# DIRECT SOLAR ENERGY

**S. C. Bhattacharya and S. Kumar**
*Energy Program, Asian Institute of Technology, Pathumthani, Thailand*

**Keywords:** Photochemistry, photovoltaics, satellite power conversion, solar cells, solar collectors, solar drying, solar energy, solar energy storage, solar environmental impacts, solar radiation, solar space heating, solar thermal power generation, solar water heating

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## Summary

Energy is defined as the capacity for doing work. Energy is needed to change a situation or condition that would otherwise exist naturally. Thus, running an air conditioner in summer to create comfortable conditions indoors requires energy. Similarly, energy is needed for running cars, televisions, ovens, and other appliances. Energy is a crucial need of modern society.

At present, conventional energy sources—coal, oil, natural gas, nuclear, and hydropower—account for about 77 percent of world primary energy consumption. Consumption has also been rising at an average annual rate of about two percent per year over the last 200 years. It is likely that the current pattern of energy consumption cannot be sustained in the future because of two major constraints. One of these is the environmental impact of heavy dependence on fossil fuels, particularly climate change; the other is depletion of reserves of fossil fuels, particularly oil. One of the most effective approaches to addressing both of these problems is the substitution of fossil fuels by renewable energy.

The most important form of renewable energy is *direct solar energy*: all other renewable energy sources, with the exceptions of tidal and geothermal energy, are indirect manifestations of direct solar energy. In view of the problems of large-scale use of fossil fuels, it is likely that by the year 2100 solar energy will emerge as the most important source of energy for humankind. Some direct solar energy technologies, for

example water heating, space heating, and photovoltaic systems, are already well established at present. Use of some of these, particularly photovoltaic systems, is growing rapidly.

The objective of this theme article is to give readers a sense of the immense potential of direct solar energy, as well as the status, promise, and problems of the wide range of technologies currently available for its utilization. The text presents the fundamentals of solar radiation and solar energy conversion technologies, as well as their applications and environmental impacts. Storage of solar energy and likely developments in direct solar energy utilization in the future are also discussed.

## 1. Introduction

### 1.1. A Brief History of Energy

The use of energy by humans for comfort and convenience started with the discovery of controlled fire. The world's per capita energy consumption remained practically unchanged for many centuries since that time, the main source of energy during this period being fuelwood. The Industrial Revolution marked the beginning of a period of slow and steady rise in world energy consumption because of mechanization, changes in lifestyle, population growth, and other factors. The Industrial Revolution also saw the emergence of coal as a major energy source, becoming the world's biggest source of primary energy around 1880. The importance of coal slowly declined in the twentieth century with the emergence of oil and fundamental changes in energy conversion technologies: oil overtook coal as the biggest source of energy in the 1960s.

Currently, conventional commercial energy sources—coal, oil, natural gas, nuclear, and hydroelectricity—account for about 85 percent of world primary energy consumption; fossil fuels (coal, oil, and natural gas) together account for about 77 percent of total energy consumption. It is widely believed that this pattern of energy consumption is not sustainable, both because of the environmental impacts of large-scale fossil fuel use and depletion of their reserves. On the other hand, world demand for energy is expected to grow over the next thirty years and beyond, making it necessary to bring about a major structural change in the global energy supply system in the years to come. For this purpose, there is an urgent need to develop alternatives to the fossil fuels. One alternative that appears set to emerge as the most important source of energy in the twenty-first century is direct solar energy.

### 1.2. Origin of Solar Energy

The origin of solar energy lies in nuclear fusion reactions taking place inside the sun; these reactions convert hydrogen nuclei to helium nuclei. The energy released as a result of these reactions is radiated by the sun in all directions, and any object in space in its path receives direct solar radiation. Although the temperature in the central regions of the sun lies in the range of 8–40 million degrees Kelvin (K), the frequency spectrum of solar radiation received perpendicularly on a surface at the earth's mean distance from the sun is similar to that from a black body at 5,777 K. The average rate at which the earth and its atmosphere intercept solar radiation is about $1.73 \times 10^{17}$ watt, corresponding to 5.4 x $10^{24}$ Joules per year. This amount is more than 12,000 times the entire world primary energy consumption in the year 2000.

Solar radiation is the main driving force behind natural processes taking place on the earth, and is the indirect source of all renewable forms of energy other than geothermal and tidal power. Even the origins of fossil fuels, which were produced as a result of the decay of plants and animals millions of years ago, lie in solar energy.

### 1.3. Solar Thermal Energy

The idea of using direct solar energy for thermal applications dates back to a few centuries before Christ (B.C.). For example, the Greeks used solar architecture in the fourth century B.C. The houses were suitably oriented so that the sun's energy was used to heat their houses in winter. Later, the Romans improved upon Greek solar architecture; they also recognized the greenhouse effect, and established the first greenhouses for growing vegetables.

Development of modern direct solar energy technologies started in the third quarter of the nineteenth century. A solar-powered steam engine system was developed in France during the 1870s. Basic concepts of flat plate collectors (as an assembly of an absorber plate, a top glass cover, and a rear layer of insulation) and concentrating collectors (using both flat reflecting mirrors and parabolic troughs) evolved in the last quarter of the nineteenth century. In the USA a solar water heater industry had appeared in California by the early twentieth century. By 1930 solar water heating was well established in Florida; in the early 1940s, about 60,000 solar water heaters were in use in Miami.

The solar power industry gradually declined in the 1950s with the advent of cheap fossil fuels and electricity, until the energy crisis of 1973 triggered a global renewal of interest in direct solar energy. While the practical utilization of solar energy before the energy crisis was mainly for water heating, the 1970s marked the beginning of a period of all-round interest in solar energy. The water heater technology itself underwent a transformation, with mass production of flat plate collectors and incorporation of advanced materials and design concepts.

The major applications of solar thermal energy so far include water heating and power generation; other applications include space heating, drying, distillation, and cooling.

### 1.4. Photovoltaics (PV)

A French experimental physicist, Edmund Becquerel, discovered the photovoltaic effect in 1839. Albert Einstein received the Nobel Prize in 1923 for his theories explaining the photoelectric effect. In 1954, researchers of Bell Laboratories of the USA developed the first crystalline silicon photovoltaic cell. A commercial PV product, 2 percent efficient, and priced at $25 per cell of 14 milliwatts each, or $1,785 per watt (1955 dollars), was announced in 1955.

The major early application of solar cells was for satellites: the first PV-powered satellite was launched in 1958. The potential role of PV systems for electrification of rural and remote areas was recognized in the early 1960s. The French installed a PV system in a village school in Niger in 1972 to run an educational television.

The energy crisis of the 1970s marked the beginning of the PV age. The world PV market has been experiencing rapid growth since then; the total world PV production increased from 6.5 MW in 1980 to about 278 MW in the year 2000. Figure 1 shows the growth of PV module production during the period 1989–2000.

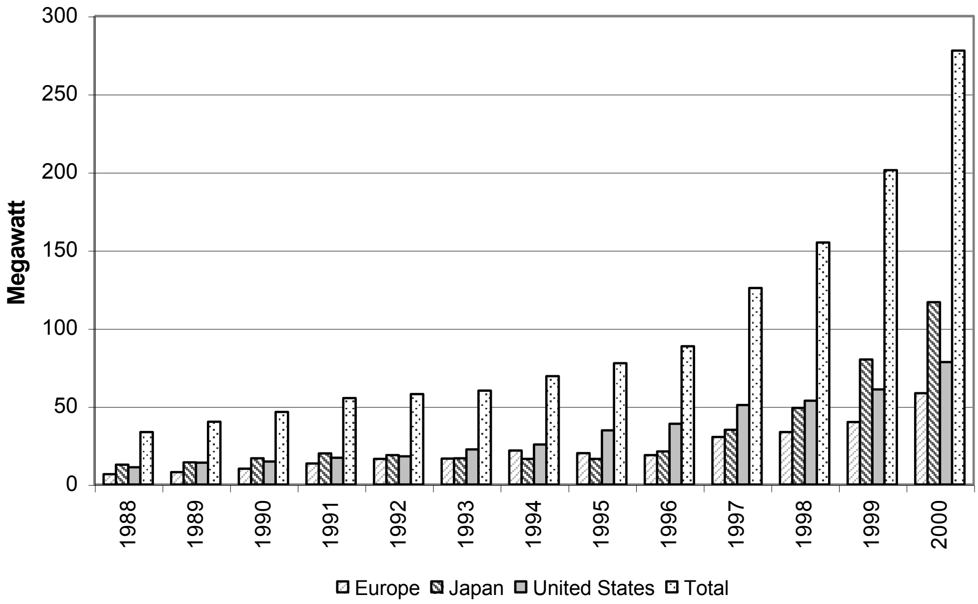


Figure 1. World PV cell/module production in megawatts, 1988–2000

PV systems are currently used around the world for a variety of applications; they are particularly suitable for situations where a relatively small amount of electricity is required in a remote location. Current applications include:

- Solar home systems for light, TV/radio, and in some cases refrigerators
- Remote power to meet community and/or small industrial/commercial demands, a service traditionally provided by diesel generators
- Powering remote communication systems, such as microwave repeaters, radio transmitters/ receivers, and telephone systems
- Pumping water for drinking or irrigation
- Cathodic protection of metallic structures.

## 1.5. The Future of Solar Energy

Solar energy technologies have made tremendous progress over the last three decades. Perhaps the most important development during this period is the utilization of solar energy for electricity production through photovoltaic and thermoelectric conversion. In the year 2000 the total global cumulative PV module installation was about 1,525 MW, while the total installed capacity of thermoelectric systems was slightly over 350 MW.

There are indications that the world is now in the process of undergoing another transition in energy supply systems, with dependence on oil likely to decrease significantly during the next two to four decades. Considering the current rate of penetration of renewable energy technologies (particularly PV, wind, and biomass) and their environmental friendliness, depletion of fossil fuels (particularly oil), the intensifying climate change debate, and worldwide public opposition to nuclear power, it is likely that increasing supplies from renewable energy sources will be of crucial importance for humankind in the twenty-first century. In terms of total contribution to world energy supplies, it is likely that direct solar will emerge as the biggest energy source towards the end of this century.

## 2. Solar Radiation

### 2.1. Sun and Earth

The sun is an "average" star of radius 0.7 million km, with a mass of about 2 x $10^{30}$ kg. It radiates energy from an effective surface temperature of about 5,777K. From the fusion furnace of the sun, energy is transmitted outward as electromagnetic radiation called "solar energy" or sunshine. At a rate of about 3.8 x $10^{23}$ kW this electromagnetic spectrum, which comprises all the energy radiated by the sun, extends from gamma rays (of wavelength $10^{-10}$ cm and lower) to radio waves (of wavelength $10^{+5}$ cm and longer). The distance between the sun and the earth varies daily, and is at a minimum on January 4 and a maximum on July 6. The earth has a radius of about 6,360 km and its total surface area is about 510 million km$^2$, of which only about 21 percent is land. The earth rotates around the sun in an elliptical orbit. Its axis of rotation is tilted at 23.45° with respect to its orbit about the sun. The earth maintains this orientation in its orbital movement. The tilted position, together with its daily rotation and yearly revolution, accounts for the varied distribution of solar radiation over the earth's surface and the variation in day length. The solar radiation on the earth's surface varies in a number of respects.

1. *During the day* (from morning to evening, with the maximum usually around noon). This is called hourly variation. The principal factor which accounts for the variation of solar radiation over the day is the rotation of the earth around its own axis. The distance that the sun's rays pass through the atmosphere is given by *air mass*. For example, in the early morning (or late evening) the sun is at a very low angle with respect to the horizontal. Therefore, the sun's rays must follow a relatively long path through the atmosphere before they reach the surface of the earth. Near noon, however, the sun is at its zenith and the sun's rays pass through only a minimum thickness of atmosphere.
2. *Daily and over the year* (or seasonal variation), primarily due to the location on the earth's surface and the sun's position. As the earth makes an elliptical orbit around the sun, there is approximately a 6.6 percent variation in the amount of solar radiation received by the earth's upper atmosphere throughout the year. Locations near the equator receive solar energy that varies less during the year than at higher latitudes, which receive radiation that varies quite significantly. This is due to the apparent motion of the sun north and south of the equator (up to 23.45°), which is also the cause of varying seasonal day length.

3. *Depending on the orientation of the surface*. Surfaces receive differing amounts of radiation depending on their orientation (or tilt) from the horizontal. Surfaces that are nearly perpendicular to the sun's radiation (or display a low angle of incidence) intercept more radiation; solar radiation collecting surfaces are therefore tilted in many cases to take advantage of this effect.
4. *Due to the presence of clouds*. Cloud directly influences the solar radiation incident on the earth's surface, and is very much dependent on both location and season.

## 2.2. Solar Radiation Estimation

An estimation of the solar radiation incident on the collecting surface is of primary importance for all solar energy applications. The energy radiated from the sun—the source—and the estimation of solar radiation above the earth's atmosphere, or extra-terrestrial radiation, is simple. They may be calculated based on the knowledge of the sun's temperature, distance of the earth from the sun, location on the earth's surface (latitude), time (hour from *solar noon*) of the day, day of the year, position of the sun in relation to the location (altitude and azimuth), and the orientation of the surface (surface tilt).

The spectral distribution of extra-terrestrial solar radiation covers wavelengths ranging from zero to infinity. Almost all of this energy (98 percent) is concentrated in a narrow wavelength band from the ultraviolet to the infrared regions of the spectrum. The solar spectrum can be divided into the following sections:

- radio, ≥ 1 mm
- far infrared, 10 μm – 1 mm
- infrared, 0.75 – 10 μm
- visible, 0.30 – 0.75 μm
- ultraviolet, 0.12 – 0.3 μm
- extreme ultraviolet, 0.01 – 0.12 μm
- soft X-rays, 0.0001 – 0.01 μm
- hard X-rays, < 0.0001 μm.

(1 m = 1000 mm = 1,000,000 μm = 10,000,000,000A°)

Radiation tables give the averaged energy over a small bandwidth, centered at a particular wavelength (λ), and the integrated fraction of the energy from wavelength 0 to λ.

As solar radiation passes through the atmosphere it is partially absorbed and scattered by the constituents of the atmosphere. The atmospheric constituents (by volume) are nitrogen (78.08 percent), oxygen (20.95 percent), argon (0.93 percent), water vapor (0.1–2.8 percent), carbon dioxide (0.0033 percent), and traces of carbon monoxide, sulfur dioxide, ozone, and other substances. The intensity of the solar radiation falling on the earth's surface is influenced by a number of factors:

- the solar spectrum, position of the sun with respect to the location and the time
- position of the location on the earth's surface
- relationship of the location (surface) with respect to the sun
- atmospheric constituents contributing to absorption and scattering of the radiation

- cloudiness and albedo.

Solar radiation incident on the earth’s horizontal surface is of two types: *direct* or *beam radiation*, and *diffuse radiation* (Figure 2). Beam radiation is solar radiation that is intercepted by a surface with negligible direction change and scattering in the atmosphere. Solar radiation, however, is partly scattered by aerosols, dust, clouds, and other matter as it passes through the atmosphere; this scattered fraction of the solar radiation is called the *diffuse radiation*. The total of diffuse and beam radiation is called *global* or *total radiation*.

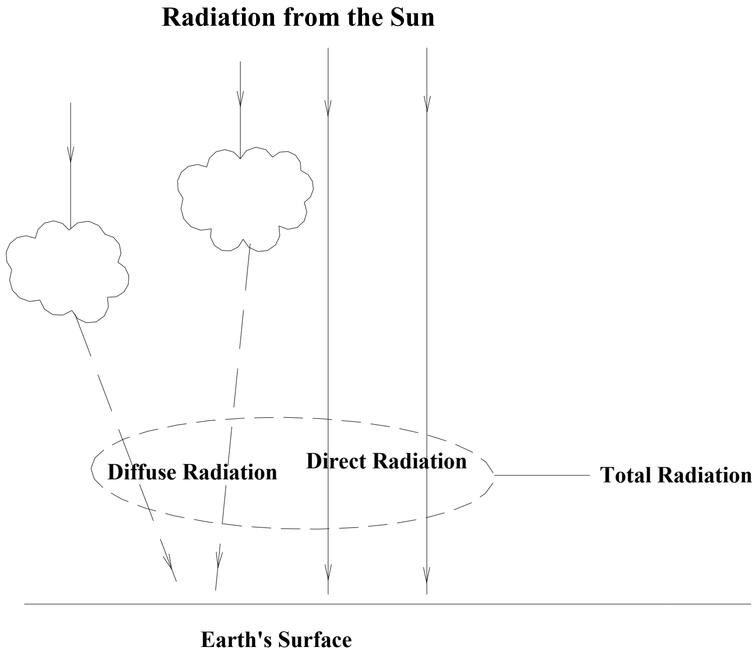


Figure 2. Direct, diffuse, and total radiation on the earth's surface

The radiation incident on a surface can be estimated by considering an *isotropic* or *anisotropic* model. The isotropic model takes into account three components: direct solar radiation from the sun, diffuse radiation from the sky, and ground-reflected radiation. The anisotropic model considers an additional component: the circum solar radiation, or diffuse radiation from the region close to the sun. Based on measured data, the correlations are now available to estimate the different components of radiation on various timescales, depending on the data available:

- estimation of monthly average daily total radiation on a horizontal surface, based on monthly average sunshine duration at a given location
- estimation of monthly average daily diffuse radiation on a horizontal surface, based on monthly average daily total radiation at a given location
- estimation of monthly average hourly total radiation on a horizontal surface, based on monthly average daily total radiation at a given location
- estimation of monthly average hourly diffuse radiation on a horizontal surface, based on monthly average daily diffuse radiation at a given location.

Radiation falling on tilted surfaces can be estimated using radiation values on a horizontal surface (on hourly or daily timescales) by considering the azimuth angle, altitude angle, day length, time of day, and latitude of location. Ground-based measurements of total, diffuse, and direct radiation as well as sunshine duration are made and compiled for easy use. As radiation data is site-specific, remote sensing techniques using satellites are also widely used to produce solar radiation maps. Generally these maps give monthly or yearly average values.

## 3. Solar Thermal Conversion

### 3.1. Solar Collectors

A solar collector is a device that utilizes solar radiation to heat a fluid substance (usually water or air). The heated fluid can then be used for various applications. This is done by absorbing the solar radiation on an absorber plate and transferring the absorbed heat to a suitable medium. An efficient solar collector traps the maximum solar radiation incident on its surface, converting it to thermal energy for use with minimum losses. If the surface area over which solar radiation is collected is nearly equal to the surface area used for absorbing the radiation, the device is said to be a *non-concentrating type* of solar collector. The most common collector of this type is the *flat plate* collector. These are suitable for applications requiring temperatures up to about 80–85 °C. When higher delivery temperatures are required, however, the intensity of radiation on the collector is increased by concentrating the incident radiation by placing an optical device between the radiant source and the absorbing surface; alternatively heat losses are controlled by reducing the surface area of the absorber, or by evacuating the region surrounding it.

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**Biographical Sketches**

**S. C. Bhattacharya** received his M.E. and Ph.D. degrees from the University of Roorkee (India) and the University of Cambridge (UK) respectively. Currently he is a Full Professor of the Energy Program of the Asian Institute of Technology. He has about 200 publications to his credit. He has served as associate editor of two international journals, *Energy* and *Energy Sources*; as the President of the International Association for Solar Energy Education; and as a Director of International Solar Energy Society. Currently he is a member of the Scientific and Technical Advisory Panel of the Global Environment Facility (GEF).

**S. Kumar** received his honours degree in mechanical engineering from the University of Madras, India, his Master of Engineering from the Asian Institute of Technology, Thailand, and his Ph.D. from the Institut National Polytechnique Toulouse, France. He had worked as Reader at the School of Energy, Environment, and Natural Resources, Madurai Kamaraj University in India, and is currently an Associate Professor and the co-ordinator of the Energy Program at the Asian Institute of Technology. He was a Program Fellow of the International Center for Theoretical Physics, Trieste, Italy, at the University of Ancona, in 1994–5. Dr Kumar has been involved in research and teaching in the area of energy for more than fifteen years. He has carried out research on solar radiation, solar heating (water and air), photovoltaics, refrigeration, heat pumps, and energy conservation. He teaches thermal processes, solar energy, energy system design, and cleaner production to postgraduate students, and is currently involved in research projects in the areas of solar drying, photovoltaics, issues related to energy and environment in the industrial sector, and heat pumps. He has co-edited many conference proceedings and newsletters on renewable energy and energy in industry. He has published more than eighty articles in international journals and for conferences, seminars and workshops, of which more than thirty-five are in international referred journals. He has reviewed articles for many international journals and has been invited to attend workshops and seminars in an expert capacity. He has been involved in organizing training programs and workshops, and is a member of Advisory and Steering Committees of many international conferences. He has carried out tests on commercial solar thermal and photovoltaic equipment. He was the Secretary/Treasurer of the International Association of Solar Energy Education from 1996 to 2000, and is listed in the Marquis *Who's Who in the World*.