar systems, thermal storage 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).

3.3.2.1.3.1 Sensible heat storage systems

These 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.

3.3.2.1.3.2 Latent heat storage systems

In these systems, thermal energy is stored 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 on the order of 100 kWh/m^3 compared to

25 kWh/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 steam.

3.3.2.1.3.3 Sorption heat storage systems

In these systems, heat is stored 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.

3.3.2.1.3.4 Thermochemical heat storage systems

In these systems, heat is stored in an endothermic chemical reaction. Some chemicals store heat 20 times more densely than water; 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 3.3.4.1.

Thermal energy storage is also used for seasonal storage. In this case, underground thermal energy storage (UTES) is used, which includes the various technologies described below.

The most frequently used storage technology, which makes use of the underground, is *aquifer thermal energy storage* (ATES). This technology uses a natural underground layer (e.g., a sand, sandstone, or chalk layer) 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 about the storage of winter cold to be used for the cooling of large office buildings and industrial processes. It can easily be explained that aquifer cold storage is gaining increasing interest: 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.

The other technologies for underground thermal energy storage are *borehole storage* (BTES), *cavern storage* (CTES), and *pit storage*. Which of these technologies is selected, depends strongly on the local geologic conditions. With borehole storage, vertical heat exchangers are inserted into the underground, which ensure the transfer of thermal energy toward and from the ground (clay, sand, rock). Ground heat exchangers are also frequently used in combination with heat pumps, where the ground heat exchanger extracts low-temperature heat from the soil. With cavern storage and pit storage, large underground water reservoirs are created in the subsoil to serve as thermal energy storage systems. These storage technologies are technically feasible, but the actual application is still limited because of the high level of investment.

3.3.2.1.4 Direction of research

Improved designs are expected to address longer lifetimes, lower installed costs, and increased temperatures. The following are some design options:

- The use of plastics in residential solar water-heating systems
- Powering air-conditioning systems using solar-energy systems, especially focusing on compound parabolic concentrating collectors
- The use of flat-plate collectors for residential and commercial hot water

- Concentrating and evacuated-tube collectors for industrial-grade hot water and thermally activated cooling.

Research to decrease the cost of solar water-heating systems is mainly oriented toward 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 ICS systems that use a load-side immersed heat exchanger and direct thermosyphon systems.

3.3.2.2 Active Solar Heating and Cooling Applications

The amount of hot water a solar heater produces depends on the type and size of the system, amount of sun available at the site, seasonal hot-water demand pattern, and installation of the system. An industrial or agricultural process heat system comprises a solar collector, intermediate heat storage, and a means of conveying the collected heat from the storage unit to the application. The solar collector is usually selected based on outlet temperature matched to the required process heat (Norton, 2001).

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

Process heat collectors are a new application field for solar thermal heat collectors. Typically, these systems require a large capacity (hence, large collector areas), low costs, and high reliability and quality. While 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 might be interesting for process heat in the range of up to 120°C.

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

Solar cooling is a specific area of application for solar thermal. Either high-efficiency flat plates or evacuated tubes can be used to drive absorption cycles to provide cooling. For a greater coefficient of performance, 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 and the need for cooling.

A number of thermally driven cooling systems have been built employing closed thermally driven cooling cycles, using solar thermal energy as the main energy source. These systems often cater to large cooling capacities of up to several hundred kW. In the last 5 to 8 years, 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 options exist in addition to sorption-based cycles for converting solar energy into useful cooling. In an ejector cycle, heat is transformed into kinetic energy of a vapour jet, which enables the refrigerant to evaporate. In a solar mechanical refrigeration cycle, a conventional vapour-compression system is driven by mechanical power that is produced with a solar-driven heat power (e.g., Rankine) cycle, in which a fluid is vapourized at an elevated pressure by heat exchange with a fluid heated by solar collectors. Finally, electricity generated by a PV system can be used to operate ordinary vapour-compression machines.

Solar energy may be used for space heating of agricultural buildings. The guiding principles are similar to the solar space heating of non-agricultural buildings. Low-cost, roof-based, air-heating solar collectors tend to be used because of the low initial investment required. To assure excellent performance, one must establish good fabrication quality control and adequately educate installers about the proper sizing of the relevant system components.

The production of potable water using solar energy has been adopted practically in remote or isolated regions. Fundamentally, three potable water extraction processes use solar energy: (1) Distillation, where water evaporated using solar heat is then condensed, thus separated from its mineral content; (2) Reverse osmosis, where a pressure gradient across a membrane causes water molecules to pass from one side to the other; larger mineral molecules cannot cross the membrane; and (3) Electrodialysis, where a selective membrane containing positive and negative ions separates water from minerals using solar-generated electricity.

Solar stills were widely used in some parts of the world (e.g., Puerto Rico) to supply water to households of up to 10 people. The modular devices supply up to 8 litres of drinking water from an area of roughly 2 m². The potential for technical improvements is to be found in reducing the cost of materials and designs. Increased reliability and better-performing absorber surfaces would slightly increase production per m². Nowadays, they are only used in developing countries, but depending on the environmental conditions their efficiency can be very low.

In appropriate insolation conditions, solar detoxification can be an effective low-cost treatment for low-contaminant waste. In *photolytic* detoxification, exposure to 1000-fold concentrated insolation destroys contaminants directly. *Photocatalytic* oxidation destroys contaminants by the ultraviolet component of insolation activating a catalyst that destroys the contaminants. Solar photocatalysis is effective for decontaminating bacterial, pesticide, organic, or chemical pollution of water supplies.

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. Using a solar thermal system to enhance humidification of air inside the box, water and salt are separated, because salt and dissolved solids from the fluid are not carried away by steam. When the steam is recondensed in the condenser, most of the energy used for evaporation is regained. This reduces the energy input for desalination, which requires temperatures of between 70° and 85°C. The specific water production rate is about 20 to 30 litres per m² absorber area per day. The specific investment is less than for the solar still, and this system is available for sizes from 500 to 50,000 litres per day. These MEH systems are now beginning to appear in the market. Also see the report on water desalination by CSP (Aqua, 2009) and discussion of SolarPACES Task VI (SolarPACES web, 2009).

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). Forced-convection dryers have higher drying rates compared to passive dryers and can be used for high production rates; but they are more complex and expensive. Free-convection dryers are simple to design and have low installation and operating costs; but the capacity per unit area of the dryer is limited and for small-scale operations only. 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).

Solar cooking is one of the most widely used solar applications in developing countries. 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. Solar cookers basically concentrate sunlight and convert it into heat, which is then trapped and used for cooking. Different types of solar cookers include box, panel, parabolic, and hybrid cookers, as well as solar kettles. In some regions, solar cooking is promoted to help slow deforestation and desertification, which are caused by using wood as fuel.

3.3.3 Photovoltaic Solar Electricity Generation

This subsection discusses photovoltaic solar electricity generation technologies and applications.

3.3.3.1 PV Technologies

Photovoltaic technologies generate electricity directly from solar radiation. PV cells take advantage of the photovoltaic effect to generate electricity. First, photons making up solar radiation are absorbed by a semiconductor material, exciting negatively charged electrons and freeing them from within their atomic structure (Figure 3.10). The excited electrons leave behind positively charged "holes," which can also migrate through the semiconductor. Second, the generated electrons and holes are separated spatially at a selective interface (or junction), which leads to a build-up of negative charge on one side of the junction and positive charge on the other side. This resulting charge separation creates an electrical potential difference (or voltage) over the interface. In most solar cells, the junction is formed by stacking two different semiconductor layers: either different forms of the same semiconductor (in a homojunction) or two different semiconductors (in a heterojunction). Homojunctions can be formed by adding different types of impurities (dopants) to the layers on both sides of the junction. The key feature of a semiconductor junction is that it has a built-in electric field that pushes/pulls electrons to one side and holes to the other side. When the two sides of the junction are contacted and an electrical circuit is formed, a current can flow—that is, electrons flow from one side of the device to the other. The combination of a voltage and a current represents electric power. Thus, when the cell is illuminated, electrons and holes are generated and collected continuously and the solar cell can generate power.

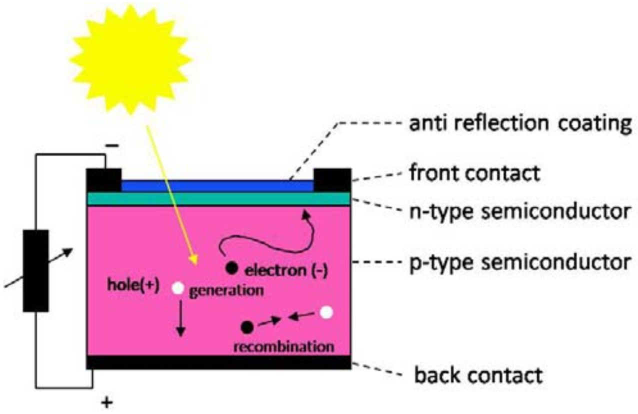


Figure 3.10: Schematic cross-section of a solar cell.

Various PV technologies have been developed in parallel and are discussed below under the headings of first- and second-generation PV—relating to the stages of research and development (R&D) maturity that the technologies represent.

3.3.3.1.1 First-generation PV

Mono- and poly(multi)crystalline silicon (Si) solar cells have dominated the PV market, with a 2008 market share of 87%. In the laboratory, the record cell conversion efficiency is up to 25% for monocrystalline silicon and 20.3% for multicrystalline cells (Green *et al.,* 2009) under standard reporting conditions (i.e., 1000 W m^{-2}, AM1.5, 25°C). A typical silicon solar cell is composed of *n*-type and *p*-type layers, and a *p-n* junction. Light absorption generates electron-hole pairs by exciting electrons from the valence band to the conduction band. The electric field across the junction separates these pairs and drives the photogenerated electrons and holes in opposite directions, causing a flow of electrons in the external circuit and thus generating electricity. The theoretical Shockley-Queisser limit of a single-junction Si solar cell is 31% conversion efficiency (Shockley and Queisser, 1961).

Several variations for higher efficiency have been developed using a heterojunction and/or back-contact structure. The heterojunction consists of a c-Si/a-Si combination—known as a heterojunction with intrinsic thin layer (HIT)—with an advantage of higher performance at high operating temperature under outdoor conditions. The highest efficiency of heterojunction solar cells is 23% for a 100-cm^2 cell (Sanyo, 2009). The back-contact structure avoids the shading effect of the top electrode, but the manufacturing process is more complicated than for the standard cell. The average efficiency of the commercial back-contact cell is reported as 23.4% (Swanson, 2004).

Wafers have decreased in thickness from 400 µm in 1990 to less than 200 µm in 2009 and have increased in area from 100 cm^2 to 240 cm^2. Modules have increased in efficiency from about 10% in 1990 to typically 13% today, with the best performers above 17%. And manufacturing facilities have increased from the typical 1 to 5 MWp annual outputs in 1990 to hundreds of MWp for today's largest factories.

Crystalline silicon modules are typically produced in a processing sequence along a value chain that starts with purified silicon, which is melted and solidified using different techniques to produce ingots or ribbons with variable degrees of crystal perfection. The ingots are then shaped into bricks and sliced into thin wafers by wire-sawing. In the case of ribbons, wafers are cut from the sheet typically using a laser. Cut wafers and ribbons are processed into solar cells and interconnected in weatherproof packages designed to last for at least 25 years. The processes in the value chain have progressed significantly during recent years, but they still have potential for further large improvements.

Module assembly is still material-intensive. The assembly must protect the cells from the outdoor environment--typically for a minimum of 25 years—while allowing the cell to function as efficiently as possible. The current standard design, using rigid glass/polymer encapsulation in an aluminium frame, fulfils these basic requirements. But it represents about 30% of the overall module cost, contains considerable embedded energy (which increases the energy payback time of the module), and is a challenge to manufacture on automated lines even at current wafer thicknesses.

3.3.3.1.2 Second-generation PV

Second-generation technologies refer to thin-film solar cells, cells that have demonstrated relatively high conversion efficiencies and potentially lower costs per watt than crystalline silicon, and cells using novel materials.

3.3.3.1.2.1 Thin-film cells

Thin films include a range of material systems, from silicon-related cells, to cadmium telluride (CdTe), to copper indium gallium diselenide (CIGS).

The *amorphous Si* (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 solar cell technology. Amorphous Si is a quasi-direct-bandgap material and hence has a high light absorption coefficient;

therefore, the thickness of an a-Si cell can be 1000 times thinner than that of a crystalline Si (c-Si) cell. Developing better efficiencies for a-Si has been limited by light-induced degradation—the Staebler-Wronski effect (Staebler and Wronski, 1977)—which originates from defect creation during electron-hole recombination and causes a maximum loss of cell efficiency of about 50%. 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 result is a stabilized efficiency of 10.1% (Meier *et al.,* 2009).

Higher efficiency has been achieved by using multijunction technologies with alloy materials, e.g., germanium and carbon, to form semiconductors with lower or higher bandgaps, respectively, to cover a wider range of the solar spectrum (Yang and Guha, 1992).

Alternative technology combining amorphous silicon with thin-film crystalline silicon (microcrystalline silicon) has recently developed in combination with sophisticated light management techniques (Meier, 1996; Yamamoto, 2003), and conversion efficiencies of more than 15% in the initial stage have been reported.

Thin-film c-Si, also known as nano- or microcrystalline, is an important PV technology, although not as commercially successful as c-Si and a-Si (Green et *al.*, 2004). These nanocrystalline cells have achieved an efficiency of 10.1%.

CdTe solar cells using a heterojunction with CdS have shown significant promise, because CdTe has a suitable energy bandgap of 1.45 electron-volts (eV) with a high coefficient of light absorption. The best efficiency of this cell is 16.7% (Green *et al.*, 2008b), and commercially available modules have an efficiency of around 10%. Goncalves *et al.* (2008) predicted that the maximum efficiency will be 17.6%, and future improvements will focus on how to further reduce manufacturing costs, which are already the lowest in the industry. The toxicity of cadmium and the relative scarcity of tellurium are issues with this technology. Although CdTe itself is not a toxic material, metallic Cd can potentially be a source of contamination. But this potential hazard is mitigated by using a glass-sandwiched module design and by recycling the entire module, as well as industrial waste.

$CuInSe_2$ (CIS) solar cells are another leading thin-film technology (Kazmerski *et al.*, 1976). Incorporating Ga and/or S to produce $CuInGa(Se,S)_2$ (CIGSS) results in the benefit of a widened bandgap depending on the composition (Dimmler and Schock, 1996). CIGS-based solar cells yield a maximum efficiency of 19.9% (Repins *et al.*, 2008), using a doubly graded layer of Ga in the absorption layer to realize both high current density and high open-circuit voltage. Due to higher efficiencies and lower manufacturing energy consumptions, CIGS cells are a promising candidate in the future. The limitation of the indium resource will be the most significant issue in the future.

3.3.3.1.2.2 High-efficiency cells

Solar cells based on GaAs and InGaP (i.e., III-V semiconductors) are also very efficient, but expensive, devices. Better results are obtained in multijunction (or tandem) cells, with semiconductors of different energy bandgaps, thus harvesting energy from a wider solar spectrum. Double- and triple-junction devices are currently being commercialized; the most-common three-junction device is GaInP/GaAs/Ge, with a record cell efficiency of 40.7% and a submodule efficiency of 27% (Green *et al.,* 2009) To achieve an economically suitable transition for terrestrial purposes, the only feasible solution is to add these cells to a concentrator system, due to the advantage that the cell efficiencies may even increase with higher irradiance (Bosi and Pelosi, 2007).

3.3.3.1.3 Novel materials

Despite the many advances discussed above, the cost of fabricating Si solar cells is still too high for many low-cost applications. An alternative approach is to use molecular and polymer-based organic solar cells. These cells are characterized by high optical absorption coefficients and potentially low manufacturing costs. Much attention has been given to these cells recently because they are expected to play a key role in the future PV market.

Dye-sensitized solar cells (DSSCs) are a very promising alternative for low-cost production of energy. State-of-the-art DSSCs have achieved conversion efficiencies of up to 12.5% (Gratzel, 2009). Despite the gradual improvements in efficiency since discovery in 1991 (O'Reagan and Grätzel 1991), long-term stability is a key issue in commercializing these PV cells against ultraviolet light irradiation and high temperature. Electricity generation by DSSCs is based on the injection of an electron from a photoexcited state of the sensitizer dye (typically a bipyridine metal complex and sometimes organic dye) that is adsorbed on the nanoporous oxide semiconductors (e.g., TiO_2) as a cathode electrode into the conduction band of the electrode semiconductor. Excited dye is regenerated by the exchange of an electron with an iodide ion, which is oxidized in this reaction to tri-iodide at a platinized counter electrode (Gratzel, 2001). The module efficiency typically ranges between 6% and 8% using a double-sided glass structure. Because the electrolyte is a key issue in determining lifetime, scientists are developing semi-solid and fully solid electrolytes. However, efficiencies are generally lower than for the Graetzel-type solar cells.

Organic PV (OPV) cells, in contrast to DSSC, use stacked solid organic semiconductors. A typical structure of an OPV cell consists of p-type and n-type semiconductors such as P3HT and C60-related materials. The absorption layer is made of a mixture of p- and n-type materials to form a nanoscale phase separation. This bulk-heterojunction structure plays a key role in improving the efficiency. The main disadvantages associated with OPV cells are low efficiency, stability, and strength compared to inorganic PV cells.

The efficiency that can be achieved in OPV cells with single-junction cells is about 5% (Li et al. 2005; Ma et al., 2005), although predictions indicate about twice that value or even higher (Forrest, 2005; Koster et al., 2006). The efficiency of OPV cells recently reached 6.5% in a tandem cell (Kim et al., 2007). Although stability is an important issue to be addressed in OPV, the cost and processing (Brabec, 2004; Krebs, 2005) of materials have caused OPV research to advance further.

3.3.3.2 PV Applications

PV power systems are classified into two major applications: 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. Historically, in the beginning stages, PV power systems were used in isolated areas, such as outer space and deserts, as independent power sources. The importance of the role of off-grid systems has been and will be recognized particularly in remote area. However, the remarkably rapid growth of grid-connected systems has led to the majority of applications.

Off-grid systems have a significant potential in the unelectrified areas of developed countries. In those areas, a centralized system may not work economically due to low population density and the lack of infrastructure for constructing the power stations and transfer lines. Figure 3.11 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 the IEA PVPS countries during 2008, only about 1% was installed in off-grid systems, and these now make up 5.5% of the cumulative installed PV capacity of the IEA PVPS countries (IEA-PVPS Task 1, 2009).

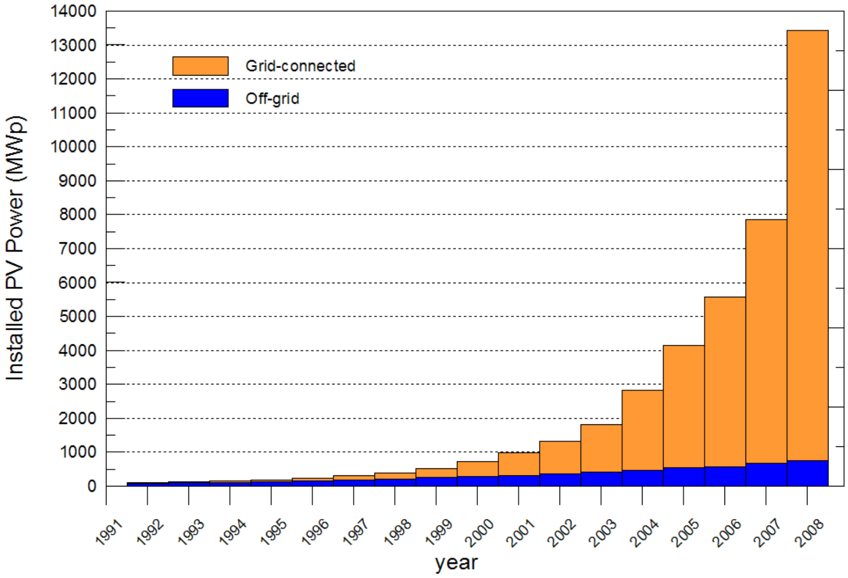


Figure 3.11: Historical trends of off-grid and grid-connected systems in the Organisation for Economic Co-operation and Development (OECD) countries (IEA-PVPS Task 1, 2009).

3.3.3.2.1 Off-grid (standalone) PV

The off-grid system provides direct current (DC) and/or alternating current (AC) power for domestic and non-domestic purposes. Off-grid domestic systems, Solar Home Systems, generally offer an economic alternative to extending the power line from an existing grid. Off-grid non-domestic systems provide power for telecommunications, water pumping, navigational aids, and other applications where small amounts of electricity have a high value. Other examples include uninterruptible power sources for information systems and communications technology, and power for cathodic protection of oil and gas pipelines.

The off-grid PV system is cost competitive with other small electricity sources. The PV system fluctuates in power depending on season, time of day, and weather; therefore, the off-grid system must have a storage system, usually batteries, to levelize its output power. The off-grid PV systems are also used in centralized hybrid systems to provide electricity to isolated village, and represent an important tool to reduce and avoid fossil fuel consumption.

3.3.3.2.2 Grid-connected PV

The grid-connected PV system uses an inverter to convert electricity from direct current (DC) as produced by the PV array to alternating current (AC), and it then supplies generated electricity to the electricity network. Electricity is often fed back to the grid when the on-site generated power exceeds the building loads.

Compared to an off-grid installation, system costs are lower because energy storage is not generally required, and also, they improve the system efficiency and decrease the environmental impact. The annual output yield ranges from 300 to 2000 kWh/kW (IEA PVPS Task 2, 2007; IEA PVPS Task 10, 2007; IEA PVPS Task 8, 2007; PV GIS, 2008) for several installation conditions in the world. The average annual performance ratio ranges from 0.7 to 0.8 (IEA PVPS Task 2, 2007).

Moreover, the grid-connected PV system is classified into two types of applications: distributed and centralized.

3.3.3.2.2.1 Distributed grid-connected PV

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 perceived 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" (BIPV) (IEA PVPS Task 7, 2002; Ecofys Netherlands BV, 2007; IEA PVPS Task 10, 2008).

The disadvantages include: greater sensitivity to grid-interconnection issues, compared to centralized systems, such as overvoltage and unintended islanding (Cobben et al., 2008; Ropp et al., 2007; Kobayashi and Takasaki, 2006); the designed output characteristic may not be optimal because the installation configuration depends on the land or roof area and configuration; and conditions in urban areas may not be suitable for PV systems, e.g., there may be issues related to shading effects (Ransome and Wohlgemuth, 2003; Keizer et al., 2007; Otani et al., 2004; Ueda et al., 2009).

3.3.3.2.2.2 Centralized grid-connected PV

Grid-connected centralized 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 (Figure 3.12).

Figure 3.12: A portion of the 42-MW grid-connected PV power plant in Moura, Portugal.

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 in large scale. In addition, the reliability of centralized PV systems is greater than distributed PV systems because they can have maintenance systems with monitoring equipment, which is a more reasonable portion of the total system cost.

The disadvantage is the cost of the installation land, especially in developed countries. At the end of 2007, Europe had more than half of all installations of grid-connected centralized systems, and about 30% of all systems have tracking arrays (including single- or double-axis tracking). The feasibility of very large-scale PV power generation systems, with capacities ranging from several megawatts to gigawatts, is also being studied (IEA PVPS Task 8, 2007).

3.3.3.2.3 Multi-functional PV and solar thermal components

Multi-functional 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; façade collectors; PV roofs; thermal energy roof systems; and solar thermal roof-ridge collectors. Currently, fundamental and applied R&D activities are also under way related to developing other products, such as transparent solar thermal window collectors, as well as facade elements that consist of vacuum-insulation panels, PV panels, heat pump, and a heat-recovery system connected to localized ventilation.

3.3.4 Concentrating Solar Power Solar Electricity Generation

This subsection discusses concentrating solar power solar electricity generation technologies and applications.

3.3.4.1 CSP Technologies

Electricity can be produced by concentrating the sun 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.

Some of the key advantages of CSP include the following:

- Can be installed in a range of capacities to suit varying applications and conditions, including 10s of kW (dish/Stirling systems) through multiple MWs (tower Brayton systems) to large centralized plants (tower and trough systems)
- Can integrate storage for operational purposes (less than 1 hour), through medium-size storage for peaking and intermediate loads (3 to 6 hours), and ultimately, for full dispatchability through thermochemical systems
- Modular and scalable components
- Use no exotic materials.

Below, we discuss the various types of CSP systems and thermal storage for these systems.

3.3.4.1.1 CSP systems

For large-scale CSP plants, the most common form of concentration is 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 described below.

3.3.4.1.1.1 Trough concentrators

Long rows of parabolic reflectors concentrate the sun on the order of 70 to 100 times onto a heat-collection element (HCE) that is mounted along the reflector's focal line. The troughs track the sun around one axis, with the axis typically 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. A 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. Land requirements are of the order of 2 km^2 for a 100 MWelec plant. Alternative heat-transfer fluids to the 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 storage in the case of molten salt (Figure 3.13).

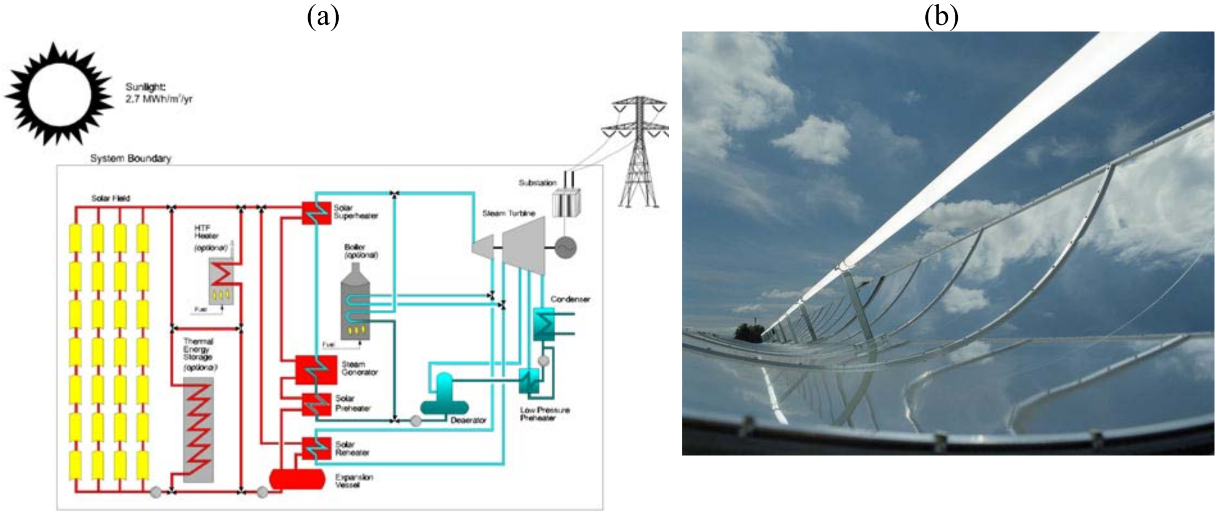


Figure 3.13: Schematic (a) showing the operation of a trough plant, and photo (b) of a trough reflector and irradiated heat-collection element (white tube). [TSU: figure 3.13a too small]

3.3.4.1.1.2 Linear Fresnel reflectors

Presently, large trough reflectors use thermal bending to achieve the curve required in the glass surface. In contrast, 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. 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 linear Fresnel reflectors is that the installed costs on a m^2 basis can be lower than trough systems. However, the annual optical performance is less than a trough.

3.3.4.1.1.3 Central receivers (or power towers)

Thermodynamic cycles used for generating electricity are more efficient at higher temperatures. Point-focus collectors such as central receivers are able to generate much higher temperatures than troughs and linear Fresnel reflectors, though requiring two-axis tracking. 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 1000°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 (Figure 3.14).

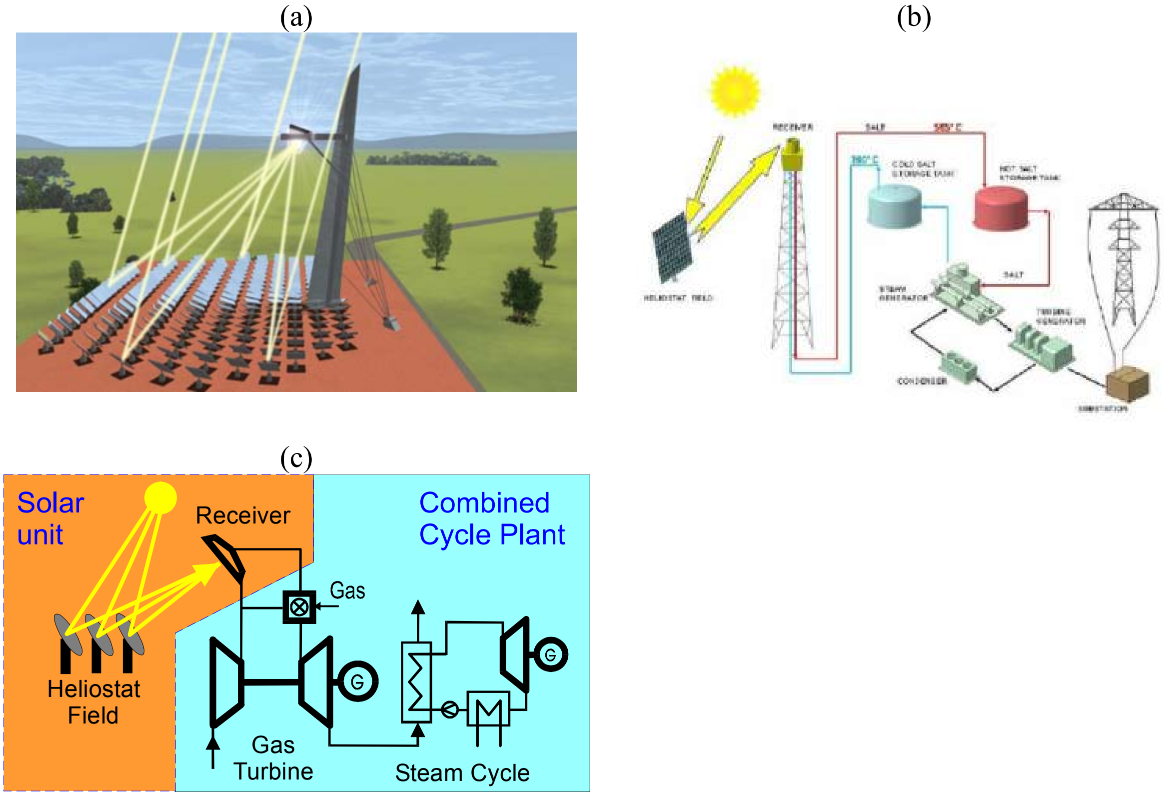


Figure 3.14: Central receiver (or power tower) technology, including: (a) an illustration of the operating principle of tracking heliostats (courtesy CSIRO); (b) a schematic of the principle of using towers and molten salts; and (c) a schematic showing the principle of using towers to drive a Brayton cycle (courtesy DLR). [TSU: Figure 3.14b is too small]

3.3.4.1.1.4 Dish systems

The dish is the ideal optical reflector and therefore is suitable for applications requiring the highest temperatures. Dish reflectors are a paraboloid and concentrate the sun 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. To date, the capacity of each Stirling engine is small—on the order of 10 to 25 kWe. The largest solar dishes have a 400 m^2 aperture and are in research facilities, with the Australian National University presently testing a solar dish with a 485 m^2 aperture (Figure 3.15).


(a) (b)

Figure 3.15: (a) Photo of a typical dish/Stirling system, and (b) a 400-m^2 dish system at Australian National University in Australia.

3.3.4.1.2 Thermal storage for CSP

An important attribute of CSP is the ability to integrate thermal storage. 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 being designed for 6 to 7.5 hours of full-load 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. Towers, with their higher temperatures, can charge and store molten salt more efficiently. Solar Tres, a 17-MW solar tower being developed in Spain, is designed for 6500 hours per year operation—or a 74% capacity factor.

In thermal storage, the heat from the solar field is stored prior to reaching the turbine. Storage takes the form of sensible, latent, or chemical (Gil et al., 2010; Medrano et al., 2010). Thermal storage for CSP systems needs to be at a temperature higher than that needed for the working fluid of the turbine. As such, systems are generally between 400° 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. 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. Compressed air energy storage (CAES) in underground caverns is another form of storage available for CSP. Although not strictly thermal, it integrates well with large-scale CSP systems where compressors are driven by turbines during the sunlight hours and then the air turbines are driven by the stored energy as required. Another form of storage associated with high-temperature CSP is thermochemical storage. This is discussed more fully in 3.3.5 and 3.7.5.

3.3.4.2 CSP Applications

Concentrating solar power can be applied from 10s of kW all the way to large centralized power stations of hundreds of MW.

3.3.4.2.1 Distributed Generation

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 can be on the order of 10 kWe, power stations having a large capacity up to 800 MW have been proposed by aggregating many modules (Figure 3.16a). 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.

Figure 3.16: (a) Rendering of aggregated dish/Stirling units, and (b) a sister tower of one to be used for powering a Brayton cycle microturbine (courtesy CSIRO).

An alternative to the Stirling engine is the microturbine based on the Brayton cycle (Figure 3.16b). The attraction of these engines for CSP is that they are already in significant production, being used for distributed generation fired on landfill gas or natural gas. In the CSP application, the air is instead heated by concentrated solar radiation from a tower or dish reflector. It is also possible to integrate with the biogas or natural gas combustor to back up the solar. Several developments are currently under way based on solar tower and microturbine combinations.

3.3.4.2.2 Centralized CSP

An attraction of CSP has been 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, the benefits of larger scale have also tended to be an inhibitor until recently because of the much larger commitments required by investors.

Table 3.3 shows the earliest commercial CSP plants, most of which are still in operation 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 presently mandate that the largest-capacity unit that can be installed is 50 MW, which is to help stimulate industry competition. In the United States, proposals have been put forward for much larger plants—280 MW in the case of troughs and 100- and 200-MW plants based on towers. Abengoa Solar has recently commissioned commercially operational towers of 10 and 20 MW, and all tower developers plan to increase capacity in line with technology development, regulations, and investment capital. Figure 3.17 provides photos of various large-scale CSP plants.

Table 3.3: Development of early trough CSP plants.

SEGS Plant	1st Year of Operation	Net Output (MW$_e$)	Solar Field Outlet Temp. (°C/°F)	Solar Field Area (m^2)	Solar Turbine Eff. (%)	Fossil Turbine Eff. (%)	Annual Output (MWh)
I	1985	13.8	307/585	82,960	31.5	-	30,100
II	1986	30	316/601	190,338	29.4	37.3	80,500
III & IV	1987	30	349/660	230,300	30.6	37.4	92,780
V	1988	30	349/660	250,500	30.6	37.4	91,820
VI	1989	30	390/734	188,000	37.5	39.5	90,850
VII	1989	30	390/734	194,280	37.5	39.5	92,646
VIII	1990	80	390/734	464,340	37.6	37.6	252,750
IX	1991	80	390/734	483,960	37.6	37.6	256,125

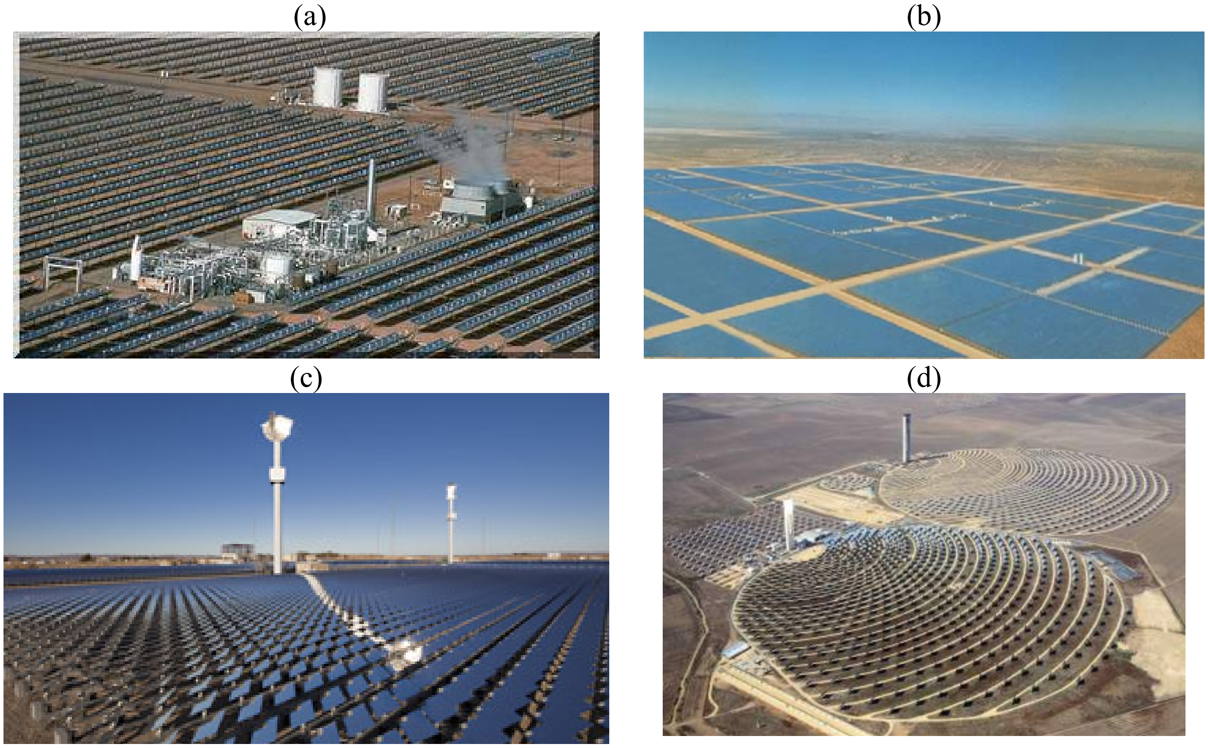


Figure 3.17: Large-scale CSP plants: (a) one of the original LUZ plants in California, operating for 20 years, showing the trough collectors and steam turbine plant; (b) an aerial view of the LUZ plants at Kramer Junction, California; (c) photo of eSolar's 5-MW demonstration plant in California; (d) aerial view of Abengoa Solar's PS10 and PS20 near Seville, Spain.

3.3.5 Solar Fuels Conversion

This subsection discusses solar fuels conversion technologies and applications.

3.3.5.1 Solar Fuels Conversion Technologies

Solar-driven methods for fuel processing include thermal decomposition, thermochemical, photochemical, electrochemical, biochemical, and hybrid reactions. Feedstocks include inorganic compounds such as water and carbon dioxide, and organic sources such as coal, biomass, and methane. The forms of solar fuels are hydrogen (H_2) gas, synthesis gas (mixed gas of H_2 and CO_2), and their derivatives such as methanol, dimethyl ether (DME), and synthesis oil.

Direct conversion of solar energy to fuel is an emerging CSP technology, and as such, it is not yet widely demonstrated or commercialized. But two options appear commercially feasible: (1) the solar hybrid fuel production system (including solar methane reforming, and solar biomass reforming/gasification), and (2) PV- or CSP-solar electrolysis. These technologies are key for reducing greenhouse gas emissions by solar fuel conversion. During the transition to a sustainable energy system, fossil fuels and concentrated solar energy are both used to produce solarized fuels. Thus, solar energy can begin to make an impact in non-electricity markets. As experience broadens with high-temperature CSP electricity generation systems, and high-temperature thermochemical technology is demonstrated through pre-commercial systems, hybrid solar fuels can begin to integrate seamlessly into the present global fuels supply chain. Ultimately, the use of fossil fuels can be phased out and hybrid solar fuels could be replaced by pure solar fuels.

The equivalent of 0.5 terawatt in the form of solar fuel can be produced by a system having 10% efficiency and equipped with a distributed collector area of 200 km × 200 km.

3.3.5.1.1 Solar hybrid fuel production system

Solar hybrid fuel—such as methanol, DME, and synthetic oil from syngas—can be produced by supplying the concentrated solar thermal energy to the endothermic process of methane- and biomass-reforming.

Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) is running a 250-kW reactor and plans to build a 4-MWchemical 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, the concept is that solar fuels can be produced in liquid form in sunbelts such as Australia and solar energy be shipped on a commercial basis to Asia and beyond.

At present, the simplest feedstock for conversion by solar energy is methane, whether from natural gas or coal-bed methane. Other possibilities are under development such as supercritical gasification of biomass and thermal decomposition of coal and petcoke.

The O_2 gas produced by electrolysis with electricity from either CSP or PV can be used for coal gasification and partial oxidation of natural gas. Electricity generated by CSP-solar electrolysis can be used in place of PV-solar electrolysis to decompose water. With the combined process of the solar electrolysis and partial oxidation of coal or methane, about 10% to 15% of solar energy is incorporated theoretically into the methanol or DME. Also, the production cost of the solar hybrid fuel can be lowered compared to the solar hydrogen produced by only the solar electrolysis process.

3.3.5.2 Solar Fuels Conversion Applications

Solar hydrogen and solar hybrid fuels can replace conventional gasoline and diesel as transportation fuels. Some solar fuels can also be used for cars using fuel cells.

Solar hydrogen is effectively an energy carrier, and as such, it is one means of solar energy storage and transport. It offers an alternative to batteries, and there are many advocates supporting the concept that hydrogen could be the ultimate transport fuel, as long as it is generated sustainably and cost effectively.

Energy storage is an issue at the solar power stations themselves. To take full advantage of energy sources such as solar, power stations must be able to store large amounts of energy for use when the sun is not shining. Thermochemical storage could play a role here, as a typical power station environment and energy flow paths can integrate thermochemistry. More advanced coal cycles such as integrated gasification combined cycle (IGCC) involve thermochemistry for separating CO_2 and H_2 production.

The solar hybrid fuels such as methanol, DME, and synthetic oil can be used as a liquid fuel. Synthetic oil can be used directly for automobiles and power station. Methanol and DME can be used for fuel cells after reforming. DME can also be used in place of liquefied petroleum gas.

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, and then on industry capacity and supply chain.

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 fuels conversion.

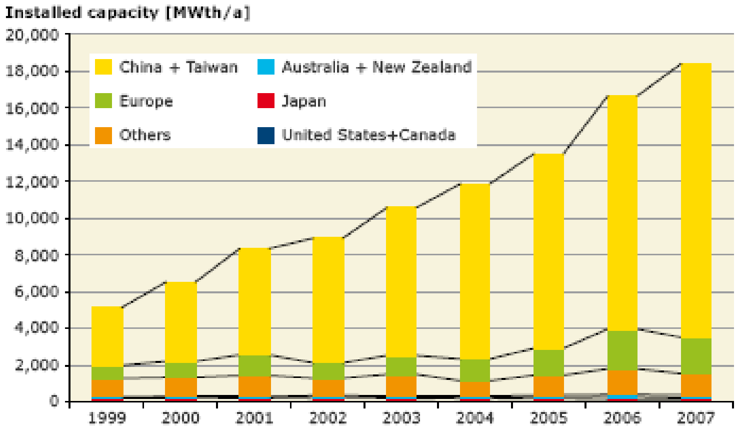
3.4.1.1 Passive Solar Technologies

At this time, no estimates are available for the installed capacity of passive solar or the energy generated through this technology.

3.4.1.2 Active Solar Heat and Cooling

The world global solar heating market totalled an estimated 19.9 GWth in 2007 (Figure 3.18) and about 19 GWth in 2008 (REN21, 2009). Flat-plate and evacuated-tube collectors accounted for 18.4 GWth, which is 92.5% of the overall market. The main markets for unglazed collectors are in the USA (0.8 GWth) and Australia (0.4 GWth). South Africa, Canada, Mexico, The Netherlands, Sweden, Switzerland, and Austria also have notable markets, but all with values below 0.1 GWth of new installed unglazed collectors in 2007.

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 with a collector area of 10 to 20 m^2. In Japan, the number of solar domestic water-heating systems is large. However, 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 one operating solar water heater for every 3.7 inhabitants.



Europe: EU-27, Albania, Macedonia, Norway, Overseas Departments of France, Switzerland;
Others: Barbados, Brazil, India, Israel, Jordan, Mexico, Namibia, South Africa, Thailand, Tunisia and Turkey

Figure 3.18: Installed solar thermal collector capacity (IEA SHCP 2009).

To make comparisons easier, the International Energy Agency's Solar Heating & Cooling Programme, together with European Solar Thermal Industry Federation (ESTIF) and other major solar thermal trade associations, decided to publish statistics in kW_{th} (kilowatt thermal) and have agreed to use a factor of 0.7 kW_{th}/m^2 to convert square meters of collector area into kW_{th}.

3.4.1.2.1 Current trends

Solar thermal energy is increasingly popular in a growing number of countries worldwide (

Table 3.4), with the worldwide market having grown continuously since the beginning of the 1990s (ESTTP, 2006). In absolute terms, China, by far, comprises most of the worldwide solar thermal market. Europe has only a small market share worldwide, despite the strong technological leadership of the European solar thermal industry and the great variety of available solar thermal technologies. North America and Oceania play an insignificant role. Among the “others,” solar thermal is mainly used in Turkey, Israel, and Brazil.

In 2007, about 15.4 GW_{th} (22 million m^2) of capacity was sold in China. This portion was 77% of the world global solar thermal market, which totalled an estimated 19.9 GW_{th}. In China, the installation rate has been growing by almost 30% per year, and at present, solar thermal systems constitute 12% of the national water-heater market in that country.

Solar hot-water systems have been installed and operated successfully at a number of hotels and public buildings in the southern regions of European Russia, East Siberia, and the Far East. The individual solar systems of hot-water supply are in great demand for country houses. Several Russian firms have begun production of solar collectors. The new concept of heat-and-power engineering could replace more than 50% of the organic fuel used during the warm season.

Table 3.4: Solar hot water installed capacity, top 10 countries and world total, 2007 (from REN 21, 2009). Note: Figures do not include swimming pool heating (unglazed collectors). Existing figures include allowances for retirements. By accepted convention, 1 million square meters =0.7 GWth. China added an estimated 14 GWth in 2008, which, along with extrapolating 2007 additions for other countries, yields a 2008 estimate of 145 GWth. Source: Werner Weiss and Irene Bergmann, and IEA Solar Heating and Cooling Programme, Solar Heat Worldwide: Markets and Contributions to Energy Supply 2007, edition 2009; also estimates by the China Renewable Energy Industries Association.

Country/EU	Additions 2007	Existing 2007
	gigawatts-thermal	
China	16	84
European Union	1.9	15.5
Turkey	0.7	7.1
Japan	0.1	4.9
Israel	0.05	3.5
Brazil	0.3	2.5
United States	0.1	1.7
India	0.2	1.5
Australia	0.1	1.2
Jordan	~0	0.6
(other countries)	< 0.5	< 3
World Total	**20**	**126**

In Europe, the market size more than tripled between 2002 and 2008 (Figure 3.19). 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.

Figure 3.19: Market development of annual solar thermal installations in the European Union (ESTIF, 2009).

The use of solar thermal energy clearly varies greatly in different countries (Figure 3.20). In China and Taiwan (80.8 GW_{th}), Europe (15.9 GW_{th}) and Japan (4.9 GW_{th}), plants with flat-plate and evacuated-tube collectors are mainly used to prepare hot water and to provide space heating. However, in North America (USA and Canada), swimming pool heating is still the dominant application, with an installed capacity of 19.8 GW_{th} of unglazed plastic collectors.

There is a growing market for unglazed solar air heating in Canada and the USA. These unglazed air collectors are used for commercial and industrial building ventilation, air heating, and agricultural applications.

Europe has the most sophisticated market for different solar thermal applications. It includes systems for hot-water preparation, plants for space heating of single- and multi-family houses and hotels, large-scale plants for district heating, as well as a growing number of systems for air conditioning, cooling, and industrial applications.

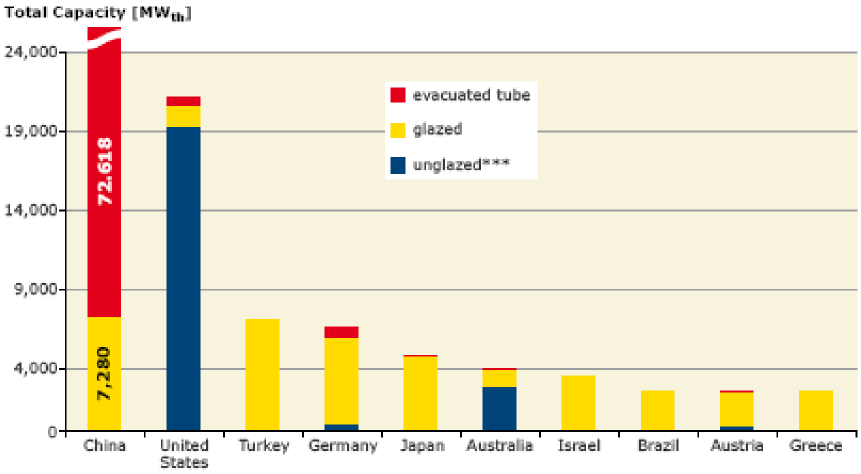


Figure 3.20: Total capacity in operation of water collectors of the 10 leading countries at the end of 2007 (IEA SHCP, 2009).

The solar thermal market in the EU and Switzerland showed strong performance in 2008, growing by 60% to 3.3 GW_{th} of new capacity (4.75 million m2 of collector area). The biggest push clearly came from the German market, which more than doubled. However, demand for solar thermal technology also grew strongly in smaller markets. Although in comparison the Austrian growth rate of 24% seems almost modest, the newly installed capacity per capita reached 29 kW_{th} per 1 000—surpassed only by Cyprus' 61 kW_{th} per 1 000 capita. Despite Austria having rather average potential with respect to its climate, building stock, and prevailing heating systems, it is more than six times ahead of the EU average, and 10 to 40 times ahead of most other countries—including those with high potential such as Italy, Spain, and France.

With 2.1 million m^2 of newly installed capacity, the German domestic market increased its share of the European market (EU27 + Switzerland) to 44% in 2008. Spain, Italy, and France overtook Greece, which was in second position in 2007. Together, these six countries currently account for 84% of Europe's solar thermal market (for comparison, these countries account for only 54% of Europe's population and 61% of its gross domestic product).

These huge gaps between neighbouring countries are not due to dramatically different technological barriers or objective conditions. Rather, the gaps are mainly due to market dynamics and conditions related to the political framework. Even in Austria, with its comparatively large stock of solar thermal capacity, there is not the slightest indication of market saturation. If the current trend in the

Austrian solar thermal market continues, Austria will reach the per capita level of Cyprus in less than a decade.

At present, other European countries such as Spain, France, Italy, and the UK are also systematically developing their solar thermal markets. However, both within Europe and at a global level, solar thermal market development has previously been characterized by huge gaps between a small number of front-runner countries and a large number of countries still in the starting blocks.

Another segment of the solar thermal market is solar pool heating using plastic unglazed absorbers. This market is dominated by the USA, where 2007 shipments of solar pool-heater collectors totalled 785 MW_{th}, with 57% of the installations in Hawaii and Florida (EIA, 2008).

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.

3.4.1.2.2 Short-medium-term solar thermal potential

According to the European Solar Thermal Technology Platform, solar thermal will cover 50% of the heating demand in Europe in the long term, when this technology will be used in almost every building—covering more than 50% of the heating and cooling demand in retrofitted buildings and 100% in new buildings. Solar thermal will also be used in district heating systems, and in commercial and industrial applications with many new and improved solar thermal technologies (ESTTP, 2008).

ESTIF set the goal of 1 m^2 solar capacity per capita in operation by 2020 as a short-medium goal, which is equivalent to a capacity of 700 kW_{th} per 1000 capita. ESTIF's Solar Thermal Action Plan for Europe offers a systematic analysis of the barriers to growth of solar thermal with existing technologies, and guidelines on how to overcome them through industry actions and public policies. It can be expected that the upcoming EU Directive will reduce these gaps and allow for a more rapid exploitation of the short-medium-term solar thermal potential. The increased market volumes will provide the solar thermal industry the means for a substantial increase in R&D investments. This will extend the boundaries of the solar thermal potential, opening the way for implementing the European Solar Thermal Technology Platform's vision for 2030.

3.4.1.3 Photovoltaic Electricity Generation

Newly installed capacity in 2008 with 5.6 GW more than doubled from 2007, with Europe, Japan, the USA, and Korea together installing 5.4 GW. This addition brought the cumulative installed PV capacity worldwide to almost 15 GW—a capacity able to generate up to 18 TWh per year. More than 80% of this capacity is installed in three leading markets: the EU27 with 9.5 GW (63%); Japan with 2.2 GW (14%); and the USA with 1.2 GW (8%). 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 buy-down incentives coupled with investment tax credits in the United States.

Figure 3.21 illustrates the cumulative installed capacity for the top seven PV markets through 2008, including Germany (5351 MW), Spain (3405 MW), Japan (2619), USA (1173 MW), Korea (352 MW), Italy (358 MW), and PR China (140 MW). Spain and Germany have seen, by far, the largest amounts of solar installed in recent years, with Spain seeing a huge surge in 2008 and Germany having experienced steady growth over the last five years. The top seven markets for 2008 additions were Spain (2671 MW), Germany (1505 MW), the USA (342 MW), Korea (274 MW), Japan (252 MW), Italy (197 MW), and France (44 MW).

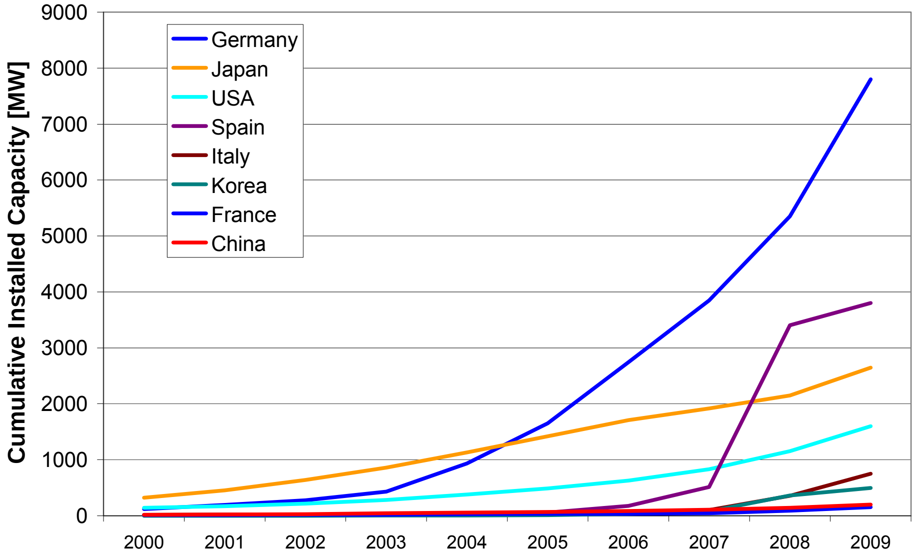


Figure 3.21: Installed PV capacity in eight markets (data source: IEA PVPS Task 1, 2009; REN21, 2009; EurObserv'ER, 2009; Jäger-Waldau, 2009)

Concentrating photovoltaics (CPV) is an emerging market with about 17 MW cumulative installed capacity at the end of 2008. The two main tracks are high-concentration > 300-suns (HCPV) and low- to medium-concentration with a concentration factor of 2 to about 300. To maximize the benefits of CPV, the technology requires high direct-normal irradiance (DNI), 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 produced and market predictions for 2009 and 2010 are 30 MW and 100 MW annual installations, respectively.

Photovoltaic market predictions at the end of 2009 for the short term until 2013 indicate a steady increase, with annual growth rates ranging between 30% and 50%. The main market drivers for the period up to 2020 are considered the following:

- The National Development and Reform Commission (NDRC) expects renewable energy to supply 15% of China's total energy demand by 2020. Specifically for installed solar capacity, the NDRC's 2007 energy plan set a target of 1,800 MW by 2020. Recently, however, these goals have been discussed as being too low, and the possibility of reaching 10,000 MW or more by 2020 seems more likely (Shen and Wong, 2009).
- The 2009 European Directive on the Promotion of Renewable Energy and the Strategic Energy Technology plan is calling for electricity in Europe for up to 12% in 2020.
- The 2009 Indian Solar Plan calls for a goal of 20 GW of solar power in 2022: 12 GW are to come specifically from ground-mounted PV and solar thermal power 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;
- USA Plans – add U.S targets.

3.4.1.4 CSP Electricity Generation

Between 1985 and 1991, some 354 MW of solar trough technology were deployed in southern California. These plants are still in commercial operation today and have demonstrated the potential for long-term viability of CSP. During this period, world energy prices dropped and remained relatively low through the 1990s. Financially, CSP technology is most viable in large-scale installations. However, with such worldwide market conditions, there were insufficient market signals or greenhouse gas incentives to support large installations. Currently, though, the emerging demand for rapid and deep cuts in GHG emissions makes the large capacities offered by CSP an advantage, and one that is being realized through a large and renewed development surge of CSP plants since about 2004.

At this time, more than 650 MW of grid-connected CSP plants are installed worldwide, with another 1800 MW under construction. 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 southwestern United States. Table 3.5 lists installed CSP plants worldwide as of the end of 2008.

Table 3.5: Global installed (operational) CSP plants (Wikipedia, 2009)

Name	**Country**	**Location**	**Technology**	**Capacity (MW)**	**Notes**
Solar Energy Generating Systems	USA	Mojave Desert California	Parabolic trough	354	Collection of 9 units
Nevada Solar One	USA	Boulder City, Nevada	Parabolic trough	64	
Andasol solar power station	Spain	Granada	Parabolic trough	100	Andasol 1 completed, 2008; Andasol 2 completed, 2009
Energia Solar De Puertollano	Spain	Puertollano, Ciudad Real	Parabolic trough	50	Completed May 2009
Alvarado 1	Spain	Badajoz	Parabolic trough	50	Completed July 2009
PS20 solar power tower	Spain	Seville	Power tower	20	Completed April 2009
PS10 solar power tower	Spain	Seville	Power tower	11	Europe's first commercial solar tower
Kimberlina Solar Thermal Energy Plant	USA	Bakersfield, California	Fresnel reflector	5	Ausra demonstration plant
Sierra SunTower	USA	Lancaster, California	Power tower	5	eSolar demonstration plant, USA's first commercial solar tower, completed August 2009
Liddell Power Station Solar Steam Generator	Australia	New South Wales	Fresnel reflector	2	electrical equivalent steam boost for coal station
Jülich Solar Tower	Germany	Jülich	Power tower	1.5	Completed December 2008

THEMIS Solar Power Tower	France	Pyrénées-Orientales	Power tower	1.4	Hybrid solar/gas electric power, using solar energy to heat the air entering a gas turbine
Puerto Errado 1	Spain	Murcia	Fresnel reflector	1.4	Completed April 2009
Saguaro Solar Power Station	USA	Red Rock Arizona	Parabolic trough	1	
Keahole Solar Power	USA	Hawaii	Parabolic trough	1	
Kibbutz Samar Power Flower	Israel	Kibbutz Samar	Power tower	0.1	
Overall Operational Capacity (MW)				**667.4**	

In 2007, after more than 15 years, the first new major CSP plants came on line with Nevada Solar One (64 MW, USA) and Planta Solar 10 (11 MW, Spain). In Spain, Royal Decree 436/2004 dated 12 March 2004 is a major driving force for CSP plant construction and expansion plans. The guaranteed feed-in tariff is 0.27 €/kWh for 25 years. In the *Plan de Energías Renovables en España* (PER) (2005 to 2010), a total capacity of 500 MW is foreseen. In 2008, at the coal-fired Liddell Power station (2,000 MW) in New South Wales, Australia, some of the station's boiler feedwater was replaced by hot water from an 18,000 m^2 CSP array. Figure 3.22 and Table 3.6 show the current and planned developments to add more CSP capacity in the near future.

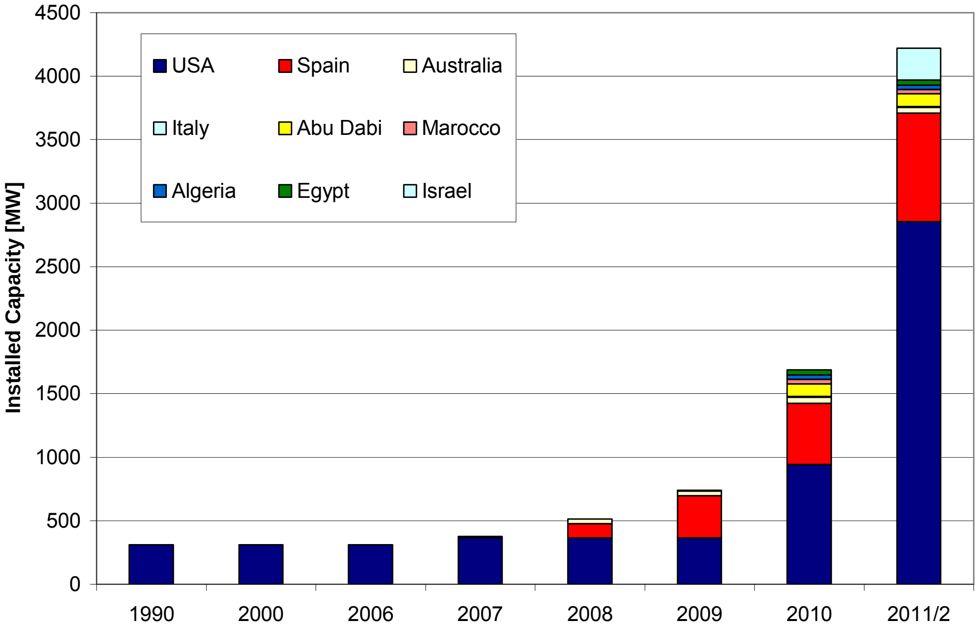


Figure 3.22: Installed and planned concentrated solar thermal electricity plants by country. (Kautto and Jäger-Waldau, 2009).

Table 3.6: CSP projects currently under construction or in test phase (Wikipedia, 2009). [TSU: other reference source is needed here]

Name	Country	Location	Technology	Capacity (MW)	Notes
Martin Next-Generation Solar Energy Center	USA	Florida	Integrated Solar Combined Cycle (ISCC)	75	Steam input into a combined cycle
Andasol 3–4	Spain	Granada	Parabolic trough	100	With heat storage
Palma del Rio 1, 2	Spain	Cordoba	Parabolic trough	100	
Majadas de Tiétar	Spain	Cacares	Parabolic trough	50	
Solnova 1, 3, 4	Spain	Seville	Parabolic trough	150	
Extresol 1-3	Spain	Torre de Miguel Sesmero (Badajoz)	Parabolic trough	150	
Helioenergy 1, 2	Spain	Ecija	Parabolic trough	100	With heat storage
Solaben 1, 2	Spain	Logrosan	Parabolic trough	100	
Valle Solar Power Station	Spain	Cadiz	Parabolic trough	100	With heat storage
Lebrija-1	Spain	Lebrija	Parabolic trough	50	
Manchasol-1	Spain	Ciudad Real	Parabolic trough	50	With heat storage
La Florida	Spain	Alvarado (Badajoz)	Parabolic trough	50	
La Dehesa	Spain	La Garrovilla (Badajoz)	Parabolic trough	50	
Aste 1A, 1B	Spain	Alcázar de San Juan (Ciudad Real)	Parabolic trough	100	
Axtesol 2	Spain	Badajoz	Parabolic trough	50	
Arenales PS	Spain	Moron de la Frontera (Seville)	Parabolic trough	50	
Serrezuella Solar 2	Spain	Talarrubias (Badajoz)	Parabolic trough	50	
El Reboso 2	Spain	El Puebla del Rio	Parabolic trough	50	

		(Seville)			
Termosol 1+2	Spain	Navalvillar de Pela (Badajoz)	Parabolic trough	100	
Helios 1+2	Spain	Ciudad Real	Parabolic trough	100	
Kuraymat Plant	Egypt	Kuraymat	ISCC	20	
Hassi R'mel integrated solar combined cycle power station	Algeria	Hassi R'mel	ISCC	25	
Beni Mathar Plant	Morocco	Beni Mathar	ISCC	20	
Gemasolar, former Solar Tres Power Tower	Spain	Fuentes de Andalucia (Seville)	Power tower	17	
Overall Capacity Under Construction (MW)				**1757**	

The average investment costs for a CSP plant are given in various projects at about 4.62 $/W (2005 $) (4 €/W; 2008 €). The project costs can increase up to 16.16 $/W (2005 $) (14 €/W 2008 €), depending on the level of storage or other backup provided. In this case, even though capital cost increases, so too does annual capacity factor; therefore, the levelized cost of energy (LCOE) does not necessarily change dramatically. Indeed, even if storage caused the LCOE to increase marginally, this increase would be more than recovered by the ability to dispatch electricity at times of peak tariffs in the market. Thus, the internal rate of return improves.

More than 50 CSP electricity projects are currently in the planning phase, mainly in North Africa, Spain, and the USA. In the USA, more than 4,500 MW of CSP are currently under power purchase agreement contracts. The different contracts specify when the projects must start delivering electricity between 2010 and 2014 (Kautto and Jäger-Waldau, 2009). In Spain, CSP projects with about 1,800 MW have provisional registration, and projects with more than 10 GW have filed grid-access applications. In Australia, the federal government has called for 1,000 MW of new solar plants, covering both CSP and PV, under the Solar Flagships program.

3.4.1.5 Solar Fuel Conversion

At this time, data are not available on installed capacity and generated energy for solar fuel conversion.

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 fuels conversion.

3.4.2.1 Passive Solar Technologies

This subsection discusses industry capacity and supply chain issues of passive solar technologies within the areas of the overall building industry, windows, and thermal storage.

3.4.2.1.1 Building industry

The building industry in most countries is fragmented and often characterized by a piecemeal approach to building design, construction, and operation. 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 usually overlooked because of the absence of any systematic 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 (HVAC) 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 improving with the adoption of computer tools. But fundamental institutional barriers remain due to the basic training of architects and engineers, which does not foster an integrated design approach.

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 (Passive House Institute web, 2009; Cepheus, 2009; PHPP, 2004).

Currently, passive technologies play 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 a new IEA Task (IEA, 2009)—SHC Task 40—ECBCS Annex 52, which focuses on net-zero energy solar buildings. In Canada, the EQuilibrium^{TM} net-zero energy home demonstration program conducted by Canada Mortgage and Housing Corporation (CMHC, 2008) has resulted in the construction of several near-net-zero energy solar homes in which passive solar design is used in a systematic manner. Figure 3.23 shows photos of one of these homes—the EcoTerra^{TM}—which is a prefabricated home (Chen et al., 2007). The prefabricated home industry can contribute to a systematic and widespread implementation of passive technologies. Passive technologies are essential in developing affordable net-zero energy homes. Passive solar gains in both the EcoTerra and homes based on the Passive House Standard are expected to reduce the heating load by about 40%. By extension, we can expect systematic passive solar design of highly insulated buildings on a community scale, with optimal orientation and form of housing to easily result in a similar energy saving of 40%.

Assembly of house modules (built in the factory and delivered to the site)

Installation of building-integrated photovoltaic/thermal roof module

Family room (direct-gain area: concrete mass 15 cm thick with ceramic tiles)

Finished house: equatorial-facing triple-glazed window area is 9.1% of heated floor area

Figure 3.23: Photos from the EcoTerra^{TM} demonstration solar house assembly and the final completed house.

Another IEA Annex—ECES IA Annex 23— was initiated in November 2009 (IEA ECES IA web, 2009). The general objective of the Annex is to ensure that energy storage techniques are properly applied in ultra-low-energy buildings and communities. Applications of these designs are foreseen in a post-Kyoto Protocol world where total CO_2 reduction is required. Proper application of energy storage is expected to increase the likelihood of sustainable building technologies.

3.4.2.1.2 Windows

Windows play a very important role in the energy balance of buildings because heat losses through them are 4 to 10 times higher than through the other elements of the building. In parallel, windows control daylight penetration and natural ventilation flow. Glazing and window technologies have progressed tremendously in the last twenty years (Hollands *et al.,* 2001). New-generation windows result in low energy losses, high daylight efficiency, solar shading, and noise reduction. However, selection of the proper glazing for a building is a tradeoff between the cooling, heating, and lighting requirements (Figure 3.24). New technologies such as transparent photovoltaics and electrochromic windows provide many possibilities in the design of solar houses and offices with abundant daylight. Another possibility is the provision of summer shading for direct-gain windows by using photovoltaic overhangs. Triple-glazed, low-emissivity, argon-filled windows with efficient framing were used in the EQuilibrium^{TM} demonstration houses, and they are expected to become more common in climates with cold winters. 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.

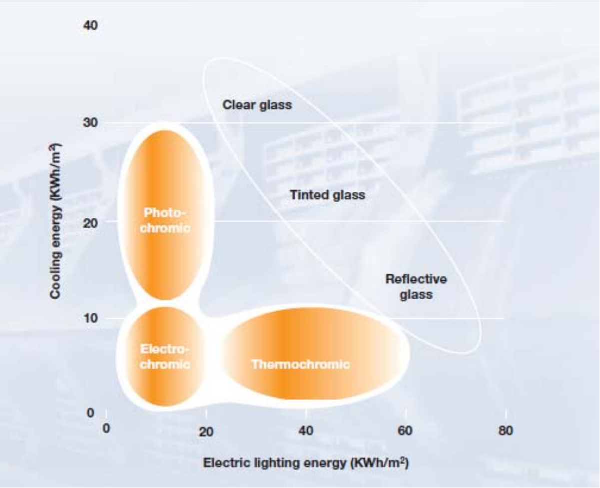


Figure 3.24: Lighting energy versus cooling energy for different glazing types (UNEP, 2007).

3.4.2.1.3 Low-temperature thermal storage

The primary materials for 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 needed 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.,* 2004). PCM in microencapsulated polymers are now on the market and can be added to plaster, gypsum, or concrete to enhance the thermal capacity of a room. For renovation, they provide 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. The EcoTerra house includes a hollow-core concrete floor slab in the basement that is actively charged with solar-heated air from its roof-integrated photovoltaic/thermal system; but the release of the heat is passive, so this is hybrid thermal storage. A combination of passive and active thermal storage may enable the use of more solar gain and facilitate reaching the net-zero energy goal in a more cost-effective manner.

3.4.2.2 Active Solar Heat and Cooling

Due to the different application modes—including domestic hot water, heating, preheating, and combined systems, as well as varying climatic conditions—a number of different collector technologies and system approaches have been developed, according to the European Solar Thermal Technology Platform, “Solar Heating and Cooling for a Sustainable Energy Future in Europe.”

Flat-plate collectors comprise more than 80% of the worldwide installed systems. In 2007, a worldwide installed capacity of 19.9 GWth corresponded to 28.4 million m2 of solar collectors. Flat-plate and evacuated-tube collectors accounted for 18.4 GWth, which is 92.5% of the overall market.

It is remarkable that the market of evacuated-tube collectors grew 23.4% compared to 2006, whereas the markets of flat-plate collectors and unglazed collectors decreased 18.3% and 7.2%, respectively. However, data of installed unglazed collectors are officially collected in only a few countries.

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 more efficient, especially 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 heaters are Australia, Greece, and the USA. The majority of exports from Greece are to Cyprus and the near-Mediterranean area. France also exports a substantial number of systems to its overseas territories. The majority of USA 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.

In Russian, the research and production association “Engineering Industry” produces solar collectors made of aluminium. One company produces aluminium-copper solar collectors, and another enterprise produces copper-steel collectors.

3.4.2.3 PV Electricity Generation

This subsection discusses the industry capacity and supply chain issues of photovoltaic technologies under the areas of overall solar cell production, thin-film module production, and polysilicon production.

3.4.2.3.1 Solar cell production

Global PV cell production reached more than 7 GW in 2008—almost doubling the 2007 production level of 3,715 MW. Figure 3.25 depicts the increase in production from 1990 through 2008, showing regional contributions (Jäger-Waldau, 2009). The five-year compound annual growth rate in production from 2003 to 2008 was more than 50%. Solar cell production capacities for wafer silicon-based solar cells represent only the cells; for thin films, the complete integrated module is considered. Only those companies that actually produce the active circuit (solar cell) are counted. Companies that purchase these circuits and make cells are not counted.

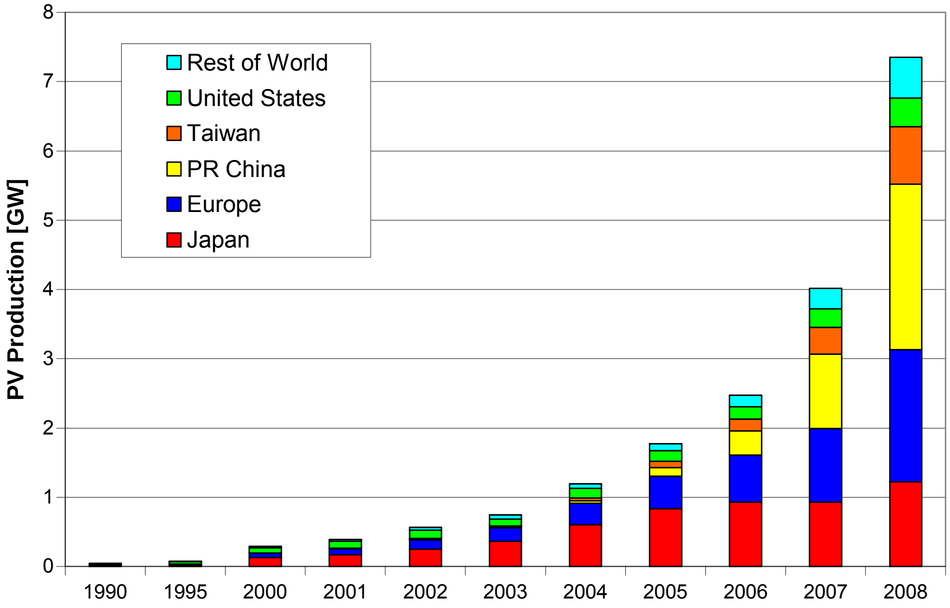


Figure 3.25: Worldwide PV production from 1990 to 2008 (Jäger-Waldau, 2009).

These estimates show a significant growth in production despite tight silicon supply and resulting high silicon costs. The announced increases of production capacities—based on a survey of about 200 companies worldwide—again accelerated in 2008 and early 2009 (Figure 3.26). Only published announcements of the respective companies and no third-party information were used. The cut-off date of the information included was February 2009. This method has the drawback that not all companies announce their capacity increases in advance and that in times of financial tightening, announcements of scale-backs in expansion plans are often delayed to prevent upsetting financial markets. Therefore, the capacity figures give a trend, but do not represent final numbers.

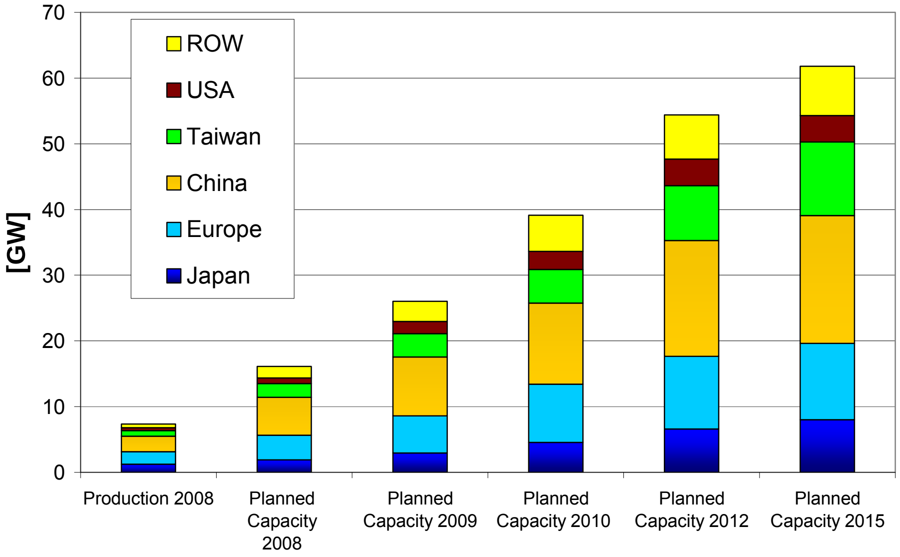


Figure 3.26: Worldwide PV production and with future planned production capacity increases.

Both Chinese (PRC) and Taiwanese PV production increased at a greater rate than the industry as a whole. The PRC is the top producer with 2 to 2.5 GW. This is significantly more than Europe with 1.5 to 1.8 GW, Japan with 1.2 to 1.5 GW, and Taiwan with 0.5 to 0.8 GW. Market estimates vary between 5 and 6 GW with shipments to first point in the market estimated at 5.5 GW (Mints, 2009).

In terms of company production, the largest producer came from Germany with 570 MW, followed by a company in China with 550 MW, an international producing company (USA / Germany / Malaysia) with 503 MW, and a Japanese company producing 470 MW.

If all current plans can be realized by 2012, China will have about 28% of the worldwide production capacity of 48 GW, followed by Europe with 22%, and Japan and Taiwan with 15% each. However, it is expected that the capacity utilization rate will further decrease from 56% in 2007 and 54% in 2008 to less than 50% in 2012.

3.4.2.3.2 Wafer-based silicon cell and module production

Worldwide, some 200 factories produce silicon wafer-based solar cells and more than 300 produce solar modules. In 2008, silicon-based solar cells and modules represented about 85% of the worldwide market (Figure 3.27). Despite a massive increase in production capacities, the total market share of wafer-based silicon is expected to decrease over the next few years.

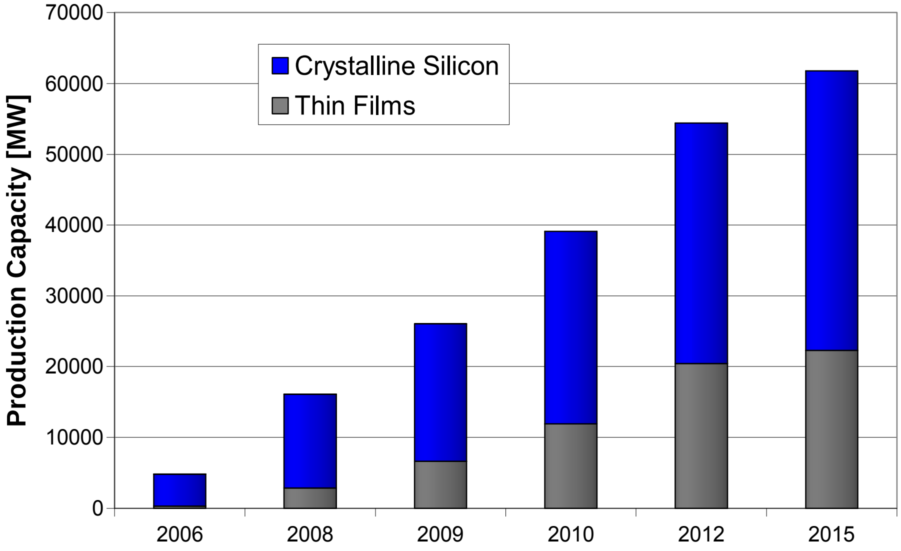


Figure 3.27: Actual and planned production capacities of thin-film and crystalline silicon-based solar modules (Jäger-Waldau, 2009).

In 2008, the main production clusters were in China, Europe, Japan, and Taiwan, accounting for more than 87% of worldwide production. With current economic constraints, the trend has accelerated to move production to Asia. If the current trend continues, only 25% of the worldwide cell production capacity will be in Europe and the USA by 2015.

Due to the nature of module manufacturing and that the heaviest components are glass and a metal frame, production capacities close to the final market are still a favourable option. However, an emerging trend is a move to large original design manufacturing (ODM) units, similar to the developments in the semiconductor industry.

3.4.2.3.3 Thin-film module production

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 10% in 2007 and 12% to 14% in 2008. Thin-film shipments in 2008 increased by 129% compared to 2007, and the utilization rate of thin-film production capacities is 60%—somewhat higher than the 54% overall utilization rate of the PV industry.

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 realised in time, thin-film production capacity could be 11.9 GW or 30% of the total 39 GW in 2010 and 20.4 GW in 2012 of a total of 54.3 GW. The first thin-film factories with GW production capacity are already under construction for various thin-film technologies.

3.4.2.3.4 Polysilicon production

The rapid growth of the PV industry since 2000 led to the situation where between 2004 and early 2008, 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 500 $/kg and consequently higher prices for PV modules. This extreme price hike triggered the massive capacity expansion, not only of established companies, but many new entrants as well.

The six companies which reported shipment figures shipped together about 43,900 metric tons of polysilicon in 2008, as reported by Semiconductor Equipment and Materials International (SEMI). In 2008, these companies had a production capacity of 48,200 metric tons of polysilicon (RTS, 2009). However, all polysilicon producers, including new entrants with current and alternative technologies, had a production capacity of more than 90,000 metric tons of polysilicon in 2008. Considering that not all new capacity actually produced polysilicon at nameplate capacity in 2008, it was estimated that 62,000 metric tons 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 metric tons of polysilicon. With an average material need of 8.7 g/Wp, this would have been sufficient for 5.3 GW of PV products.

The regional distribution of the polysilicon production capacities are as follows: China 20,000 metric tons, Europe 17,500 metric tons, Japan 12,000 metric tons, USA 37,000 metric tons (RTS, 2009; Chinese Academy of Science, 2009).

Projected silicon production capacities available for solar in 2010 vary between 99,500 metric tons (PV News, 2008) and 245,000 metric tons (EuPD, 2008). In addition, the possible solar cell production will depend on the material use per Wp.

3.4.2.4 CSP Electricity Generation

When considering industry capacity, it is important to factor in that CSP 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, metallurgists, and others. Often, the material or components used in the collectors are already mass-produced, such as glass mirrors.

The CSP industry commenced when the first commercial trough/oil plants were installed and commissioned between 1985 and 1991. Nine individual plants, making up a combined 354 MW, were built by Luz, and they continue to operate today, although with new owners.

The next commercial plant was the 64-MW Nevada Solar One, built and owned by Acciona, and commissioned in 2007 in Nevada, USA. This plant uses, for the first time, troughs constructed of aluminium rather than steel for the structural components. Several years ago, there were only a handful of companies involved in the supply chain for CSP components and construction. Now, however, strong competition is emerging and many companies are now claiming to be capable of supplying components. Nonetheless, the large evacuated tubes (heat-collection elements) designed specifically for use in trough/oil systems for power generation remain a specialized component, and only two companies are capable of supplying large orders of tubes. The trough concentrator itself comprises know-how in both structures and thermally sagged glass mirrors. And although more companies are now offering new trough designs and considering alternatives to conventional rear-silvered glass (such as new polymer-based reflective films), the essential technology 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 the long and successful commercial history, trough/oil technology is presently the technology leader.

Linear Fresnel and central receivers 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. Apart from Abengoa Solar with PS10 and PS20, the new players presently have projects at the demonstration level. The accepted standard was for large heliostats, but new players are pursuing much smaller heliostats for the cost reductions potentially afforded through mass production. The diverse range of companies now interested in heliostat development ranges 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 toward 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 just a few years, the CSP industry has gone from negligible activity to over 1,400 MW either commissioned or under construction, with the diversity of sites shown in Figure 3.28. 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 renewable energy independent power producers such as Acciona, and utilities such as Iberdrola and Florida Power & Light are making plays through various mechanisms for a role in the market. Figure 3.29 illustrates the relative maturity of the various CSP technologies and shows how the CSP market may develop over time.

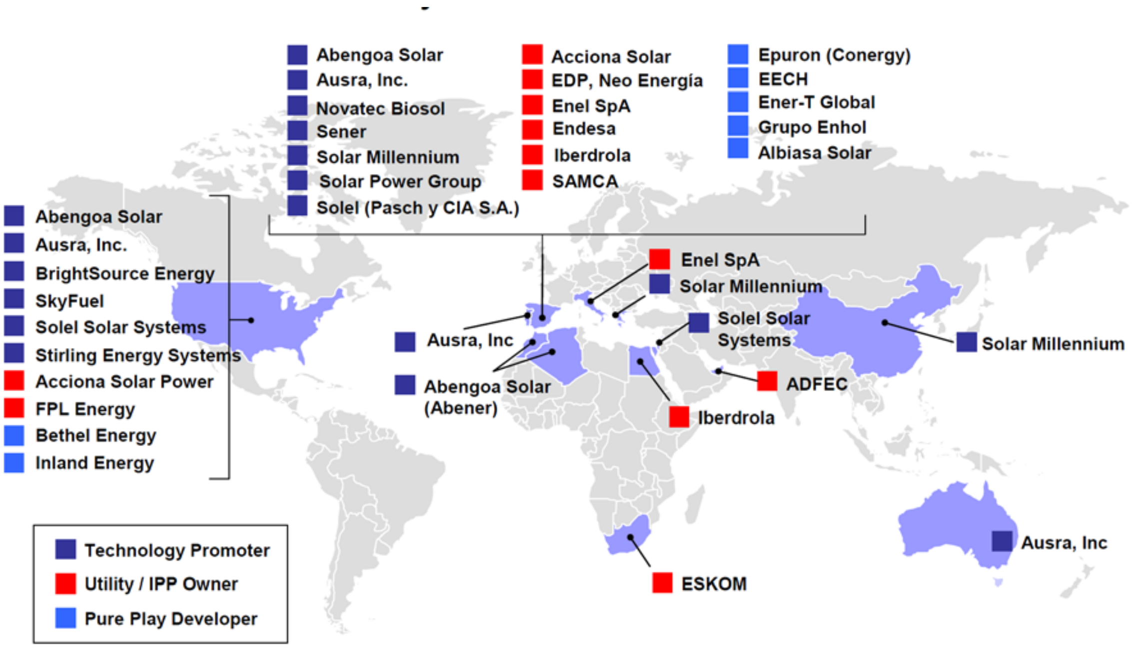


Figure 3.28: The global nature of the CSP industry is shown in this illustration. (Courtesy Emerging Energy Research, 2007).

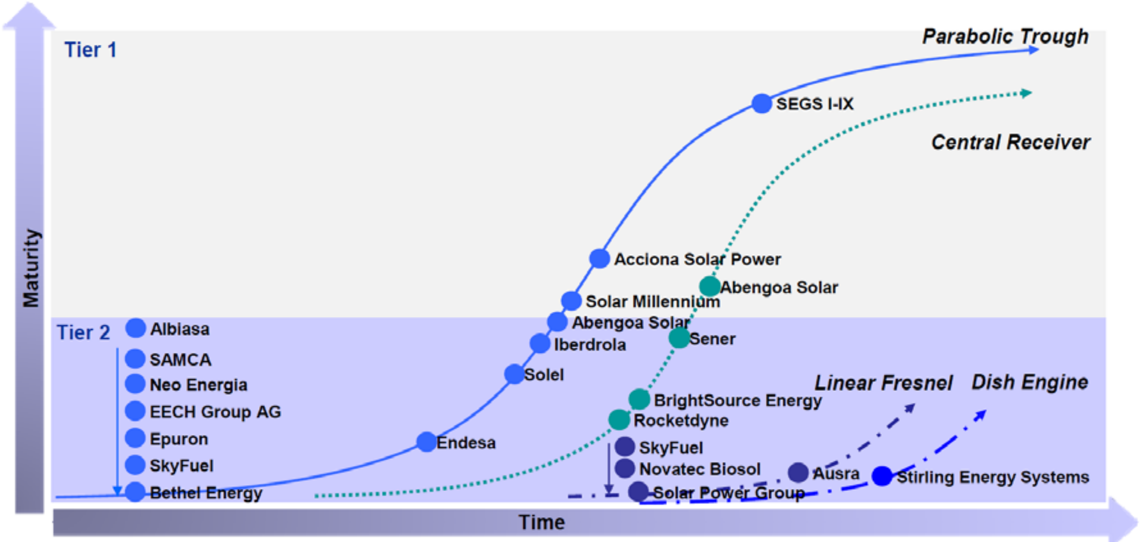


Figure 3.29: Illustrates the relative maturity of the various CSP technologies and shows how the CSP market may develop over time.

The supply chain is not limited by raw materials, because the majority of required materials are glass, steel/aluminium, and concrete. At present, Schott and Solel are the only two recognized suppliers of evacuated tubes with sufficient capacity to supply tubes to service several hundred MW/yr. However, expanded capacity can be introduced fairly readily through new factories with an 18-month lead time.

3.4.2.5 Solar Fuel Conversion

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 solar towers, with solar fuels requiring a different reactor at the focus and different downstream processing and control. However, much of the downstream technology would come from expertise in the petrochemical industry. The scale of solar fuels demonstration plants is being ramped up to build confidence for industry, which will eventually expand operations.

3.5 Integration into Broader Energy System

This section discusses how direct solar energy technologies are part of the broader energy framework, focusing specifically on building-integrated solar energy, low-capacity energy demand, and district heating and other thermal loads.

3.5.1 Building-Integrated Solar Energy

Before considering how solar energy is integrated with other energy technologies, it is important to consider how it is integrated within the building envelope and with energy-conservation methods. 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 will be converted to electricity; the remaining roughly 80% will be available as low-temperature heat to be transferred to the fluid being heated. The resulting unit will produce both heat and electricity and require 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.

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), after surveying the opinions of more than 170 architects and engineers who examined a slate of 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.

The idea of the net-zero energy solar building has sparked recent interest. Such buildings will send as much excess electrical energy (from PV) to the grid as the energy they draw over the year. An International Energy Agency Task has been set up to consider ways of achieving this goal (IEA web, 2009). Recent examples for the Canadian climate have been provided by Athienitis (2008). Starting from a building meeting 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 as well as cooling in the summer. Figure 3.30 shows a house that is expected to meet the requirements for a net-zero energy solar building.

Figure 3.30: Photo of the Eco-Terra home in Quebec, Canada, illustrating at least four types of solar technology integrated into one building and designed to achieve zero net-energy consumption over one year (Athienitis, 2008).

3.5.2 Low-Capacity Electricity Demand

Solar energy is an abundant potential source of renewable energy, and it is available in all areas of the world. However, solar energy technologies are relatively expensive compared to other energy technologies and are economically viable only in certain areas. There is a need to further develop solar energy technologies, such as to increase the efficiency of solar energy generation and to reduce the capital cost of solar energy technologies. This would allow more countries to increase the amount of solar energy in their fuel mix. There can be comparative advantages for using solar energy rather than fossil fuels in many developing countries. Within a country, the comparative advantages are higher in rural areas compared to urban areas. Indeed, solar energy has the advantage to provide small and decentralized supplies, as well as large centralized ones. It can be very well adapted to small and decentralized demand. Most solar technologies are modular; with PV, for example, there are no large economies of scale.

For rural electrification, a common approach is to consider any mature technology and to make the final choice based on economic efficiency. This approach does not consider all consumers and does not necessarily lead to sustainable development for the country or for the area to be electrified.

In some developing countries, particularly those that are not oil producers, solar energy and other forms of renewable energy can be the most appropriate. If electricity demand exceeds supply, the lack of electricity can prevent development of many economic sectors. Even in countries with high solar energy potential, renewable energy is 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. In such cases, it is reasonable to keep the electricity generated near the source to provide high power to cover industrial needs.

Applications that have low power consumption, such as lighting in rural areas, can then primarily be satisfied using on-site PV—even if the business plan for the electrification of the concerned rural area indicates that a connection to the grid would be more profitable. Furthermore, the criteria to determine the most-suitable technological option for the electrification of 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.

3.5.3 District Heating and Other Thermal Loads

3.5.3.1 Solar water heater systems

In Australia, China, Greece, Israel, and the USA, solar water heaters make a significant contribution to residential energy demand. The power output from 100,000 m^2 of flat-plate solar collectors is on the order of 50 MW during the middle of the day (assuming 1,000 W/m^2 incident radiation and 50% collector efficiency). Thus, the peak power capacity of solar water heaters in a number of countries already exceeds 1,000 MW. The impact of the installation of a large number of solar domestic water heaters on the operation of an electricity grid depends on the load management strategies of the utility.

For a utility that uses centralized load switching to manage electric water-heater load, the impact of solar water heaters is limited to fuel savings. If a utility does not use load switching, then the installation of a large number of 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 implementation of solar water heating can benefit both the customer and the utility. Another benefit to utilities is emissions reduction, because solar water heating will displace the marginal and most-polluting generating plant used to produce peak-load power.

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).

3.5.3.2 Biomass and solar thermal electricity

Combining biomass and solar thermal energy could provide zero-emissions, high-capacity-factor solutions well suited to areas with less frequent direct-beam solar radiation. In the short term, such areas often have high biomass availability due to increased rainfall (from the thick cloud cover). On the other hand, solar technology is much more land efficient and greatly reduces the need for biomass growing area and biomass transport cost. It is likely that some optimum ratio of solar thermal electricity and biomass supply would 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, reducing the need for occasional fuel supply for each individual solar thermal electricity system.

3.5.4 PV Generation Characteristics and Smoothing Effect

PV system generation at a single point varies periodically in a day and a year, but also randomly according to weather conditions. The variation of PV generation is supposed to have a large impact on voltage and power flow of the local transmission/distribution system from the early penetration stage, and supply-demand balance in a total power system operation in the deep penetration stage. The impact of supply-demand balance might be a critical constraint of PV integration into a power system.

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 slight correlation and cancel each other (Figure 3.31). Otani et al. (1998) analyzed the non-correlational irradiation/generation characteristics of several PV systems/sites that are dispersed spatially.

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.

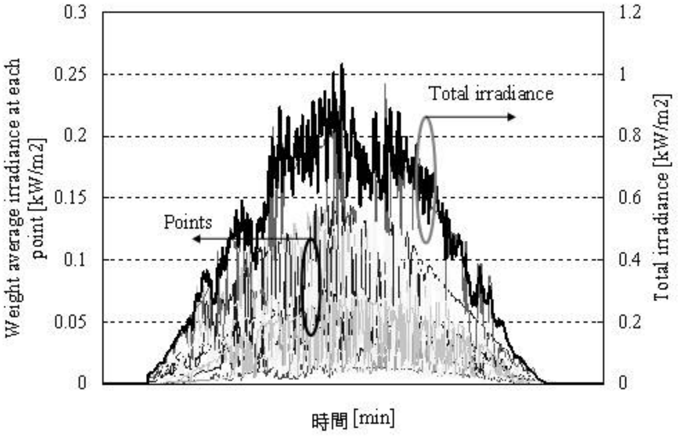


Figure 3.31: Image of smoothing effect of multiple PV systems

However, the critical impact on supply-demand balance of a power comes from the total generation of the PV system of a power system.

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, which assumes the total PV generation as the weighted sum of the each measurement by the Voronoi cell area. Collecting reliable measurement data with sufficient time-resolution and time-synchronization, the smoothed generation characteristics of the PV penetration will be analyzed precisely and will contribute to the economical and reliable integration of PV into the energy system.

3.6 Environmental and Social Impacts

The section first discusses the environmental impacts of direct solar technologies, then describes potential social impacts.

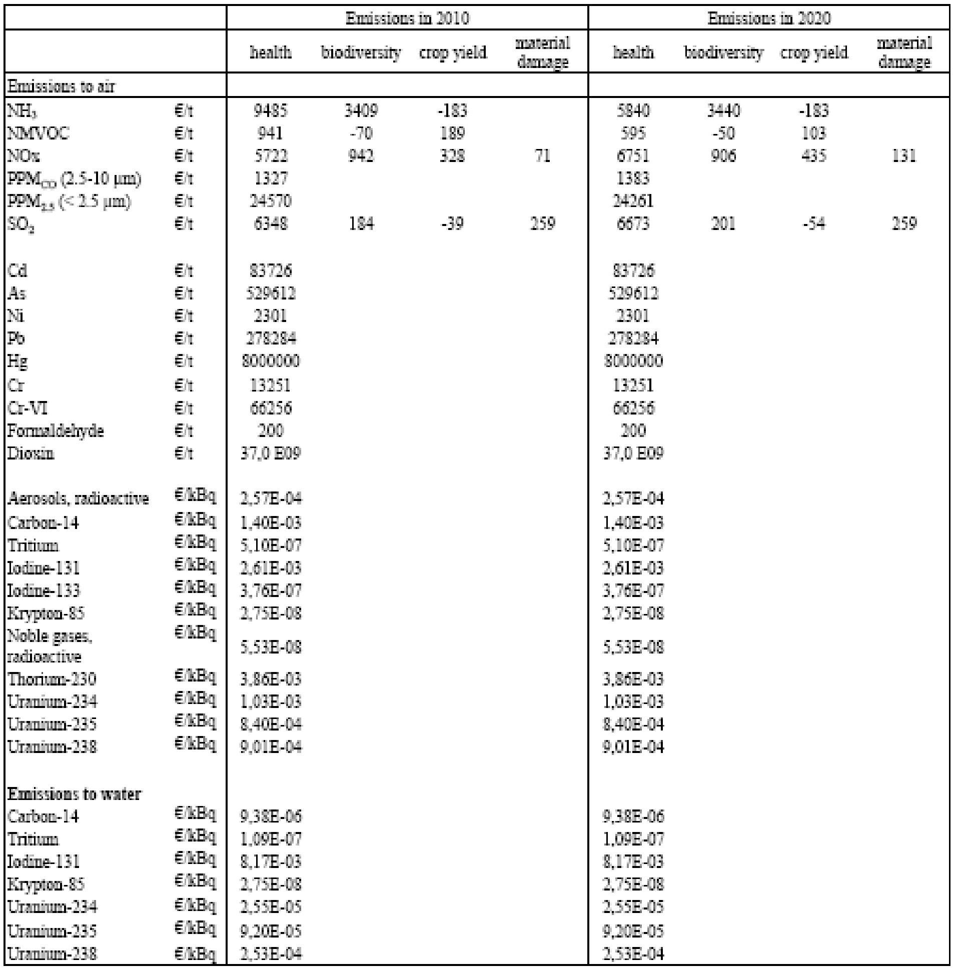
3.6.1 Environmental Impacts

3.6.1.1 Clean energy benefit estimates

No consensus exists on the premium, if any, that society should pay for cleaner energy. However, in recent years, there has been progress in analysing environmental damage costs, thanks to several major projects to evaluate the externalities of energy in the USA and Europe (Gordon, 2001). Although solar energy has been considered desirable because it poses a much smaller environmental burden than conventional sources of energy, this argument has almost always been justified by qualitative appeals. Fortunately, this has begun to change.

Results for damage costs per kilogram of pollutant were presented by the International Solar Energy Society (ISES) in Gordon (2001). Table 3.7 correspond to the "uniform world model," with a regional average (land and water) population density of 80 persons per km2. For other regions, these numbers should be scaled according to population density.

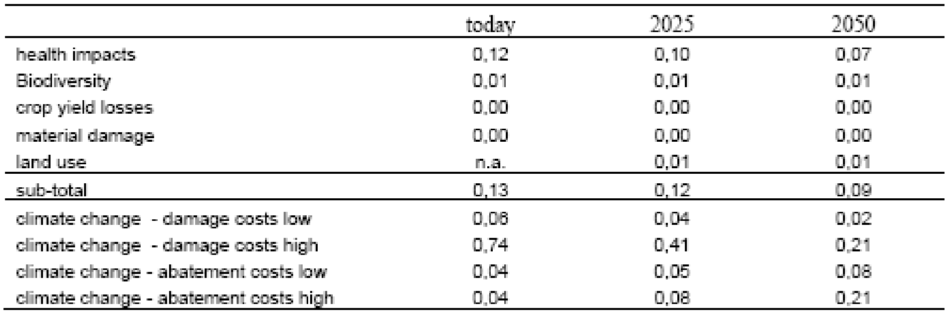
Table 3.7: Unit damage costs for air pollutants in €2000 per elementary flow (source: NEEDS, 2009).



		Emissions in 2010				Emissions in 2020			
		health	biodiversity	crop yield	material damage	health	biodiversity	crop yield	material damage
Emissions to air									
NH_3	€/t	9485	3409	-183		5840	3440	-183	
NMVOC	€/t	941	-70	189		595	-50	103	
NO_x	€/t	5722	942	328	71	6751	906	435	131
PPM_{co} (2.5-10 µm)	€/t	1327				1383			
$PPM_{2.5}$ (< 2.5 µm)	€/t	24570				24261			
SO_2	€/t	6348	184	-39	259	6673	201	-54	259
Cd	€/t	83726				83726			
As	€/t	529612				529612			
Ni	€/t	2301				2301			
Pb	€/t	278284				278284			
Hg	€/t	8000000				8000000			
Cr	€/t	13251				13251			
Cr-VI	€/t	66256				66256			
Formaldehyde	€/t	200				200			
Dioxin	€/t	37,0 E09				37,0 E09			
Aerosols, radioactive	€/kBq	2,57E-04				2,57E-04			
Carbon-14	€/kBq	1,40E-03				1,40E-03			
Tritium	€/kBq	5,10E-07				5,10E-07			
Iodine-131	€/kBq	2,61E-03				2,61E-03			
Iodine-133	€/kBq	3,76E-07				3,76E-07			
Krypton-85	€/kBq	2,75E-08				2,75E-08			
Noble gases, radioactive	€/kBq	5,53E-08				5,53E-08			
Thorium-230	€/kBq	3,86E-03				3,86E-03			
Uranium-234	€/kBq	1,03E-03				1,03E-03			
Uranium-235	€/kBq	8,40E-04				8,40E-04			
Uranium-238	€/kBq	9,01E-04				9,01E-04			
Emissions to water									
Carbon-14	€/kBq	9,38E-06				9,38E-06			
Tritium	€/kBq	1,09E-07				1,09E-07			
Iodine-131	€/kBq	8,17E-03				8,17E-03			
Krypton-85	€/kBq	2,75E-08				2,75E-08			
Uranium-234	€/kBq	2,55E-05				2,55E-05			
Uranium-235	€/kBq	9,20E-05				9,20E-05			
Uranium-238	€/kBq	2,53E-04				2,53E-04			

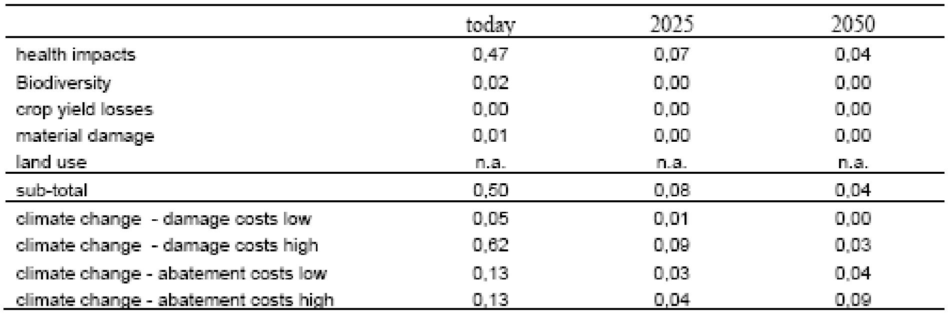
Gordon also presented results for damage costs per kilowatt-hour. The results of studies such as NEEDS (2009), summarized in Table 3.8, confirm that this is usually the case, but not always. There are no explicit results for solar thermal, but there is no reason to expect larger damage costs than for wind and PV.

Table 3.8: Quantifiable external costs: photovoltaic, tilted-roof, single-crystalline silicon, retrofit, average European conditions; in €ct2000/kWh (NEEDS,2009).



	today	2025	2050
health impacts	0,12	0,10	0,07
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
sub-total	0,13	0,12	0,09
climate change - damage costs low	0,08	0,04	0,02
climate change - damage costs high	0,74	0,41	0,21
climate change - abatement costs low	0,04	0,05	0,08
climate change - abatement costs high	0,04	0,08	0,21

Table 3.9: Quantifiable external costs: concentrated solar thermal power; in €ct2000/kWh (NEEDS, 2009).



	today	2025	2050
health impacts	0,47	0,07	0,04
Biodiversity	0,02	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.
sub-total	0,50	0,08	0,04
climate change - damage costs low	0,05	0,01	0,00
climate change - damage costs high	0,62	0,09	0,03
climate change - abatement costs low	0,13	0,03	0,04
climate change - abatement costs high	0,13	0,04	0,09

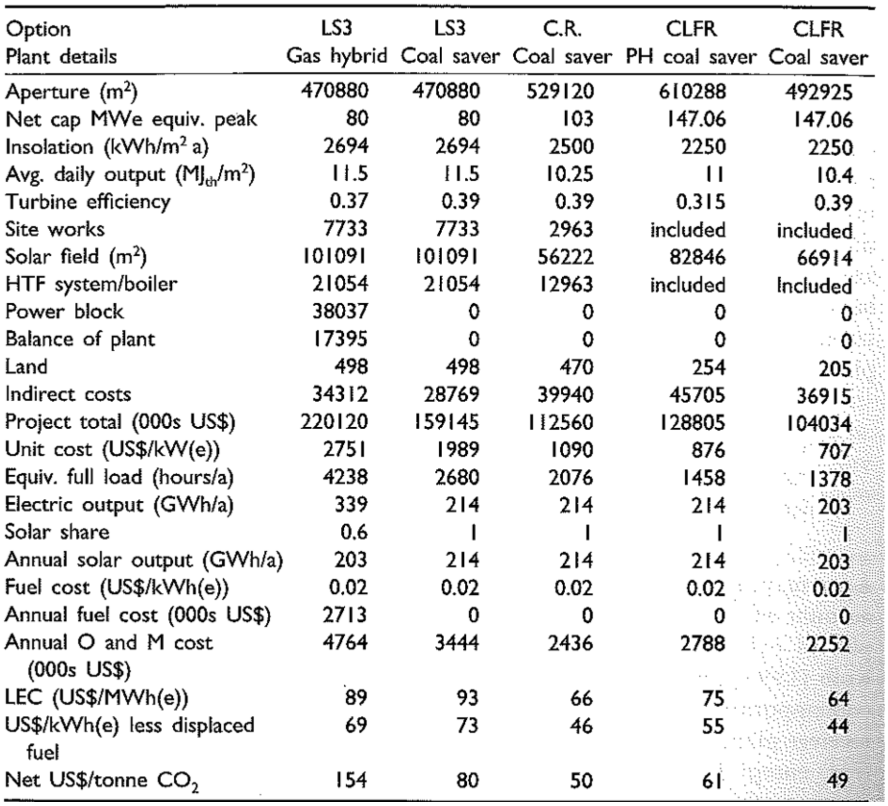
It is possible to factor environmental and social costs and benefits into an ordinary financial analysis, but this is rarely done (Gordon, 2001). A critical error is that the economics of renewable energy systems are often calculated without reference to their environmental benefits. This omission constitutes a very strong bias in favour of polluting technologies. Relying on traditional levelized-cost accounting for all aspects of energy is untenable without a wider cost/benefit analysis that includes all inputs and outputs.

Environmental benefits must ultimately be included in a rational marketplace. However, many of these benefits cannot be applied across the spectrum in different areas related to energy; this is because they tend to be location specific, and hence, sensitive to local conditions. Conventional energy generation and distribution may reap these benefits by merging with other technologies related to energy efficiency.

One approach that takes account of emissions is to estimate the cost of carbon avoidance—shown in

Table **3.10**, for example, for existing or near-term solar thermal electricity technology (taken from Kolb, 1998; Mills and Dey, 1999).

Table 3.10: Characteristics of six types of hybrid solar thermal electric plants, with their calculated emissions avoidance costs at a fuel cost of US$ 0.02 per kWh(e).



Option Plant details	LS3 Gas hybrid	LS3 Coal saver	C.R. Coal saver	CLFR PH coal saver	CLFR Coal saver
Aperture (m^2)	470880	470880	529120	610288	492925
Net cap MWe equiv. peak	80	80	103	147.06	147.06
Insolation (kWh/m^2 a)	2694	2694	2500	2250	2250
Avg. daily output (MJ_{th}/m^2)	11.5	11.5	10.25	11	10.4
Turbine efficiency	0.37	0.39	0.39	0.315	0.39
Site works	7733	7733	2963	included	included
Solar field (m^2)	101091	101091	56222	82846	66914
HTF system/boiler	21054	21054	12963	included	Included
Power block	38037	0	0	0	0
Balance of plant	17395	0	0	0	0
Land	498	498	470	254	205
Indirect costs	34312	28769	39940	45705	36915
Project total (000s US$)	220120	159145	112560	128805	104034
Unit cost (US$/kW(e))	2751	1989	1090	876	707
Equiv. full load (hours/a)	4238	2680	2076	1458	1378
Electric output (GWh/a)	339	214	214	214	203
Solar share	0.6	1	1	1	1
Annual solar output (GWh/a)	203	214	214	214	203
Fuel cost (US$/kWh(e))	0.02	0.02	0.02	0.02	0.02
Annual fuel cost (000s US$)	2713	0	0	0	0
Annual O and M cost (000s US$)	4764	3444	2436	2788	2252
LEC (US$/MWh(e))	89	93	66	75	64
US$/kWh(e) less displaced fuel	69	73	46	55	44
Net US$/tonne CO_2	154	80	50	61	49

All energy technologies have land requirements that differ quite significantly. A recent study reviewed and updated the land-transformation metric for conventional- and renewable-fuel cycles for generating electricity (Fthenakis and Kim, 2009). The study shows that the PV life cycle of power plants in the U.S. Southwest involves less disturbance of land than do conventional and other renewable-fuel cycles. Even under average U.S. solar irradiation, the land requirement of PV is less than that of coal-based fuel cycles. In contrast to the fossil- and nuclear-fuel cycles, PV does not disturb land by extracting and transporting fuel to the power plants. Furthermore, PV eliminates the necessity of reclaiming mine lands or securing additional lands for waste disposal. Accounting for secondary effects— including water contamination, change of the forest ecosystem, and accidental land contamination—makes the advantages of the PV cycle even greater than those described herein. Further investigation is needed to assess these impacts on a regional and global level.

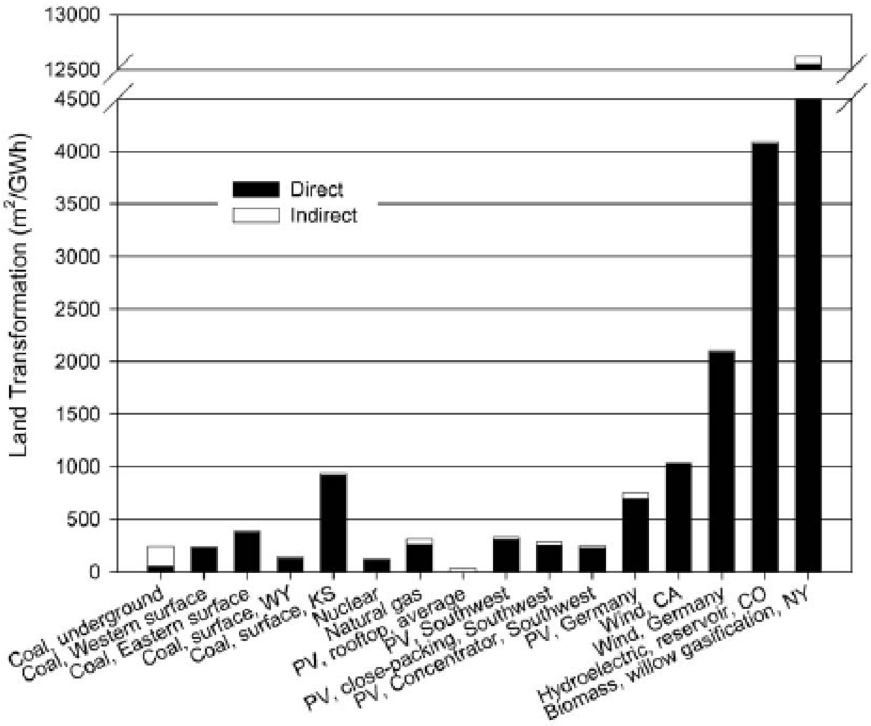


Figure 3.32: Life-cycle land transformation for fuel cycles based on 30-year timeframe (U.S. cases, unless otherwise specified). The estimates for PV are based on multicrystalline PV modules with 13% efficiency. The reference case refers to a ground-mount installation with the U.S. Southwest insolation of 2400 kWh/m^2/year, whereas the rooftop case is based on the U.S. average insolation of 1800 kWh/m^2/year. For Germany, the insolation of Brandis, 1120 kWh/m^2/year, has been used. The packing ratio of the close-packing case is 2.1, compared with 2.5 for the reference case. The estimate for wind is based on a capacity factor of 0.24 for California and 0.2 for Germany (Fthenakis *et al.,* 2009).

3.6.1.2 Passive solar technology

Higher insulation levels provide many benefits in addition to reducing heating loads and associated costs (Danny, 2006). The small rate of heat loss associated with high levels of insulation 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 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.

3.6.1.3 Active solar heat 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.

3.6.1.4 PV electricity generation

PV systems do not generate any type of solid, liquid, or gaseous by-products during the production of the electricity. Also, they do not emit noise or use non-renewable resources during operation. However, two topics need to be considered: (1) the emission of pollutants and the use of energy during the production of the PV modules, and (2) the possibility of recycling the PV module materials when the systems are decommissioned.

The energy payback time for a complete installed PV systems ranges from 0.8 to 2.7 years, taking into account its use in locations having moderate solar irradiation levels around 1,700 kWh/m^2/year (Fthenakis and Alsema, 2006). Perpiñan *et al.* (2009) show payback times of grid-connected PV systems that range from 2 to 5 years for the latitude and global irradiation ranges of geographical areas between -10^o to 10^o longitude, and 30^o to 45^o latitude. The emission of CO_2 for one PV power unity is between 40 and 180 g CO_2-eq/kWh (Fthenakis and Kim, 2007).

The PV industry uses some toxic and explosive gases, as well as corrosive liquids, in its production lines—for instance, silane, NF_3, HF, Cd, Pb, Se, Cu, Ni, and Ag. The presence and amount of those materials depend strongly on the cell type. However, the intrinsic needs of the productive 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. Predictions are that between 80% and 96% of the glass, EVA, and metals (Te, Se, and Pb) will be recycled. Other metals, such as Cd, Te, Sn, Ni, Al, and Cu, should be saved or they can be recycled by other methods.

3.6.1.5 CSP electricity generation

The environmental consequences of solar power stations vary depending on the technology. Land use is often quoted as an issue; however, the cost of land generally represents only a very minor cost proportion of the whole plant. A 100-MW CSP plant would require 2 km^2 of land. However, the land does need to be relatively flat (particularly for linear trough and Fresnel systems), near transmission lines and roads for construction traffic, and not on environmentally sensitive land. For Rankine-cycle systems, a water source for cooling is desirable; however, it is not mandatory, and dry or hybrid cooling can be used at an additional cost. Tower and dish Brayton and Stirling systems are being developed for their ability to operate efficiently without water. Although the mirror area itself is typically only about 25% to 35% of the land area occupied, the site of a solar plant will generally be arid. Thus, it is not suitable for other agricultural pursuits, which might be the case for wind farms. For this kind of system, sunny deserts close to the electricity infrastructure are needed. In California, the Mojave Desert is ideal. As CSP plant capacity is increased, the economics of longer electricity transport distances improves, and so, more distant siting could be possible. Attractive sites exist in many regions of the world, including southern Europe, northern African countries, the Middle East, Australia, China, and the southwestern USA.

However, the availability of water is a critical issue that must be addressed for large-scale CSP deployment because CSP plants require a continuous water supply for their steam generation, cooling, and cleaning of the solar mirrors. To address water limitations and environmental regulations, air cooling or a combination of wet/dry hybrid cooling can be used. However, dry cooling performs least efficiently during the summer months, when solar energy is most abundant and the plants should have the greatest output to meet the higher electricity demand (WorleyParsons, 2008).

3.6.1.6 Solar Fuels

[AUTHORS: At present, we do not have content for the environmental impact of solar fuels.]

3.6.2 Social Impacts

Solar energy has the potential to meet rising energy demands and decrease greenhouse gas emissions in the industrialized world. But in addition, 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 approximately 1.6 billion people who do not have access to electricity and the more than 2 billion people who rely on traditional biomass for home cooking and heating needs (IEA, 2002).

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, high household fuel expenditures, and pose fire and poisoning risks. One 15-W compact fluorescent light bulb supplies light output equivalent to more than 100 simple kerosene lamps (Mills, 2003). 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 microenterprise opportunities. Use of solar lighting can represent a significant cost savings to households over the lifetime of the technology compared to kerosene, and can reduce the 190 million metric tons 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 recent disaster situations to provide safety, care, and comfort to victims in the United States 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, 2003).

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). 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 (ESMAP, 2003; Brower *et al.,* 1997). Risks to women collecting fuel include injury, snake bites, landmines, and sexual violence (Manual, 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 diarrheal 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 centers.

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.

The high capital costs of solar systems are often cited as a barrier to increased deployment, and donor programs have experienced issues with fully subsidized systems falling into disrepair (Nieuwenhout *et al.,* 2000). If appropriate financing and after-sales services are offered, markets for solar home systems can develop independently of donor programs. However, market conditions vary widely, and limits of market size and purchasing power can require funds and organizational support from the government or donor agency to yield substantial dissemination of systems (van der Vleuten *et al.,* 2007). Another alternative to user-owned systems, purchased individually or with donor assistance, is ownership by an energy service company, who owns and maintains the system and sells the energy services to the customers (Martinot *et al.,* 2001, Gustavsson and Ellegard, 2004). This arrangement eliminates the need for users to provide up-front capital and increases user satisfaction through proper system maintenance.

3.7 Prospects for Technology Improvements and Innovation

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

3.7.1 Passive Solar 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 (see Table 3.11 for a general summary):

- Reduction of thermal conductance through use of dynamic exterior night insulation (night shutters)
- Use of evacuated glazing units
- Translucent glazing systems that may include materials that change solar/visible transmittance with temperature (including a possible phase change) while providing increased thermal resistance in the opaque state.

Considering cooling-load reduction in solar buildings, advances are possible in areas such as the following:

- Use of cool roof technologies involving materials with high solar reflectivity and emissivity
- More systematic use of heat dissipation techniques such as use of the ground and water as a heat sink
- Use of advanced pavements and outdoor structures to improve the microclimate around the buildings and decrease urban ambient temperatures
- Advanced solar control devices allowing penetration of daylight, but not of the thermal energy.

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 will be to maximize energy storage per unit volume/mass of material so that such materials can be integrated in lightweight wood-framed homes that are common in cold-climate areas. The challenge for such materials will be 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.

As explained in sections 3.4.1.1 and 3.4.2.1, increasingly larger window areas become possible and affordable with the recent drop in prices of highly efficient double-glazed and triple-glazed low-e argon-filled windows. These increased window areas make systematic solar-gain control essential in mild-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 motorized 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.

Anticipatory control of solar buildings based on real-time weather forecasting—usually one day ahead—will become increasingly possible and feasible with the adoption of building automation systems. For example, in the case of the Alstonvale EQuilibrium demonstration house (Candanedo and Athienitis, 2010), the room-temperature set-point can be lowered during the night when a sunny day is expected so as to allow more direct solar gains to be stored. Such control increases the effective thermal storage of a solar home and improves comfort by reducing the room-temperature peak. One-day weather prediction from agencies such as Environment Canada is now highly reliable and available through the internet to building automation systems. Advanced control systems may also optimize the operation of the passive cooling systems and techniques during the summer period. For example, the appropriate use of night ventilation may decrease the cooling needs up to 40% (Santamouris and Asimakopoulos, 1996).

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 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, active solar-gain control, HVAC system control, and hybrid ventilation at different stages of the design of a solar building. Indeed, the systematic adoption of these technologies and their optimal integration is essential as we move toward the goal of cost-effective solar buildings with net-zero annual energy consumption (IEA SHC Task 40 / ECBCS Annex 52).

Expected advances over the next 5, 10, and 15 years are summarized in Table 3.11.

Table 3.11: Possible scenarios for evolution of passive solar technologies over 15 years

Technology	5 years	10 years	15 years
Glazings and Fenestration Systems	Double low-e argon glazings become dominant in mild-moderate and cold climates Triple-glazed windows start becoming more common in cold climates Window areas on equatorial facades start approaching 30%–50% of façade area	New technologies such as electrochromic coatings and transparent photovoltaics begin to be widely introduced in window products	Widespread and systematic design of fenestration systems as the basis for achieving energy-positive buildings
Daylighting and Solar-Gain Control Systems	Motorized shading and its automatic control begins to be introduced on a broad scale in office buildings and solar homes New louver and glazing designs to optimize daylight transmission at	Active solar-gain control begins to become coordinated with HVAC and lighting control widely	Daylighting and solar-gain control systems become highly marketable building features as essentials of a high-quality indoor environment, particularly systems that are highly tunable to occupant needs and

	specific solar-angle ranges		preferences
Building-Integrated Thermal Storage	Thermal mass that can be used in both passive and active mode (e.g., with hollow cores) begins to become more common Phase-change materials in plaster becomes more common in cold climates	Control strategy (e.g., night setback of room temperature and predictive control) are considered at the design stage when thermal mass is sized	
Integration of Passive Solar Technologies with Whole-Building Systems	Integrated thermal-daylighting design of office buildings Design of buildings both for optimizing direct gains in winter and reducing cooling loads in summer through natural or hybrid ventilation Use of cool roof coatings to reduce cooling loads	Integrated thermal-structural design of buildings (e.g., concrete buildings) becomes widely influenced by passive solar design and night cooling	Passive design becomes fully integrated with the energy design, architectural design, and operation of the building; architecture and engineering programs evolve to reflect this change

3.7.2 Active Solar Heat and Cooling

The vision of the European Solar Thermal Technology Platform (ESTTP, 2006) is to establish the "Active Solar Building" as a standard for new buildings by 2030, where an Active Solar Building covers 100% of its demand for heating (and cooling, if any) with solar energy.

For existing buildings, ESTTP fosters the Active Solar Renovation, achieving massive reductions in energy consumption through energy-efficiency measures and passive solar energy. The goal is also to cover substantially more than 50% of the remaining heating and/or cooling demands with active solar energy.

Heat storage represents a key technological challenge, because the wide deployment of Active Solar Buildings largely depends on developing cost-effective and practical solutions for seasonal heat storage. The ESTTP 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.

In the future, active solar systems—such as thermal collectors, PV panels, and photovoltaic-thermal (PVT) systems—will be the obvious components of roof and façades. And they 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 the thermal energy storage through the application of advanced materials (e.g., phase-change materials). One central control system will lead to optimal regulation of the whole heating, ventilation, and air-conditioning (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 heating for industrial processes (SHIP) is currently at a very early stage of development. Worldwide, less than a hundred operating solar thermal systems for process heat are reported, with a total capacity of about 24 MW_{th} (34,000 m^2). Most systems are experimental and relatively small scale. However, great 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.

In the short term, SHIP will mainly be used for low-temperature processes, ranging from 20° 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 a published study (Werner, 2006), about 30% of the total industrial heat demand is required at temperatures below 100°C, which could theoretically be met with SHIP using current technologies. And 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 potential would provide a significant solar contribution to industrial energy requirements. Substantial potential 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 radiation and high conventional energy costs.

Currently, about 9% of the total heating needs in Europe are covered by block and district heating systems. This share is much higher in a number of countries, especially Eastern Europe and Scandinavia. The prevalence of Scandinavian countries is surprising, because solar radiation is lower in this region than in Southern Europe. Within district heating systems, solar thermal energy can be produced on a large scale and with particularly low specific costs, even at high latitudes, such as in Sweden and Denmark. Only a very minor share (less than 1%) of the solar thermal market in Europe is linked to district heating systems, but these systems make the most of large-scale solar heating plants.

3.7.3 PV Electricity Generation

This subsection discusses photovoltaic technology improvements and innovation within the areas of solar PV cells as well as the entire PV system.

3.7.3.1 Solar PV cells

In the Strategic Research Agenda for Photovoltaic Solar Energy Technology (EU PV Technology Platform, 2007), future technologies are categorized into Emerging and Novel technologies. “Emerging” technologies have passed a proof-of-concept phase or can be considered as mid-term options for the two established solar cell technologies—crystalline Si and thin-film solar cells. These emerging concepts are based on extremely low-cost materials and processes, and include technologies such as dye-sensitized solar cells and organic solar cells. The main development challenge for organic cells is achieving a sufficiently high (intrinsic and extrinsic) stability in combination with a reasonable efficiency—where "sufficient" varies with the application. Therefore, the application of organic cells for power generation may be reached in the longer term, whereas commodity applications and niche markets are expected in the early stage. "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 technologies include various applications of hybrid cells, quantum dots (QDs), and plasmonic solar cells. In this subsection, only the "Novel" solar cells are surveyed as a future technology.

3.7.3.1.1 Hybrid solar cells

These cells combine nanostructures of both organic and inorganic materials, resulting in the unique properties of inorganic semiconductor nanoparticles with organic/polymeric materials (Arici et al., 2003). In addition, low-cost synthesis, processability, and versatile manufacturing of thin-film devices make them attractive (Sariciftci et al., 1992; Yu et al., 1995]. Inorganic semiconductor nanoparticles may also have high absorption coefficients and particle-size-induced tunability of the optical bandgap. Photovoltaic devices of 7- to 60-nm elongated CdSe nanocrystals and regioregular poly(3-hexylthiophene) (P3HT) composite have been reported (Huynh et al., 2002) with a power conversion efficiency of 1.7% under simulated AM1.5 illumination.

3.7.3.1.2 Quantum dots

These solar cells have the potential to increase the maximum attainable thermodynamic conversion efficiency of solar photon conversion by up to about 66%. This boost is due to quantum mechanical effects in nanometer-size semiconductors, where strong correlation between electron-hole pairs is more significant than in bulk semiconductors. QD solar cells include several possibilities, such as multiple-exciton generation and intermediate-band solar cells. Metal chalcogenide semiconductors such as CdS (Huynh et al., 1999; Wijayantha et al., 2004; Baker and Kamat, 2009), CdSe (Chen et al., 2006), PbS (Robel et al., 2006; Plass et al., 2002), and PbSe (Hoyer and Koenenkamp, 1995) have received considerable attention for QD application. When the sizes of these materials are decreased down to the QD region, the quantum confinement effect makes it possible to generate multiple electron-hole pairs per photon through the impact ionization effect (Schaller and Klimov, 2004). The intermediate-band solar cell (Luque 1997) uses two photon absorptions—one of which is expected to be low-energy photons that allow electrons confined in the mini-band formed in the coupled QDs to escape into the mobile states, resulting in the use of a wide range of the solar spectrum and thus, high efficiency. InGaAs quantum dots embedded in a GaAs matrix have given evidence of lower-energy absorption (Okada, 2008). Although the expected efficiency is very high (more than 40%), the current efficiency status is lower than for conventional solar cells, and it will take time for the higher efficiencies of these new concepts to be realized.

3.7.3.1.3 Plasmonic solar cells

A surface plasmon can be described as a combination of the collective oscillations of electrons in the conduction band of metals and electromagnetic fields. They occur at the interfaces between metals and a dielectric. When a surface plasmon is excited, electromagnetic fields of light are enhanced. Surface plasmons have been proposed as a means to increase the photoconversion efficiency in solar cells by: (1) shifting energy in the incoming spectrum toward the wavelength region where the collection efficiency is maximal, or (2) increasing the absorbance by enhancing the local field intensity. This technology could be beneficial for organic solar cells and dye-sensitized solar cells, where the light absorption predominantly occurs in a very thin layer in the interfacial region.

3.7.3.2 PV system technologies

A PV system is composed of the PV module, as well as the balance of system, which includes storage, system utilization, and the energy network. The system must be reliable, cost effective, attractive, and mesh with the electric grid in the future (EU PV Technology Platform, 2007; New Energy and Industrial Technology Development Organization, 2009; U.S. Photovoltaic Industry Roadmap Steering Committee, 2001; U.S. Department of Energy, 2008; Kroposki, 2008; Navigant Consulting Inc., 2006).

Table **3.12** summarizes the PV system development needed over the next 20 years.

At the component level, a major objective of balance-of-system (BOS) development is to extend the lifetime of BOS components for grid-connected applications to that of the modules, typically 20 to 30 years. The highest priority is given to developing inverters, storage devices, and new designs for specific applications such as building-integrated PV. For systems installed in isolated, off-grid areas, 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); in addition, approaches are needed for integrating the storage component into the module, thus providing a single streamlined product that is easy to use in off-grid and remote applications. Moreover, devices for storing large amounts of electricity (over 1 MWh) 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 assure 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 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 such as the Smart Grid. Furthermore, very-large-scale PV (VLS-PV) systems will be required that have capacities ranging from several megawatts to gigawatts, and practical project proposals need to be developed for implementing VLS-PV systems in desert regions (Komoto, 2009). In the long term, VLS-PV will play an important role in the worldwide energy network (Water and Climate Security, 2007).

1 **Table 3.12:** Development of PV system technologies over the next 20 years.

Technology	5 years	10 years	Over 20 years
Components and System Use	Increased inverter reliability and lifetime to achieve (over 20 years) Low-cost electronic components through the application on new designs strategies and new semiconductors (e.g., SiC, GaN). Low-cost support structures, cabling, and electrical connections for grid-connected PV systems. PV inverters optimized for new PV module technologies. Standardizing system components to facilitate economies of scale in manufacture and simplify replacement. Component development for minimizing system losses (e.g., modules with tolerance to partial shading, modules for operation at high DC voltage). Low-cost control and monitoring of system output, including using appropriate measurement protocols. Tools for early fault detection. Prefabricated ready-to-install units, particularly for large grid-connected	Increased inverter reliability and lifetime to achieve (over 30 years) New concept such as AC PV modules with integrated inverters that can be produced in very high numbers at low cost, advanced modules for BIPV applications, and multi-functional, self-cleaning, construction elements, new design solutions. Strategies for centralized system monitoring (e.g., Web-based). Updating fault detection tools for advanced system designs. Development of new function for stability and control of electrical grids at high PV penetrations. Billing and metering schemes for PV in off-grid PV systems.	Modules with integrated storage, providing extended service lifetimes (over 40 years).

	systems Adaptation of battery management systems for new generations of batteries, and highly reliable, low-maintenance components for off-grid systems.		
Network & Storage	Computer programmers to forecast output, and validation of forecast algorithms. Assessment of long-term average local radiation potentials and forecasts of solar irradiation. Assessment of value of PV electricity, including for meeting peak demand, and as an uninterruptible power supply when combined with a storage device.	PV system output energy forecasting method for future energy network. Interaction of PV with other decentralized generation. Development of power electronics and control strategies for improving the quality of grid electricity at high PV penetration. Management of island micrograms with high share of PV generators. Development of efficient incentive management for PV systems.	Development of technologies for high-capacity storage (>1 MWh) and alternative storage technologies. Development of technologies for very-large-scale system.
Standards and Quality Assurance Socio-Economic Aspects and Enabling Research	Performance, energy rating, qualification and safety standards for PV modules, PV building elements, concentrator systems incl. trackers and PV inverters/AC modules. In-line process and production control techniques and procedures. Guidelines for specifications and quality assurance of materials, wafers and cells, modules, components for concentrator systems and	Guidelines for production equipment. Develop further in-line process and production control techniques and procedures. Improve certification schemes, in particular for system Recycling processes (new components) and economic and logistical aspects of PV module and component reuse and recycling.	

	BOS components. Recycling processes.	Public awareness and information dissemination schemes relating to large-scale deployment of PV technology	

3.7.4 CSP Electricity Generation

CSP is a proven technology at the utility scale. The longevity of components has been established over two decades; operation and maintenance (O&M) aspects are understood; and there is enough operational experience to have enabled O&M cost-reduction studies to not only 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, 2003) have concluded that cost reductions will come from technology improvement, economies of scale, and mass production. Other needed innovations related to systems, power cycles, and collectors are discussed below.

3.7.4.1 Beam-Down solar concentration system

The Solar Concentration Off-Tower (SCOT), also called the Reflective Tower or Beam-Down optical configuration, was first proposed by WIS (Israel). A hyperboloid reflector is installed at the tower top, redirecting the concentrated solar radiation toward a lower focal region near ground level. The Beam-Down concept is attractive because the heavy receiver may be placed on or near the ground; furthermore, the heating medium does not need to be pumped to the top of the tower.

However, the Beam-Down system has some technological difficulties, such as the mechanical integrity of the central reflector against the wind force, and a wider focus due to the dilution of the beam concentration at the receiver aperture. To solve these problems, multi-ring reflector technology has been proposed.

Some temperature ejection system is needed for the central reflector, because the reflector is irradiated by middle-level flux (100 kW/m^2) of a slightly concentrated solar beam from the heliostat field. A heat-resistant-type reflector should be developed.

3.7.4.2 Power cycles

CSP is a technology driven 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. Although CSP works with turbine cycles of 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 of around 37%, leading to design-point solar-to-electric efficiencies on 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 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 limits of these fluids (around 600°C for present molten salts) for advanced steam-turbine cycles, 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 (see Sec. 3.9.4).

3.7.4.3 Collectors

The objective for collectors 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. Capital 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 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 may be found in ECOstar, a report by DLR et al. (2005). Table 3.13 summarizes key developments for CSP technologies needed over the next 20 years.

Table 3.13: Development of CSP technologies over the next 20 years.

Technology	5 years	10 years	20 years
Trough	Continued rollout of existing trough technology providing much of the critical mass for the CSP industry. Improved selective surfaces. Improved heat-transfer fluids. Storage enables peak and intermediate-load dispatchability.	Very-large-capacity plants become the norm. Fluids and processes developed to reduce need for heat exchangers and multiple tank storage. Longer-term storage becomes cheaper and mandatory. High-temperature selective surfaces suitable for operation in air.	Opportunities for continued improvements in trough efficiency are minimal and cost reductions are mainly through economies of scale and mass production. The scale of the CSP industry affords development of improved steam turbines specifically for solar operation.

Linear Fresnel	First commercial plants in operation. Applied engineering to reduce costs. Improved inverted cavity designs developed.	Larger plants under deployment. Mass production of Fresnel reflector segments begins to occur and costs fall. Advanced secondary reflectors in receivers allow higher operating temperatures.	
Central Receiver	Higher-temperature steam operation in commercial plants. Larger plants installed and operational. Investigation of optimal heliostat size revisited as higher temperatures sought. Commercial-scale molten-salt towers demonstrated. Tower Brayton and tower thermochemical systems demonstrated.	Multiple solar towers now in operation based on steam or molten salt, with storage. Move to commercial-scale tower Brayton on back of high-temperature receiver development. Use of towers for first commercial-scale thermochemical systems.	Anticipate tower installation rate now outstripping troughs as benefits of higher temperatures realised.
Dish	Dish/Stirling reliability questions overcome as hours continue to be logged on multiple dish installations. First commercial-scale dish/Stirling farms. Demonstration of dish Brayton and dish thermochemical. Larger dishes deployed and economics better understood.	Commercial farms of dish-powered heat engines now under deployment.	

3.7.5 Solar Fuels Conversion

Solar-driven fuel processing methods include thermal decomposition, thermochemical, photochemical, electrochemical (solar electrolysis using PV or CSP), biochemical, and hybrid reactions.

Solar electrolysis using PV or CSP is nearly feasible commercially, but production costs are still 1.5 to 2 times oil at US$100/bbl. For solar electrolysis, the photoelectrochemical (PEC) cell is the future technology innovation. The solar thermochemical cycles of a metal-oxide-based cycle, the hybrid-sulfur cycle, and the solar electrolysis of water are the promising processes for future "clean" hydrogen mass production. Other candidates as future technology innovation for solar fuel conversion are producing biofuels from modified photosynthetic microorganisms, and developing chemical solar cells for fuel production. Both approaches have the potential to provide fuels with solar energy conversion efficiencies much better than those based on field crops. Artificial solar-driven fuel production will require biomimetic nanotechnology, where scientists must develop a series of fundamental and technological advanced multi-electron redox catalysts coupled to photochemical elements.

3.7.5.1 Solar thermochemical cycles of metal-oxide-based cycle

A number of solar reactors applicable to solar thermochemical cycles of a metal-oxide-based cycle have been developed, including:

- Solar reactor by HYDROSOL I and II EU projects,
- Solar reactor for ZnO/Zn process,
- Tokyo Tech rotary-type solar reactor, and
- Counter-Rotating-Ring Receiver/Reactor/Recuperator (CR5).

3.7.5.2 Solar thermochemical cycle of hybrid-sulfur cycle

The hybrid-sulfur cycle is a two-step water-splitting process. It uses an electrochemical, instead of a thermochemical, reaction for one of the two steps (hybrid thermochemical cycle). Sulfur 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 reaction 2.

3.7.5.3 Solar-powered production of molecular hydrogen from water

Electrochemical water splitting powered by conventional electricity or PV arrays produces molecular hydrogen at the cathode, while organic-compound oxidation under mild conditions occurs at the anode in competition with the production of oxygen.

3.7.5.4 Hydrogen production from water using a photoelectrochemical cell

The radiation needs to be converted into a suitable form of energy. Solar radiation can be converted into chemical energy such as H_2 by a photoelectrochemical cell. A PEC cell is fabricated using an electrode absorbing the solar light, two catalytic films, and a membrane separating H_2 and O_2.

3.7.5.5 Biomimetic photosynthetic technologies

SOLAR-H2 integrates two frontline research topics: artificial photosynthesis in man-made biomimetic systems, and photobiological H_2 production in living organisms. H_2 production by these methods on a relevant scale is still distant, but has vast potential. The scientific risk is high and the research is very demanding. Thus, the overall objective is to explore, integrate, and provide the basic science needed to develop these novel routes and advance them toward new horizons.

3.7.6 Other Potential Future Applications

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 (Glaser, 1968). NASA and the U.S Department of Energy 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 gigawatts 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 photovoltaic cells, highly efficient solid-state microwave power electronics, and lower-cost space launch vehicles.

3.8 Cost Trends

This section provides cost trends for the five direct solar technology areas.

3.8.1 Passive Solar Technologies

The discussion in this subsection is covered under the areas of heating and daylighting.

3.8.1.1 Heating

High-performance building envelopes entail greater up-front construction costs, but lower energy-related costs during the lifetime of the building (Danny, 2006). The total up-front 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 up-front cost will be compensated for to some extent by reduced energy costs over the lifetime of the building.

Figure 3.33 compares differences in the life-cycle costs when additional heating costs are computed for each level of insulation relative to the highest level of insulation considered. Although the specific incremental construction costs that should be used in any given location will differ from those used in Figure 3.33, there is very little difference in the life-cycle cost if insulation levels moderately worse or moderately better than the least-cost level are chosen. Although the life-cycle cost associated with the highest insulation level is not the smallest life-cycle cost, it is not substantially greater than the minimum life-cycle cost when the fuel cost is 15 USD/GJ or 20 USD/GJ, and is less than the life-cycle cost at low levels of insulation.

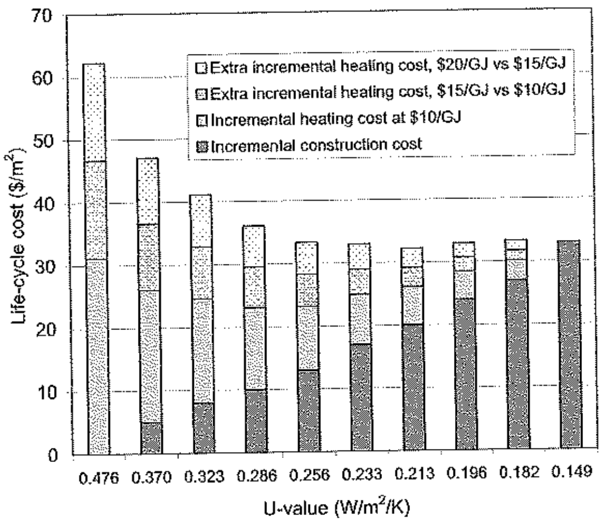


Figure 3.33: Comparison of incremental life-cycle costs of walls with increasing amounts of insulation.

Differences in life-cycle costs are influenced by the length of time over which life-cycle costs are computed and by the rate of inflation in energy costs. A 30-year timeframe was chosen in Figure 3.33 because mortgages in North America are typically of this duration. However, much longer mortgages are common in Europe, and in any case, the lifespan of the building should be closer to 100 years. Figure 3.34 compares the incremental life-cycle costs for different levels of insulation for 30- and 100-year life spans; the highest insulation level provides the lowest or close to the lowest life-cycle cost.

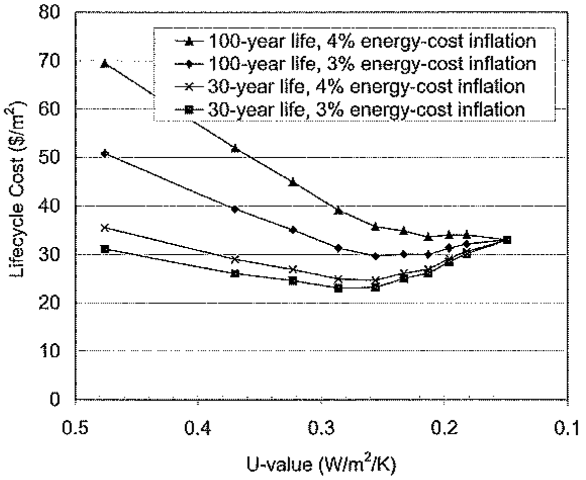


Figure 3.34: Comparison of incremental life-cycle costs of walls with increasing amounts of insulation for 30- and 100-year life spans.

The main conclusion of these figures is that it is justified to require insulation levels substantially in excess of the level that is calculated to minimize life-cycle cost (Danny, 2006).

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. 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 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, it is indeed possible for savings in the cost of mechanical systems to offset all or much of the additional cost of the high-performance envelope.

For example, Davis Energy Group was challenged as part of the Pacific Gas and Electric's Advanced Customer Technology Test to improve an initial design for a house that already met California's strict Title 24 energy code. A long list of small improvements—including efficient appliances, thicker insulation, and better windows—eliminated any need for the $2,050 furnace and its associated ducts and equipment. The designers had set up a package of potential energy-savings measures that were not cost effective from just their energy savings, even though they each reduced cooling loads. These measures included superwindows to block summer heat and ceramic tile to store "coolth" in the house for use during daily heat peaks. Seven such measures cost $2,600; but from a whole system perspective, they eliminated the last $1,500 worth of air conditioner and $800 of its future upkeep costs, which almost fully made up for the cost of the measures. This example emphasizes the point that even though individual efficiency measures may have large costs, counting their energy and capital-cost savings can turn them into attractive investments. The Davis Energy Group house proved very comfortable, even in a severe hot spell (Rocky Mountain Institute, 2004).

3.8.1.2 Daylighting

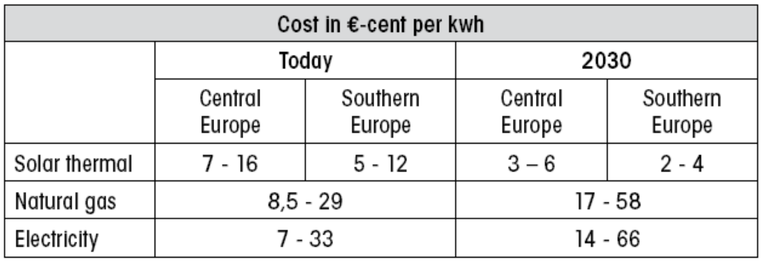
The economic benefit of daylighting is enhanced by the fact that it reduces electricity demand the most when the sunlight is strongest. This is also when the daily peak in electricity demand tends to occur (Danny, 2006). Several authors report measurements and simulations with annual electricity savings from 50% to 80%, depending on the hours and the location. Daylighting can lead to a reduction in cooling loads if solar heat gain is managed (Duffie and Beckman, 1991). 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.

3.8.2 Active Solar Heat and Cooling

Solar processes are generally characterized by high first cost and low operating costs (Duffie and Beckman, 1991). Most solar energy processes require an auxiliary (i.e., conventional) energy source, so that the system includes both solar and conventional equipment and the annual loads are met by a combination of the energy sources.

Table 3.14 shows a range of prices for heat generated by a solar thermal system, compared to the current price of gas and electricity for the end user, and the price projected for 2030. Inflation is not considered according to the European Solar Thermal Technology Platform, "Solar Heating and Cooling for a Sustainable Energy Future in Europe."

Table 3.14: Cost per kWh for solar thermal, gas, and electricity - today and 2030.



Cost in €-cent per kwh				
	Today		2030	
	Central Europe	Southern Europe	Central Europe	Southern Europe
Solar thermal	7 - 16	5 - 12	3 – 6	2 - 4
Natural gas	8,5 - 29		17 - 58	
Electricity	7 - 33		14 - 66	

The costs of solar heat include all taxes, installation, and maintenance. The range of costs is wide because the total costs vary greatly, depending on factors such as the following:

- Quality of products and installation,
- Ease of installation,
- Available solar radiation (e.g., latitude, number of sunny hours, orientation and tilt of the collectors),
- Ambient temperature, and
- Use patterns determining the heat load.

By 2030, technological progress and economies of scale are assumed to lead to about a 60% reduction in costs (Figure 3.35).

Although important cost reductions in solar thermal energy can be achieved through R&D and economies of scale,

Table 3.14 shows why ESTTP's priority is to enable the large-scale use of solar thermal energy by developing a mass market of new applications, such as Active Solar Buildings, solar cooling, process heat, and desalination.

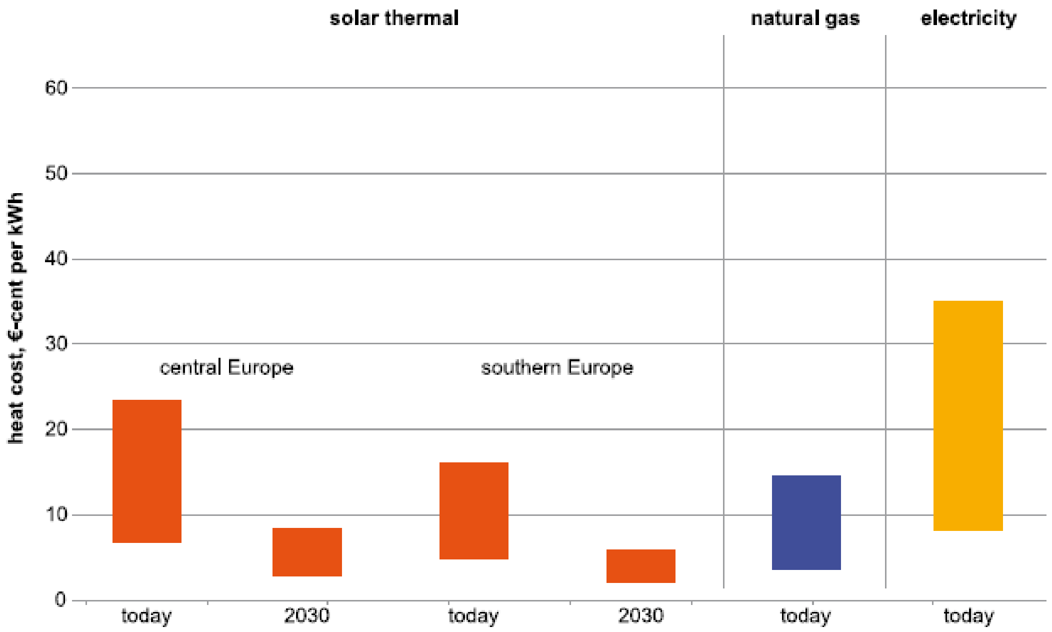


Figure 3.35: Range of costs for solar and other technologies—today and 2030 (ESTIF, 2009).

Over the last decade, for each 50% increase in installed capacity of solar water heaters, investment costs have fallen 20%. In particular, combination systems have benefited from these cost reductions and have increased their market share. Further research, development, and demonstration (RD&D) investment can help to further drive down these costs. Cost reductions are expected to stem from the following: direct building integration (façade and roof) of collectors; improved manufacturing processes; and new advanced materials, such as polymers for collectors.

Furthermore, potential for cost reduction can be seen by the mass production of standardized (i.e., kit) systems, which reduce the need for on-site installation and maintenance work (Figure 3.36).

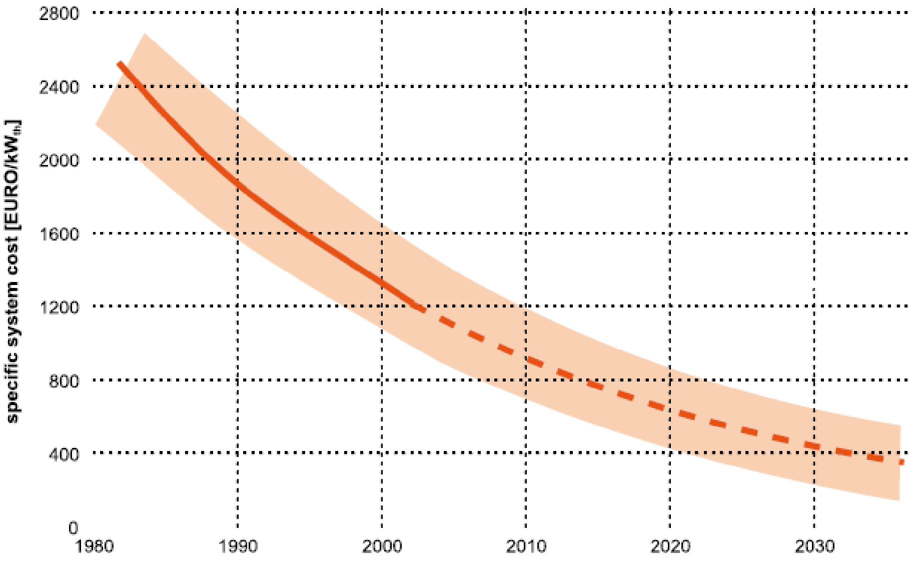


Figure 3.36: Costs of small solar thermal systems, past and projected to 2030 (Institut für Thermodynamik und Wärmetechnik (ITW), University of Stuttgart).

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 can be achieved if R&D efforts are increased over the next few years.

Henning (2004) indicates the following costs for solar collectors, support structures, and piping (excluding storage systems, heat exchangers, and pumps):

- Solar-air collectors, 200 to 400 €/m^2
- Flat-plate or stationary compound parabolic collectors, 200 to 500 €/m^2
- Evacuated-tube collectors, 450 to 1,200 €/m^2

Table **3.15** gives illustrative costs of solar thermal energy, and

Table **3.16** summarizes cost and performance data for a variety of solar thermal systems in Germany.

Table 3.15: Illustrative costs of solar thermal energy.

System cost ($/m² or €/m²)	System efficiency	Cost of thermal energy (cents or eurocents/kWh)								
		1100kWh/m²/year			1650kWh/m²/year			2200kWh/m²/year		
		interest rate			interest rate			interest rate		
		0.04	0.06	0.08	0.04	0.06	0.08	0.04	0.06	0.08
400	0.2	17.1	19.7	22.5	11.4	13.1	15.0	8.5	9.8	11.2
	0.4	8.5	9.8	11.2	5.7	6.6	7.5	4.3	4.9	5.6
	0.6	5.7	6.6	7.5	3.8	4.4	5.0	2.8	3.3	3.7
800	0.2	34.2	39.4	45.0	22.8	26.2	30.0	17.1	19.7	22.5
	0.4	17.1	19.7	22.5	11.4	13.1	15.0	8.5	9.8	11.2
	0.6	11.4	13.1	15.0	7.6	8.7	10.0	5.7	6.6	7.5
1200	0.2	51.3	59.0	67.5	34.2	39.4	45.0	25.6	29.5	33.7
	0.4	25.6	29.5	33.7	17.1	19.7	22.5	12.8	14.8	16.9
	0.6	17.1	19.7	22.5	11.4	13.1	15.0	8.5	9.8	11.2

Table 3.16: System costs, cost of heat, solar utilization, and solar fraction for solar thermal DHW or space heating systems in Germany.

System	Collector area (m²)	System cost (€ per m² of collector)	Cost of heat (€/kWh)	Solar utilization	Solar fraction
Small DHW	4-5	800-1300	0.13-0.62	40-20%	50-80%
Large DHW	100-1600	400-900	0.09-0.23	55-25%	20-60%
Combisystem, diurnal storage	15		0.40-0.50	25-18%	20-50%
Combisystem, seasonal storage	20-80	900-1900		23-12%	70-100%
District heat, no seasonal storage	100-1000	400-500	0.10-0.13		7-10%
District heat, with seasonal storage	3000-6000 (540-6000)	620-800	0.18-0.30 (0.16-0.42)	25-28%	50% (30-62%)

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.

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 (Danny, 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.

3.8.3 PV Electricity Generation

PV prices decreased dramatically over the last 30 years—the average global PV module prices dropped from about 22 USD/W in 1980 to the current level of less than 4 USD/W. From 1990 to 2008, the average global price of PV modules used for power applications (modules > 75 W) dropped from 9.32 to 3.65 USD/W (2008 USD). The PV module learning curve in Figure 3.37 indicates a progress ratio of 80%, and consequently, a learning rate of 20%, which means that the price is reduced by 20% for each doubling of cumulative sales (Surek, 2005).

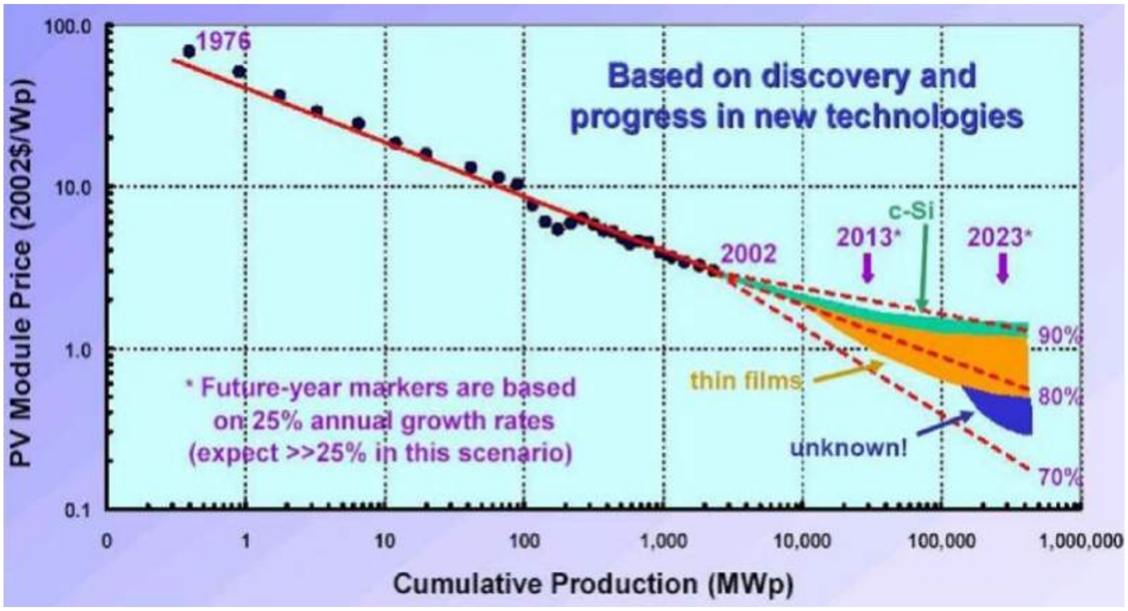


Figure 3.37: Learning curve for PV modules (Surek, 2005).

Figure 3.38 depicts the increase in production from 1990 through 2008, showing regional contributions. Even more dramatically, as module prices have decreased, production has increased and market penetration has increased.

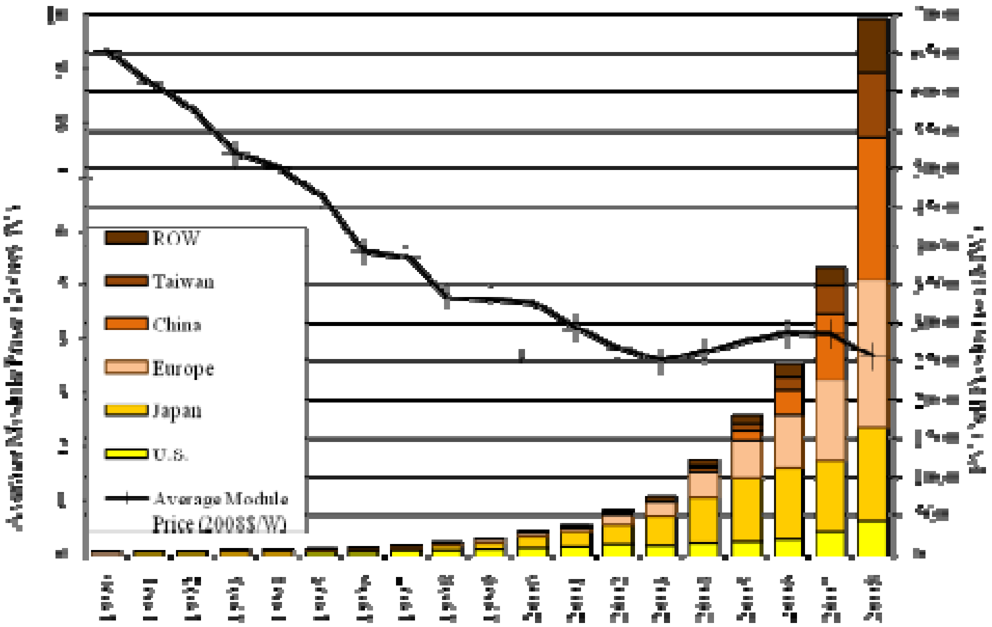


Figure 3.38: PV module prices have fallen as PV cell production has increased (Navigant Consulting Inc. 2008, PV News 1993, 2001, 2006, 2008, 2009). Production data: Prometheus Institute and Greentech Media, PV News:. Module price data: Navigant Consulting, April 2008.

PV module manufacturing costs are projected to continue to drop and are expected to be at or below 1.50 USD/W for all major technologies by 2015 (Table 3.17). Both thin-film and crystalline silicon technologies have numerous pathways for realizing continued technological innovation and cost

Table 3.17: Module manufacturing costs and price forecast per peak watt in 2008 US$ (Greentech, 2009).

Technology	2008	2010	2012	2015
Crystalline Silicon				
Global vertically integrated multicrystalline silicon (mc-Si)	2.12 / 3.43	1.87 / 2.41	1.66 / 2.02	1.43 / 1.71
European mc-Si	2.74 / 3.43	2.17 / 2.41	1.81 / 2.02	1.54 / 1.71
Asian mc-Si	3.11 / 3.43	2.08 / 2.41	1.60 / 2.02	1.33 / 1.71
Supermono c-Si	2.24 / 3.83	1.89 / 2.89	1.65 / 2.47	1.41 / 2.03
Thin Films				
Amorphous silicon (a-Si)	1.80 / 3.00	1.45 / 1.79	1.21 / 1.47	1.02 / 1.33
Copper indium gallium diselenide (CIS/CIGS)	1.26 / 2.81	0.98 / 2.19	0.89 / 1.77	0.80 / 1.51
Cadmium telluride (CdTe)	1.25 / 2.51	1.13 / 2.10	1.00 / 1.72	0.89 / 1.48

reductions. In addition, third-generation technologies could come into the market in the longer term at even lower cost/price levels.

The average installed cost of PV systems has also decreased significantly over the past couple of decades and is projected to continue decreasing rapidly as PV technology and markets mature. For example, Wiser et al. (2009) studied some 37,000 grid-connected, customer-sited PV projects in the United States, representing 363 MW of capacity. They found that the capacity-weighted average costs of PV systems installed in the USA declined from 10.5 USD/W in 1998 to 7.6 USD/W in 2007. This decline was primarily attributable to a drop in non-module (BOS) costs.

Figure 3.39 compares average installed costs in Japan (5.9 USD/W), Germany (6.6 USD/W), and the USA (7.9 USD/W) for residential PV systems completed in 2007. The lower costs in Japan and Germany can be attributed to their larger, more mature markets with lower non-R&D market barriers, including factors such as improved distribution channels, installation practices, interconnection, siting, and permitting.

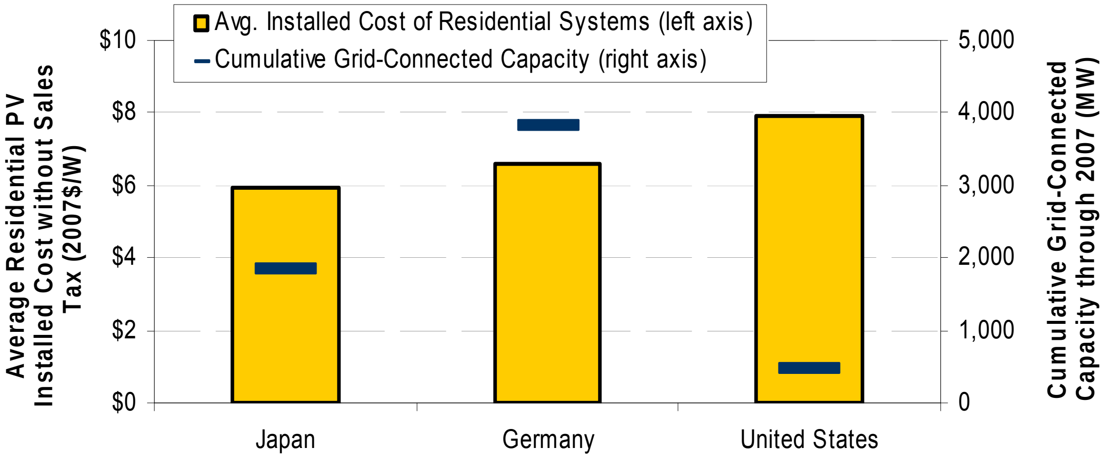


Figure 3.39: Average installed cost of residential PV systems completed in 2007, in Japan, Germany, and the USA (Wiser et al., 2009).

Since the second half of 2008, PV system prices have decreased considerably. This decrease is due to the increased competition between PV companies because of huge increases in production capacity and production overcapacities. The fourth-quarter 2009 average PV system price in Germany dropped to 3,125 €/kWp (2005 US $: 3,618 $/kWp) (Bundesverband Solarwirtschaft, 2009). In 2009, thin-film projects were realized as low as 2.72 $/Wp (2005 US $; 3 $/Wp in 2009 $) (New Energy Finance, 2009). The resulting levelized cost of energy (LCOE) varied between 0.145 and 0.363 $/Wp (0.16 and 0.40 $/Wp in 2009 $).

The goal of the U.S. Department of Energy (DOE) Solar Energy Technology Program expressed in its Technology Plan is to make PV-generated electricity cost-competitive with conventional energy sources in the USA by 2015. Specific energy cost targets for various market sectors are 0.08 to 0.10 USD/kWh for residential, 0.06 to 0.08 USD/kWh for commercial, and 0.05 to 0.07 USD/kWh for utilities.

Funding of PV R&D over the past decades has supported innovation and gains in PV cell quality, efficiencies, and price. Public budgets for R&D programs in the IEA Photovoltaic Power Systems Programme countries collectively reached about 330 million USD, with the USA, Germany, and Japan contributing 138, 61, and 39 million USD, respectively (IEA PVPS, 2008).

3.8.4 CSP Electricity Generation

Solar thermal electricity systems are a complex technology operating in a complex resource and financial environment, so many factors affect life-cycle cost calculations (Gordon, 2001). A study for the World Bank (World Bank GEF, 2006) suggested four phases in cost reduction for CSP technology and that cost competitiveness with fossil fuel could be reached by 2025.

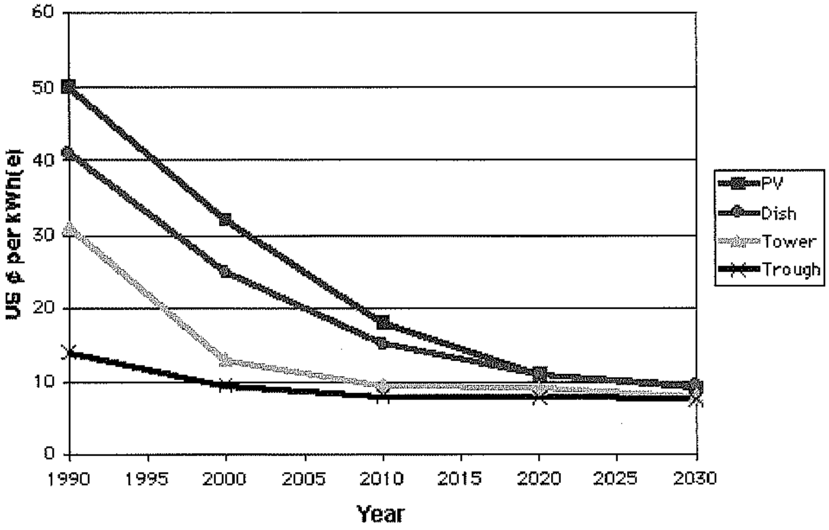


Figure 3.40: Energy cost (in U.S. cents per kWh) for PV and three CSP technologies from 1990 to 2030.

Currently, the average cost for installing a CSP plant is roughly 4 million USD/MW. For example, the total investment for the 354-MW Solar Electric Generating Station plant in California (installed from 1985 to 1991) was 1.25 billion USD (nominal, not adjusted for inflation). For the 64-MW Nevada Solar One plant installed in 2007, construction and associated costs amounted to 260 million USD.

Project costs in Europe are around 4.62 $/W (2005 $) (4.0 2008 €/W), but can reach 16.16 $/W (2005 $) (14 €/W; 2008 €) depending on the total storage capacity and the type of fossil back-up. Average LCOE values in 2009 were 0.254 to 0.346 $/W (0.22 to 0.30 €/kWh) (New Energy Finance 2009).

The U.S. DOE CSP initiative that funds R&D projects with U.S. companies is focusing on thermal storage, trough component manufacturing, and advanced CSP systems and components (US Department of Energy, 2008). The projects are expected to reduce today's 0.12 to 0.14 USD/kWh energy costs to 0.07 to 0.10 USD /kWh by 2015 and to less than 0.07 USD/kWh with 12 to 17 hours of storage by 2020. The European Union is pursuing similar goals through a comprehensive RD&D program.

3.8.5 Solar Fuels Conversion

A long-sought goal of energy research has been to find a method to produce hydrogen economically by splitting water using sunlight as the source of energy. Approaches to carry out this kind of solar fuels conversion range from well-established chemical engineering practices with near-term predictable costs, to long-term basic photochemical processes, the details of which are still speculative. Thus, the goal remains elusive because near-term systems tend to have high costs, while the costs of advanced long-term systems are not well defined.

Molecules are more convenient to transport over long distances than electrons, and a smooth transition to a carbon-neutral transport sector without the need to change the existing infrastructure is most easily achieved. In this sense, solar hybrid fuels such as methanol, DME, and synthetic oil are commercially feasible compared to solar hydrogen.

3.8.5.1 Solar hybrid fuels

The production cost for solar hybrid fuels and solar hydrogen by solar electrolysis are nearly commercially feasible. However, implementing these processes on a large scale generally involves significant capital and energy costs. The combination of capital costs to provide concentrated solar energy and the elaborate and expensive plants required to carry out the chemical processes puts a heavy financial burden on this approach. Alternately, if sunlight is used in non-concentrated systems, the cost per unit area of the converter must be very low to make a viable system. However, when the solar chemical process is applied without solar concentration, each reaction would be controlled and operated in a vast area. In the solar hybrid fuel production, both systems are applied where solar light is concentrated or non-concentrated.

3.8.5.2 PV-solar electrolysis

The rejection of hydrogen as a solution to global warming by becoming the medium of wind and solar was made when gasoline was priced at 1 USD/gallon. From wind energy, H2 by the electrolysis of water and steam would now cost less than 3 USD for an amount equivalent in energy to that in a gallon of gasoline ("equivalent"). From PV, H_2 would be dropping in price from 8 to 5 USD/equivalent as the efficiency of PV increases toward 20%. Solar thermal would produce hydrogen for about half the price of PV.

3.8.5.3 Solar thermochemical cycles

Hydrogen is acclaimed to be an energy carrier of the future. Currently, it is mainly produced by fossil fuels, which release climate-changing emissions. Thermochemical cycles, such as the hybrid-sulfur cycle and a metal-oxide-based cycle, along with electrolysis of water are the most-promising processes for "clean" hydrogen mass production for the future. In a comparison study, both thermochemical cycles were operated by CSP for multistage water splitting. The electricity required for the electrolysis was produced by a parabolic trough power plant. For each process investment, operating and hydrogen production costs were calculated on a 50-MW_{th} scale. The study points out the 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. Hydrogen production costs were obtained that range from 3.9 to 5.6 €/kg for the hybrid-sulfur cycle, 3.5 to 12.8 €/kg for the metal-oxide-based cycle, and 2.1 to 6.8 €/kg for electrolysis.

3.9 Potential Deployment

In this section, various future deployment scenarios through 2050 are compared with each other. However, most scenarios do not have a holistic approach to include all renewable and non-renewable energy sources in the scenario. Therefore, the estimated investment needs to realize the various scenarios differ significantly per kWh generated, depending on the development and/or integration burden into the existing energy supply system.

The potential of direct solar energy is often underestimated. This is because of the wide range of technologies and various applications of direct solar energy, and because most scenarios only look into common indicators such as the share of primary energy, electricity, heat, or transport fuel from renewable energy sources. These indicators do not consider that a number of applications of direct solar energy may contribute only small numbers to these indicators, but that the value provided—and, consequently, the reason why people use them—is much higher. In addition, Martinot et al. (2007) explain that the different scenario targets use different accounting methods, which lead to quite different outcomes.

One example is the difference between the International Energy Agency (IEA) method and the British Petroleum (BP) method used for their Statistical Review of World Energy to account for primary energy (British Petroleum, 2008). Because renewable energy sources (except biomass) do not require a combustion power plant, the IEA method simply accounts the electricity as primary energy. The only exceptions are geothermal and nuclear power stations, where the following conventions are used:

The primary energy equivalent of nuclear energy is calculated from the gross generation by assuming a 33% conversion efficiency, i.e., 1 TWh = (0.086 ÷ 0.33) Mtoe (million tonnes of oil equivalent). In the case of electricity produced from geothermal heat, if the actual geothermal efficiency is not known, then the primary equivalent is calculated assuming an efficiency of 10%, so 1 TWh = (0.086 ÷ 0.1) Mtoe.

On the other hand, the BP method counts the "equivalent primary energy" of fossil fuels needed to generate electricity. BP uses a correction factor of 2.6, which is equivalent to the average energy loss in a power plant.

The IEA method appears to be more commonly used in the scenario literature. But authors often do not explain which method is used, which causes confusion in comparing different scenarios and distorts the numbers. In addition, some scenarios do not differentiate between the different solar energy applications and list everything under solar, such as the "Shell energy scenarios to 2050" (Shell, 2008).

Another issue is how distributed stand-alone generation of solar electricity and low-temperature solar heat are accounted for. In addition, storage is never considered in these studies. These indicators are rarely used in scenarios, but they are becoming more important as these applications grow in use. As already pointed out in section 3.4, the IEA's Solar Heating & Cooling Programme, together with the European Solar Thermal Industry Federation and other major solar thermal trade associations, has decided to publish statistics in kW_{th} (kilowatt thermal) and has agreed to use a factor of 0.7 kW_{th}/m^2 to convert square meters of collector area into kW_{th}. However, an issue that remains unresolved is what statistical number to use for the primary energy part of heat—either the total produced or the actual used.

Currently, the main market drivers are the various national support programmes for solar-powered electricity systems or low-temperature solar heat installations. These programmes either support the installation of the systems or the generated electricity. The scenarios for the potential deployment of the technology depend strongly on public support to develop markets, which can then drive down costs along the learning curves. It is important to remember that learning curves depend on actual production volume, not on time!

The markets for the different solar technologies vary significantly between the technologies. But they also vary regionally for the same technology. This fact leads to very different thresholds and barriers for becoming competitive with existing technologies.

The investment needs are taken from the IEA *Energy Technology Perspectives* 2008 (IEA, 2008). The reference scenario reflects the developments that will occur with the energy and climate policies that have been implemented in 2008; the ACT scenario considers global stabilization of CO_2 emissions by 2050; and the BLUE scenario considers a global 50% reduction of CO_2 by 2050. RDD&D stands for research, development, demonstration, and deployment.

3.9.1 Policies to Achieve Goals

[AUTHORS: This text is still being developed.]

3.9.2 Trends in Low-Temperature Solar Thermal

Investment needs are listed below, followed by descriptions of the trend of solar thermal's potential within different timeframes (Table 3.18). It should be highlighted that passive solar gains are not included in these statistics, because this technology reduces the demand and is not part of the supply chain considered by the energy statistics.

The IEA (2008) estimates the following investment needs in its Energy Technology Perspectives.

- ACT scenario: RDD&D and investment costs between 2005 and 2030: $ 255–280 billion and commercial investment costs between 2035 and 2050: $ 305–340 billion.
- BLUE scenario: RDD&D and investment costs between 2005 and 2020: $ 255–280 billion and commercial investment costs between 2035 and 2050: $ 645–680 billion.

Table 3.18: Evolution of the cumulative low-temperature solar capacities until 2050 (Greenpeace 2008, IEA 2008 scenarios). Note: [1]Calculated from heat supply in PJ/a and 850 full-load hours annually.

Name of Scenario And Year	2000	2010	2020	2030	2050
	Cumulative Installations in GW_{th}				
Greenpeace[1] (reference scenario 2008)		112	360	640	1,200
Greenpeace ([r]evolution scenario 2008)		300	2,160	5,630	13,680
IEA Reference Scenario (2008)					650
IEA ACT Map (2008)			650		1,500
IEA Blue Map (2008)			650		3,000
Shell (Scramble)			330	4,250	15,360
Shell (Blueprints)	0	163	1,150	3,600	12,090

In its Strategic Research Agenda (ESTTP, 2008), the European Solar Thermal Technology Platform formulated the following medium-long-term solar thermal potential. As considered by ESTIF, solar thermal could cover 50% of the heating demand in Europe in the long term when this technology will be used in almost every building—covering more than 50% of the heating and cooling demand in retrofitted buildings and 100% in new buildings. Solar thermal will also be used in district heating systems, and in commercial and industrial applications with many new and improved solar thermal technologies.

Overcoming a series of technological barriers will make it possible to achieve a wide market introduction at competitive costs of advanced solar thermal applications such as the following:

- Active Solar Building, covering at least 100% of their thermal energy with solar, and in some cases, providing heat to neighbours
- High solar-fraction space heating for building renovations
- Wide use of solar for space cooling
- Wide use of solar for heat-intensive services and industrial process heat, including desalination and water treatment.

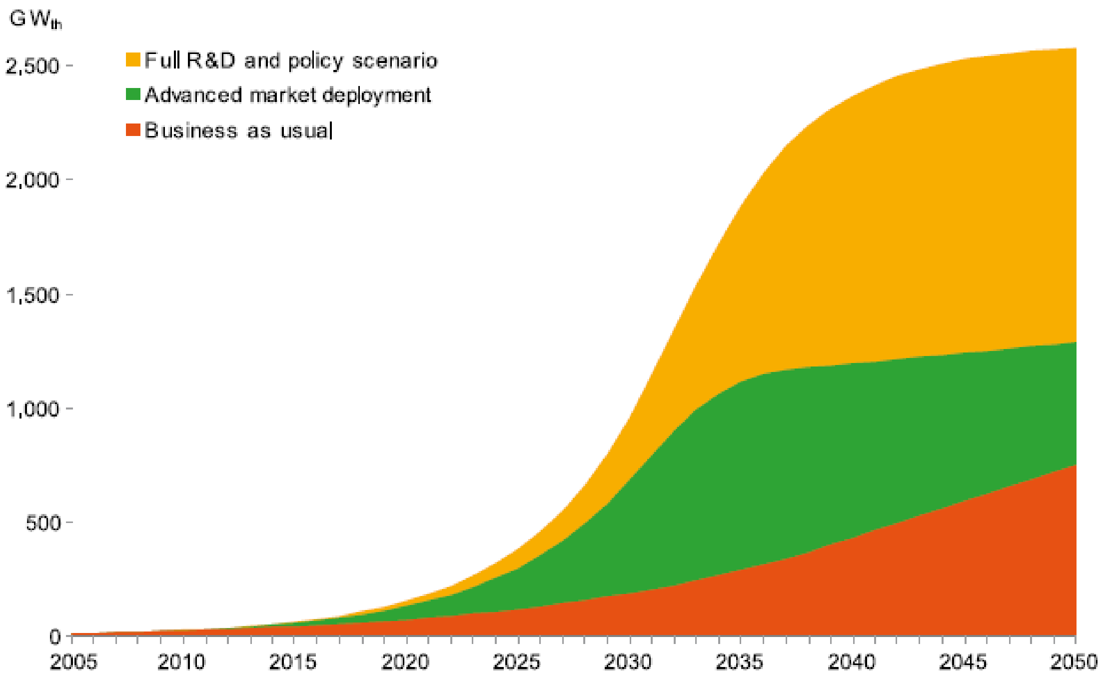


Figure 3.41: Growth in solar thermal energy use in different scenarios (ESTIF, 2009).

These are the key elements of the ESTTP Vision, Deployment Roadmap, and Strategic Research Agenda. Figure 3.41 shows the ESTIF scenarios.

Based on political support mechanisms, technical developments based on increased R&D and on independent report calculations of the ESTTP show realistic growths rates of 20% in the solar thermal market. These growth rates would lead to an installed capacity of 970 GW_{th} by 2030 in the EU. Based on the EU-25 heat demand of the year 2004 (ESTIF, 2009), these solar thermal collectors could supply about 8% of the total heating demand. Combined energy-conservation measures and increased efficiency in the building sector (i.e., 40% decrease in heat demand compared to 2004) would enable solar thermal systems to supply about 20% of the overall heat demand in EU-27 by 2030.

The long-term potential (2050) of solar thermal is to provide for about 50% of the EU´s heat demand. To achieve this goal, an installed capacity of 2576 GW_{th}, or 8 m^2 per inhabitant, would be necessary.

3.9.3 Trends in Photovoltaics

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. However, the market barriers and deployment options differ quite significantly depending on the kind of application. Table 3.19 and Table 3.20 show scenarios developed for PV electrical capacities and generated electricity.

Table 3.19: Evolution of the cumulative solar PV electrical capacities (GW) until 2050 (Greenpeace 2008 and IEA 2008 scenarios).

Name of Scenario	2000	2010	2020	2030	2050
and Year	Cumulative Installations in GW				
Greenpeace (reference scenario 2008)	1.00	10	50	86	153
Greenpeace ([r]evolution scenario 2008)	1.00	21	270	920	2,900
Greenpeace (advanced scenario 2008)	1.00	21	290	1,500	3,800
IEA Reference Scenario (2008)	1.00	10	30	< 60	non-competitive
IEA ACT Map (2008)	1.00	22	80	130	600
IEA Blue Map (2008)	1.00	27	130	230	1,150

Table 3.20: Evolution of the solar PV electricity until 2050 (Greenpeace 2008 and IEA 2008 scenarios).

Name of Scenario	2000	2010	2020	2030	2050
and Year	Electricity in TWh				
Greenpeace (reference scenario 2008)	1.40	13	68	120	213
Greenpeace ([r]evolution scenario 2008)	1.40	26	386	1,351	4,349
Greenpeace (advanced scenario 2008)	1.40	26	406	2,100	5,320
IEA Reference Scenario (2008)	1.40	14	42	120	170
IEA ACT Map (2008)	1.40	31	110	250	1410
IEA Blue Map (2008)	1.40	38	180	440	2,670
Shell* (Scramble)	n.a.	n.a.	170	2,170	7,830
Shell (Blueprints)	n.a.	83	580	1,830	6,170

3.9.3.1 Off-Grid (Rural Electrification)

According to the World Bank, 1.6 billion people worldwide have no access to electricity in their homes, which represents more than one-quarter of the world's population (The World Bank, 2006). Four out of five people without electricity live in rural areas of the developing world, especially in peripheral urban and isolated rural areas. The lack of electricity deprives people of basic necessities such as refrigeration, lighting, and communication and, consequently, it hampers development. Reaching the unelectrified rural population is often only possible through distributed energy systems, due to low potential electricity demand and economic development in these areas, and sometimes, for political reasons, grid extension is not a feasible option.

The use of PV systems to generate electricity for mini-grids or off-grid with solar home systems (SHSs) is an excellent option for improving this situation. A World Bank analysis (The World Bank IEG, 2008) of selected countries showed that the use of electricity from SHSs for lighting purposes is, by far, more cost effective than lighting with kerosene lamps or extending the grid.

Nevertheless, people implementing rural electrification often give greater priority to projects with minimized initial costs to maximise the number of beneficiaries; but they do not take into account the total cost over the lifetime of a generation system. The cost distribution of high initial-investment costs for PV electricity systems and almost no operational costs is therefore a disadvantage and requires special financing mechanisms that are still not common practice. To unlock the large potential of PV deployment, Martinot et al. (2002) suggested the following successful policies and regulatory frameworks to support renewable energies:

- Policies that promote production-based incentives, rather than investment-based incentives, are more likely to spur the best industry performance and sustainability.
- Power-sector regulatory policies for renewable energy should support independent power producer/power purchase agreement (IPP/PPA) frameworks that provide incentives and long-term stable tariffs for private power producers.
- Regulators need skills to understand the complex array of policy, regulatory, technical, financing, and organizational factors that influence whether renewable energy producers are viable.
- Financing for renewable power projects is crucial, but elusive.

In addition to the current market development programmes in the grid-connected markets, the European Photovoltaic Technology Platform developed a "Renewable Energy Purchase Agreement Tariff" to expand the potential rural electrification PV markets to overcome the financing barriers (Moner-Girona, 2008).

However, it should be mentioned that an analysis in the field of rural PV electrification shows poor-quality installations and equipment. This fact has contributed to the spread of a false concept in some areas that PV systems “do not work.” In this way, the success of implementing and popularizing SHS in developing countries needs more than policies and financial support. In particular, it also needs an institutional on-site framework that allows the following conditions to be met: commercial availability, ease in getting replacement parts, existence of local technical capacity to install, and maintenance and collection of monthly fee.

3.9.3.2 Grid-connected

[AUTHORS: This text is still being developed.]

3.9.3.3 Investment Needs

The IEA estimates the following investment needs in its *Energy Technology Perspectives*:

- ACT scenario: RDD&D and investment costs between 2005 and 2035: $ 180–222 billion and commercial investment costs between 2035 and 2050: $ 495–550 billion.
- BLUE scenario: RDD&D and investment costs between 2005 and 2030: $ 185–222 billion and commercial investment costs between 2035 and 2050: $ 980–1,040 billion.

3.9.4 Trends in Concentrating Solar Power

Trends and potential for CSP capacities are shown in Table 3.21 and Table 3.22. The deployment of CSP technology is limited by the regional availability of good-quality sunlight with high direct-normal irradiance of 2,000 kWh/m2 or more in the Earth's "Sun Belt." Despite this requirement, space is not a constraint for deploying this technology. However, the availability of water is a critical issue that must be addressed for large-scale CSP deployment because CSP plants require a continuous water supply for their steam generation, cooling, and cleaning of the solar mirrors. To address water limitations and environmental regulations, air cooling or a combination of wet/dry hybrid cooling can be used. However, dry cooling performs least efficiently during the summer months, when solar energy is most abundant and the plants should have the greatest output to meet the higher electricity demand (WorleyParsons 2008). [TSU: Redundancy with section 3.6.1.5, p.66, lines 38-44]

Air cooling and wet/dry hybrid cooling systems offer highly viable alternatives to wet cooling and can eliminate up to 90% of the water usage (US Department of Energy, 2009). The penalty in electricity costs for steam-generating CSP plants range between 2% and 10%, depending on the actual geographical plant location, electricity pricing, and effective water costs (Richter et al., 2009). The penalty for linear Fresnel designs has not yet been analyzed, but it is expected to be somewhat higher than for troughs because of the lower operating temperature. Conversely, power towers should have a lower cost penalty because of their higher operating temperature.

Given their size of typically 50 to 300 MW, CSP plants need to be linked to the transmission network. Therefore, developing the grid infrastructure is critical to the widespread implementation of CSP. According to a study by the German Aerospace Centre (DLR, 2006), about 10% of the generated electricity will be lost by high-voltage direct-current transmission from the Middle East-North Africa (MENA) countries to Europe over a distance of 3000 km. In 2050, twenty power lines with 5,000-MW capacity each could provide about 15% of the European electricity demand. The total investment for a power transport capacity of 700 TWh/year was calculated at € 350 billion for the CSP plants and € 45 million for the transmission lines.

Table 3.21: Evolution of the cumulative CSP capacities until 2050 (Greenpeace 2008, IEA 2008 scenarios).

Name of Scenario	**2000**	**2010**	**2020**	**2030**	**2050**
and Year	**Cumulative Installations in GW**				
Greenpeace (reference scenario 2008)	0.35	2	8	12	17
Greenpeace ([r]evolution scenario 2008)	0.35	5	83	199	801
Greenpeace (advanced scenario 2008)	0.35	5	100	315	2,100
IEA Reference Scenario (2008)	0.35	n.a.	n.a.	< 10	competitive
IEA ACT Map (2008)	0.35	n.a.	n.a.	250	380
IEA Blue Map (2008)	0.35	n.a.	n.a.	250	630

Table 3.22: Evolution of the electricity generated by CSP until 2050 (Greenpeace 2008, IEA 2008 scenarios). Note: [1]50% of total solar energy is heat, 20% electricity from CSP and 30% electricity from PV.

Name of Scenario	2000	2010	2020	2030	2050
and Year	Electricity in TWh				
Greenpeace (reference scenario 2008)	0.63	5	26	54	95
Greenpeace ([r]evolution scenario 2008)	0.63	9	2,670	1,172	5,255
Greenpeace (advanced scenario 2008)	0.63	9	320	1,860	12,770
IEA Reference Scenario (2008)	n.a.	n.a.	n.a.	< 15	25
IEA ACT Map (2008)	n.a.	n.a.	n.a.	625	890
IEA Blue Map (2008)	n.a.	n.a.	n.a.	810	2,080
Shell[1] (Scramble)	n.a.	n.a.	110	1,450	5,220
Shell (Blueprints)	n.a.	56	390	1,220	4,110

The IEA estimates the following investment needs in its Energy Technology Perspectives:

- ACT scenario: RDD&D and investment costs between 2005 and 2030: $ 265–315 billion and commercial investment costs between 2035 and 2050: $ 190–215 billion.
- BLUE scenario: RDD&D and investment costs between 2005 and 2030: $ 260–300 billion and commercial investment costs between 2035 and 2050: $ 290–330 billion.

3.9.5 Trends in Solar Fuels

To some extent, solar fuels are a natural progression from CSP used for electricity generation. The processes required to produce solar fuels are high temperature above 600°C and with many of the processes well above 1,000°C. Thus, towers and dishes are the preferred concentrator technologies for solar fuels. As towers increase their operating temperature for conventional CSP steam-generation systems up toward temperatures of 600°C for supercritical steam, the lessons and experience gained will be beneficial for moving beyond steam to solar fuels.

Solar fuels are valuable because they convert solar energy into a form that is more transportable and storable than electricity. In addition, solar fuels can be used in a much wider variety of higher-efficiency applications than just Rankine cycles, and they can be used to power gas-turbine combined cycles or fuel cells for electricity generation with 50% higher efficiency than Rankine cycles, as well as used as transport fuels or in industrial processes. Figure 3.42 illustrates possible pathways for solar fuel production.

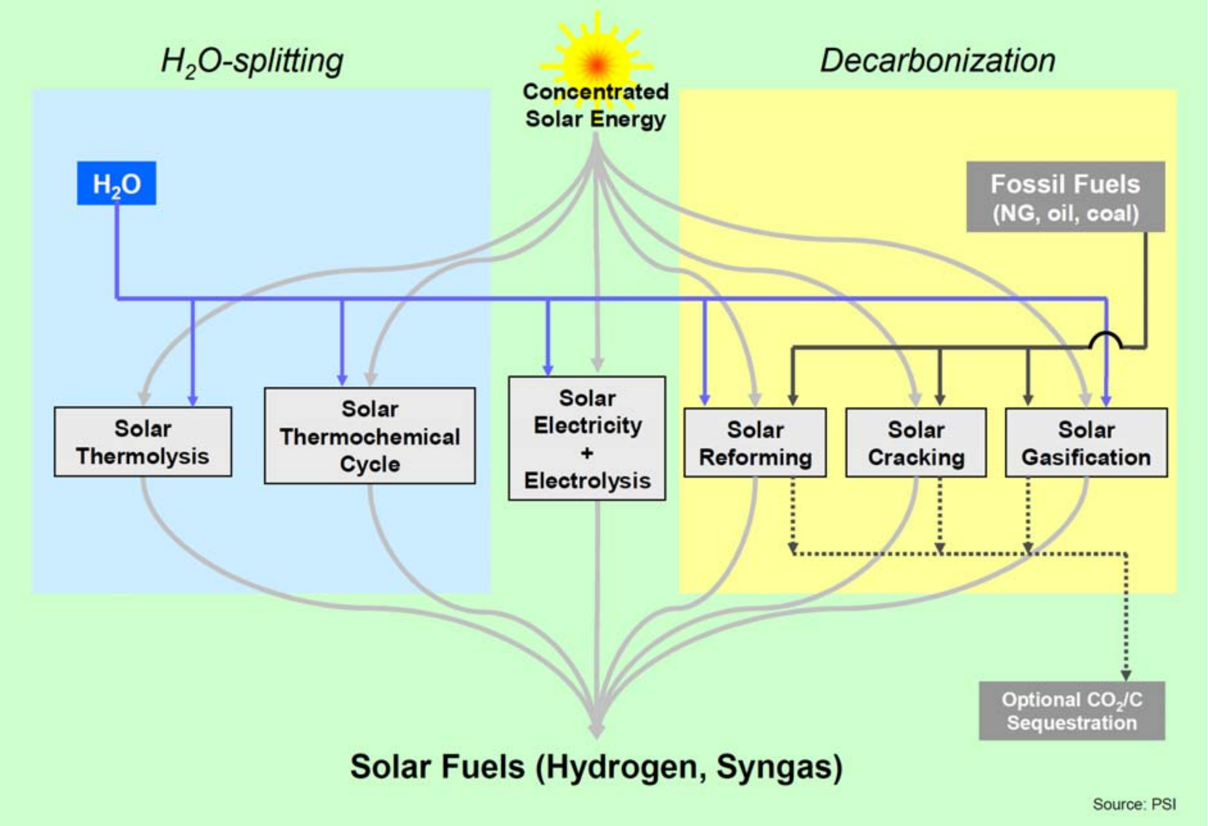


Figure 3.42: Thermochemical routes for solar hydrogen production, indicating the chemical source of H_2: H_2O for solar thermolysis and solar thermochemical cycles; fossil or biomass fuels for solar cracking, and a combination of fossil/biomass fuels and H_2O for solar reforming and solar gasification. For solar decarbonization processes, optional CO_2/C sequestration is considered. All of those routes involve energy-consuming (endothermic) reactions that use concentrated solar radiation as the energy source of high-temperature process heat.

There has been considerable discussion on the merits of hydrogen as a future fuel. Regardless of whether it is hydrogen itself or in the form of some other hydrogen carrier such as methanol in the meantime, hydrogen is attracting enormous funding due to its long-term potential.

Both the U.S. Department of Energy and the European Commission have a clear vision of the hydrogen economy, with firm targets for hydrogen production costs. The U.S. target for 2017 is 3 US$/gge (gasoline gallon equivalent; 1 gge is about 1 kg H_2), and the EU target for 2020 is 3.50 €/kg H_2. The economics of large-scale solar hydrogen production has been assessed in numerous studies, which indicate that the solar thermochemical production of hydrogen can be competitive compared with the electrolysis of water using solar-generated electricity. It can become competitive with conventional fossil-fuel-based processes at current fuel prices, especially if credits for CO_2 mitigation and pollution avoidance are applied (SolarPACES, 2009).

As part of the transitional path, solar thermochemical processes are today demonstrating the production of solar reforming of natural gas to provide a cleaner version of the more conventional gas-to-liquids processes (GTL) (Stein, 2009). The global market for GTL (non-solar) is growing at an annual rate of 13.0% (Gainer, 2009), and the GTL products price is 20 to 25$/bbl (crude oil price; 19$/bbl) (Abdul Rahman, 2008). Thus, conventional GTL is nearing competitiveness with oil in some circumstances. A cost study on solar reforming of natural gas to produce solar H_2 showed future costs of 4.5 to 4.7 cents/kWh, which is about 20% more expensive than conventionally produced hydrogen (Moller, 2006). This indicates that the cost of large-scale solar GTL products are within the competitive range once carbon costs are considered.

3.9.6 Long-Term Deployment in the Context of Carbon Mitigation

Figure 3.43 shows the solar PV energy contribution to global supply in carbon stabilization scenarios from a review of literature in primary energy units (EJ).

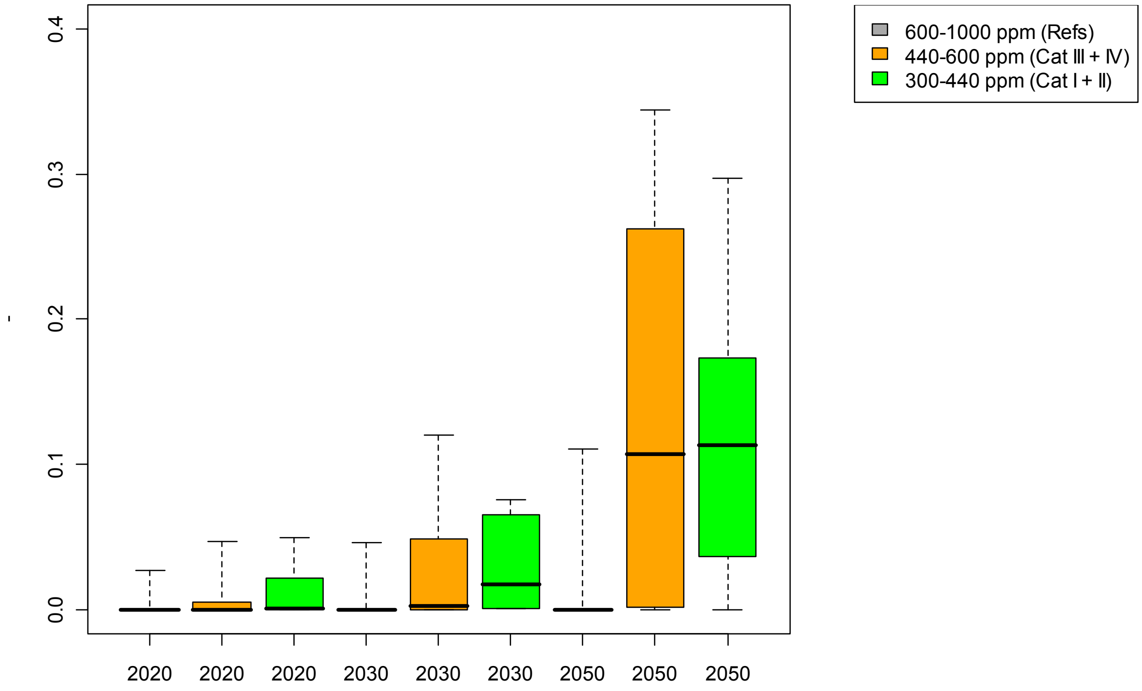


Figure **3.44** shows the same data as a proportion of the total electricity supply. Finally, Figure 3.45 shows the solar thermal energy (CSP) contribution to global supply in carbon stabilization scenarios from a review of literature in primary energy units (EJ).

The reference-case projections of solar energy role in the electricity global energy supply have a very wide range. Nevertheless, the average is 1 EJ in 2020, 5 EJ in 2030, and around 40 EJ in 2050. Both PV and CSP show a spectacular growth after 2030, when it is expected that the technologies are mature enough to reach the market. The contribution of PV is similar to that of CSP in 2020 and 2030, but the projections of 2050 show a bigger contribution for CSP (about 65%).

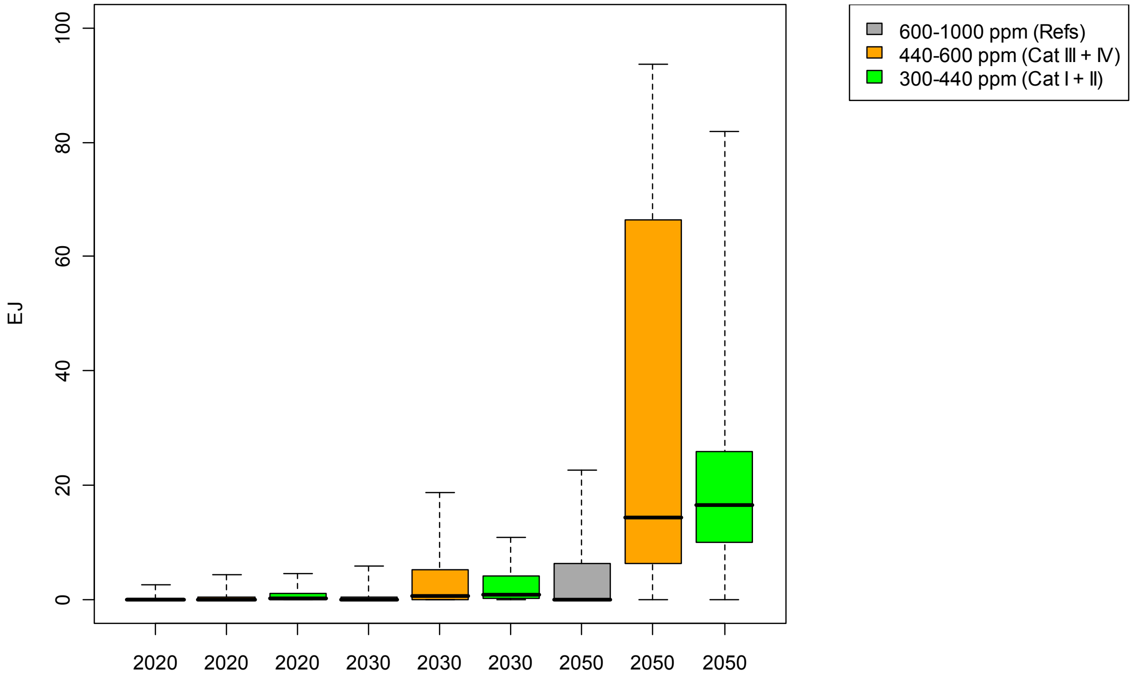


Figure 3.43: Global supply of solar PV energy in carbon stabilization scenarios.

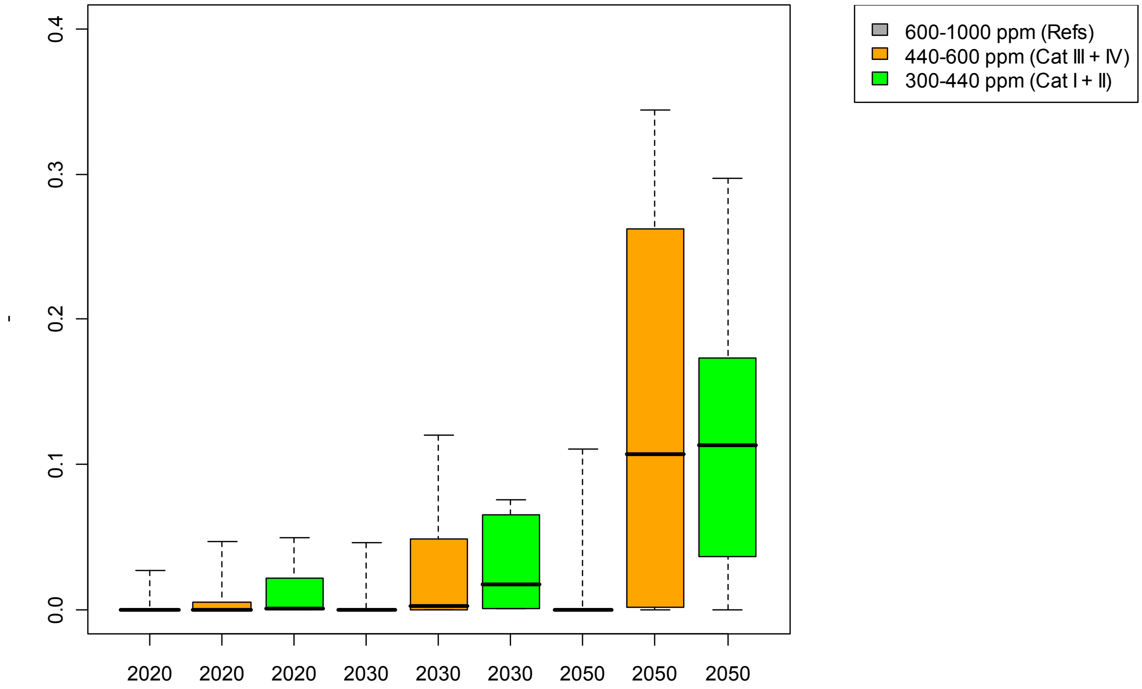


Figure 3.44: Solar PV electricity share in total global electricity supply. [TSU: Title on y-axis missing]

There is a huge difference in the potential contribution of solar energy in the global electricity supply when different stabilization ranges are considered. When the carbon limits considered are decreased, the solar contribution grows spectacularly. In fact, Figure 3.43 shows that the contribution of solar PV would be extremely low in the 600-1000 ppm-CO_2 stabilization scenario.

The growth is shown in 2050, when the solar PV median contribution is around 20 EJ (~ 10% of global electricity supply) in the 440 to 600 and 300 to 440 ppm-CO_2 stabilization ranges, while only 2 EJ (~ 0% of global electricity supply) in the 600 to 1000 ppm-CO_2 stabilization range. The contribution of solar PV found in 2020 and 2030 is very low in all scenarios, being always lower than 7 EJ.

It should be highlighted the huge variation among the studies used in Figure 3.43. These variations are probably due to the different approaches used to generate these scenarios, but also to the difficulties found by the modelling tools used in these studies to address the technical and economic viability of solar energy. This variation is especially big in the solar PV contribution in 2050 for the 440 to 600 ppm-CO_2 stabilization scenario, which ranges from 7 to 70 EJ, depending on the study considered. In the most-stringent 300 to 440 ppm-CO_2 stabilization scenario, the solar PV supply in 2050 varies from 10 to 23 EJ equivalent to 5 to 18% of global electricity supply.

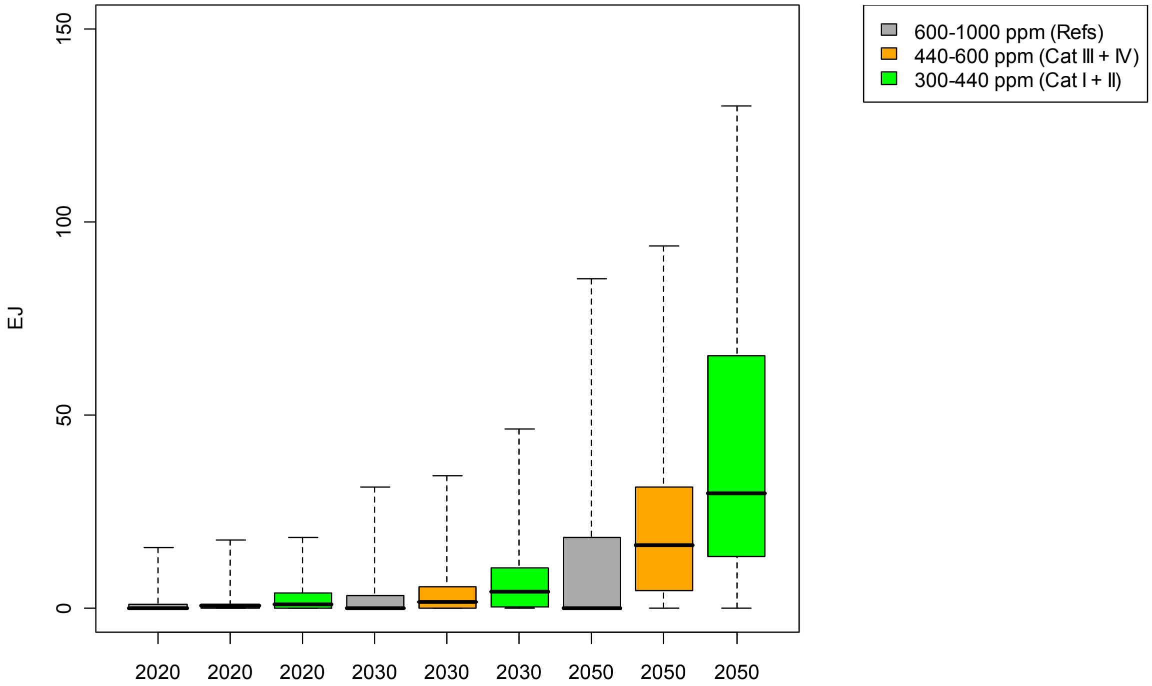


Figure 3.45: Global supply of solar thermal energy (CSP) in carbon stabilization scenarios.

When considering the potential contribution of thermal solar energy in the global electricity supply with different stabilization ranges, the growth with time seems to have a better slope, showing already a contribution in 2030. Again, when the carbon limits considered are decreased, the solar contribution grows. In 2050, the median results of the different scenarios show an extremely low contribution if the 600 to 1000 ppm-CO_2 stabilization scenario is considered, but the contribution is already around 20 EJ with the 440 to 600 ppm-CO_2 stabilization, and 35 EJ with the most-stringent scenario.

Once more, the variation among the studies included in Figure 3.45 is very important. For example, in the most-stringent scenario in 2050, the contribution of solar thermal to the global supply of electricity ranges from 18 to 70 EJ.

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