Chapter 1

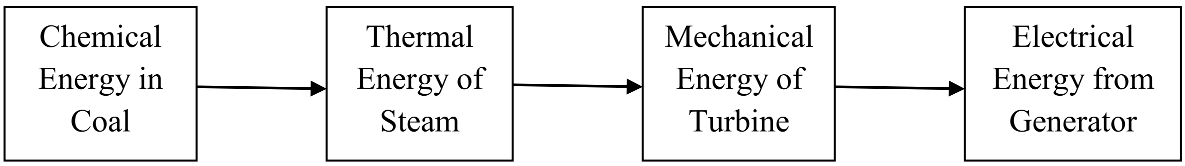
Introduction

1.1 The Energy

We are aware about several activities tacking place in nature. These "activities" have some form of "motion" of particles or objects. Energy is the cause behind motion of particles or objects. Energy is the capability to produce motion, force, work; change in shape, change in form, etc.

We notice that energy exists in many forms such as chemical energy, nuclear energy, solar energy, mechanical energy, electrical energy, internal energy in body, bio-energy in vegetables and animal bodies, thermal energy, etc. We also observe the various activities around us are "energy transformations". Green plants capture solar energy and convert it in food and fuel which contain chemical energy. We also observe energy chains comprising of several energy links. Each link represents an energy transformation and the energy chain has several energy links between raw energy and usable energy.

For example coal is extracted from nature. Coal energy chain by thermal power plant route is:



Energy chain – coal to electric energy

Energy exists in several forms. Energy transformations are responsible for various activities.

The concept of energy has been derived from classical physical while explaining "Work"

Work is performed when a particle or an object moves work is energy in transit.

Energy is cause of work. Energy is necessary for performing "work". Energy is capability to perform "work".

The world energy has been adopted from Greek language. In Greek, "en" means "in" and "ergon" means "work". "en-ergon" means "in-work" or "work content". En-ergon was simplified to the word Energy.

1.2 Thermodynamics and Energy Analysis

Thermodynamics is a branch of energy science which deals with conversion of heat into mechanical work or vice-versa. Heat is thermal energy. The first law of thermodynamics is related with the conservation of energy.

The second law of thermodynamics states that different forms of energy have different quality of energy. In most of the energy conversion processes, these fundamental laws of thermodynamics are applicable.

1.2.1 First law of Thermodynamics

The First Law of Thermodynamics is:

“Heat and work are mutually convertible but since energy can neither be created nor destroyed, the total energy associated with an energy conversion remains constant".

Let us review the statements of the first law of thermodynamics.

1. Energy exists in many forms, e.g. electrical energy, thermal energy, mechanical energy, chemical energy.

2. In an energy conversion process one form of energy is transformed to another.

3. Energy cannot be created newly, Energy cannot be destroyed.

4. In a closed system, total energy remains unchanged.

This is the principle of conservation of Energy.

These considerations are summarized in words as follows

Change in the amount of energy contained within the system during some time interval	=	Net amount of energy transferred in across the system boundary by heat transfer during the time interval	−	Net amount of energy transferred out across the system boundary by work during the time interval

The energy balance can be expressed in symbols as

$$\Delta E = E_{in} - E_{out} \tag{1.1}$$

1.2.2. The Second Law of Thermodynamics

The second law of thermodynamics states that processes occur in a certain direction, not in any direction. A process does not occur unless it satisfies both the first and the second laws of thermodynamics. Bodies that can absorb or reject finite amounts of heat isothermally are called thermal energy reservoirs or heat reservoirs

The second law of thermodynamics states that the various forms of energy differ in quality. The following statements are derived from the second law of thermodynamics.

1. Various forms of energy are not identical. Some are more useful for obtaining work. Others are less useful. For example electrical energy is more useful. Energy in the environment is worthless.

2. Various energy conversion processes differ in efficiency. The efficiency of energy conversion process depends upon the type of input energy and the type of output energy.

3. Every energy conversion is accompanied by exchange 'of certain heat with surroundings. Energy losses are released to surroundings in the form of heat. Rejected heat increases internal energy of the environment.

4. The internal energy of the environment is worthless.

5. In every energy conversion process some energy is converted into worthless form.

6. Spontaneous energy conversion process are irreversible.

The second law of thermodynamics states that each form of energy possesses certain quality. The quality of various forms of energy differs. In an energy conversion process, though the energy is conserved the quality of energy is deteriorated.

1.3 Measurements and Units

The progress of science and technology is associated with the systems of dimensions, measurement, units and standardizations. Physical sciences involve precise measurements. Scientist use measurements for observation, experimentation and analysis. Engineers use the measurements for practical use, design, construction, operation, organization, etc.

Energy exists in different forms and appears as work during the transit from one form to another. Power is the time rate of energy flow/energy conversion or work. Each form of energy has certain associated quantities.

In 1960, the International System of units (SI) was introduced. In SI units all forms of energy are measured in terms of the same unit joule (J). This has made energy calculations very simple and the easy. In SI system following units are used for energy, work and power

Energy	joule (J)
Power	watt (W)
Force	newten (N)
1 J = 1 W.s = 1 N.m	

Joule is relatively small unit and we need multiples and prefixes for expressing large measurements occurring in practice. Following standard prefixes in table 1.1 are used very often in Energy Technology as recommended by SI.

Table 1.1 Standard prefixes for higher quantities.

K	*M*	*G*	*T*	*P*	*E*
kilo	mega	giga	tera	peta	exha
10^3	10^6	10^9	10^{12}	10^{15}	10^{18}

More than fifty per cent of commercial energy is transmitted and supplied through electrical power system. Hence the following units based on SI are most widely used practical units though they not listed in the base/derived energy units of SI.

1kWh = 1 kilowatt.houre = 10^3 watt.hour = 10^3x 3600 watt.second = 36000000 joules = 3.6x10^6 J= 3.6 MJ	1MWd = 1 megawatt.day = 10^6 watt.day = 10^6W x3600s x24h = 86.4 GJ(gega.joule)	1 W.yr = 1 watt.year = 1 W x 1 yr = 1 W x (31.56 x10^6 s) = 31.6 MJ (mega.joule)

Table 1.2 Various commonly used units of energy are:

Joule	J	Tonne. Petrol. equivalent	tpe
Kilowatt.houre	kWh	Megawatt.day	MWd
electronvolt	eV	tonne. coal. equivalent	tce
erg	erg	gram.mass	g.mass
Calory	cal	horsepower hour	hp,h
kilogram.meter	kgm	thermie = M cal	th
British Thermal Unit	BTU		

1	2	3	4	5	6	7	8	9	10	11
Equal to One	*J*	*kWh*	*eV*	*erg*	*cal*	*kgm*	*BTU*	*tce*	*MWd*	*g.mass*
J		$2,78 \times 10^{-7}$	$6,24 \times 10^{18}$	1×10^{7}	$2,39 \times 10^{-1}$	$1,02 \times 10^{-1}$	$9,48 \times 10^{-4}$	$3,41 \times 10^{-11}$	$1,16 \times 10^{-11}$	$1,11 \times 10^{-14}$
kWh	$3,6 \times 10^{6}$		$2,25 \times 10^{25}$	$3,60 \times 10^{13}$	$8,601 \times 10^{5}$	$3,67 \times 10^{5}$	$3,41 \times 10^{3}$	$1,23 \times 10^{-4}$	$4,17 \times 10^{-5}$	$4,01 \times 10^{-8}$
eV	$1,60 \times 10^{-19}$	$4,45 \times 10^{-26}$		$1,60 \times 10^{-12}$	$3,83 \times 10^{-20}$	$1,63 \times 10^{-20}$	$1,52 \times 10^{-22}$	$5,46 \times 10^{-30}$	$1,85 \times 10^{-30}$	$1,78 \times 10^{-33}$
erg	$1,00 \times 10^{-7}$	$2,78 \times 10^{-14}$	$6,24 \times 10^{11}$		$2,39 \times 10^{-8}$	$1,02 \times 10^{-8}$	$9,48 \times 10^{-11}$	$3,41 \times 10^{-18}$	$1,16 \times 10^{-18}$	$1,11 \times 10^{-21}$
cal	$4,186 \times 10^{0}$	$1,16 \times 10^{-6}$	$2,61 \times 10^{19}$	$4,19 \times 10^{7}$		$4,27 \times 10^{-1}$	$3,97 \times 10^{-3}$	$1,43 \times 10^{-10}$	$4,84 \times 10^{-11}$	$4,66 \times 10^{-14}$
kgm	$9,807 \times 10^{0}$	$2,72 \times 10^{-6}$	$6,12 \times 10^{19}$	$9,81 \times 10^{7}$	$2,34 \times 10^{0}$		$9,29 \times 10^{-3}$	$3,35 \times 10^{-10}$	$1,14 \times 10^{-10}$	$1,09 \times 10^{-13}$
BTU	$1,055 \times 10^{3}$	$2,93 \times 10^{-4}$	$6,57 \times 10^{21}$	$1,05 \times 10^{10}$	$2,52 \times 10^{2}$	$1,07 \times 10^{2}$		$3,60 \times 10^{-8}$	$1,22 \times 10^{-8}$	$1,17 \times 10^{-11}$
tce	$2,93 \times 10^{10}$	$8,14 \times 10^{3}$	$1,83 \times 10^{29}$	$2,93 \times 10^{17}$	$7,000 \times 10^{9}$	$2,99 \times 10^{9}$	$2,78 \times 10^{7}$		$3,93 \times 10^{-1}$	$3,26 \times 10^{-4}$
MWd	$8,64 \times 10^{10}$	$2,400 \times 10^{4}$	$5,93 \times 10^{29}$	$8,64 \times 10^{17}$	$2,06 \times 10^{10}$	$8,81 \times 10^{9}$	$8,19 \times 10^{7}$	$2,95 \times 10^{0}$		$9,61 \times 10^{-4}$
g.mass	$8,99 \times 10^{13}$	$2,50 \times 10^{7}$	$5,61 \times 10^{32}$	$8,99 \times 10^{20}$	$2,15 \times 10^{13}$	$9,17 \times 10^{12}$	$8,51 \times 10^{10}$	$3,07 \times 10^{3}$	$1,04 \times 10^{3}$	

Meaning :
BTU = British Thermal Unit ;
tce = tonne coal equivalent
tpe = tonne petroleum equivalent ;
MWd = megawatt.day
kWh = kilo Watt.hour
hp.h = horse-power.hour
amu = atomic mass unit
th = thermic (Mcal)

$3,6 \times 10^6 = 3.6 \times 10^6$
Comma = Decimal point

Table 1.3 Conversion factors for Joule (J) to other units of energy.

Example 1.1 A System is supplied with 10 kWh of electrical energy, 10 BTU of thermal energy, 5 kgm of mechanical energy. What is the total energy in the system?

Solution:

10 kWh = 10 x 3.6 x 10^6 J	= 36,000,000 J
10 BTU = 10 x 1.055 x 10^3 J	= 10,550 J
5 kgm = 5 x 9.867 J	= 49 J
Total Energy in the system	= 36010599 J

1.4 Fossil Energy Sources

Fossil energy sources are concentrated energy sources that evolved from animal and plant remains over very long periods of time. These sources include oil, gas, hard coal, brown coal and turf. The base materials for fossil energy sources could only develop because of their conversion through solar radiation over millions of years. In this sense, fossil energy sources are a form of stored solar energy.

From a chemical point of view, fossil energy sources are based on organic carbon compounds. Burnt in conjunction with oxygen, they not only generate energy in the form of heat but also always produce the greenhouse gas carbon dioxide as well as other exhaust gases.

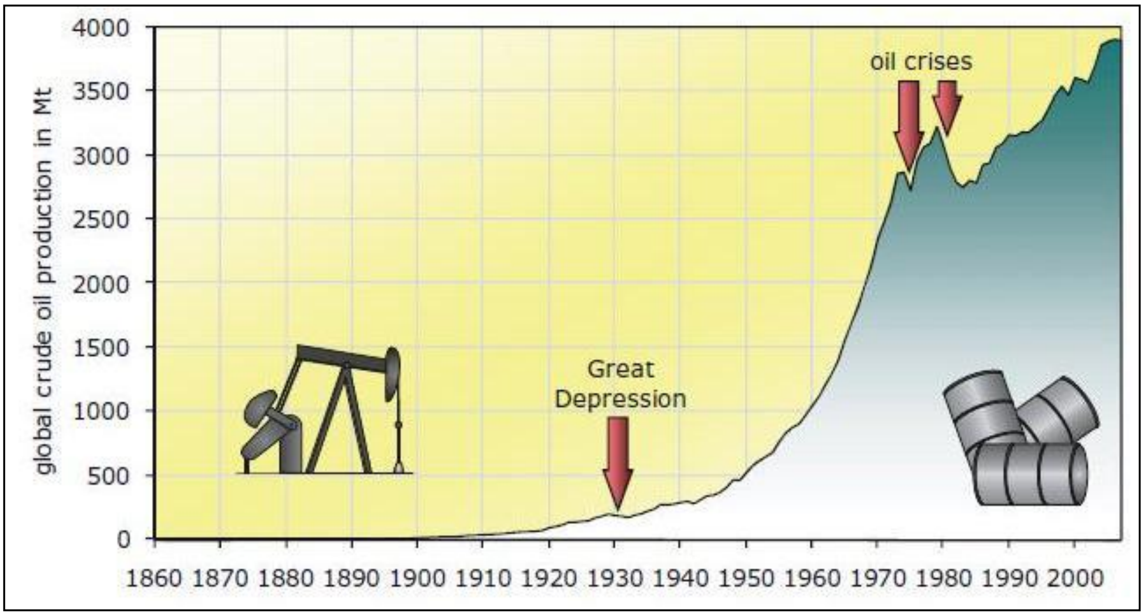


Figure 1.2 Oil productions since 1860

1.5 Renewable Energies

The supplies of fossil energies, such as oil, natural gas and coal, are limited. They will be depleted within a few decades and then cease to exist. Renewable energy sources, on the other hand, 'renew' themselves on their own. For example, if a hydropower plant takes the power of the water from a river, the river will not stop flowing. The energy content of the river renews itself on its own because the sun evaporates the water and the rain feeds the river again. Renewable energies are also referred to as 'regenerative' or 'alternative' energies. Other renewable energies include wind power, biomass, the natural heat of the earth and solar energy. Even the sun will eventually disappear in around four billion years. Compared to the few decades that fossil energy sources will still be available to us, this time period seems infinitely long.

Incidentally, renewable energies have been used by mankind for considerably longer than fossil fuels, although the current systems for using these fuels are vastly more advanced than in the past. Therefore, it is not renewable energies that are new but rather the knowledge that in the long term renewable energies are the only options for a safe and environmentally compatible energy supply.

Renewable energy can be defined as: energy obtained from the continuous or repetitive currents of energy recurring in the natural environment, and it replenished at the same rate as it used.

1.6 Renewable Energies Sources

The three sources of renewable energies give rise to a multitude of very different energy flows and carriers due to various energy conversion processes occurring in nature. In this respect, for instance, wind energy and hydropower, as well as, ocean current energy (as energy flows) and solid or liquid biofuels (as energy carrier; i.e. stored solar energy) all represent more or less conversions of solar energy (Fig. 1.2). Fig. 1.3 shows the difference in how four countries use key forms of energy to cover their energy needs.

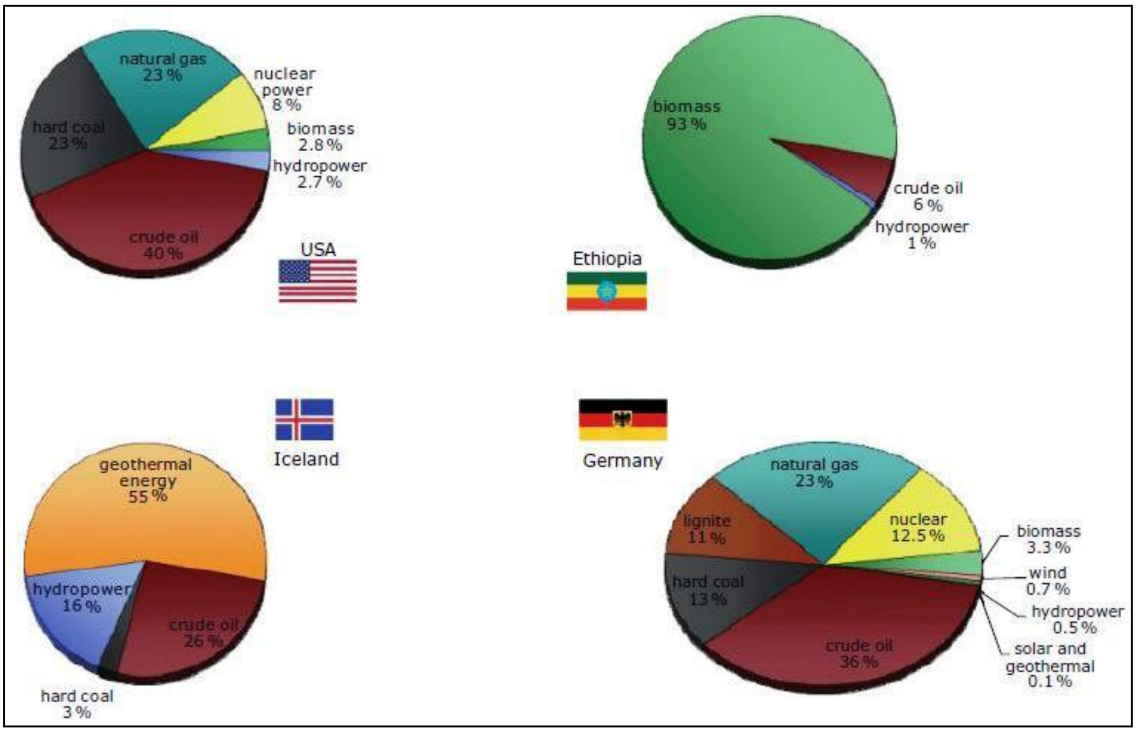
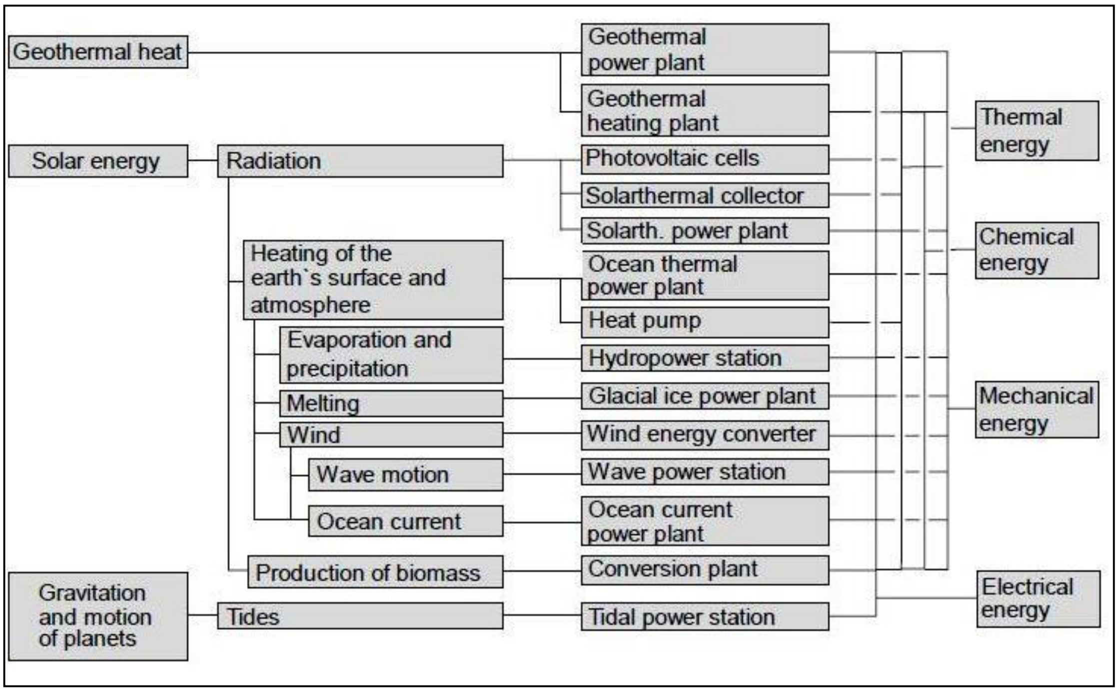


Fig. 1.3 Percentage of different energy sources covering primary energy requirements in Ethiopia, Germany, Iceland and the USA in 2005.



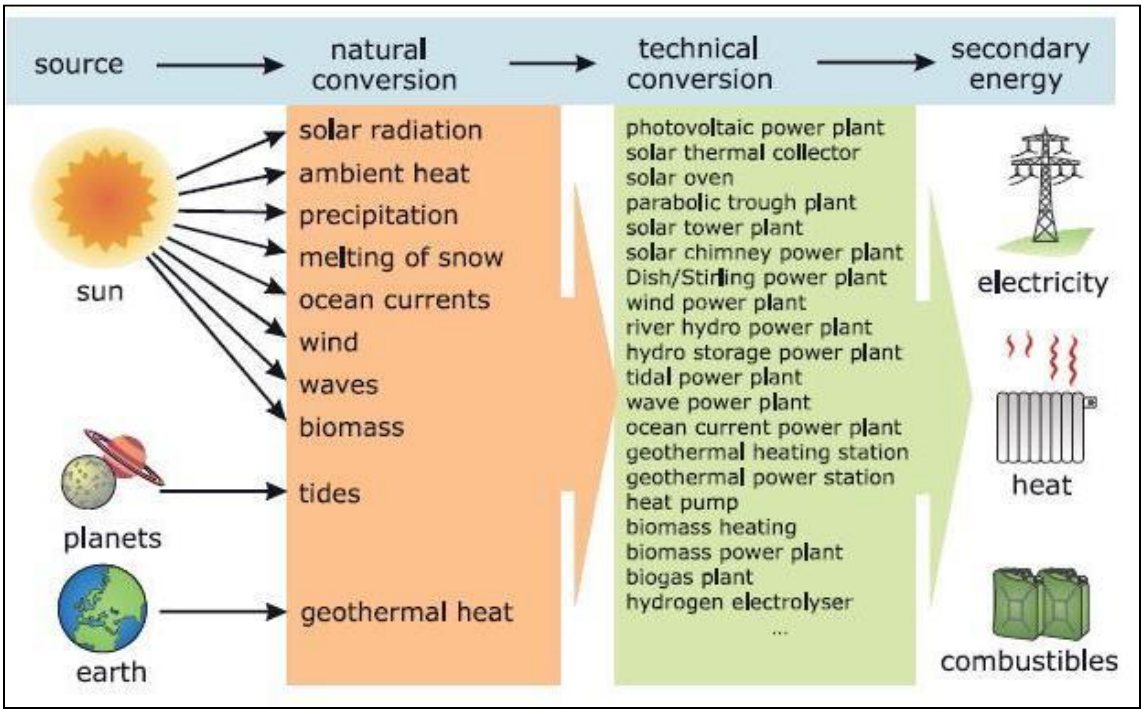


Fig. 1.2 Options of using renewable energies for the provision of useful energy.

1.7 Renewable Energy and the Environmental Problems

A few years ago, most environmental analysis and legal control instruments concentrated on conventional pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulates, and carbon monoxide (CO). Recently, however, environmental concern has extended to the control of hazardous air pollutants, which are usually toxic chemical substances harmful even in small doses, as well as to other globally significant pollutants such as carbon dioxide (CO_2). Additionally, developments in industrial processes and structures have led to new environmental problems. Carbon dioxide as a greenhouse gas plays a vital role in global warming. Studies show that it is responsible for about two thirds of the enhanced greenhouse effect. A significant contribution to the CO_2 emitted to the atmosphere is attributed to fossil fuel combustion. (See Fig. 1.4). Table 1.4. shows the annual marginal average emissions rates for 2002.

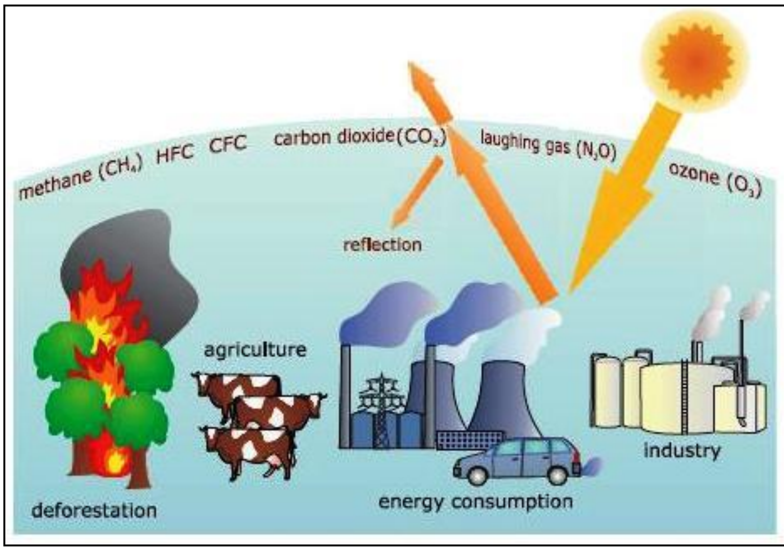


Fig. 1.4 Causes of anthropogenic greenhouse effects due to human activities.

Pollutant	A Major Impact of This Pollutant	Marginal Emissions Rate (kg/MWh)
SO_2	Acid rain	1.48
NO_X	Smog, asthma	0.5
CO_2	Global climate change	606.8

Table 1.4. The annual marginal average emissions rates for 2002

1.7.1 Acid Rain

Acid rain is a form of pollution depletion in which SO_2 and NO_x produced by the combustion of fossil fuels are transported over great distances through the atmosphere and deposited via precipitation on the earth, causing damage to ecosystems that are exceedingly vulnerable to excessive acidity. Therefore, it is obvious that the solution to the issue of acid rain deposition requires an appropriate control of SO_2 and NO_x pollutants. These pollutants cause both regional and transboundary problems of acid precipitation.

Recently, attention also has been given to other substances, such as volatile organic compounds (VOCs), chlorides, ozone, and trace metals that may participate in a complex set of chemical transformations in the atmosphere, resulting in acid precipitation and the formation of other regional air pollutants. It is well known that some energy-related activities are the major sources of acid precipitation. Additionally, VOCs are generated by a variety of sources and comprise a large number of diverse compounds. Obviously, the more energy we expend, the more we contribute to acid precipitation; therefore, the easiest way to reduce acid precipitation is by reducing energy consumption

1.7.2 Ozone Layer Depletion

The ozone present in the stratosphere, at altitudes between 12 and 25 km, plays a natural equilibrium-maintaining role for the earth through absorption of ultraviolet (UV) radiation (240–320 nm) and absorption of infrared radiation. A global environmental problem is the depletion of the stratospheric ozone layer, which is caused by the emissions of chlorofluorocarbons (CFCs), halons (chlorinated and brominated organic compounds), and NOx. Ozone depletion can lead to increased levels of damaging UV radiation reaching the ground, causing increased rates of skin cancer and eye damage to humans, and is harmful to many biological species. It should be noted that energy-related activities are only partially (directly or indirectly) responsible for the emissions that lead to stratospheric ozone depletion. The most significant role in ozone depletion is played by the CFCs, which are mainly used in air conditioning and refrigerating equipment as refrigerants, and NOx emissions, which are produced by the fossil fuel and biomass combustion processes, natural denitrification, and nitrogen fertilizers.

In 1998, the size of the ozone hole over Antarctica was 25 million km^2. It was about 3 million km^2 in 1993. Researchers expect the Antarctic ozone hole to remain severe in the next 10–20 years, followed by a period of slow healing. Full recovery is predicted to occur in 2050; however, the rate of recovery is affected by the climate change.

1.7.3 Global climate change

The term greenhouse effect has generally been used for the role of the whole atmosphere (mainly water vapor and clouds) in keeping the surface of the earth warm. Recently, however, it has been increasingly associated with the contribution of CO_2, which is estimated to contribute about 50% to the anthropogenic greenhouse effect. Additionally, several other gases, such as CH_4, CFCs, halons, N_2O, ozone, and peroxyacetylnitrate (also called greenhouse gases) produced by the industrial and domestic activities can contribute to this effect, resulting in a rise of the earth's temperature. Increasing atmospheric concentrations of greenhouse gases increase the amount of heat trapped (or decrease the heat radiated from the earth's surface), thereby raising the surface temperature of the earth. The earth's surface temperature has increased by about 0.6°C over the last century, and as a consequence the sea level is estimated to have risen by perhaps 20 cm. These changes can have a wide range of effects on human activities all over the world.

1.7.4 Nuclear Energy Hazards

Nuclear energy, although non-polluting, presents a number of potential hazards both during the production stage and mainly for the disposal of radioactive waste. Nuclear power environmental effects include the effects on air, water, ground, and the biosphere (people, plants, and animals). Nowadays, in many countries, laws govern any radioactive releases from nuclear power plants. In this section some of the most serious environmental problems associated with electricity produced from nuclear energy are described. These include only effects related to nuclear energy and not emissions of other substances due to the normal thermodynamic cycle.

1.8 Forecast of Future Energy

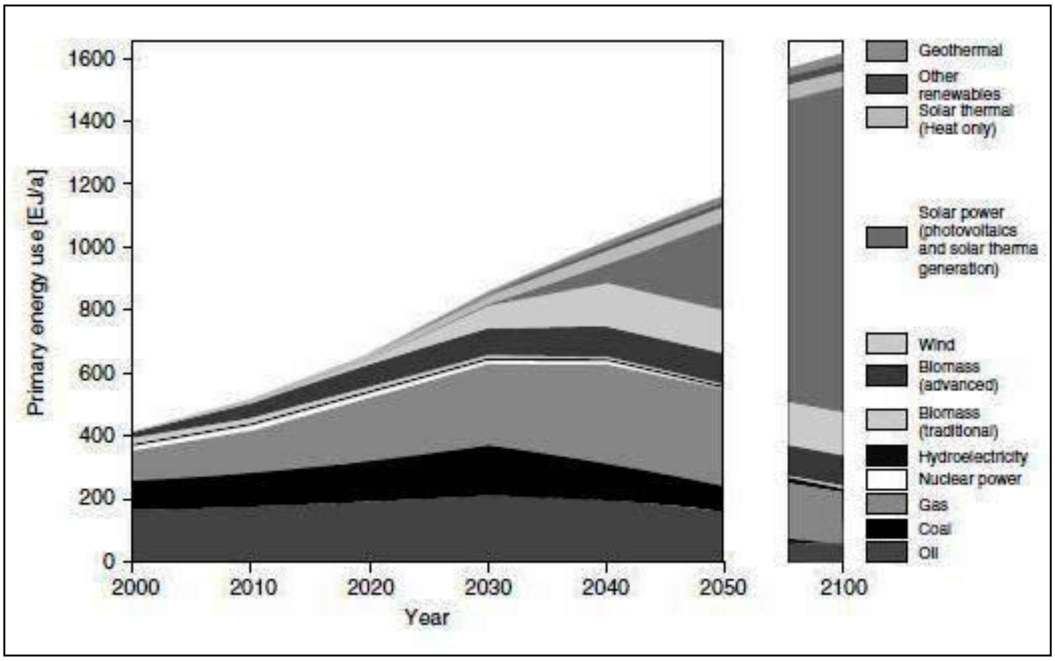
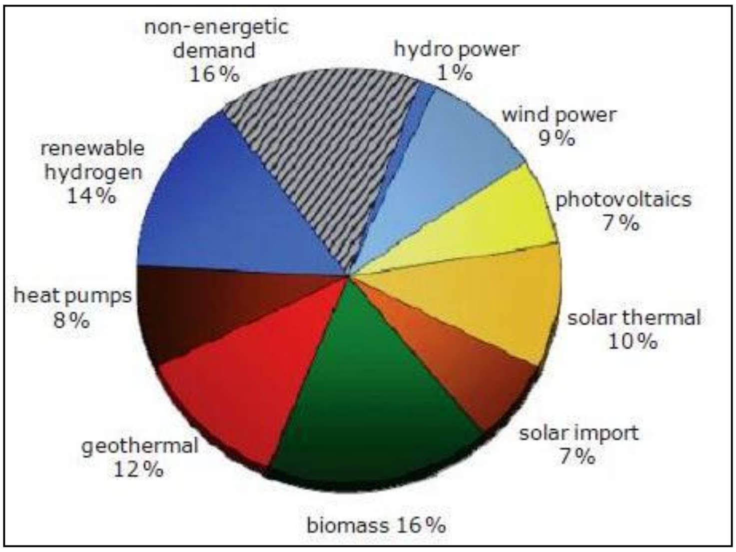


Fig. 1.5 The global energy mix for year 2050 and 2100 according to WBGU.

Fig. 1.6 Possible share of renewable energies in primary energy consumption in 2050 in Germany.



Chapter 2

Solar Radiation Analysis

2.1 The Sun

The sun is a sphere of intensely hot gaseous matter with a diameter of 1.39 x 10^9 m (see **Fig. 2.1**). The sun is about 1.5 x 10^8 km away from earth, so, because thermal radiation travels with the speed of light in a vacuum (300,000 km/s), after leaving the sun solar energy reaches our planet in 8 min and 20 s. As observed from the earth, the sun disk forms an angle of 32 min of a degree. This is important in many applications, especially in concentrator optics, where the sun cannot be considered as a point source and even this small angle is significant in the analysis of the optical behavior of the collector.
The sun has an effective black-body temperature of 5760 K. The temperature in the central region is much higher. In effect, the sun is a continuous fusion reactor in which hydrogen is turned into helium. The sun's total energy output is 3.8 x 10^{20} MW, which is equal to 63 MW/m^2 of the sun's surface. This energy radiates outward in all directions. The earth receives only a tiny fraction of the total radiation emitted, equal to 1.7 x 10^{14} kW; however, even with this small fraction, it is estimated that 84 min of solar radiation falling on earth is equal to the world energy demand for one year (about 900 EJ). As seen from the earth, the sun rotates around its axis about once every four weeks.
As observed from earth, the path of the sun across the sky varies throughout the year. The shape described by the sun's position, The most obvious variation in the sun's apparent position through the year is a north-south swing over 47° of angle (because of the 23.5° tilt of the earth axis with respect to the sun), called declination (see Section 2.2). The north-south swing in apparent angle is the main cause for the existence of seasons on earth.

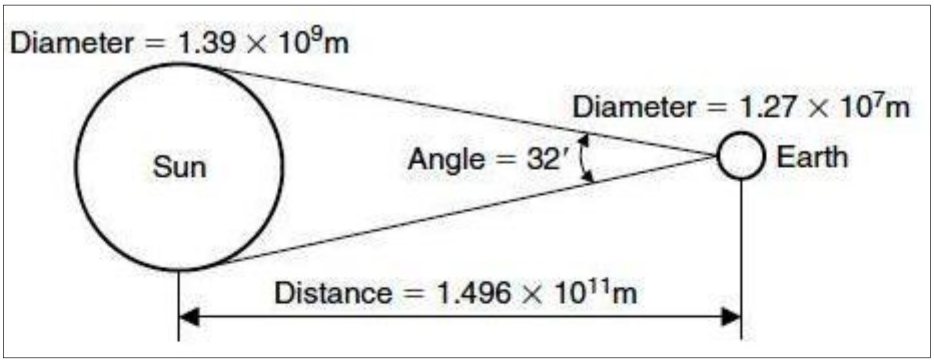


Fig. 2.1 Sun-earth relationship.

Knowledge of the sun's path through the sky is necessary to calculate the solar radiation falling on a surface, the solar heat gain, the proper orientation of solar collectors, the placement of collectors to avoid shading, and many more factors that are not of direct interest in this book. The objective of this chapter is to describe the movements of the sun relative to the earth that give to the sun its east-west trajectory across the sky. The variation of solar incidence angle and the amount of solar energy received are analyzed for a number of fixed and tracking surfaces. The environment in which a solar system works depends mostly on the solar energy availability. Therefore, this is analyzed in some detail.

2.2 Basic Earth Sun Angles

In order to understand what follows for calculations of solar radiations, the definitions of some of the basic terms are given.

Poles of the earth: The ends of the axis of rotation of the earth mark two important points on the earth's surface. They are called the poles of the earth, one as North, while the other as south.

Earth's Equator: It is an imaginary great circle normal to the earth's axis, dividing the distance between the earth's poles along its surface into two equal parts. The equator divides the earth into two hemispheres called Northern and Southern hemispheres.

Meridian: It is necessary to select some reference location on the earth for helping in locating a particular position. The location of Royal Observatory Greenwich, outside of London, has been universally accepted as a reference point. An imaginary great circle passing through this point and the two poles, intersecting the equator at right angles, is called the prime (or Greenwich) meridian. Similar great circles have been drawn at intervals of 15° through the two poles.

Longitude: It is the angular distance of the location, measured east or west from the prime meridian.

Basic Earth Sun angle: The position of a point P on the earth's surface with respect on the sun's rays is known at any instant if the latitude (ϕ) and hour angle (ω) for the point, and the sun's declination (δ) are known. These fundamental angles are shown by Fig. 2.2. Point P represents a location on the Northern hemisphere

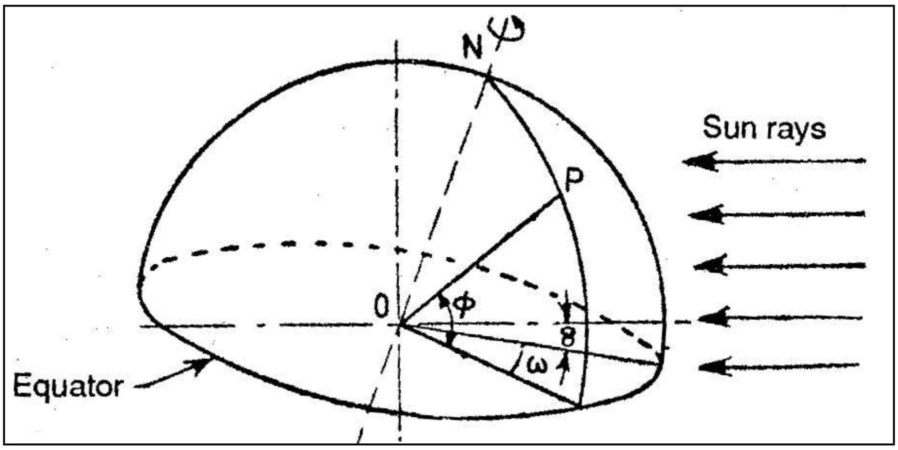


Fig 2.2. Latitude, hour angle and sun's declination.

The latitude (ϕ) of a point on the surface of the earth is its angular distance north or. south of the equator measured from the centre of the earth. It is the angle between the line OP and the projection of OP on the equatorial plane. Point O represents the centre of the earth.

The hour angle (ω) is the angle through which the earth must turn to .bring the meridian of a point directly in line with the sun's rays. It is the angle measured in the earth's equatorial plane between the projection of OP and the projection of a line from the centre of the sun to the centre of the earth. At solar noon the hour angle is 0 and it expresses the time of a day with respect to solar noon. It is measured positively westward from the observer and it may be expressed in,

hours, minutes, and seconds degrees, minutes, radians

One hour is equivalent to $\frac{2\pi}{24} = 0.262\, rad., or\ \frac{360^o}{24} = 15^o$ and consequently $1\, min = 1\acute{5}, 4min = 1^o$

The Sun's declination (δ): is the angular distance of the sun's rays north (or south) of the equator. It is the angle between a line extending from the centre of the sun to the centre of the earth, and the projection of this line upon the earth's equatorial plane.
This is the direct consequence of the tilt and it would vary between 23.5° on June 22, to - 23.5° on December 22. At the time of winter solstice, the sun rays would be 23.5° south of the earth's equator (δ = -23.5°) At the time of summer solstice ,the sun's rays would be 23.5° north of the earth's equator (δ = 23 5°). At the equinoxes, the sun's declination would be zero. Fig. 2.3 shows approximately the variation of the sun's declination through the year.

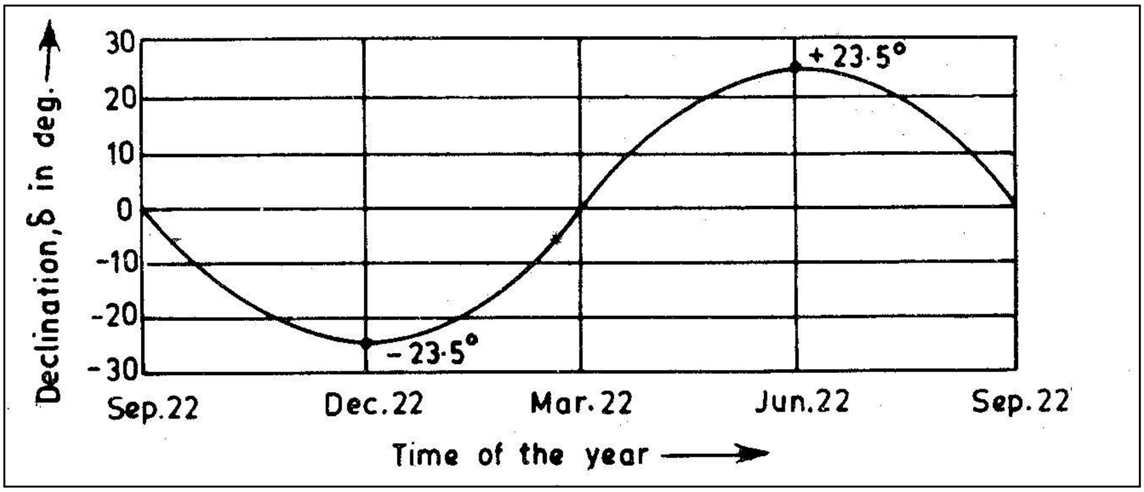


Fig 2.3 Variation of sun's declination.

The declination, in degrees, for any given day may be calculated from the approximate equation:

$$\delta = 23.45 \, sin\left[360 \times \frac{284+n}{365}\right] \qquad (2.1)$$

where n is the day of the year, [e.g. June 21, 1980 is the 173th (31 + 29 + 31 + 30 + 31 + 21) day of 1980, i.e. n = 173]. See Table 2.1.

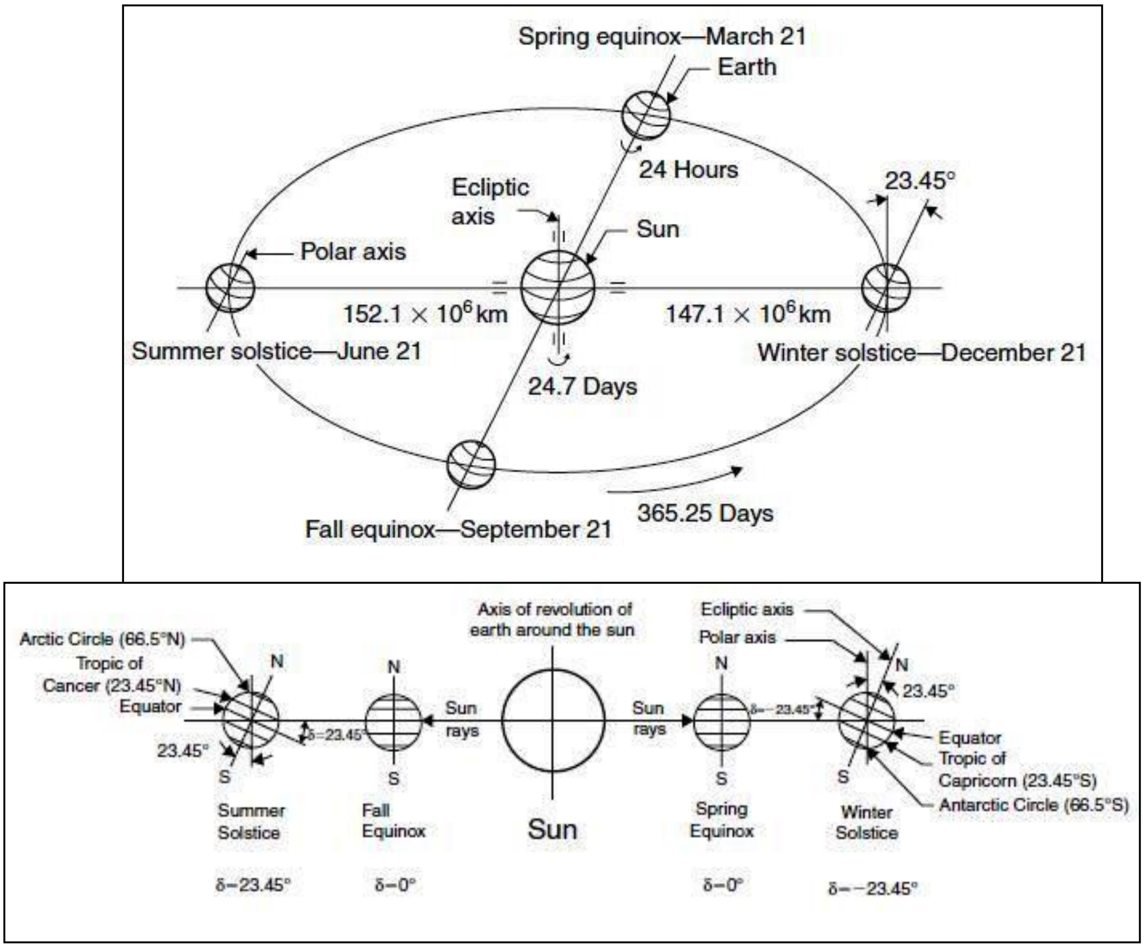


Figure 2.4 Annual motion of the earth about the sun.

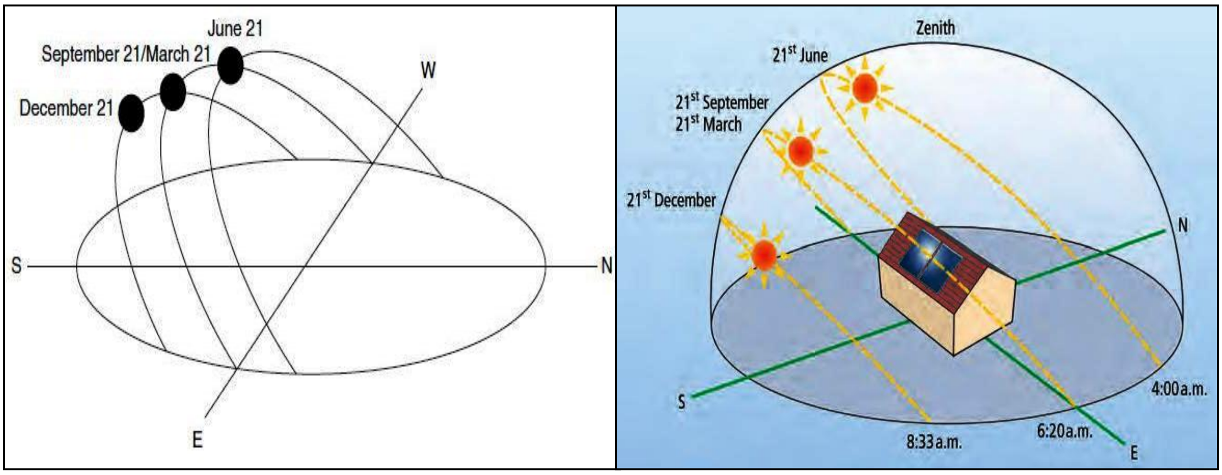


Figure 2.5 Annual changes in the sun's position in the sky (northern hemisphere).

Table 2.1 Day Number and Recommended Average Day for Each Month

Month	Day number	Average day of the month		
		Date	*N*	δ (deg.)
January	*i*	17	17	−20.92
February	31 + *i*	16	47	−12.95
March	59 + *i*	16	75	−2.42
April	90 + *i*	15	105	9.41
May	120 + *i*	15	135	18.79
June	151 + *i*	11	162	23.09
July	181 + *i*	17	198	21.18
August	212 + *i*	16	228	13.45
September	243 + *i*	15	258	2.22
October	273 + *i*	15	288	−9.60
November	304 + *i*	14	318	−18.91
December	334 + *i*	10	344	−23.05

2.3 Determination of Solar Time

All the values of time in solar energy computations are expressed in terms of apparent solar time (this is also known as true solar time). Thus we would be required to convert the clock time to the local solar time.

Greenwich meridian (zero longitude) is taken as reference for the time and time reckoned from mid night is known as universal time or Greenwich civil time (GCT or GMT). Such time is expressed on an hour scale from 0^h to 24^h.

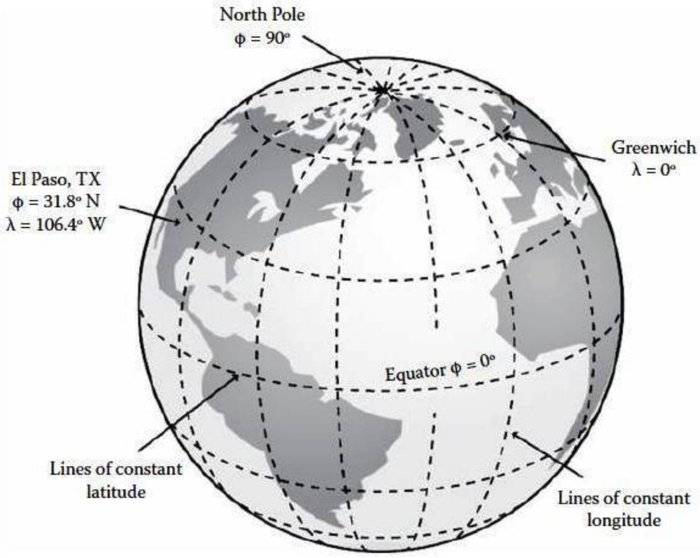


Figure 2.6 Earth coordinate system.

Local civil time (LCT or LMT) is reckoned from the longitude of the place on any particular meridian. On a particular place LCT is more advanced than at a point westward. The difference amounts to four minutes of time for each degree difference in longitude.

Time as measured by the apparent diurnal motion of the sun is called **Apparent Solar Time** or **Solar Time**. It is the time that would be shown by a sun dial whereas a civil day is precisely 24 hours, a solar day is slightly different due to irregularities of the earth's rotation, obliquity of the earth orbit and other factors, in other words due to the elliptical shape of the earth's orbit and to its increase in velocity at the perihelion, the length of the apparent solar day, *i.e.* the interval between two successive passages of the sun through the meridian, is not constant. Local civil time may deviate from true solar time by as much as 4.5^{o} because even if the length of any apparent solar day and its corresponding mean solar day differ little, the effect is cumulative.

The difference between local solar time LST and local civil time LCT is called the equation of time. Thus

$$LST = LCT + \text{Eq. of time} \qquad (2.2)$$

Table 2.2 shows weekly values of the equation of time for the year 1958, along with the values of the declination. For practical purposes, these values may be used for any year.

At a given locality, watch time may differ from civil time. Clocks are usually set for the same reading through an entire zone covering about 15^{o} of longitude. The time kept in each zone is the local civil time of a selected meridian near the centre of the zone. Such time is called standard time.

Local civil time is:

$$LCT = \text{Standard time} \pm (L_{st} - L_{local}) \times 4 \qquad (2.3)$$

and solar time

$$LST = \text{standard time} + E \pm (L_{st} - L_{local}) \times 4 \qquad (2.4)$$

(+ sign for west and - for east)

Where

E = the equation of time in minutes

L_{st} = the standard meridian for the local time zone,

L_{local} = the longitude of the location in question in degrees west or east.

Positive sign is for western and negative sign for eastern hemisphere.

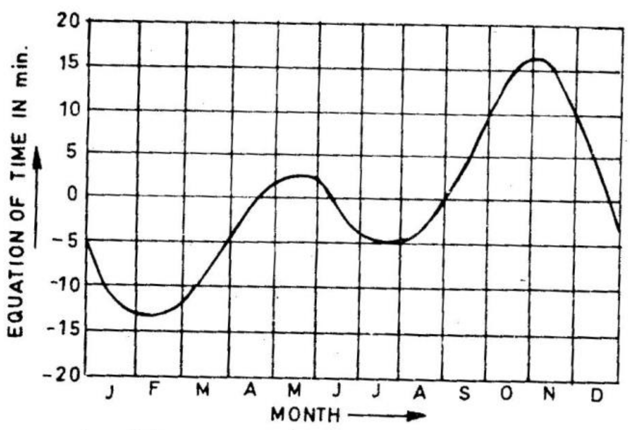


Fig. 2.6 Shows equation of time correction.

Hence we conclude that the time specified in all the sun-angle relationship is solar time, which does not coincide with the local clock time. It is necessary to convert standard time to solar time by applying two corrections. First there is a constant correction for any difference in longitude between the location and the meridian on which the local standard time is based (e.g. 82.5°E for India). The second correction is from the equation of time which takes into account the various perturbations in the earth's orbit and the rate of rotation which affect the time, the sun appears to cross the observer's meridian. This correction is obtained from published charts.

Table 2.2. Suns declination and equation of time.

Day→	*1*		*8*		*15*		*22*	
Month	*Dec. Deg : Min*	*Eq. of time Min : Sec*	*Dec. Deg : Min*	*Eq. of time Min : Sec*	*Dec. Deg : Min*	*Eq. of time Min : Sec*	*Dec. Deg : Min*	*Eq. of time Min : Sec*
January	– (23 : 08)	– (3 : 16)	– (22 : 20)	– (6 : 26)	– (21 : 15)	– (9 : 12)	– (19 : 50)	– (11 : 27)
February	– (17 : 18)	– (13 : 34)	– (15 : 13)	– (14 : 14)	– (12 : 55)	– (14 : 15)	– (10 : 27)	– (13 : 41)
March	– (7 : 51)	– (12 : 36)	– (5 : 10)	– (11 : 0)	– (2 : 25)	– (9 : 14)	0 : 21	–(7 : 12)
April	4 : 16	– (4 : 11)	6 : 56	– (12 : 07)	9 : 30	– (0 : 15)	11 : 57	1 : 19
May	14 : 51	2 : 50	16 : 53	3 : 31	18 : 41	3 : 44	20 : 14	3 : 30
June	21 : 57	2 : 25	22 : 47	1 : 15	23 : 17	– (0 : 09)	23 : 27	– (1 : 40)
July	23 : 10	– (3 : 33)	22 : 37	– (4 : 48)	21 : 2	– (5 : 45)	20 : 25	– (6 : 19)
August	18 : 12	– (6 : 17)	16 : 21	– (5 : 40)	14 : 17	– (4 : 35)	12 : 02	– (3 : 04)
September	8 : 33	– (0 : 15)	5 : 58	2 : 03	3 : 19	4 : 29	0 : 36	6 : 58
October	– (2 : 54)	10 : 02	– (5 : 36)	12 : 11	– (8 : 15)	13 : 59	– (10 : 48)	15 : 20
November	– (14 : 12)	16 : 20	– (16 : 22)	16 : 16	– (18 : 18)	15 : 29	– (19 : 59)	14 : 02
December	– (21 : 41)	11 : 14	– (22 : 28)	8 : 26	– (23 : 14)	5 : 13	– (23 : 27)	1 : 47

Example 2.1

Determine the local solar time corresponding to 10:00 a.m. on February 8 for a location India at 87.5° east longitude. The standard meridian for the local time zone is 82°.5'.

Solution

LCT = Slandered time - (L_{st} - L_{loc}) x 4 = 10.00 - (82.5 - 87.5) x 4

= 10.00 + 20' = 10:20 A.M.

From table (2.1), Eq. of time = - (14 min. 14 sec.)

LST = LCT+E = 10:20 - (14m 14s) = 10h 5m 46s

Example 2,2

Determine the LST and declination at Bhopal (latitude 23° 15' N, longitude 77° 30' E) at 12.30 on June 19. The standard meridian for the local time zone is 82°.30'.

Solution

LCT = standard time - (L_{st} - L_{loc}) x 4 = 12h 30m - (82° 30' - 77° 30') x 4

= 12h 30m - (5) x 4 = 12h 30m – 20m = 12:10

Local solar time is given by
LST = LCT + Eq. of time
From Table (2.1), equation of time *E* can be interpolated.
For June 19,   E = (1':01")
Hence

LST = 12h 10m - (1m 1s) = 12h 8m 59s

Declination δ can be found by using the equation,

$$\delta = 23.45\, sin\left[360\ \times \frac{284+n}{365}\right] = 23.45\, sin\left[360\ \times \frac{284+170}{365}\right]$$

$$= 23.45\, sin[446] = 23.45 \sin 86$$

$$= 23.45\ \times 0.9976 = 23.43^{\circ}$$

2.4 Derived solar angles

Besides the three basic angles, latitude, hour angle and sun's declination, certain additional angles are also useful in solar radiation analysis. If we stand at any place on the earth, the sun appears to move from horizon to horizon, and if we trace the path of the sun on the plane of the earth we get a semi-circular arc, as shown in Fig. 2.7. The three additional angles are shown in figure and are defined as follows.

Altitude angle α (solar altitude): It is a vertical angle between the projection of the sun's rays on the horizontal plane and the direction of sun's rays (passing through point).

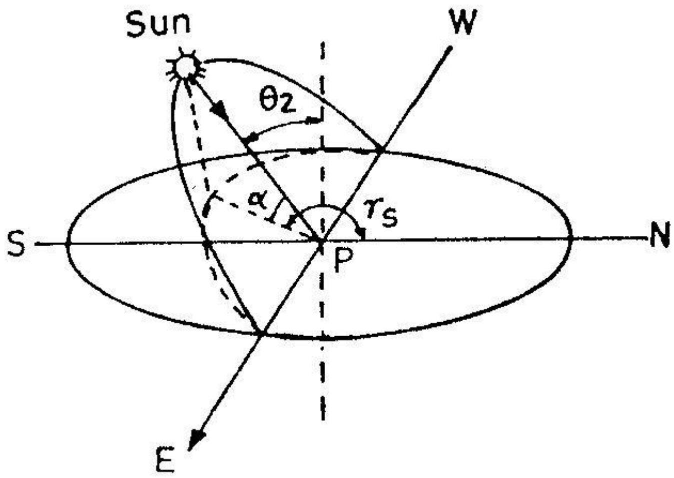


Fig. 2.7. Definitions and suns zenith. Altitude and azimuth angles.

Zenith angle (θ_z): It is complementary angle of sun's altitude angle. It is a vertical angle between the sun's rays and a line perpendicular to the horizontal plane through the point, *i.e.* the angle between the beam from the sun and the vertical

$$\theta_z = \frac{\pi}{2} - \alpha$$

Solar azimuth angle γ_z: It is the solar angle in degrees along the horizon east or west of north or it is a horizontal angle measured from north to the horizontal projection of the sun's rays. This angle is positive when measured west wise.

The derived solar angles can be represented in terms of three basic angles.

Fig. 2.8 shows a coordinate system with the z-axis coincident with the earth's axis. The *xy*-plane coincides with the earth's equatorial plane. The vector H_n representing the noon sun's rays lie in the *xy*-plane. The vector *PN* pointing north from point *P* is perpendicular to *OP* and lies in the plane containing *OP* and the z-axis.

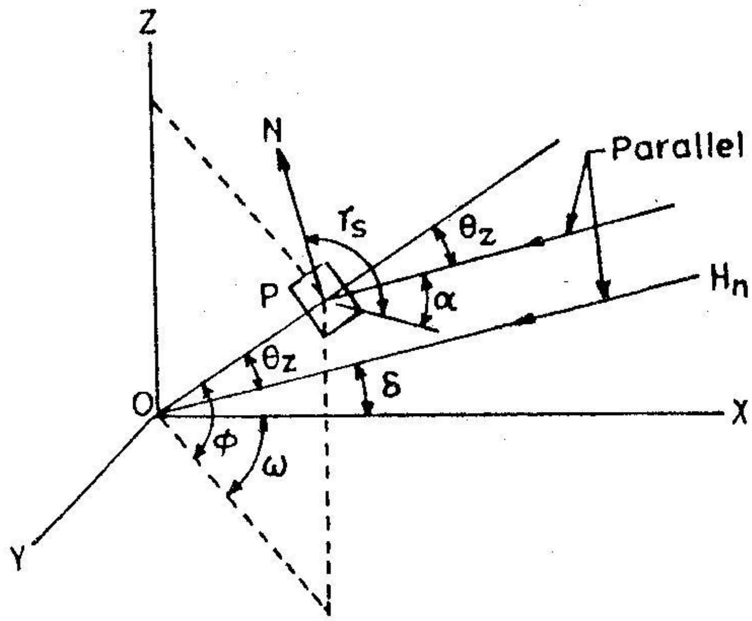


Fig. 2.8. Relation of a point on the earth's surface to Sun's rays.

Let a_1, b_1 and c_1 be the direction cosines of *OP* with respect to the x,y, and z-axes. Also let a_2, b_2 and c_2 be the corresponding direction cosine of H_n, thus

$a_1 = \cos\phi \cos\omega$,	$b_1 = \cos\phi \sin\omega$,	$c_1 = \sin\phi$
$a_2 = \cos\delta$,	$b_2 = 0$,	$c_2 = \sin\delta$

The sun's zenith angle θ_z is the angle between the vector *OP* and H_n. By a common equation from the analytic geometry, we have

$$\cos\theta_z = a_1a_2 + b_1b_2 + c_1c_2$$

Thus $$\cos\theta_z = \cos\phi \cos\omega \cos\delta + \sin\phi \sin\delta$$

Since $\theta_z = \pi/2 - \alpha$, we may write

$$\cos\theta_z = \sin\alpha = \cos\theta \cos\omega \cos\delta + \sin\phi \sin\delta \qquad (2.5)$$

By similar methods, we may show that the sun's azimuth (γs) in **Fig. 2.8** is given by the relations,

	$\cos \gamma_s = \sec \alpha (\cos \phi \sin \delta - \cos \delta \sin \phi \cos \omega)$	(2.6)
and	$\sin \gamma_s = \sec \alpha \cos \delta \sin \omega$	(2.7)

Equations (2.5) to (2.7) allow calculation of the sun's zenith, altitude and azimuth angles, if the declination, hour angle and latitude are known. If applying these equations, attention must be given to correct signs for the latitude and declination angles. If north latitudes are considered positive and south latitudes negative, the declination will be positive for the summer period between the vernal equinox and autumnal equinox (March 22 to September 22 approximately) and negative at other times.
For non-horizontal surfaces, the other angles, such as incident angle slope angle, surface azimuth angle etc. are important angles (**Fig. 2.9**).

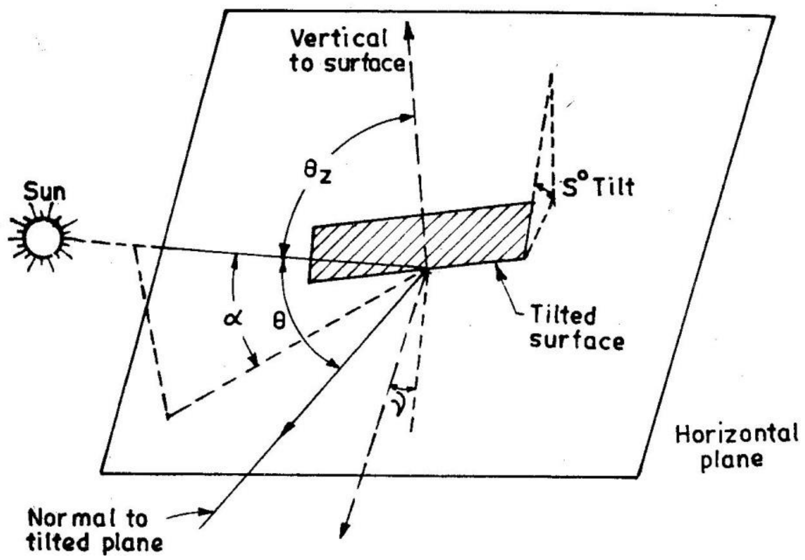


Fig. 2.9. Schematic representation of the solar *S*°*,* zenith angle θ_z, angle of incidence θ, the solar altitude angle α and the surface azimuth angle γ.

Surface Azimuth angle (γ): It is the angle of deviation of the normal to the surface from the local meridian, the zero point being south, east positive and west negative.

Incident angle (θ) It is the angle being measured between the beam of rays and normal to the plane.

Slope (s): The angle between the horizontal and the plane *(i.e.* the slope).

From spherical geometry the relation between θ and other angles is given by the equation:

$$\cos\theta = \sin\delta \sin\phi \cos s - \sin\delta \cos\phi \sin s \cos y$$
$$+ \cos\delta \cos\phi \cos s \cos\omega + \cos\delta \sin\phi \sin s \cos\gamma \cos\omega$$
$$+ \cos\delta \sin s \sin\gamma \sin\omega \quad (2.8)$$

Where
ϕ = latitude (north positive)
δ = declination (north positive)
ω= hour angle, it is positive between solar mid night and noon, otherwise negative.

At solar noon ω being zero and each hour equating 15° of longitude with morning positive and afternoon negative *(e.g.* $\omega = +15°$ for 11:00 and $\omega = -37.5°$ for (14;30) hour angle ω can be expressed mathematically as :

$$\omega = 15\,(12\text{-}LST)$$

In many cases, the equation relating these angles is simplified.
For example, for fixed flat plate collectors which face the equator, the last term drops out. For vertical surfaces, s = 90° and the first and third terms drop out. For horizontal surfaces where s = 0°, only the first and third terms remain and the angle of incidence *(i.e.* zenith, angle of the sun) is

$$\cos\theta_z = \sin\delta \sin\phi \cos s + \cos\delta \cos\phi \cos s \cos\omega \quad (2.9)$$
$$= \sin\alpha$$
i.e.
$$\cos\theta = \cos\theta_z = \sin\alpha \quad (2.10)$$

Useful relationship for the angle of incidence on surfaces sloped to the north or south can be derived from the fact that surface with slope s to the north or south have the same angular relationship to beam radiation on a horizontal surface at artificial latitude of (ϕ - *s).* Modifying equation (2.9)

$$\cos\theta_T = \cos(\phi - s)\cos\delta \cos\omega + \sin(\phi - s)\sin\delta \quad (2.11)$$

It is to be noted here that s, is measured from the horizontal to the plane of the surface in equation, and is positive when slope is towards the south.

2.5. Sunrise, Sunset and Day Length

At the time of sunrise (or sunset), the zenith angle, θ_z = 90°. Substituting this in equation (2.9), Sunrise hour angle,

$$\cos\omega_s = -\frac{\sin\phi\ \sin\delta}{\cos\phi\ \sin\delta} = -\tan\phi\ \tan\delta$$

$$\omega_s = \cos^{-1}(-\tan\phi\ \tan\delta) \qquad (2.12)$$

The day length is

$$T_d = 2\omega_s$$

$$T_d = \frac{2}{15}\cos^{-1}(-\tan\phi\ \tan\delta) \qquad (2.13)$$

Therefore, the length of the day is a function of latitude and solar declination.

The hour angle at sunrise or sunset on an inclined surface $\omega st'$ will be lesser than the value obtained by equation (2.12) if the corresponding incidence angle comes out to be more than 90°. Under this condition, by putting θ = 90° in Equation (3.8.4), or one of its simpler versions. Thus, for an inclined surface facing south, substituting θ= 90°, in equation (2.8), we obtain

$$\omega_{st} = \cos^{-1}(-\tan(\phi - s)\ \tan\delta) \qquad (2.14)$$

The corresponding day length (in hours) is then given by

$$T_d = \frac{2}{15}\cos^{-1}(-\tan(\phi - s)\ \tan\delta) \qquad (2.15)$$

From equation (2.8) we can derive for south facing surface

$$\cos\theta T = \cos(\phi - s)\cos\delta\cos\omega + \sin(\phi - s)\ \sin\delta \qquad (2.15)$$

Example 2.3

Calculate the angle made by beam radiation with normal to a fiat plate collector on December 1, at 9.00 AM. solar time for a location at 28° 35' N. The collector is tilted at an angle of latitude plus 10°, with the horizontal and is pointing due south.

Solution

γ = 0, since collector is pointing due south.

Equation applicable is,

$$\cos\theta_T = \cos(\phi - s)\cos\delta\cos\omega + \sin(\phi - s)\ \sin\delta \qquad \text{(i)}$$

Declination on December 1 *(n* = 335), can be obtained by:

$$\delta = 23.45\sin\left[360\ \times\frac{284+n}{365}\right] = 23.45\sin\left[360\ \times\frac{284+335}{365}\right] = -22{,}11^o$$

Hour angle ω corresponding to 9.00 hr = 45°
Substituting these values in equation (i),

$\cos \theta_T = \cos (28.58° - 38.58°) \cos (-22.11°) \cos 45° + \sin (-22.11°) \sin (28.58° - 38.58°)$
$= \cos 10° \cos 22.11° \cos 45° + \sin 22.11° \sin 10°$
$= 0.6451 + 0.0653 = 0.7104$
$\theta_T = 44.72°$

Example 2.4
Calculate the sun's altitude angle and azimuth angle at 7:30 a.m. solar time on August1 for a location at 40 degrees north latitude.
Solution
Given data $\phi = 40°$ N
$\omega = 15 \times (12-7.5) = 67° 30'$
Declination can be found by

$$\delta = 23.45\, sin\left[360\ \times \frac{284+n}{365}\right] = 23.45\, sin\left[360\ \times \frac{284+213}{365}\right] = 23.45 \times 0.7638 = 17.91°$$

$\cos \theta_z = \sin \alpha = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta$
Total altitude angle α:
$\sin \alpha = \cos 40 \cos 17.91° \cos 67.5 + \sin 40 \sin 18.75$
$= 0.7660 \times 0.9515 \times 0.3827 + 0.6428 \times 0.3075 = 0.4766$
$\alpha = 28.46°$
Solar azimuth angle (γ_s)
$\text{Sin}\ \gamma_s = \sec \alpha \cos \delta \sin \omega$
$= \sec 28.93 \cos 17.91 \sin 67.5$
$= 1.1374 \times 0.9515 \times 0.9238 = 0.9998$
$\gamma_s = 88{,}85°$

Example 2.5
Determine the solar time and azimuth angle for sunrise on August 1, for a location of 40° N latitude.
Solution
At sunrise or, sunset α = 0, we have the equation

$\sin \alpha = \cos \phi \cos \delta \cos \omega s + \sin \phi \sin \delta$
$\cos \omega s = - \tan \phi \tan \delta$

$\delta = 17.91°$ as calculated in example 2.4
$\cos \omega_s = - \tan 40 \tan 17.91 = 0.3231 \times 0.8990$
$= 105.73°$
Sunrise occurs at 105.73/15 = 7.048 hours prior to solar noon or at 4:32 a.m. solar time and sunset occurs at 7:28 p.m. solar time.

Azimuth angle γs for sunrise, *i.e.* $\alpha = 0$

$\sin \gamma_s = \sec \alpha \cos \delta \sin \omega$

$= \cos \delta \sin \omega$

$= \cos 17.91 \sin 105.73°$

$= 0.9625 \times 0.9576 = 0.92119$

$\gamma_s = 67.174$ east of north

Example 2.6

Calculate the day length at location (latitude 28° 35' N, longitude = 77° 12' E). on December 1.

Solution

Day length is given by the expression

$$T_d = \frac{2}{15} cos^{-1}(-tan\phi \ tan\delta)$$

Declination 0 on Dec. 1 *(i.e. n* = 335)

$$\delta = 23.45 \ sin\left[360 \ \times \frac{284+n}{365}\right] = 23.45 \ sin\left[360 \ \times \frac{284+335}{365}\right] = -22.107^o$$

$$T_d = \frac{2}{15} cos^{-1}(-tan 28{,}58 \ \tan(-22.107)) = \frac{2 \times 77}{15} = 10.3 \ hrs$$

2.1 Extraterrestrial Solar Radiation

The amount of solar energy per unit time, at the mean distance of the earth from the sun, received on a unit area of a surface normal to the sun (perpendicular to the direction of propagation of the radiation) outside the atmosphere is called the **solar constant**, I_{sc}. This quantity is difficult to measure from the surface of the earth because of the effect of the atmosphere.

Solar constant I_{sc}= 1353 W/m^2 = 4871 kJ/m^2 = 1165 kcal/hr m^2

The total radiation, H_o, incident on an extraterrestrial horizontal surface during a day can be obtained by equation

$$H_o = \frac{24}{\pi} I_{SC}\left[\left\{1 + 0.033 \ cos\left(\frac{360 \ n}{365}\right)\right\}\left(cos\phi \ cos\delta \ sin\omega_s + \frac{2\pi\omega_s}{360} sin\phi \ sin\delta\right)\right]$$

Where

H_o = the average monthly insolation at the top of the atmosphere

I_{sc} = solar constant per hour

n = day of the years

ω_s = sunrise hour angle

Estimation of average solar radiation on the earth

The average solar radiation is

$$H_{av} = H_o\left(a + b\frac{\bar{n}}{N}\right)$$

Where
H_{av} = monthly average horizontal solar radiation
n = average daily hours of bright sunshine for same period
N = maximum daily hours of bright sunshine for the same period, or N = day length T_d
a and b = the modified constants depending upon the location.

Constant a and b for various locations and climate conditions can be obtained from slandered tables.

Example
Determine the value of H_{av} over a horizontal surface for June 22, at the latitude of 10° N, if a = 0.3, b = 0.51 and n/N = 0.55.
Solution

$$H_o = \frac{24}{\pi}I_{SC}\left[\left\{1 + 0.033\ cos\left(\frac{360\ n}{365}\right)\right\}\left(cos\phi\ cos\delta\ sin\omega_s + \frac{2\pi\omega_s}{360}sin\phi\ sin\delta\right)\right]$$

δ = +23.5° (on June 22)
Sunrise hour angle,

$$\omega_s = cos^{-1}(-tan\phi\ tan\delta) = cos^{-1}(-tan10\ tan23.5) = cos^{-1}(-0.1767 \times 0.4348)$$
$$= cos^{-1}(-0.0766)$$
$$\omega_s = 94.39^o$$

n = 172 for June 22

$$H_o = \frac{24}{3.14}I_{SC}\left[\left\{1 + 0.033\ cos\left(\frac{360\ \times 172}{365}\right)\right\}\left(cos10\ cos23.5\ sin94.39 + \frac{2 \times 3.14 \times 94.39}{360}sin10\ sin23.5\right)\right]$$

$$= \frac{24}{3.14}I_{SC}[\{1 + 0.033\ (-9.837)\}(0.9848 \times 0.9171 \times 0.997 + 1.65 \times 0.1736 \times 0.3987)]$$

$$H_o = \frac{24}{3.14}I_{SC} \times 0.9816$$

The value of I_{sc} is 1353 W/m^2

$$H_o = \frac{24}{3.14} \times 1353 \times 0.9816 = 10143\ \text{W/m}^2\ \text{day}$$

$$H_{av} = 10143(0.3 + 0.51 \times 0.55) = 5883\ W/m^2day$$

Chapter 3

Solar Energy Collectors

Solar collectors are special kinds of heat exchangers that transform solar radiation energy to internal energy of the transport medium. The major component of any solar system is the solar collector. This is a device that absorbs the incoming solar radiation, converts it into heat, and transfers the heat to a fluid (usually air, water, or oil) flowing through the collector. The solar energy collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment or to a thermal energy storage tank, from which it can be drawn for use at night or on cloudy days.
There are basically two types of solar collectors:

1- non-concentrating or stationary and 2- concentrating.

A non-concentrating collector has the same area for intercepting and absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux. Concentrating collectors are suitable for high-temperature applications. Solar collectors can also be distinguished by the type of heat transfer liquid used (water, non-freezing liquid, air, or heat transfer oil) and whether they are covered or uncovered. A large number of solar collectors are available on the market. A comprehensive list is shown in Table 3.1

Table 3.1 Solar Energy Collectors

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat-plate collector (FPC)	Flat	1	30–80
	Evacuated tube collector (ETC)	Flat	1	50–200
	Compound parabolic collector (CPC)	Tubular	1–5	60–240
Single-axis tracking			5–15	60–300
	Linear Fresnel reflector (LFR)	Tubular	10–40	60–250
	Cylindrical trough collector (CTC)	Tubular	15–50	60–300
	Parabolic trough collector (PTC)	Tubular	10–85	60–400
Two-axis tracking	Parabolic dish reflector (PDR)	Point	600–2000	100–1500
	Heliostat field collector (HFC)	Point	300–1500	150–2000
Note: Concentration ratio is defined as the aperture area divided by the receiver/absorber area of the collector.				

3.1 Stationary collectors

Solar energy collectors are basically distinguished by their motion—stationary, single-axis tracking, and two-axis tracking—and the operating temperature. First, we'll examine the stationary solar collectors. These collectors are permanently fixed in position and do not track the sun. Three main types of collectors fall into this category

1. Flat-plate collectors (FPCs).
2. Stationary compound parabolic collectors (CPCs).
3. Evacuated tube collectors (ETCs).

3.1.1 Flat-Plate Collectors (FPCs)

A typical flat-plate solar collector is shown in Figure 3.1. When solar radiation passes through a transparent cover and impinges on the blackened absorber surface of high absorptivity, a large portion of this energy is absorbed by the plate and transferred to the transport medium in the fluid tubes, to be carried away for storage or use. The underside of the absorber plate and the two sides are well insulated to reduce conduction losses.

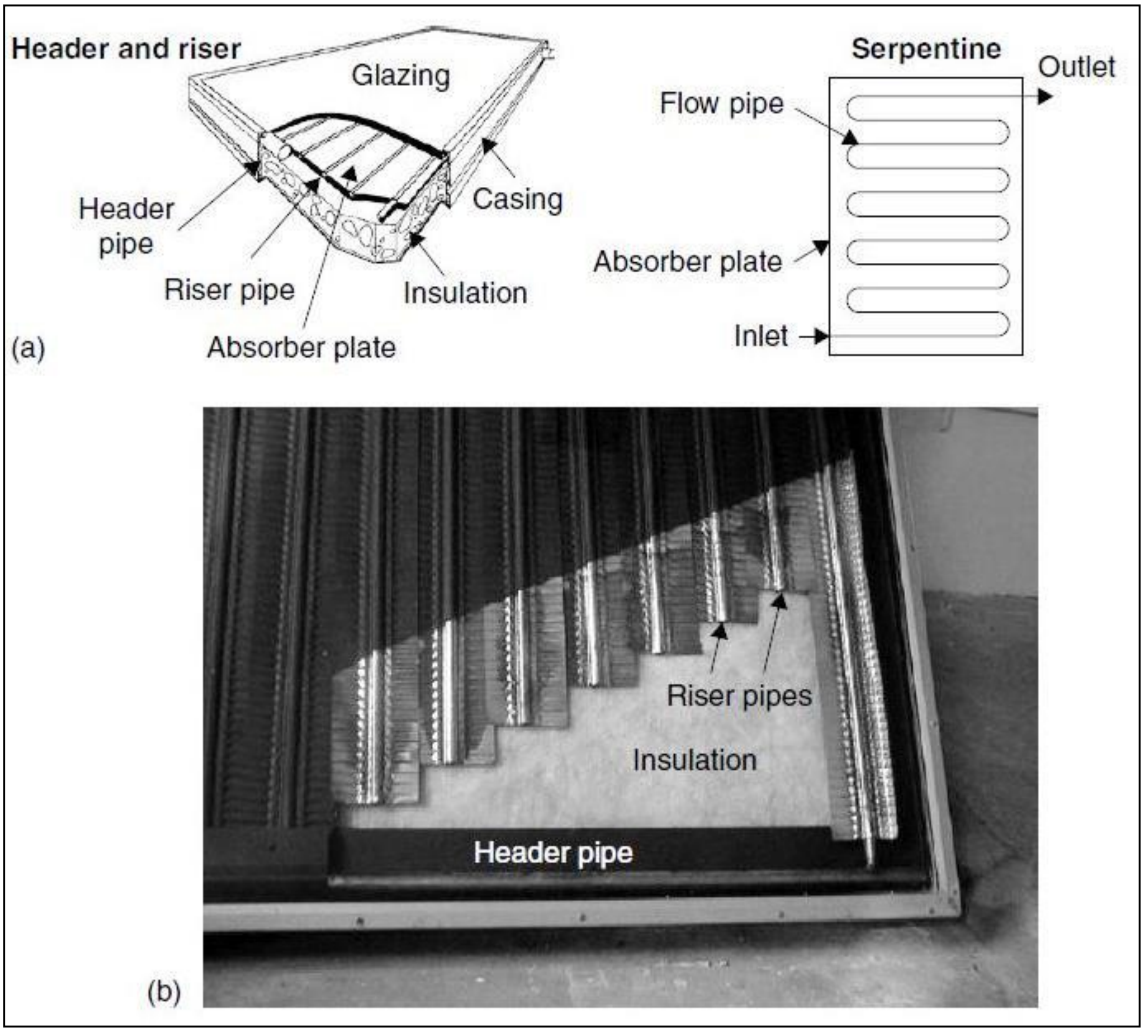


Figure 3.1 Typical flat-plate collector. (a) Pictorial view of a flat-plate collector. (b) Photograph of a cut header and riser flat-plate collector.

The liquid tubes can be welded to the absorbing plate or they can be an integral part of the plate. The liquid tubes are connected at both ends by large-diameter header tubes. The header and riser collector is the typical design for flat-plate collectors. An alternative is the serpentine design shown on the right-hand side of Figure 3.1a. This collector does not present the potential problem of uneven flow distribution in the various riser tubes of the header and riser design, but serpentine collectors cannot work effectively in thermosiphon mode (natural circulation) and need a pump to circulate the heat transfer fluid (see Chapter 5). The absorber plate can be a single sheet on which all risers are fixed, or each riser can be fixed on a separate fin, as shown in Figure 3.1b.
The transparent cover is used to reduce convection losses from the absorber plate through the restraint of the stagnant air layer between the absorber plate and the glass. It also reduces radiation losses from the collector because the glass is transparent to the shortwave radiation received by the sun, but it is nearly opaque to longwave thermal radiation emitted by the absorber plate (greenhouse effect).
The advantages of flat-plate collectors are that they are inexpensive to manufacture, they collect both beam and diffuse radiation, and they are permanently fixed in position, so no tracking of the sun is required. The collectors should be oriented directly toward the equator, facing south in the Northern Hemisphere and north in the Southern Hemisphere. The optimum tilt angle of the collector is equal to the latitude of the location, with angle variations of 10° to 15° more or less, depending on the application. If the application is solar cooling, then the optimum angle is latitude -10° so that the sun will be perpendicular to the collector during summertime, when the energy will be mostly required. If the application is space heating, then the optimal angle is latitude +10° ; whereas for annual hot water production, it is latitude +5° , to have relatively better performance during wintertime, when hot water is mostly required.

The main components of a flat-plate collector, as shown in Figure 3.2, are the following:

1. **Cover**: One or more sheets of glass or other radiation-transmitting material.
2. **Heat removal fluid passageways**: Tubes, fins, or passages that conduct or direct the heat transfer fluid from the inlet to the outlet.
3. **Absorber plate**: Flat, corrugated, or grooved plates, to which the tubes, fins, or passages are attached. A typical attachment method is the embedded fixing shown in the detail of Figure 3.2. The plate is usually coated with a high-absorptance, low-emittance layer.
4. **Headers or manifolds**: Pipes and ducts to admit and discharge the fluid.
5. **Insulatio:** Used to minimize the heat loss from the back and sides of the collector.
6. **Containe:** The casing surrounds the aforementioned components andprotects them from dust, moisture, and any other material.

Flat-plate collectors have been built in a wide variety of designs and from many different materials. They have been used to heat fluids such as water, water plus antifreeze additive, or air. Their major purpose is to collect as much solar energy as possible at the lowest possible total cost. The collector should also have a long effective life, despite the adverse effects of the sun's ultraviolet radiation and corrosion and clogging because of acidity, alkalinity, or hardness of the heat transfer fluid, freezing of water, or deposition of dust or moisture on the glazing and breakage of the glazing from thermal expansion, hail, vandalism, or other causes. These causes can be minimized by the use of tempered glass.

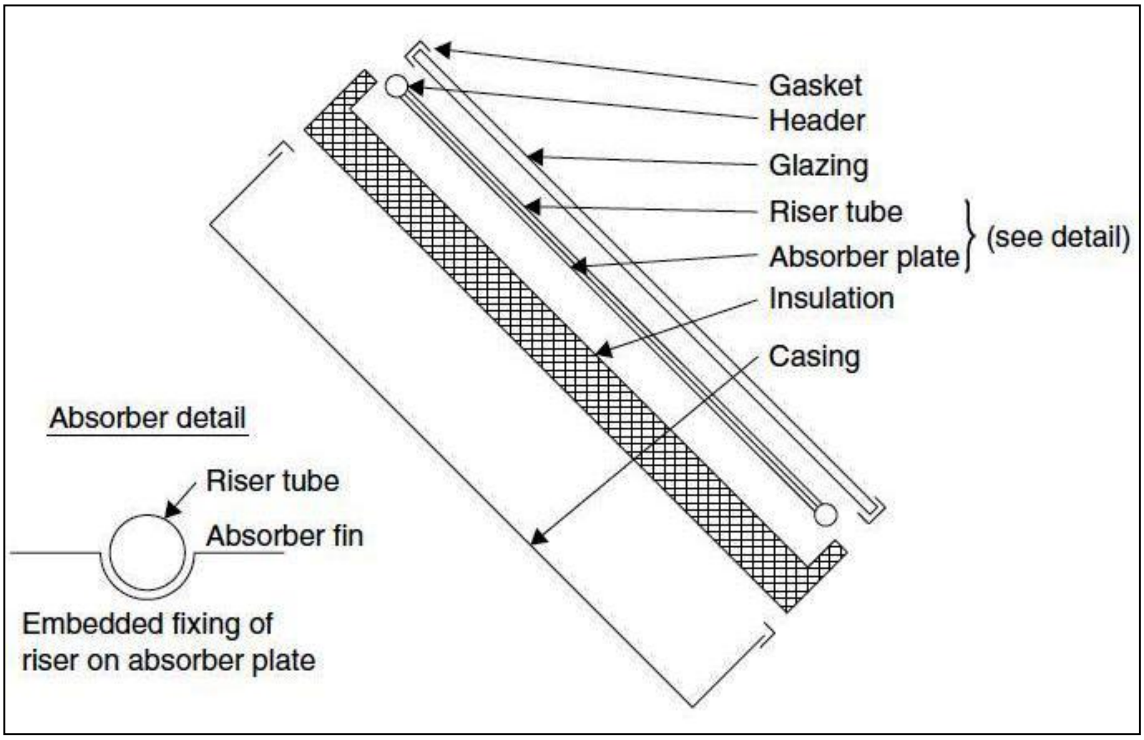


Figure 3.2 Exploded view of a flat-plate collector and absorber details.

Glazing materials

Glass has been widely used to glaze solar collectors because it can transmit as much as 90% of the incoming shortwave solar irradiation while transmitting virtually none of the longwave radiation emitted outward by the absorber plate. Window glass usually has high iron content and is not suitable for use in solar collectors. Glass with low iron content has a relatively high transmittance for solar radiation (approximately 0.85–0.90 at normal incidence), but its transmittance is essentially zero for the longwave thermal radiation (5.0–50 μm) emitted by sun-heated surfaces.

Plastic films and sheets also possess high shortwave transmittance, but because most usable varieties also have transmission bands in the middle of the thermal radiation spectrum, they may have longwave transmittances as high as 0.40. Additionally, plastics are generally limited in the temperatures they can sustain without deteriorating or undergoing dimensional changes. Only a few types of plastics can withstand the sun's

ultraviolet radiation for long periods. However, they are not broken by hail or stones, and in the form of thin films, they are completely flexible and have low mass.
The commercially available grades of window and greenhouse glass have normal incidence transmittances of about 0.87 and 0.85, respectively. For direct radiation, the transmittance varies considerably with the angle of incidence. Antireflective coatings and surface texture can improve transmission significantly.
The effect of dirt and dust on collector glazing may be quite small, and the cleansing effect of an occasional rainfall is usually adequate to maintain the transmittance within 2–4% of its maximum value. Dust is collected mostly during summertime, when rainfall is less frequent, but due to the high magnitude of solar irradiation during this period, the dust protects the collector from overheating.
The glazing should admit as much solar irradiation as possible and reduce the upward loss of heat as much as possible. Although glass is virtually opaque to the longwave radiation emitted by the collector plates, absorption of that radiation causes an increase in the glass temperature and a loss of heat to the surrounding atmosphere through radiation and convection.

Collector absorbing plates

The collector plate absorbs as much of the irradiation as possible through the glazing, while losing as little heat as possible upward to the atmosphere and downward through the back of the casing. The collector plates transfer the retained heat to the transport fluid. To maximize the energy collection, the absorber of a collector should have a coating that has high absorptance for solar radiation (short wavelength) and a low emittance for re-radiation (long wavelength). Such a surface is referred as a selective surface. The absorptance of the collector surface for shortwave solar radiation depends on the nature and color of the coating and on the incident angle. Usually black color is used.
By suitable electrolytic or chemical treatment, surfaces can be produced with high values of solar radiation absorptance (α) and low values of longwave emittance (ε). Essentially, typical selective surfaces consist of a thin upper layer, which is highly absorbent to shortwave solar radiation but relatively transparent to longwave thermal radiation, deposited on a surface that has a high reflectance and low emittance for longwave radiation. Selective surfaces are particularly important when the collector surface temperature is much higher than the ambient air temperature. The cheapest absorber coating is matte black paint; however, this is not selective, and the performance of a collector produced in this way is low, especially for operating temperatures more than 40°C above ambient.
An energy-efficient solar collector should absorb incident solar radiation, convert it to thermal energy, and deliver the thermal energy to a heat transfer medium with minimum losses at each step. It is possible to use several design principles and physical mechanisms to create a selective solar-absorbing surface. Solar absorbers referred to as tandem absorbers, are based on two layers with different optical properties. A semiconducting or dielectric coating with high solar absorptance and high infrared transmittance on top of a nonselective, highly reflecting material such as metal

constitutes one type of tandem absorber. Another alternative is to coat a non-selective, highly absorbing material with a heat mirror that has a high solar transmittance and high infrared reflectance.

Today, commercial solar absorbers are made by electroplating, anodization, evaporation, sputtering, and applying solar selective paints. Of the many types of selective coatings developed, the most widely used is black chrome Much of the progress in recent years has been based on the implementation of vacuum techniques for the production of fin-type absorbers used in low-temperature applications. The chemical and electrochemical processes used for their commercialization were readily taken over from the metal finishing industry.

The requirements of solar absorbers used in high-temperature applications, however—namely, extremely low thermal emittance and high temperature stability—were difficult to fulfill with conventional wet processes. Therefore, large-scale sputter deposition was developed in the late 1970s. Nowadays, the vacuum techniques are mature, are characterized by low cost, and have the advantage of being less environmentally polluting than the wet processes.

Collector construction

For fluid-heating collectors, passages must be integral with or firmly bonded to the absorber plate. A major problem is obtaining a good thermal bond between tubes and absorber plates without incurring excessive costs for labor or materials. The materials most frequently used for collector plates are copper, aluminum, and stainless steel. UV-resistant plastic extrusions are used for low-temperature applications. If the entire collector area is in contact with the heat transfer fluid, the thermal conductance of the material is not important.

The convective heat loss in a collector is relatively insensitive to the spacing between the absorber and the cover in the range of 15–40 mm. The back insulation of a flat-plate collector is made from fiberglass or a mineral fiber mat that will not outgas at elevated temperatures. Building-grade fiberglass is not satisfactory because the binders evaporate at high temperature and then condense on the collector cover, blocking incoming solar radiation.

Figure 3.3 shows a number of absorber plate designs for solar water and air heaters that have been used with varying degrees of success. Figure 3.3a shows a bonded sheet design, in which the fluid passages are integral to the plate to ensure good thermal conduct between the metal and the fluid. Figures 3.3b and 3.3c show fluid heaters with tubes soldered, brazed, or otherwise fastened to upper or lower surfaces of sheets or strips of copper (see also the details in Figure 3.2). Copper tubes are used most often because of their superior resistance to corrosion.

Thermal cement, clips, clamps, or twisted wires have been tried in the search for low-cost bonding methods. Figure 3.3d shows the use of extruded rectangular tubing to obtain a larger heat transfer area between tube and plate. Mechanical pressure, thermal cement, or brazing may be used to make the assembly. Soft solder must be avoided because of the high plate temperature encountered at stagnation conditions, which could melt the solder.

The major difference between air- and water-based collectors is the need to design an absorber that overcomes the heat transfer penalty caused by lower heat transfer coefficients between air and the solar absorber. Air or other gases can be heated with flat-plate collectors, particularly if some type of extended surface (Figure 3.3e) is used to counteract the low heat transfer coefficients between metal and air.

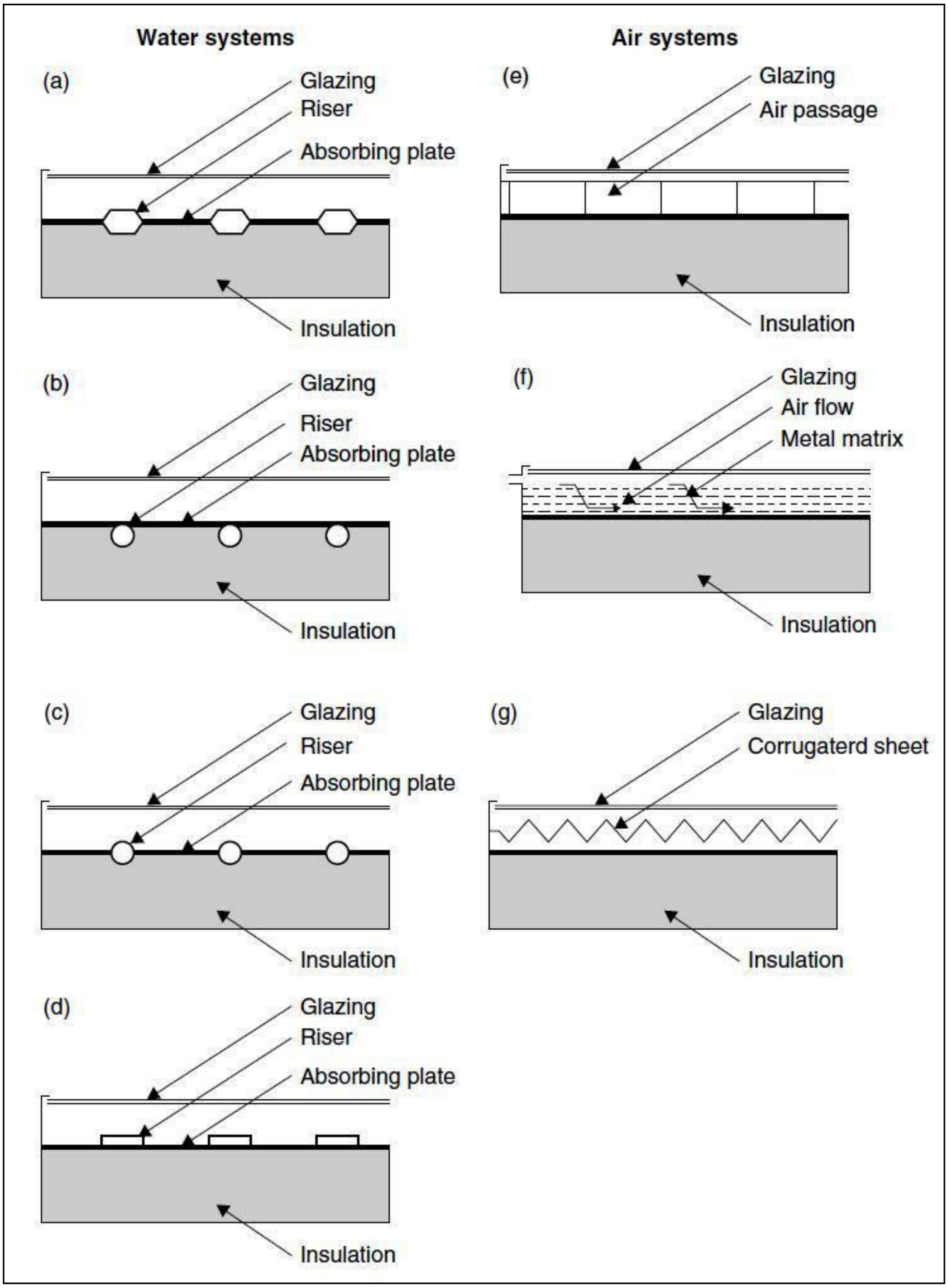


Figure 3.3 Various types of flat-plate solar collector absorber configurations for water and air.

Metal or fabric matrices (Figure 3.3f), thin corrugated metal sheets (Figure 3.3g), or porous absorbers may be used, with selective surfaces applied to the latter when a high level of performance is required. The principal requirement of these designs is a large contact area between the absorbing surface and the air. The thermal capacity of air is much lower than water, hence larger volume flow rates of air are required, resulting in higher pumping power.

Reduction of heat loss from the absorber can be accomplished either by a selective surface to reduce radiative heat transfer or by suppressing convection.

Flat-plate collectors (FPCs) are by far the most-used type of collector. Flat−plate collectors are usually employed for low-temperature applications, up to 80^{o}C, although some new types of collectors employing vacuum insulation or transparent insulation (TI) can achieve slightly higher values.

Lately some modern manufacturing techniques such as the use of ultrasonic welding machines have been introduced by the industry that improves both the speed and the quality of welds. This is used for welding of fins on risers, to improve heat conduction. The greatest advantage of this method is that the welding is performed at room temperature; therefore, deformation of the welded parts is avoided.

3.1.2 Compound Parabolic Collectors (CPCs)

Compound parabolic collectors (CPCs) are non-imaging concentrators. They have the capability of reflecting to the absorber all of the incident radiation within wide limits. The necessity of moving the concentrator to accommodate the changing solar orientation can be reduced by using a trough with two sections of a parabola facing each other, as shown in Figure 3.5.

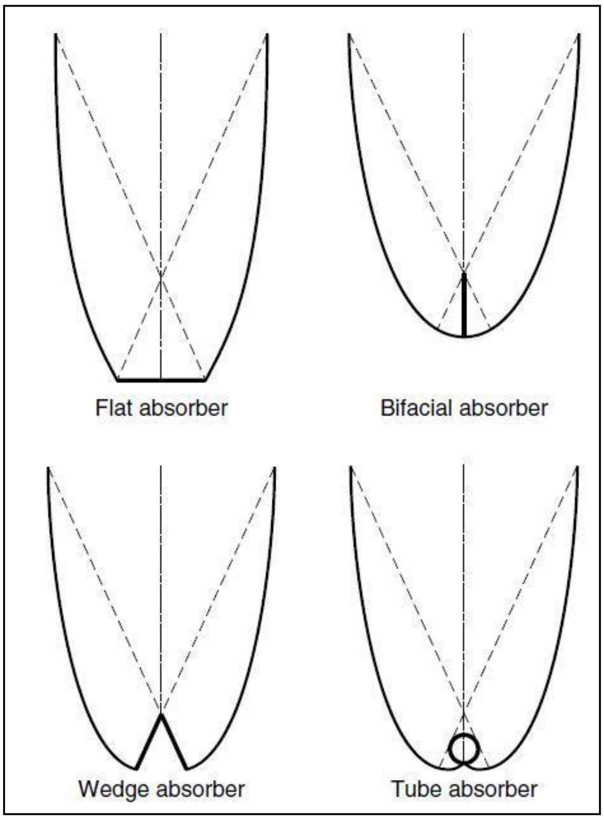


Figure 3.5 Various absorber types of CPCs.

Compound parabolic concentrators can accept incoming radiation over a relatively wide range of angles. By using multiple internal reflections, any radiation entering the aperture within the collector acceptance angle finds its way to the absorber surface located at the bottom of the collector. The absorber can take a variety of configurations. It can be flat, bifacial, wedge, or cylindrical, as shown in Figure 3.5.

Two basic types of CPC collectors have been designed: symmetric and asymmetric. CPCs usually employ two main types of absorbers: the fin type with a pipe and tubular absorbers. The fin type can be flat, bifacial, or wedge, as shown in Figure 3.5 for the symmetric type, and can be single channel or multichannel.

Compound parabolic collectors should have a gap between the receiver and the reflector to prevent the reflector from acting as a fin conducting heat away from the absorber. Because the gap results in a loss of reflector area and a corresponding loss of performance, it should be kept small. This is more important for flat receivers.

For higher-temperature applications a tracking CPC can be used. When tracking is used, this is very rough or intermittent, since the concentration ratio is usually small and radiation can be collected and concentrated by one or more reflections on the parabolic surfaces.

Compound parabolic collectors can be manufactured either as one unit with one opening and one receiver (see Figure 3.5) or as a panel (see Figure 3.6a). When constructed as a panel, the collector looks like a flat-plate collector, as shown in Figure 3.6b.

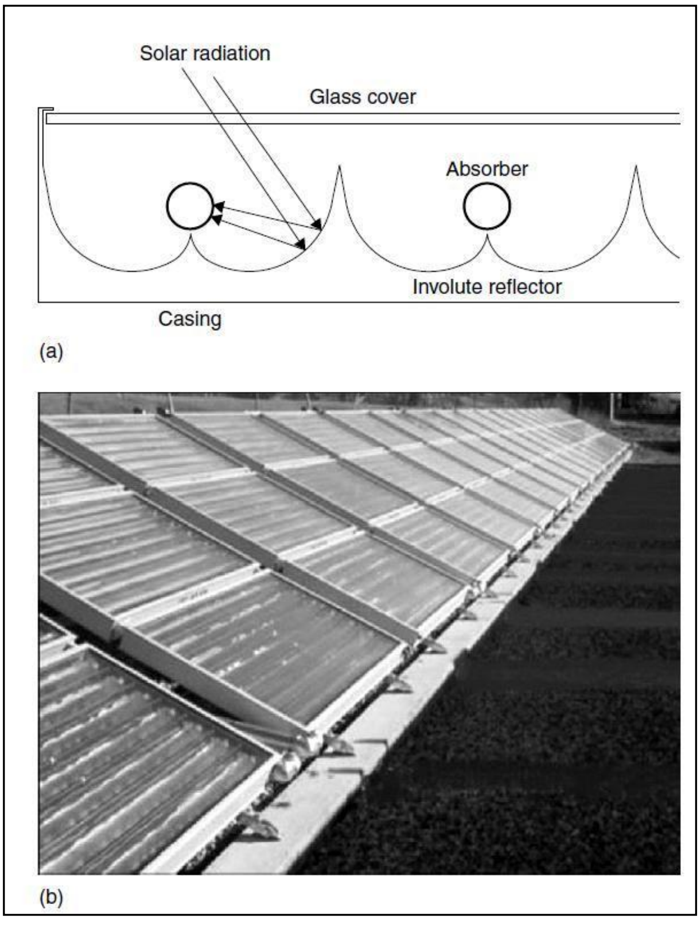


Figure 3.6 Panel CPC collector with cylindrical absorbers. (a) Schematic diagram. (b) Photo of a CPC panel collector installation.

3.1.3 Evacuated Tube Collectors (ETCs)

Conventional simple flat-plate solar collectors were developed for use in sunny, warm climates. Their benefits, however, are greatly reduced when conditions become unfavorable during cold, cloudy, and windy days. Furthermore, weathering influences, such as condensation and moisture, cause early deterioration of internal materials, resulting in reduced performance and system failure. Evacuated heat pipe solar collectors (tubes) operate differently than the other collectors available on the market. These solar collectors consist of a heat pipe inside a vacuum-sealed tube, as shown in Figure 3.7.

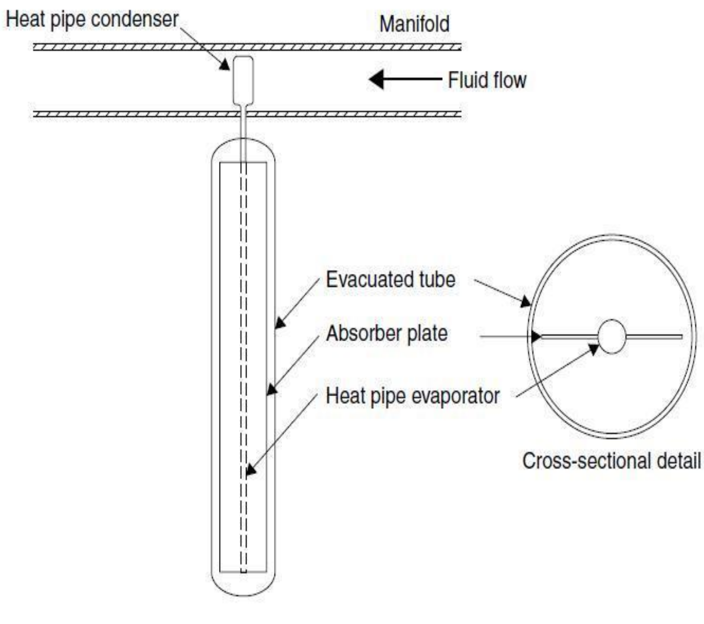


Figure 3.7 Schematic diagram of an evacuated tube collector.

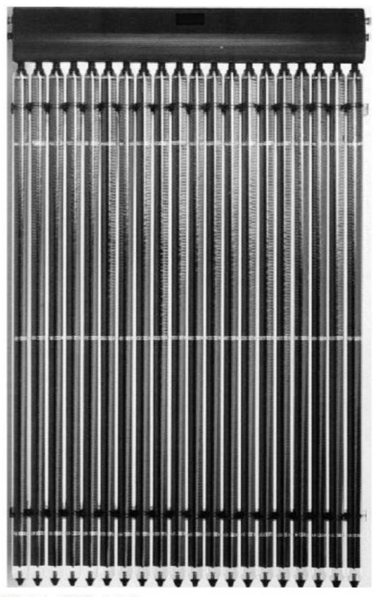


Figure 3.8 Actual ETC installation.

In an actual installation, many tubes are connected to the same manifold as shown in Figure 3.8. Evacuated tube collectors (ETCs) have demonstrated that the combination of a selective surface and an effective convection suppressor can result in good performance at high temperatures. The vacuum envelope reduces convection and conduction losses, so the collectors can operate at higher temperatures than flat-plate collectors. Like flat-plate collectors, they collect both direct and diffuse radiation. However, their efficiency is higher at low incidence angles.

This effect tends to give evacuated tube collectors an advantage over flat-plate collectors in terms of daylong performance. Evacuated tube collectors use liquid-vapor phase change materials to transfer heat at high efficiency. These collectors feature a heat

pipe (a highly efficient thermal conductor) placed inside a vacuum-sealed tube. The pipe, which is a sealed copper pipe, is then attached to a black copper fin that fills the tube (absorber plate). Protruding from the top of each tube is a metal tip attached to the sealed pipe (condenser). The heat pipe contains a small amount of fluid (e.g., methanol) that undergoes an evaporating-condensing cycle. In this cycle, solar heat evaporates the liquid and the vapor travels to the heat sink region, where it condenses and releases its latent heat. The condensed fluid returns to the solar collector and the process is repeated. When these tubes are mounted, the metal tips project into a heat exchanger (manifold), as shown in Figure 3.7. Water or glycol flows through the manifold and picks up the heat from the tubes. The heated liquid circulates through another heat exchanger and gives off its heat to a process or water stored in a solar storage tank. Another possibility is to use the ETC connected directly to a hot water storage tank.
Because no evaporation or condensation above the phase-change temperature is possible, the heat pipe offers inherent protection from freezing and overheating. This self-limiting temperature control is a unique feature of the evacuated heat pipe collector.
Evacuated tube collectors consist of a heat pipe inside a vacuum-sealed tube. The characteristics of a typical collector are shown in Table 3.2. Evacuated tube collectors on the market exhibit many variations in absorber shape. Evacuated tubes with CPC reflectors are also commercialized by several manufacturers.

Table 3.2 Characteristics of Typical Evacuated Tube Collector System

Parameter	Value
Glass tube diameter	65 mm
Glass thickness	1.6 mm
Collector length	1965 mm
Absorber plate material	Copper
Coating	Selective
Absorber area	0.1 m^2

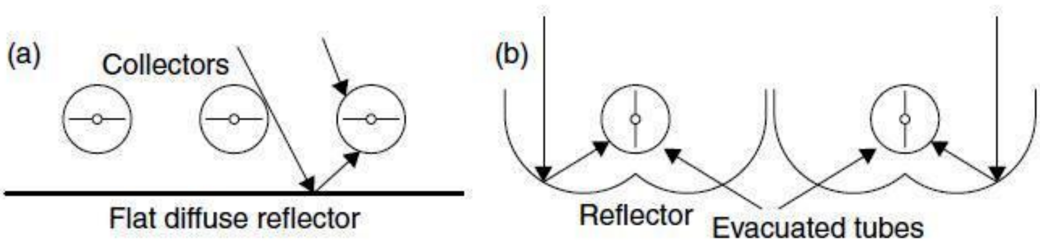


FIGURE 3.9 Evacuated tube collectors array with reflectors. (a) Flat diffuse reflector. (b) CPC reflector.

One such design, presented recently in an attempt to reduce cost and increase lifetime, consists of an all-glass Dewar type evacuated tube collector. This uses two concentric glass tubes, and the space in between the tubes is evacuated, creating a vacuum jacket. In this type of ETC, the selective coating is deposited onto the outside surface of a glass tube domed at one end. This tube is then inserted into a second, larger-diameter domed glass tube and the tubes are joined at the open end. The advantage of this design is that it is made entirely of glass and it is not necessary to penetrate the glass envelope to extract heat from the tube, eliminating leakage losses and keeping it cheaper than the single-envelope system. However, these are suitable only for low-pressure systems and have the disadvantages that the tubes cannot be drained; if one tube breaks, all the working fluid may be lost (Morrison, 2001). This is also called a wet tube ETC. A variation of the wet tube ETC is a normal single-glass ETC in which water (or any other fluid) flows through the collector in either a U tube or coaxial pipe.

As ETCs are relatively expensive. The cost effectiveness of these collectors can be improved by reducing the number of tubes and using reflectors to concentrate the solar radiation onto the tubes. A diffuse reflector (reflectivity, ρ=0.6) mounted behind the tubes, spaced one tube diameter apart, as shown in Figure 3.9a, increases the absorbed energy in each tube by more than 25% for normal incidence. This system also presents a 10% increase in energy collection over a full day because of incidence angle effects. Greater enhancement per tube can be achieved by using CPC-type reflectors, as shown in Figure 3.9b. Evacuated tube arrays with stationary concentrators may have stagnation temperatures exceeding 300° C.

Evacuated tube collectors are produced in a variety of sizes, with outer diameters ranging from 30 mm to about 100 mm. The usual length of these collectors is about 2 m.

3.2 Sun-tracking concentrating collectors

Energy delivery temperatures can be increased by decreasing the area from which the heat losses occur. Temperatures far above those attainable by flat plate collectors can be reached if a large amount of solar radiation is concentrated on a relatively small collection area. This is done by interposing an optical device between the source of radiation and the energy-absorbing surface.

Concentrating collectors exhibit certain advantages over the conventional flat plate type.

The main advantages are as follows:

1. The working fluid can achieve higher temperatures in a concentrator system than a flat-plate system of the same solar energy-collecting surface. This means that a higher thermodynamic efficiency can be achieved.
2. It is possible with a concentrator system to achieve a thermodynamic match between temperature level and task. The task may be to operate thermionic, thermodynamic, or other higher-temperature devices.

3. The thermal efficiency is greater because of the small heat loss area relative to the receiver area.
4. Reflecting surfaces require less material and are structurally simpler than flat-plate collectors. For a concentrating collector, the cost per unit area of the solar-collecting surface is therefore less than that of a flat plate collector.
5. Owing to the relatively small area of receiver per unit of collected solar energy, selective surface treatment and vacuum insulation to reduce heat losses and improve the collector efficiency are economically viable.

Their disadvantages are:
1. Concentrator systems collect little diffuse radiation, depending on the concentration ratio.
2. Some form of tracking system is required to enable the collector to follow the sun.
3. Solar reflecting surfaces may lose their reflectance with time and may require periodic cleaning and refurbishing.

Many designs have been considered for concentrating collectors. Concentrators can be reflectors or refractors, can be cylindrical or parabolic, and can be continuous or segmented. Receivers can be convex, flat, cylindrical, or concave and can be covered with glazing or uncovered. Concentration ratios, i.e., the ratio of aperture to absorber areas, can vary over several orders of magnitude, from as low as slightly above unity to high values on the order of 10,000. Increased ratios mean increased temperatures at which energy can be delivered, but consequently, these collectors have increased requirements for precision in optical quality and positioning of the optical system.
The collectors falling into this category are:
1. Parabolic trough collector.
2. Parabolic dish.
3. Central receiver.

3.2.1 Parabolic Trough Collectors (PTCs)
To deliver high temperatures with good efficiency a high-performance solar collector is required. Systems with light structures and low-cost technology for process heat applications up to 400° C could be obtained with parabolic trough collectors (PTCs). PTCs can effectively produce heat at temperatures between 50°C and 400°C.
Parabolic trough collectors are made by bending a sheet of reflective material into a parabolic shape. A black metal tube, covered with a glass tube to reduce heat losses, is placed along the focal line of the receiver (see Figure 3.13). When the parabola is pointed toward the sun, parallel rays incident on the reflector are reflected onto the receiver tube. The concentrated radiation reaching the receiver tube heats the fluid that circulates through it, thus transforming the solar radiation into useful heat. It is sufficient to use a single-axis tracking of the sun; therefore, long collector modules are produced. The collector can be oriented in an east-west direction, tracking the sun from north to south, or in a north-south direction, tracking the sun from east to west. The

advantages of the former tracking mode is that very little collector adjustment is required during the day and the full aperture always faces the sun at noon but the collector performance during the early and late hours of the day is greatly reduced, due to large incidence angles (cosine loss). North-south oriented troughs have their highest cosine loss at noon and the lowest in the mornings and evenings, when the sun is due east or due west. Photographs of PTC collectors are shown in Figure 3.14.

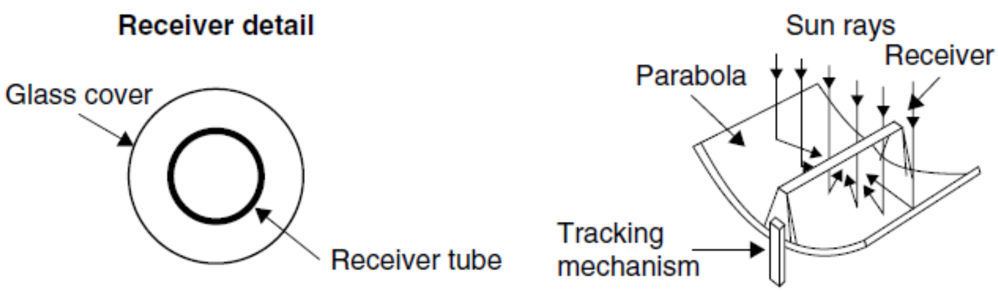
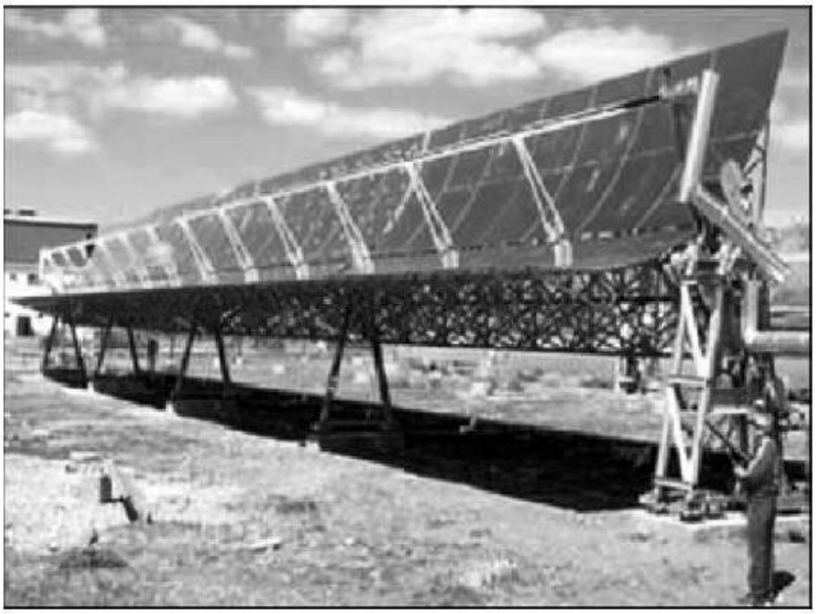
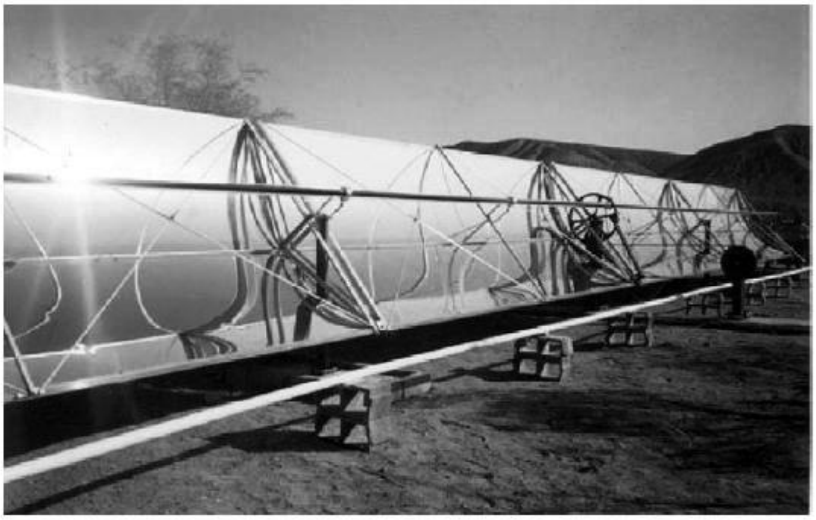


FIGURE 3.13 Schematic of a parabolic trough collector.



(a)



(b)

FIGURE 3.14 Photos of actual parabolic trough collectors. (a) The EuroTrough (from www.sbp.de/en/html/projects/detail.html?id=1043). (b) An Industrial Solar Technology collector.

3.2.3 Parabolic Dish Reflectors (PDRs)

A parabolic dish reflector (PDR), shown schematically in **Figure 3.20a**, is a point-focus collector that tracks the sun in two axes, concentrating solar energy onto a receiver located at the focal point of the dish. The dish structure must fully track the sun to reflect the beam into the thermal receiver. For this purpose, tracking mechanisms similar to the ones described in the previous section are employed in double, so the collector is tracked in two axes. A photograph of a Eurodish collector is shown in **Figure 3.20b**.

The receiver absorbs the radiant solar energy, converting it into thermal energy in a circulating fluid. The thermal energy can then be either converted into electricity using an engine-generator coupled directly to the receiver or transported through pipes to a central power conversion system. Parabolic dish systems can achieve temperatures in excess of 1500°C. Because the receivers are distributed throughout a collector field, like parabolic troughs, parabolic dishes are often called *distributed receiver systems*. Parabolic dishes have several important advantages:

1. Because they are always pointing at the sun, they are the most efficient of all collector systems.
2. They typically have concentration ratios in the range of 600 to 2000 and thus are highly efficient at thermal-energy absorption and power conversion systems.
3. They are modular collector and receiver units that can function either independently or as part of a larger system of dishes.

The main use of this type of concentrator is for parabolic dish engines. A parabolic dish engine system is an electric generator that uses sunlight instead of crude oil or coal to produce electricity. The major parts of a system are the solar dish concentrator and the power conversion unit.

Parabolic dish systems that generate electricity from a central power converter collect the absorbed sunlight from individual receivers and deliver it via a heat transfer fluid to the power conversion systems. The need to circulate heat transfer fluid throughout the collector field raises design issues such as piping layout, pumping requirements, and thermal losses.

3.2.4 Heliostat Field Collectors (HFCs)

For extremely high inputs of radiant energy, a multiplicity of flat mirrors, or heliostats, using altazimuth mounts can be used to reflect their incident direct solar radiation onto a common target, as shown in Figure 3.21. This is called the heliostat field or central receiver collector. By using slightly concave mirror segments on the heliostats, large amounts of thermal energy can be directed into the cavity of a steam generator to produce steam at high temperature and pressure. The concentrated heat energy absorbed by the receiver is transferred to a circulating fluid that can be stored and later used to produce power.

Central receivers have several advantages:
1. They collect solar energy optically and transfer it to a single receiver, thus minimizing thermal energy transport requirements.
2. They typically achieve concentration ratios of 300 to 1500 and so are highly efficient, both in collecting energy and in converting it to electricity.
3. They can conveniently store thermal energy.
4. They are quite large (generally more than 10 MW) and thus benefit from economies of scale.

Each heliostat at a central receiver facility has from 50 to 150 m2 of reflective surface, with four mirrors installed on a common pillar for economy, as shown in Figure 3.22. The heliostats collect and concentrate sunlight onto the receiver, which absorbs the concentrated sunlight, transferring its energy to a heat transfer fluid. The heat transport system, which consists primarily of pipes, pumps, and valves, directs the transfer fluid in a closed loop among the receiver, storage, and power conversion systems. A thermal storage system typically stores the collected energy as sensible heat for later delivery to the power conversion system. The storage system also decouples the collection of solar energy from its conversion to electricity. The power conversion system consists of a steam generator, turbine generator, and support equipment, which convert the thermal energy into electricity and supply it to the utility grid.

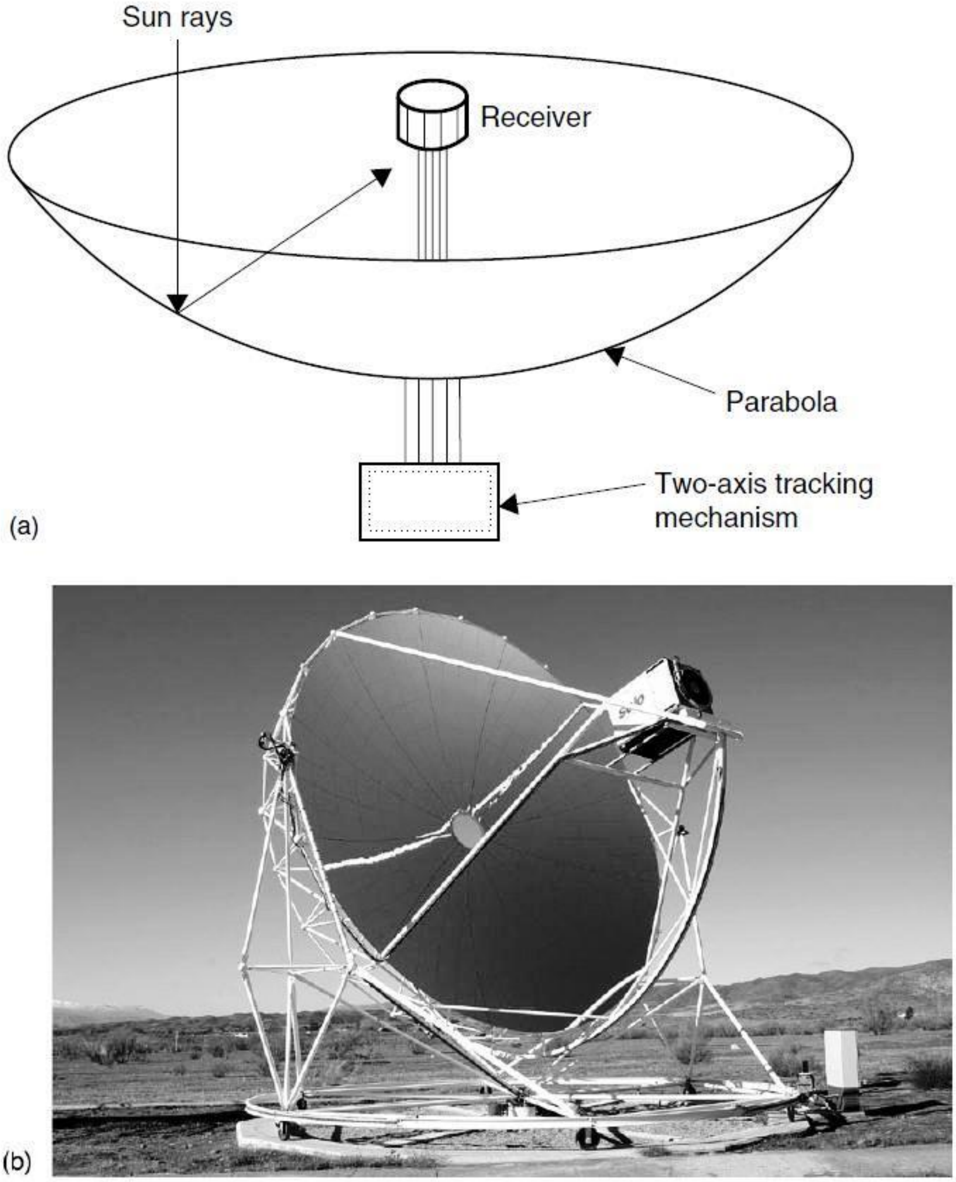


FIGURE 3.20 Parabolic dish collector. (a) Schematic diagram. (b) Photo of a Eurodish collector (from www.psa.es/webeng/instalaciones/discos.html).

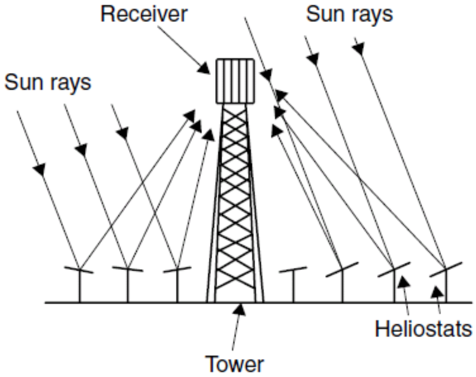


FIGURE 3.21 Schematic of central receiver system.

FIGURE 3.22 Detail of a heliostat.

3.4 Solar water heating systems

3.4.1 Passive systems

Two types of systems belong to this category: thermosiphon and the integrated collector storage systems.

3.4.1.1 Thermosiphon systems

A Thermosiphon system is heat carried by water or transfer fluid and use natural convection to transport it from the collector to storage. The thermosiphoning effect occurs because the density of water drops with the increase of the temperature.
Therefore, by the action of solar radiation absorbed, the water in the collector is heated and thus expands, becoming less dense, and rises through the collector into the top of the storage tank. There it is replaced by the cooler water that has sunk to the bottom of the tank, from which it flows down the collector. Circulation is continuous as long as the sun is shining. Thermosiphon systems shown schematically in Figure 3.25.

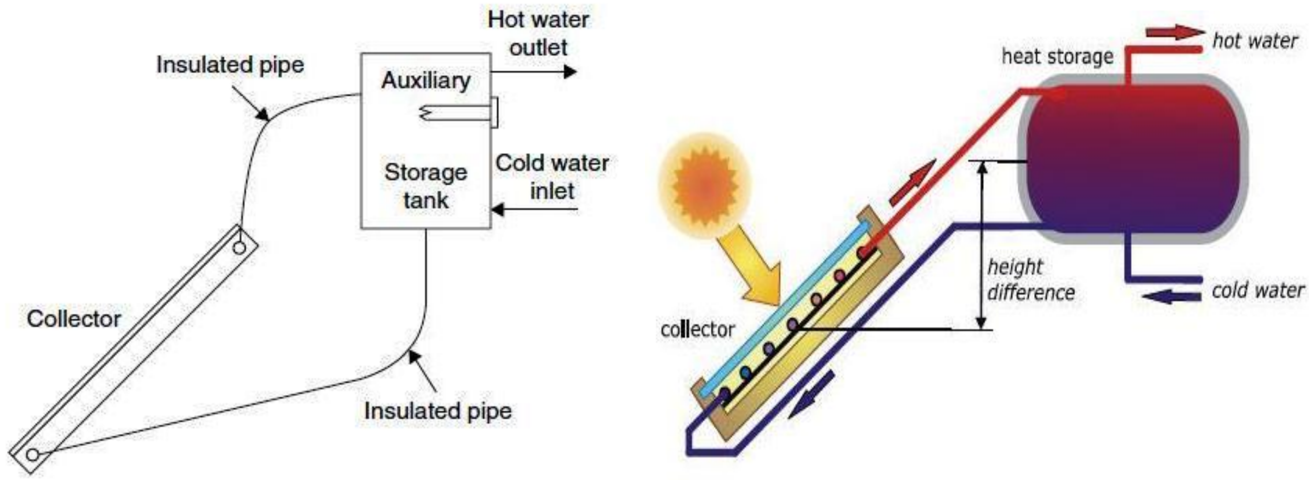


Figure 3.25 Schematic diagram of a thermosiphon solar water heater.

Since the driving force is only a small density difference, larger than normal pipe sizes must be used to minimize pipe friction. Connecting lines must also be well insulated to prevent heat loss and sloped to prevent formation of air pockets, which would stop circulation.
The advantages of thermosiphon systems are

1- They do not rely on pumps and controllers, are more reliable, and have a longer life than forced circulation systems.
2- They do not require an electrical supply to operate and they naturally modulate the circulation flow rate in phase with the radiation levels.

The main disadvantage of thermosiphon systems is

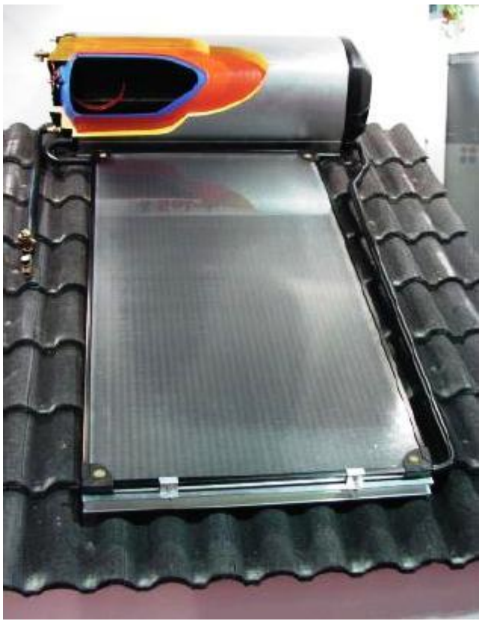
1- They are comparatively tall units, which makes them not very attractive aesthetically.
2- the quality of the water used. As the system is open, extremely hard or acidic water can cause scale deposits that clog or corrode the absorber fluid passages.

The two types of thermosiphon systems are pressurized and unpressurized. In pressurized thermosiphon units, the make-up water is from city mains or pressure units and the collectors and storage tanks must be able to withstand the working pressure.

When city water is used directly, pressure-reducing and relief valves must be installed to protect the system because the pressure can be greater than the working pressure of the collectors and storage tank. In gravity systems, usually installed where the city water supply is intermittent, a cold water storage tank is installed on top of the solar collector, supplying both the hot water cylinder and the cold water needs of the house. This makes the collector unit taller and less attractive.

Typical collector configurations include flat plate, shown in Figure 3.26a, and evacuated tube collectors, shown in Figure 3.26b.

a)



b)

Figure 3.26 Thermosiphon system configurations. (a) Flat-plate collector configuration. (b) Evacuated tube collector configuration.

3.4.1.2 Integrated Collector Storage Systems

Integrated collector storage (ICS) systems use the hot water storage as part of the collector, i.e., the surface of the storage tank is used also as the collector absorber as shown in **figure 3.27**.

As in all other systems, to improve stratification, the hot water is drawn from the top of the tank and cold make-up water enters the bottom of the tank on the opposite side. Usually, the storage tank surface is selectively coated to minimize heat loss.

The main disadvantage of the ICS systems is the high thermal losses from the storage tank to the surroundings, since most of the surface area of the storage tank cannot be thermally insulated, because it is intentionally exposed to be able to absorb solar radiation. In particular, the thermal losses are greatest during the night and overcast days with low ambient temperatures. Due to these losses, the water temperature drops substantially during nighttime, especially during the winter. Various techniques have been used to keep this from happening.

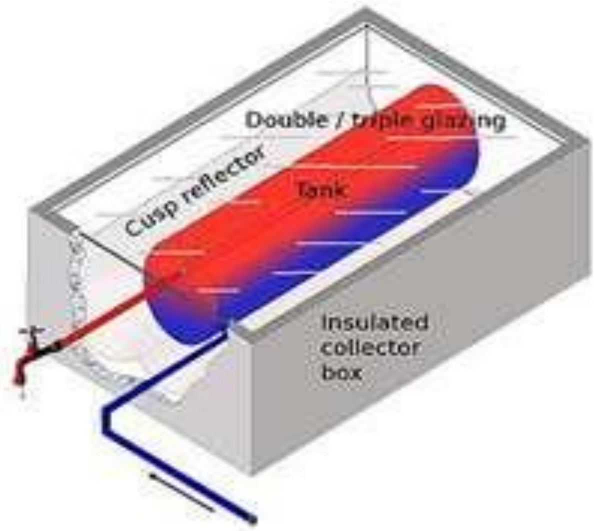


Figure 3.27 Integrated collector storage (ICS) systems

3.4.2 Active systems

In active systems, water or a heat transfer fluid is pumped through the collectors. These are usually more expensive and a little less efficient than passive systems, particularly if antifreeze measures are required. Additionally, active systems are more difficult to retrofit in houses, especially where there is no basement, because space is required for the additional equipment, such as the hot water cylinder. **<u>Five types</u>** of systems belong in this category: **direct circulation systems, indirect water heating systems, air systems, heat pump systems, and pool heating systems**. Before giving the details of these systems, the optimum flow rate is examined.

5.2.1 Direct Circulation Systems

A schematic diagram of a direct circulation system is shown in Figure 3.28. **In this system**, a pump is used to circulate potable water from storage to the collectors when there is enough available solar energy to increase its temperature and then return the heated water to the storage tank until it is needed. Because a pump is used to circulate the water, the collectors can be mounted either above or below the storage tank.

Direct circulation systems often use a single storage tank equipped with an auxiliary water heater, but two-tank storage systems can also be used. An important feature of this configuration is the spring-loaded check valve, which is used to prevent reverse thermosiphon circulation energy losses when the pump is not running.

Direct circulation systems can be used with water supplied from a cold-water storage tank or connected directly to city water mains. Pressure-reducing valves and pressure relief valves are required, however, when the city water pressure is greater than the working pressure of the collectors. Direct water heating systems should not be used in areas where the water is extremely hard or acidic, because scale (calcium) deposits may clog or corrode the collectors.

Direct circulation systems can be used in areas where freezing is infrequent.

For extreme weather conditions, freeze protection is usually provided by recirculating warm water from the storage tank. This loses some heat but protects the system. A special thermostat that operates the pump when the temperature drops below a certain value is used in this case. Such recirculation freeze protection should be used only for locations where freezing occurs rarely (a few times a year), since stored heat is dumped in the process. A disadvantage of this system occurs in cases when there is a power failure, in which case the pump will not work, and the system could freeze. In such a case, a dump valve can be installed at the bottom of the collectors to provide additional protection.

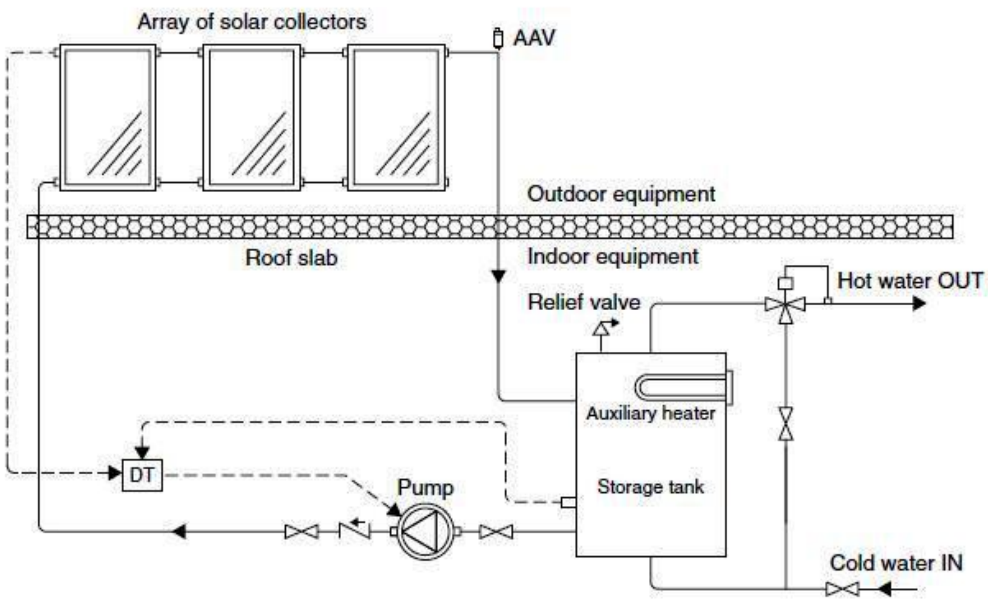


Figure 3.28 Direct circulation system.

5.2.2 Indirect Water Heating Systems

A schematic diagram of indirect water heating systems is shown in Figure 3.29 and figure 3.30. **In this system,** a heat transfer fluid is circulated through the closed collector loop to a heat exchanger, where its heat is transferred to the potable water. The most commonly used heat transfer fluids are **water–ethylene glycol** solutions, although other heat transfer fluids such as **silicone oils** and **refrigerants** can be used. When fluids that are non-potable or toxic are used, double-wall heat exchangers should be employed; this can be two heat exchangers in series. The heat exchanger can be located inside the storage tank, around the storage tank (tank mantle), or external to the storage tank. It should be noted that the collector loop is closed; therefore, an expansion tank and a pressure relief valve are required. Additional over–temperature protection may be needed to prevent the collector heat–transfer fluid from decomposing or becoming corrosive.
Systems of this type using water–ethylene glycol solutions are preferred in areas subject to extended freezing temperatures, because they offer good freeze protection. These systems are more expensive to construct and operate, since the solution should be checked every year and changed every few years, depending on the solution quality and system temperatures achieved.

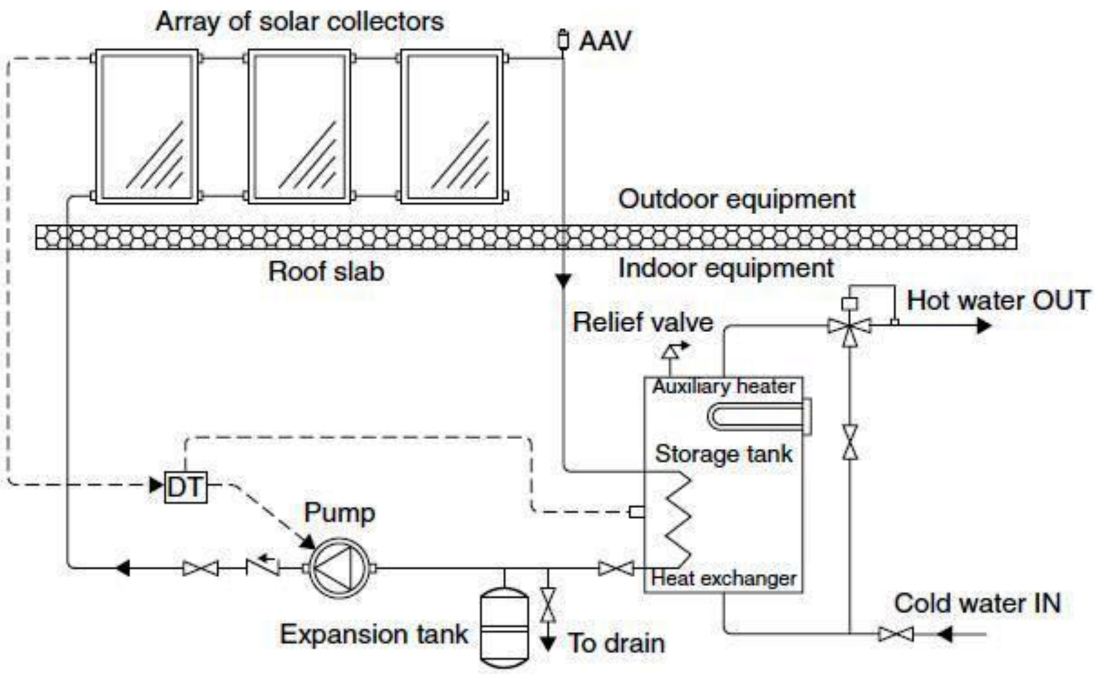


Figure 3.29 Indirect water heating system.

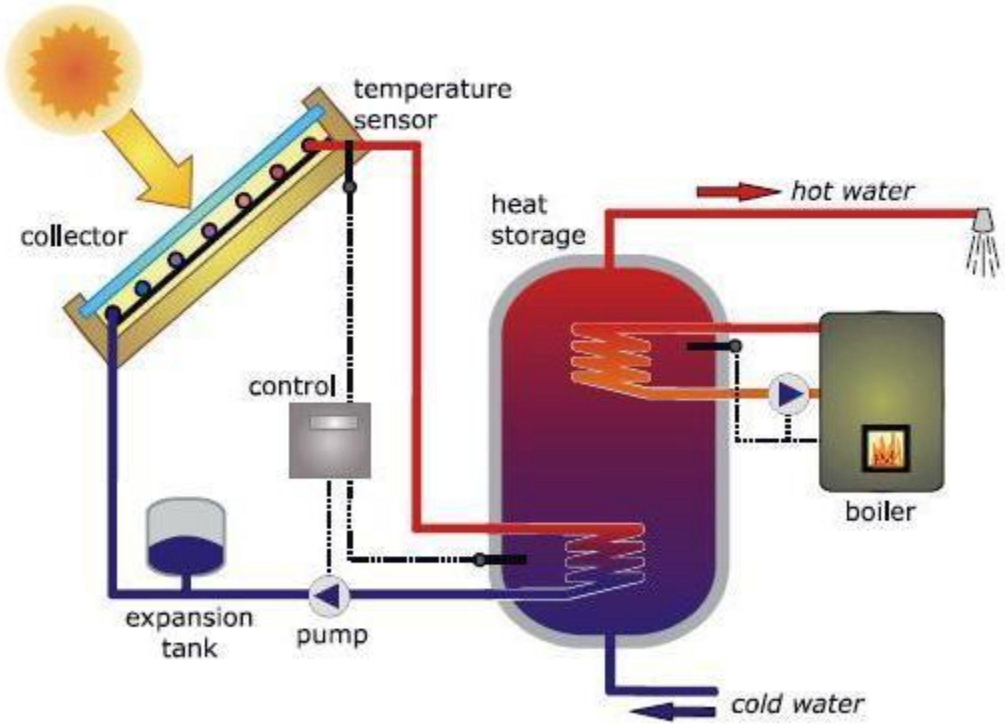


Figure 3.30 Pumped solar thermal system for heating domestic hot water.

5.2.3 Air Water-Heating Systems

Air systems are indirect water heating systems because air, circulated through air collectors and via ductworks, is directed to an air-to-water heat exchanger. In the heat exchanger, heat is transferred to the potable water, which is also circulated through the heat exchanger and returned to the storage tank. Figure 3.31 shows a schematic diagram of a double storage tank system. This type of system is used most often because air systems are generally used for preheating domestic hot water and hence the auxiliary heater is used in only one tank, as shown.

The advantages of this system are that air does not need to be protected from freezing or boiling, is non-corrosive, does not suffer from heat transfer fluid degradation, and is free. Additionally, the system is more cost effective because no safety values or expansion vessels are required.

The disadvantages are that airhandling equipment (ducts and fans) needs more space than piping and pumps, air leaks are difficult to detect, and parasitic power consumption (electricity used to drive the fans) is generally higher than that of liquid systems.

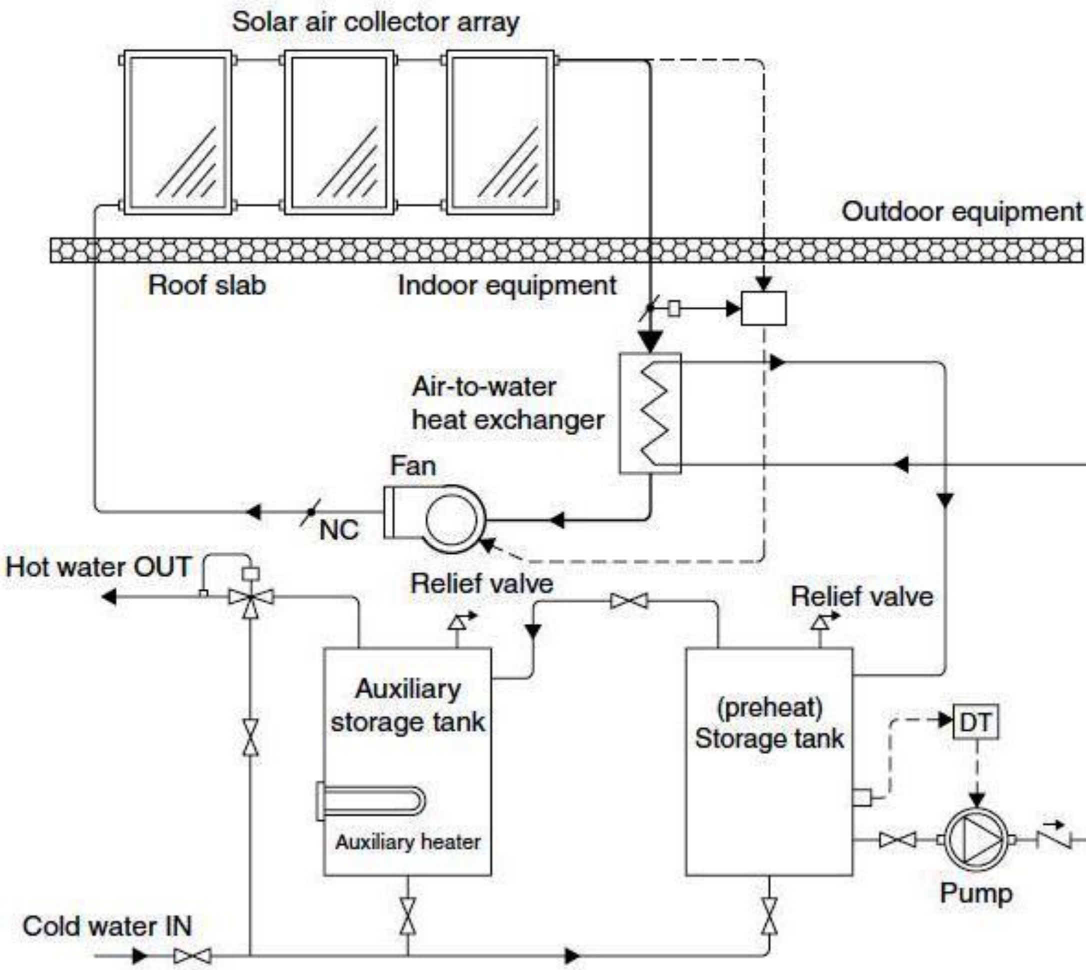


Figure 3.31 Air system.

5.2.4 Heat Pump Systems

Heat pumps use mechanical energy to transfer thermal energy from a source at a lower temperature to a sink at a higher temperature. The bigger advantage of electrically driven heat pump heating systems, compared to electric resistance heating or expensive fuels, is that the heat pump's coefficient of performance (COP; ratio of heating performance to electrical energy) is greater than unity for heating; so it yields 9 to 15 MJ of heat for each kilowatt hour of energy supplied to the compressor, which saves on purchase of energy.

The original system concept, was a system with direct evaporation of the working fluid of the heat pump in the solar collector. The condenser of the heat pump was actually a heat exchanger wrapped around the storage tank. In this way, the initial system cost and the parasitic energy requirements of the system are minimized. A possible disadvantage of this system is that the condenser heat transfer is limited by the free convection from the tank wall, which can be minimized by using a large heat transfer area in the tank.

A more important disadvantage of this system is that the heat pump refrigeration circuit must be evacuated and charged on site, which requires special equipment and expertise.

This disadvantage is removed by using compact solar heat pump systems. These incorporate an evaporator mounted outside the water storage tank with natural convection air circulation. This system needs to be installed outdoors, and if installed adjacent to the ventilation duct outlet of a building, it can also work as a waste heat recovery unit. The advantages of this system are that it has no parasitic energy requirement and, because the system is packaged, all its components are assembled in the factory and thus the system is pre-charged. The installation of this system is as simple as a conventional electric water heater because the unit requires no high-power electrical connection.

5.2.5 Pool Heating Systems

Solar pool heating systems require no separate storage tank, because the pool itself serves as storage. In most cases, the pool's filtration pump is used to circulate the water through solar panels or plastic pipes. For daylong operation, no automatic controls are required, because the pool usually operates when the sun is shining. If such controls are employed, they are used to direct the flow of filtered water to the collectors only when solar heat is available. This can also be achieved by a simple manually operated valve. Normally, these kinds of solar systems are designed to drain down into the pool when the pump is switched off; thus the collectors are inherently freeze protected.
The primary type of collector design used for heating swimming pools is the rigid black plastic panels made from polypropylene. Additionally, plastic pipes or tube-on-sheet panels can be used. In all cases, however, a large area is required and the roof of a nearby building can be used for this purpose. See figure 3.32.

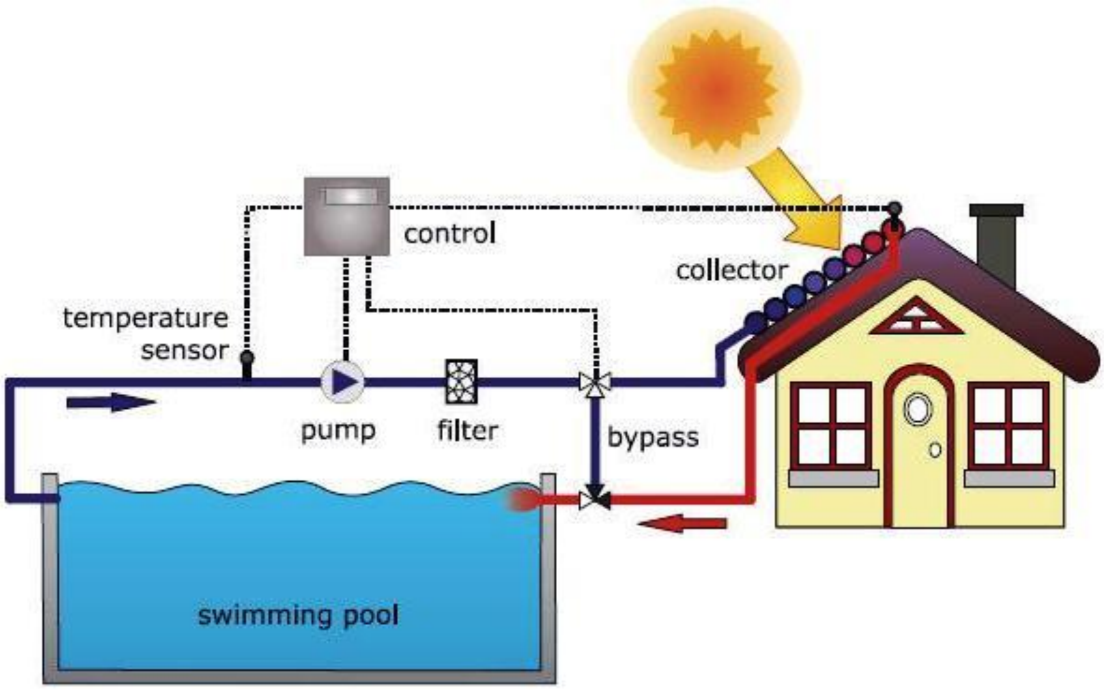


Figure 3.32 System for swimming pool heating using solar energy.

5.3 Heat storage systems

Thermal storage is one of the main parts of a solar heating, cooling, and power generating system. Because for approximately half the year any location is in darkness, heat storage is necessary if the solar system must operate continuously. For some applications, such as swimming pool heating, daytime air heating, and irrigation pumping, intermittent operation is acceptable, but most other uses of solar energy require operating at night and when the sun is hidden behind clouds.

Usually the design and selection of the thermal storage equipment is one of the most neglected elements of solar energy systems. It should be realized, however, that the energy storage system has an enormous influence on overall system cost, performance, and reliability. Furthermore, the design of the storage system affects the other basic elements, such as the collector loop and the thermal distribution system.

A storage tank in a solar system has several functions, the most important of which are:

1- Improvement of the utilization of collected solar energy by providing thermal capacitance to alleviate the solar availability and load mismatch and improve the system response to sudden peak loads or loss of solar input.
2- Improvement of system efficiency by preventing the array heat transfer fluid from quickly reaching high temperatures, which lower the collector efficiency.

Generally, solar energy can be stored in liquids, solids, or phase-change materials (PCM). Water is the most frequently used storage medium for liquid systems, even though the collector loop may use water, oils, water-glycol mixtures, or any other heat transfer medium as the collector fluid. This is because water is inexpensive and non-toxic and it has a high storage capacity, based on both weight and volume. Additionally, as a liquid, it is easy to transport using conventional pumps and plumbing. For service water heating applications and most building space heating, water is normally contained in some type of tank, which is usually circular. Air systems typically store heat in rocks or pebbles, but sometimes the structural mass of the building is used.

An important consideration is that the temperature of the fluid delivered to the load should be appropriate for the intended application. The lower the temperature of the fluid supplied to the collectors, the higher is the efficiency of the collectors.

The location of the storage tank should also be given careful consideration. The best location is indoors, where thermal losses are minimal and weather deterioration will not be a factor. If the tank cannot be installed inside the building, then it should be located outside above the ground or on the roof. Such a storage tank should have a good insulation and good outside protection of the insulation. The storage tank should also be located as close as possible to the collector arrays to avoid long pipe runs.

5.3.1 Air System Thermal Storage

The most common storage media for air collectors are rocks. Other possible media include PCM, water, and the inherent building mass. Gravel is widely used as a storage medium because it is abundant and relatively inexpensive.

In cases where large interior temperature swings can be tolerated, the inherent structure of the building may be sufficient for thermal storage. Loads requiring no storage are usually the most cost-effective applications of air collectors, and heated air from the collectors can be distributed directly to the space. Generally, storage may be eliminated in cases where the array output seldom exceeds the thermal demand

The main requirements for gravel storage are good insulation, low air leakage, and low pressure drop. Many different designs can fulfill these requirements. The container is usually constructed from concrete, masonry, wood, or a combination of these materials. Airflow can be vertical or horizontal. A schematic diagram of a vertical flow bed is shown in Figure 3.33. In this arrangement, the solar-heated air enters at the top and exits from the bottom. This tank can work as effectively as a horizontal flow bed. In these systems, it is important to heat the bed with the hot air flow in one direction and to retrieve the heat with airflow in the opposite direction. In this way, pebble beds perform as effective counter-flow heat exchangers.

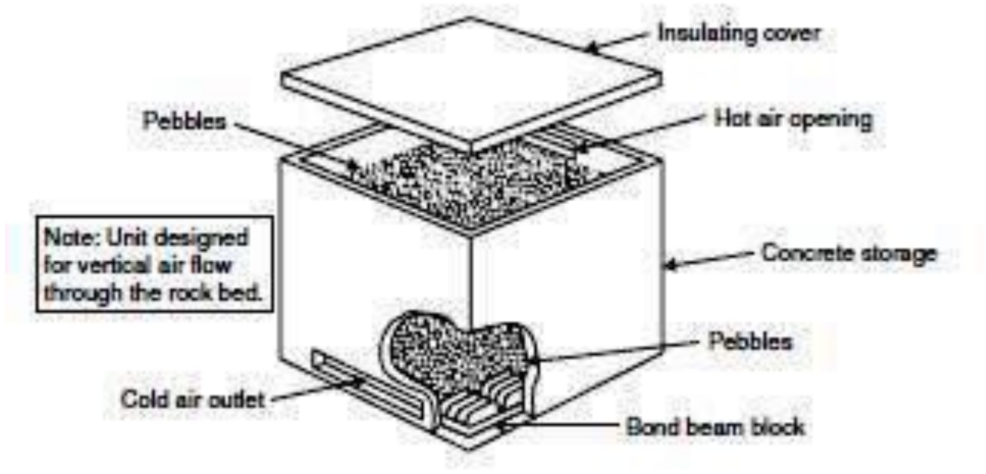


Figure 3.33 Vertical flow packed rock bed.

The size of rocks for pebble beds range from 35 to 100 mm in diameter, depending on airflow, bed geometry, and desired pressure drop. The volume of the rock needed depends on the fraction of collector output that must be stored. For residential systems, storage volume is typically in the range of 0.15–0.3 m^3 per square meter of collector area. For large systems, pebble beds can be quite large and their large mass and volume may lead to location problems.

Other storage options for air systems include phase change materials and water. PCMs are functionally attractive because of their high volumetric heat storage capabilities, since they require only about one tenth the volume of a pebble bed.

Water can also be used as a storage medium for air collectors through the use of a conventional water-to-air heat exchanger to transfer heat from the air to the water in the storage tank. This option has two advantages:

1. Water storage is compatible with hydronic heating systems.
2. It is relatively compact; the required storage water volume is roughly one third the pebble bed's volume

5.3.2 Liquid System Thermal Storage

Two types of water storage for liquid systems are available: pressurized and unpressurized. Other differentiations include the use of an external or internal heat exchanger and single or multiple tank configurations. Water may be stored in copper, galvanized metal, or concrete tanks. Whatever storage vessel is selected, however, this should be well insulated and large tanks should be provided with internal access for maintenance. Recommended U value is 0.16 W/m^2-K.

Pressurized systems are open to city mains water supply. Pressurized storage is preferred for small service water heating systems, although in cases like Cyprus, where the water supply is intermittent, it is not suitable. Typical storage size is about 40 to 80L per square meter of collector area. With pressurized storage, the heat exchanger is always located on the collector side of the tank. Either internal or external heat exchanger configurations can be used.

Two principal types of internal heat exchanger exist: an immersed coil and a tube bundle, as shown in Figure 3.34.

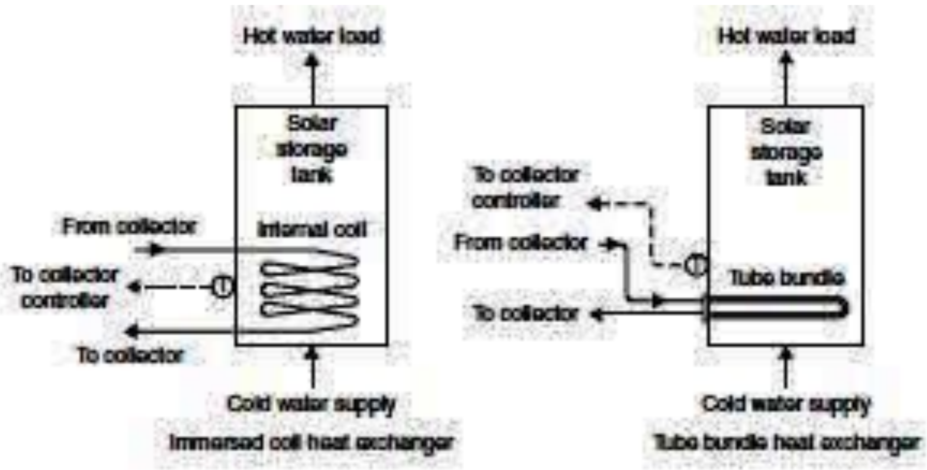


Figure 3.34 Pressurized storage with internal heat exchanger.

Sometimes, because of the required storage volume, more than one tank is used instead of one large one, if such a large-capacity tank is not available. Additional tanks offer, in addition to the extra storage volume, increased heat exchanger surface (when a heat exchanger is used in each tank) and reduced pressure drop in the collection loop. A multiple-tank configuration for pressurized storage is shown in Figure 3.35. It should be noted that the heat exchangers are connected in a reverse return mode to improve flow balance.

An external heat exchanger provides greater flexibility because the tank and the exchanger can be selected independently of other equipment (see Figure 3.36). The disadvantage of this system is the parasitic energy consumption, in the form of electrical energy, that occurs because of the additional pump.

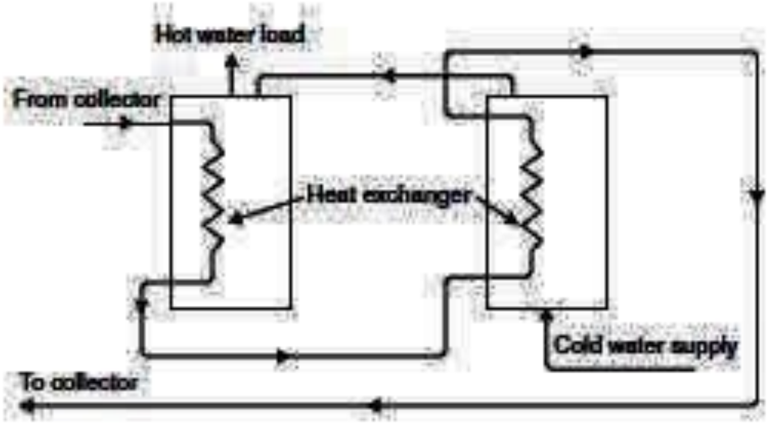


Figure 3.35 Multiple-tank storage arrangements with internal heat exchangers.

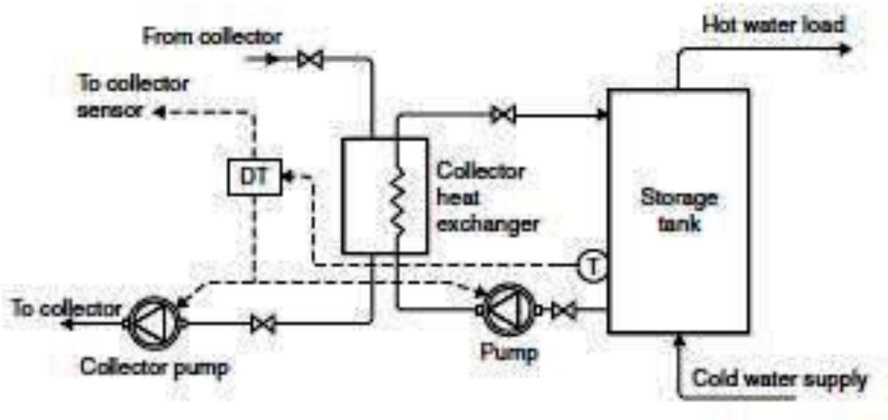


Figure 3.36 Pressurized storage system with external heat exchanger.

For small systems, an internal heat exchanger–tank arrangement is usually used, which has the advantage of preventing the water side of the heat exchanger from freezing. However, the energy required to maintain the water above freezing is extracted from storage, thus the overall system performance is decreased. With this system, a bypass can be arranged to divert cold fluid around the heat exchanger until it has been heated to an acceptable level of about 25°C. When the heat transfer fluid is warmed to this level, it can enter the heat exchanger without causing freezing or extraction of heat from storage. If necessary, this arrangement can also be used with internal heat exchangers to improve performance.

For systems with sizes greater than about 30 m^3, unpressurized storage is usually more cost effective than pressurized. This system, however, can also be employed in small domestic flat-plate collector systems, and in this case, the make-up water is usually supplied from a cold water storage tank located on top of the hot water cylinder.

Unpressurized storage for water and space heating can be combined with the pressurized city water supply. This implies the use of a heat exchanger on the load side of the tank to isolate the high-pressure mains′ potable water loop from the low-pressure collector loop. An unpressurized storage system with an external heat exchanger is shown in Figure 3.37. In this configuration, heat is extracted from the top of the solar storage tank and the cooled water is returned to the bottom of the tank so as not to distract stratification. For the same reason, on the load side of the heat exchanger, the water to be heated flows from the bottom of the backup storage tank, where relatively cold water exists, and heated water returns to the top. Where a heat transfer fluid is circulated in the collector loop, the heat exchanger may have a double-wall construction to protect the potable water supply from contamination. A differential temperature controller controls the two pumps on either side of the heat exchanger. When small pumps are used, both may be controlled by the same controller without overloading problems. The external heat exchanger shown in Figure 3.37 provides good system flexibility and freedom in component selection. In some cases, system cost and parasitic power consumption may be reduced by an internal heat exchanger.

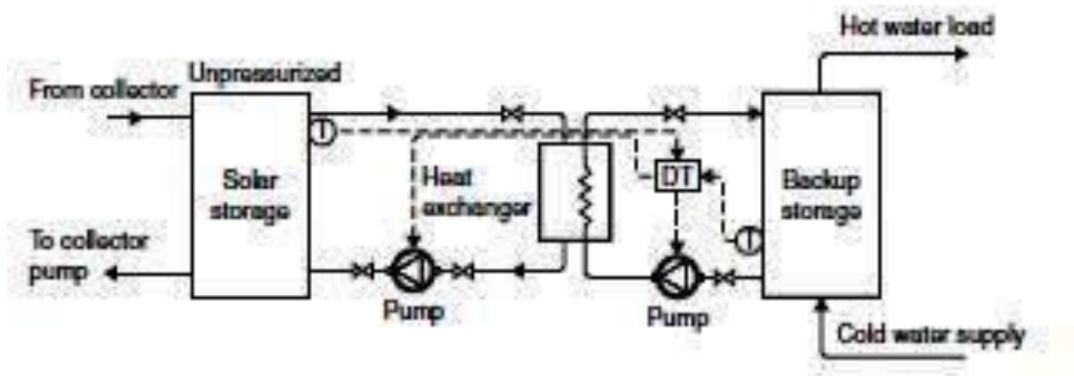


Figure 3.37 Unpressurized storage system with external heat exchanger.

Stratification is the collection of hot water to the top of the storage tank and cold water to the bottom. This improves the performance of the tank because hotter water is available for use and colder water is supplied to the collectors, which enables the collector to operate at higher efficiency. Another category of hot water stores is the so-called solar combistores. These are used mainly in Europe for combined domestic hot water preparation and space heating

5.3.3 Thermal Analysis of Storage Systems

For fully mixed or unstratified energy storage, the capacity (Q_s) of a liquid storage unit at uniform temperature, operating over a finite temperature difference (T_s) is given by:

$$Q_s = \left(Mc_p\right)_s \Delta T_s$$

where
M: mass of storage capacity (kg)

The temperature range over which such a unit operates is limited by the requirements of the process. The upper limit is also determined by the vapor pressure of the liquid.

An energy balance of the storage tank gives

$$\left(Mc_p\right)_s \frac{dT_s}{dt} = Q_u + Q_l + Q_{tl}$$

where
Q_u: rate of collected solar energy delivered to the storage tank (W).
Q_l: rate of energy removed from storage tank to load (W).
Q_{tl}: rate of energy loss from storage tank (W).
The rate of storage tank energy loss is given by

$$Q_{tl} = (UA)_s(T_s - T_{env})$$

where
$(UA)_s$: storage tank loss coefficient and area product (W/°C).
T_{env}: temperature of the environment where the storage tank is located (°C).

To determine the long-term performance of the storage tank, equation may be rewritten in finite difference form as

$$\left(Mc_p\right)_s \frac{T_{s-n} - T_s}{\Delta t} = Q_u + Q_l + Q_{tl}$$

$$T_{s-n} = T_s + \frac{\Delta t}{\left(Mc_p\right)_s}\left[Q_u - Q_l - (UA)_s(T_s - T_{env})\right]$$

where
T_{s-n} : new storage tank temperature after time interval Δt (°C).

This equation assumes that the heat losses are constant in the period Δt. The most common time period for this estimation is an hour because the solar radiation data are also available on an hourly basis.

Example

A fully mixed water storage tank contains 500 kg of water, has a *UA* product equal to 12 W/°C, and is located in a room that is at a constant temperature of 20°C. The tank is examined in a 10 h period starting from 5 am where the Q_u is equal to 0, 0, 0, 10, 21, 30, 40, 55, 65, 55 MJ. The load is constant and equal to 12 MJ in the first 3 h, 15 MJ in the next 3 h, and 25 MJ the rest of time. Find the final storage tank temperature if the initial temperature is 45°C.

Solution

The estimation time interval is 1 h. Using Eq. (5.34) and inserting the appropriate constants, we get

$$T_{s-n} = T_s + \frac{\Delta t}{(Mc_p)_s}[Q_u - Q_l - (UA)_s(T_s - T_{env})]$$

$$T_{s1} = 45 + \frac{1}{500 \times 4.18 \times 10^{-3}}\left[0 - 12 - 12\frac{3600}{10^6}(45 - 20)\right] = 38.7\ C^o$$

By inserting the initial storage tank temperature (45°C), Q_u, and Q_l according to the problem, Table in below can be obtained.

Hour	Q_u (MJ)	Q_l (MJ)	T_s (°C)	Q_{tl} (MJ)
			45	
5	0	12	38.7	1.1
6	0	12		
7	0	12		
8	10	15		
9	21	15		
10	30	15		
11	40	25		
12	55	25		
13	65	25		
14	55	25	86.4	2.3

Therefore, the final storage tank temperature is 86.4°C. For these calculations, the use of a spreadsheet program is recommended.

5.4 Module and array design

5.4.1 Module Design

Most commercial and industrial systems require many collectors to satisfy the heating demand. Connecting the collectors with just one set of manifolds makes it difficult to ensure drainability and low pressure drop. It would also be difficult to balance the flow so as to have the same flow rate through all collectors.

A module is a group of collectors that can be grouped into parallel flow and combined series-parallel flow. Parallel flow is more frequently used because it is inherently balanced, has a low pressure drop, and can be drained easily. Figure 3.38 illustrates the two most popular collector header designs: external and internal manifolds.

Generally, flat-plate collectors are made to connect to the main pipes of the installation in one of the two methods shown in Figure 3.83. The **external manifold** collector has a small-diameter connection because it is used to carry the flow for only one collector. Therefore, each collector is connected individually to the manifold piping, which is not part of the collector panel. The **internal manifold** collector incorporates several collectors with large headers, which can be placed side by side to form a continuous supply and return manifold, so the manifold piping is integral with each collector. The number of collectors that can be connected depends on the size of the header.

External manifold collectors are generally more suitable for small systems. **Internal manifolding** is preferred for large systems because it offers a number of advantages. These are cost savings because the system avoids the use of extra pipes (and fittings), which need to be insulated and properly supported, and the elimination of heat losses associated with external manifolding, which increases the thermal performance of the system.

It should be noted that the flow is parallel, but the collectors are connected in series. When arrays must be greater than one panel high, a combination of series and parallel flow may be used, as shown in **Figure 3.39**. This is a more suitable design in cases where collectors are installed on an inclined roof.

The choice of series or parallel arrangement depends on the temperature required from the system. Connecting collectors in parallel means that all collectors have as input the same temperature, whereas when a series connection is used, the outlet temperature from one collector n (or row of collectors) is the input to the next collector (or row of collectors).

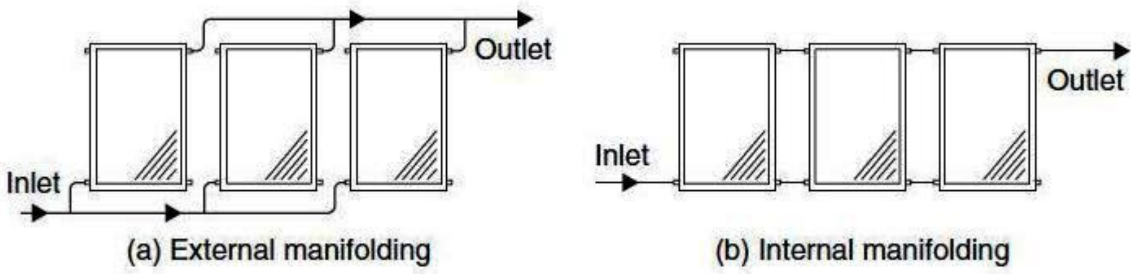


Figure 3.38 Collector manifolding arrangements for parallel flow modules.

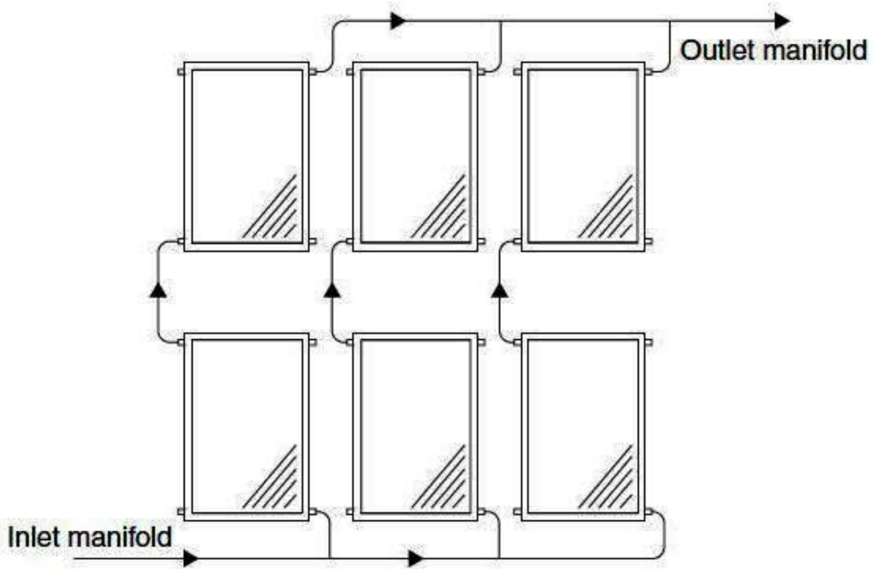


Figure 3.39 Collector manifolding arrangement for combined series-parallel flow modules.

5.4.2 Array Design

An array usually includes many individual groups of collectors, called modules, to provide the necessary flow characteristics. To maintain balanced flow, an array or field of collectors should be built from identical modules. Basically, two types of systems can be used: **direct return and reverse return**. In **direct return**, shown in **Figure 3.40**, balancing valves are needed to ensure uniform flow through the modules. The balancing valves must be connected at the module outlet to provide the flow resistance necessary to ensure filling of all modules on pump start up. Whenever possible, modules must be connected in a reverse-return mode, as shown in **Figure 3.41**. The **reverse return** ensures that the array is self-balanced, as all collectors operate with the same pressure drop: i.e., the first collector in the supply manifold is the last in the return manifold, the second on the supply side is the second before last in the return, and so on. With proper design, an array can drain, which is an essential requirement for drain-back and drain down freeze protection. For this to be possible, piping to and from the collectors must be sloped properly. Typically, piping and collectors must slope to drain with an inclination of 20 mm per linear meter.

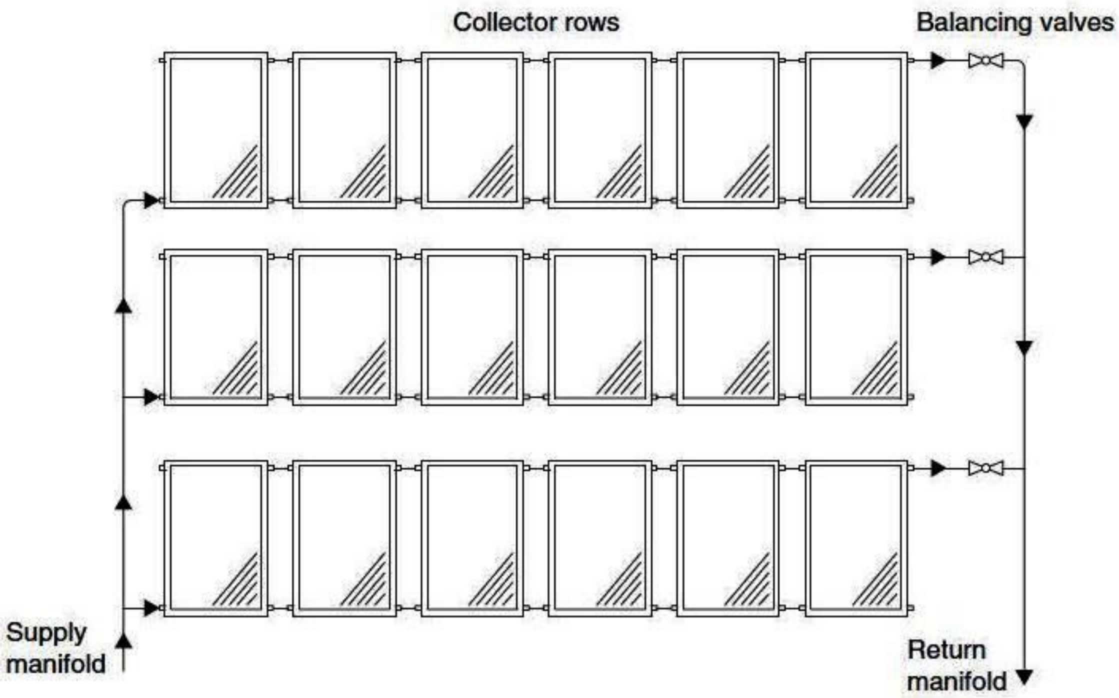


Figure 3.40 Direct-return array piping.

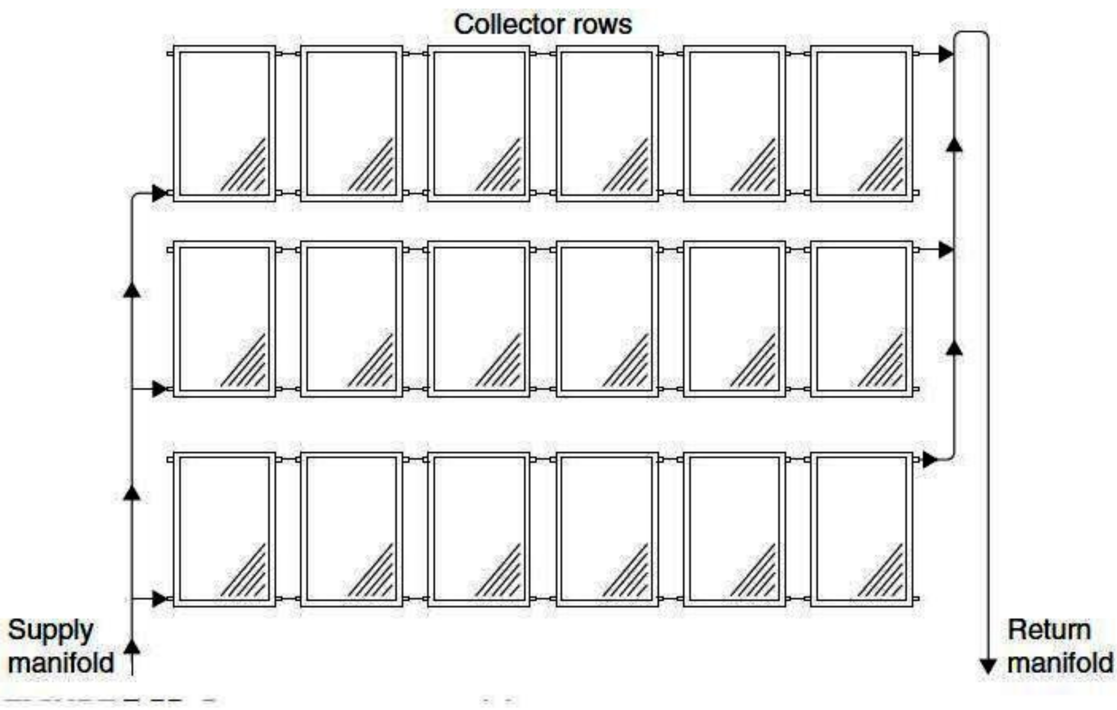


Figure 3.41 Reverse-return array piping.

5.5 Differential temperature controller

The basis of solar energy system control is the **differential temperature controller (DTC)**. This is simply a fixed temperature difference (ΔT) thermostat with hysteresis. The differential temperature controller is a comparing controller with at least two temperature sensors that control one or more devices.

Typically, one of the sensors is located at the top side of the solar collector array and the second at the storage tank, as shown in Figure 3.42. On unpressurized systems, other differential temperature controllers may control the extraction of heat from the storage tank. Most other controls used in solar energy systems are similar to those for building services systems.

The differential temperature controller monitors the temperature difference between the collectors and the storage tank. When the temperature of the solar collectors exceeds that of the tank by a predetermined amount (usually 4–11°C), the differential temperature controller switches the circulating pump on. When the temperature of the solar collectors drops to 2–5°C above the storage temperature, the differential temperature controller stops the pump.

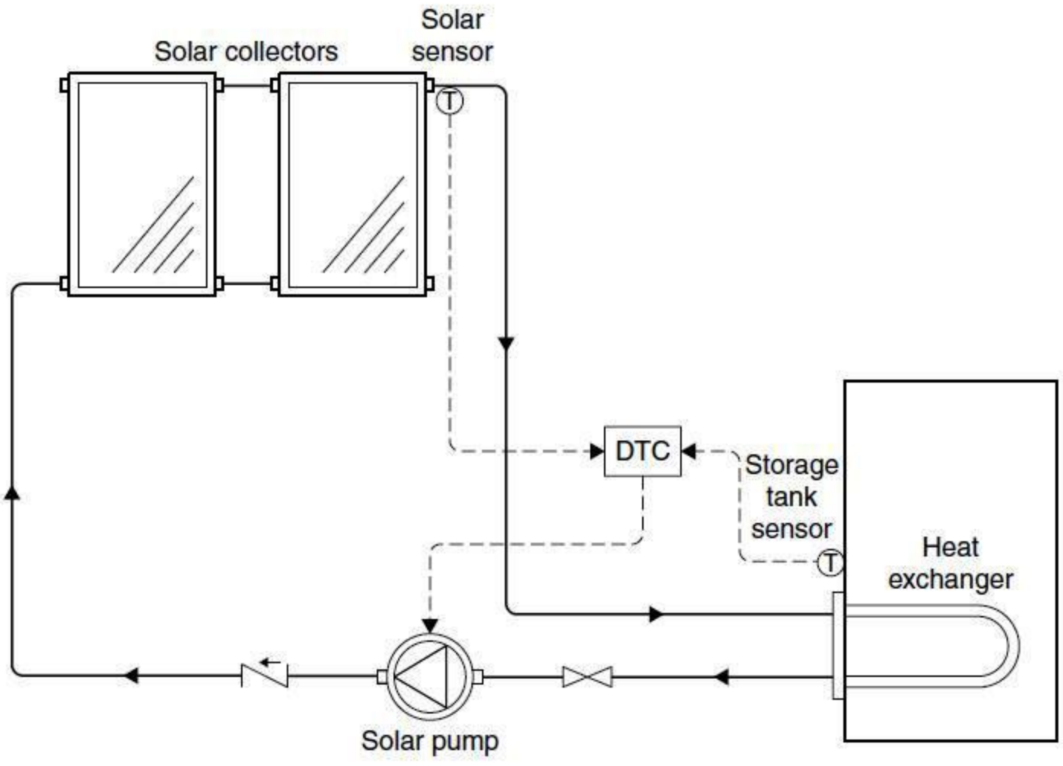


Figure 3.42 Basic collector control with a differential temperature controller

5.5.1 Placement of Sensors

Proper placement of the collector temperature sensor is important for good system operation. The sensor must have a good thermal contact with the collector plate or piping. Collector sensors may be located on the collector plate, on a pipe near the collector, or in the collector outlet pipe. The best of all is on the collector plate, but this is not the easiest, because dismantling and modification on one collector of the array is required, which would need to be done on site.

The easiest and perhaps the best point for the location of the sensor is on the pipe leaving the collector. Usually, a T piece is used and the sensor is placed in a deep well with a few drops of oil, which ensures good contact, as shown in Figure 3.43a, or on the side of the T piece, as shown in Figure 3.43.

The storage tank sensor should be located near the bottom of the storage tank, at about one third of its height. If the system uses an internal heat exchanger, the sensor is located above the heat exchanger. Ideally, this sensor should identify if there is still water in the tank, which can be heated by solar energy. Therefore, the location indicated is considered a good compromise because a lower location would give a false reading even with the slightest demand, which will be replaced by make-up (cold) water, whereas a higher location would leave a lot of water at a low temperature, even if solar energy is available.

A freeze protection sensor, if used, should be located in such a position so as to detect the coldest liquid temperature. Two suitable locations are the back of the absorber plate and the entry pipe to the collector from the supply manifold.

The over-temperature sensor can be located either at the top part of the storage tank or on the collector exit pipe. For the latter, the sensor is located in a similar location and manner as the collector temperature sensor.

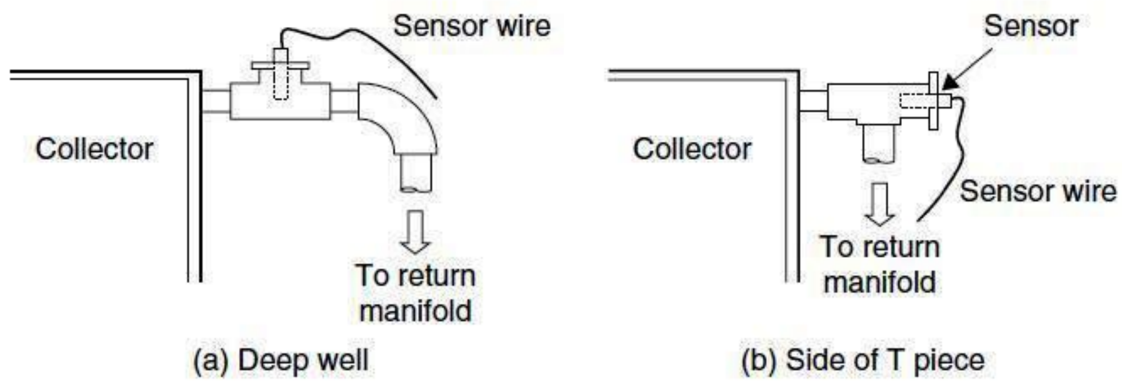


Figure 3.43 Placement of collector sensor.

5.6 Hot water demand

The most important parameter that needs to be considered in the design of a water heating system is the hot water demand over a certain period of time (hourly, daily, or monthly). The energy demand, D, required for the generation of sanitary hot water can be obtained if the volumetric consumption, V, is known for the required time period. Also required are the temperatures of the cold water supplied by public mains, T_m, and the water distribution, T_w. Then,

$$D = V \rho c_p (T_w - T_m)$$

If the two temperatures in above equation are known for a particular application, the only parameter on which the energy demand depends is the hot water volumetric consumption. This can be estimated according to the period of time investigated. For example, for the monthly water demand, the following equation can be used:

$$V = N_{days} N_{persons} V_{person}$$

where

N_{days}: number of days in a month.

$N_{persons}$: number of persons served by the water heating system.

V_{person}: Volume of hot water required per person.

The volumetric consumption, V, varies considerably from person to person and from day to day. It has to do with the habits of the users, the weather conditions of a locality, and various socioeconomic conditions. It can be estimated by considering the hot water use for various operations. Typical operations and consumption for residential usage are given in Table 3.3. More details and other applications, such as water consumption in hotels, schools, and others.

In addition to the quantities shown in Table 3.3 hot water is consumed in automatic dish washing and clothes washing, but these quantities of hot water are produced by the washer with electricity as part of the washing process. By using the data shown in Table 3.3 for a four-person family and normal daily tasks consisting of two food preparations, two manual dish washings, one shower for each person, and two face or hand washings per person per day, the low, medium, and high demand values in liters per person shown in Table 3.4 can be obtained. The maximum consumption case is where the shower for each person is replaced with a bath for each person per day.

In hourly simulations, the hourly distribution of hot water demand is required. Although the hot water demand is subject to a high degree of variation from day to day and consumer to consumer, it is impractical to use anything but a repetitive load profile. This is not quite correct during the summer period, when the consumption pattern is somewhat higher. However, during this period, the temperature requirement for hot water is not as high as during winter. Consequently, the total thermal energy requirement is reasonably constant throughout the year. The demand profile usually used in hour simulations is the Rand profile, illustrated in **Figure 3.44**. This assumes a daily hot water consumption of 120 L at 50 °C for a family of four (30 L/person).

Table 3.3 Typical Residential Usage of Hot Water per Task

Use	Flow (L)
Food preparation	10–20
Manual dish washing	12–18
Shower	10–20
Bath	50–70
Face and hand washing	5–15

Table 3.4 Hot Water Daily Demand for a Family of Four Persons in Liters per Person

Guideline	Low	Medium	High
Normal consumption	26	40	54
Maximum consumption	66	85	104

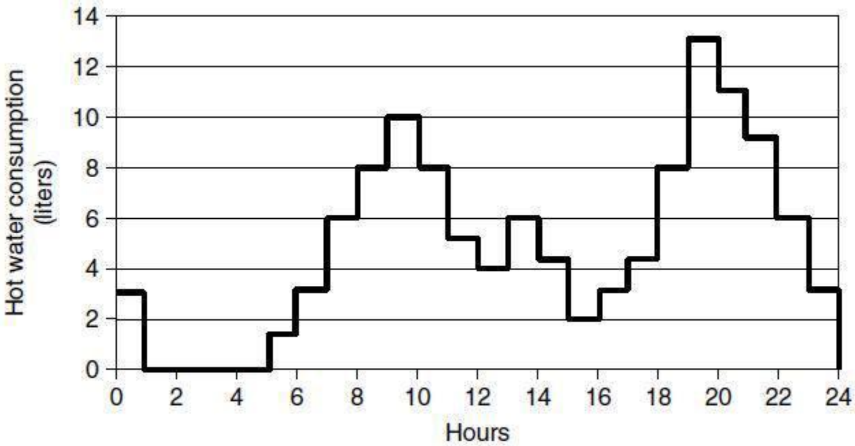


Figure 5.31 Hot water daily consumption profile.

Example

Estimate the hot water energy demand for a family of four, with medium normal consumption, cold water mains supply of 18°C, and water distribution temperature of 45°C.

Solution

According to Table 3.4, the consumption per day per person is 40 L. Therefore, the daily demand, *V*, is 160 L/d or 0.16 m^3/d.

$$D = V\,\rho\,c_p\,(T_w - T_m) = 0.16 \times 1000 \times 4.18(45 - 18)$$

$$= 18057.6 kJ/dy = 18.06 \text{MJ/dy}$$

5.9 Practical considerations

Installation of large collector arrays presents specific piping problems. This section examines issues related to the installation of pipes, supports, and insulation; pumps; valves; and instrumentation. Generally, the plumbing involved in solar energy systems is conventional, except in cases where a toxic or nonpotable heat transfer fluid is circulated in the collector loop. A general guide is that the less complex the system is, the more trouble free its operation will be.

5.9.1 Pipes, Supports, and Insulation

The material of a solar energy system piping may be copper, galvanized steel, stainless steel, or plastic. All pipes are suitable for normal solar system operation except plastic piping, which is used only for low temperature systems, such as swimming pool heating. Another problem related to plastic piping is its high coefficient of expansion, which is 3–10 times as high as that for copper pipes and causes deformation at high temperatures. Piping that carries potable water may be copper, galvanized steel, or stainless steel. Untreated steel pipes should not be used because they corrode rapidly.

System piping should be compatible with the collector piping material to avoid galvanic corrosion; for example, if the collector piping is copper the system piping should also be copper. If dissimilar metals must be joined, dielectric couplings must be used.

Pipes can be joined with a number of different methods, such as threaded, flared compression, hard soldered, and brazed. The method adopted also depends on the type of piping used; for example, a threaded connection is not suitable for copper piping but is the preferred method for steel pipes.

Pipes are usually installed on roofs; therefore, the piping layout should be designed in such a way as to allow expansion and contraction, have the minimum roof penetration, and keep the roof integrity and weatherability. A way to estimate the amount of expansion is indicated earlier in this chapter; the supports selected for the installation, however, have to allow for the free movement of the pipes to avoid deformation. An easy way to account for the expansion contraction problem is to penetrate the roof at about the center of the solar array and allow for two equal lengths of loops on each side of the penetration point. If the pipes must be supported on the roof, this must be done in a way so as not to penetrate the weatherproof roof membrane. For this purpose, concrete pads can be constructed on which the pipe supports can be fitted.

Another important issue related to the installation of collector array piping is the pipe insulation. Insulation must be selected to have adequate *R* value to minimize heat losses. Other issues to be considered are insulation availability and workability, and because the insulation is exposed to the weather, it must have a high UV durability and low permeability by water. The last factors are usually obtained by installing a suitable protection of the insulation, such as aluminum waterproofing. Areas that require special attention in applying the waterproofing are joints between collectors and piping, pipe tees and elbows, and special places where valves and sensors protrude through the waterproofing. The types of insulation that can be used are glass fiber, rigid foam, and flexible foam.

5.9.2 Pumps

For solar energy systems, centrifugal pumps and circulators are used. Circulators are suitable for small domestic-size systems. Construction materials for solar system pumps depend on the particular application and fluid used in the circuit.

Potable water and drain-down systems require pumps made from bronze, at least for the parts of the pump in contact with the water. Pumps should also be selected to be able to work at the operating temperature of the system.

5.9.3 Valves

Special attention must be paid to the proper selection and location of valves in solar energy systems. Careful selection and installation of a sufficient number of valves are required so that the system performs satisfactorily and is accessible for maintenance procedures. Using too many valves, however, should be avoided to reduce cost and pressure drop. The various types of valves required in these systems are isolation valves, balancing valves, relief valves, check valves, pressure reducing valves, air vents, and drain valves. These are described briefly here.

- **Isolation valves**. Isolation or shutoff valves are usually gate of quarterturn ball valves. These should be installed in such a way so as to permit certain components to be serviced without having to drain and refill the whole system. Special attention is required so as not to install isolation valves in a way that would isolate collectors from pressure-relief valves.
- **Balancing valves**. Balancing or flow-regulating valves are used in multirow installations to balance the flow in the various rows and ensure that all rows received the required quantity of flow. As already seen in this chapter, the use of these valves is imperative in direct return systems. The adjustment of these valves is done during commissioning of the system. For this purpose, flow rate or pressure may need to be measured for each row, so the system must have provisions for these measurements. After the balancing valves are adjusted, their setting must be locked to avoid accidental modification. The easiest way to do this is to remove the valve handle.
- **Relief valves**. Pressure safety or relief valves are designed to allow escape of water or heat transfer fluid from the system when the maximum working pressure of the system is reached. In this way, the system is protected from high pressure. This valve incorporates a spring, which keeps the valve closed. When the pressure of the circuit fluid exceeds the spring stiffness, the valve is lifted and allows a small quantity of the circulating fluid to escape so as to relieve the pressure. Two types of relief valves are available: the adjustable type and the preset type. The preset type comes in a number of relief pressure settings, whereas the adjustable type needs pressure testing to adjust the valve spring stiffness to the required relief pressure. The relief valve may be installed anywhere along the closed loop system. Attention should be paid to the fact that the discharge of such a valve will be very hot or even in a steam state, so the outlet should be piped to a drain or container. The latter is preferred because it

gives an indication to the service personnel that the valve opened and they should look for possible causes or problems. The use of a tank is also preferred in systems with antifreeze, because the fluid is collected in the tank.

- **Check valves**. Check valves are designed to allow flow to pass in only one direction. In doing so, flow reversal is avoided. This valve comes in a number of variations, such as the swing valve and the spring-loaded valve. Swing valves require very little pressure difference to operate but are not suitable for vertical piping, whereas spring-loaded valves need more pressure difference to operate but can be installed anywhere in the circuit.
- **Pressure-reducing valves**. Pressure-reducing valves are used to reduce the pressure of make-up city water to protect the system from overpressure. These valves should be installed together with a check valve to avoid feeding the city circuit with water from the solar energy system.
- **Automatic air vents**. Automatic air vents are special valves used to allow air to escape from the system during fill-up. They are also used to eliminate air in a closed circuit system. This valve should be installed at the highest point of the collector circuit. Automatic air vent valves are of the float type, where water or the circulating fluid keeps the valve closed by forcing a bronze empty ball against the valve opening. When air passes through the valve, the bronze empty ball is lowered because of its weight and allows the air to escape.
- **Drain valves**. Drain valves are used in drain-down systems. These are electromechanical devices, also called solenoid valves, that keep the valve closed as long as power is connected to the valve (normally open valves). When the valve is de-energized, a compression spring opens the valve and allows the drain of the system.

5.9.4 Instrumentation

Instrumentation used in solar energy systems varies from very simple temperature and pressure indicators, energy meters, and visual monitors to data collection and storage systems. It is generally preferable to have some kind of data collection to be able to monitor the actual energy collected from the solar energy system.

Visual monitors are used to provide instantaneous readings of various system parameters, such as temperatures and pressures at various locations in the system. Sometimes, these are equipped with data storage. Energy meters monitor and report the time-integrated quantity of energy passing through a pair of pipes. This is done by measuring the flow rate and the temperature difference in the two pipes. Most of energy meters must be read manually, but some provide an output to a recorder.

Automatic recording of data from a number of sensors in a system is the most versatile but also the most expensive system. This requires an electrical connection from the various sensors to a central recorder. Some recorders also allow processing of the data. Nowadays, systems are available that collect and display results online on the Internet. These are very helpful in monitoring the state of the system, although they add to the total system cost. In countries where schemes such as the guaranteed solar results operate, where the solar energy system provider guarantees that the system will provide a certain amount of energy for a number of years, however, this is a must.

Chapter Four
Solar Space Heating and Cooling

The two principal categories of building solar heating and cooling systems are:

1- **Passive system** is applied to buildings that include, as integral parts of the building, elements that admit, absorb, store, and release solar energy and thus reduce the needs for auxiliary energy for comfort heating.
2- **Active systems** are the ones that employ solar collectors, storage tank, pumps, heat exchangers, and controls to heat and cool the building.

4.1 Thermal load estimation

When estimating the building thermal load, adequate results can be obtained by calculating heat losses and gains based on a steady-state heat transfer analysis. For more accurate results and for energy analysis, however, transient analysis must be employed, since the heat gain into a conditioned space varies greatly with time, primarily because of the strong transient effects created by the hourly variation of solar radiation. Many methods can be used to estimate the thermal load of buildings. The most well known are the heat balance, weighting factors, thermal network, and radiant time series. In this book, only the heat balance method is briefly explained. Additionally, the degree day method, which is a more simplified one used to determine the seasonal energy consumption, is described. Before proceeding, however, the three basic terms that are important in thermal load estimation are explained.

Heat gain

Heat gain is the rate at which energy is transferred to or generated within a space and consists of sensible and latent gain. Heat gains usually occur in the following forms:

1. Solar radiation passing through glazing and other openings.
2. Heat conduction with convection and radiation from the inner surfaces into the space.
3. Sensible heat convection and radiation from internal objects.
4. Ventilation and infiltration.
5. Latent heat gains generated within the space.

Thermal load

The thermal load is the rate at which energy must be added or removed from a space to maintain the temperature and humidity at the design values. The cooling load differs from the heat gain mainly because the radiant energy from the inside surfaces, as well as the direct solar radiation passing into a space through openings, is mostly absorbed in the space. This energy becomes part of the cooling load only when the room air receives the energy by convection and occurs when the various surfaces in the room attain higher temperatures than the room air. Hence, there is a time lag that depends on the storage characteristics of the structure and interior objects and is more significant when the heat capacity (product of mass and specific heat) is greater. Therefore, the peak cooling load can be considerably smaller than the maximum heat gain and occurs much later than the maximum heat gain period. The heating load behaves in a similar manner as the cooling load.

Heat extraction rate

The heat extraction rate is the rate at which energy is removed from the space by cooling and dehumidifying equipment. This rate is equal to the cooling load when the space conditions are constant and the equipment is operating. Since the operation of the control systems induces some fluctuation in the room temperature, the heat extraction rate fluctuates and this also causes fluctuations in the cooling load.

Methods of thermal load estimation

1- The heat balance method
2- The transfer function method
3- Heat extraction rate and room temperature
4- Degree day method
5- Building heat transfer

4.1.1 Space heating and service hot water

Depending on the conditions that exist in a system at a particular time, the solar systems usually have five basic modes of operation:

1. When solar energy is available and heat is not required in the building, solar energy is added to storage.
2. When solar energy is available and heat is required in the building, solar energy is used to supply the building load demand.
3. When solar energy is not available, heat is required in the building, and the storage unit has stored energy, the stored energy is used to supply the building load demand.
4. When solar energy is not available, heat is required in the building, and the storage unit has been depleted, auxiliary energy is used to supply the building load demand.
5. When the storage unit is fully heated, there are no loads to meet, and the collector is absorbing heat, solar energy is discarded.

4.1.2 Air systems

A schematic of a basic solar air heating system with a pebble bed storage unit and auxiliary heating source is shown in **Figure 4.1**. In this case, the various operation modes are achieved by the use of the dampers shown. Usually, in air systems, it is not practical to have simultaneous addition and removal of energy from the storage. If the energy supplied from the collector or storage is inadequate to meet the load, auxiliary energy can be used to top up the air temperature to cover the building load. As shown in **Figure 4.1**, it is also possible to bypass the collector and storage unit when there is no sunshine and the storage tank is completely depleted and use the auxiliary alone to provide the required heat.

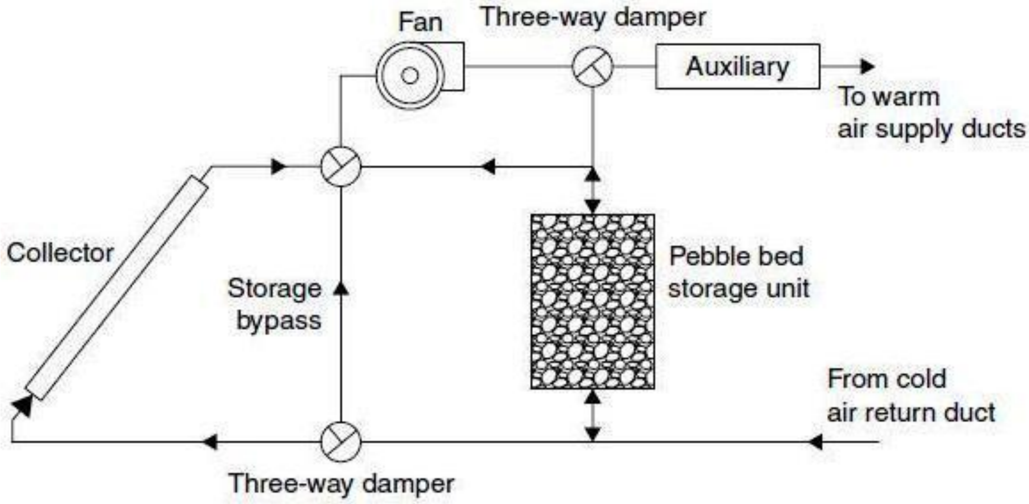


Figure 4.1 Schematic of basic hot air system.

4.1.3 Water systems

Many varieties of systems can be used for both solar space heating and domestic hot water production. When used for both space and hot water production and because solar-heated water can be added to storage at the same time that hot water is removed from storage to meet building loads, the system allows independent control of the solar collector-storage and storage-auxiliary-load loops. Usually, a bypass is provided around the storage tank to avoid heating the storage tank, which can be of considerable size, with auxiliary energy.

A schematic diagram of a solar heating and hot water system is shown in **Figure 4.2**. Control of the solar heating system is based on two thermostats: the collector-storage temperature differential and the room temperature. The collector operates with a differential thermostat.

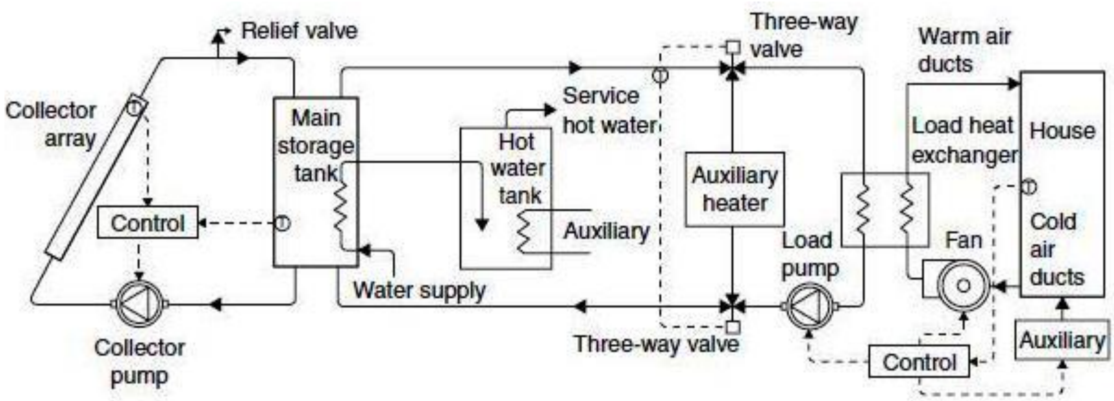


Figure 4.2 Schematic diagram of a solar space heating and hot water system.

4.1.4 Location of auxiliary heater

One important consideration concerning the storage tank is the decision as to the best location for the auxiliary heater. This is especially important for solar space-heating systems because larger amounts of auxiliary energy are usually required and storage tank sizes are large. For maximum utilization of the energy supplied by an auxiliary source, the location of this energy input should be at the load, not at the storage tank. The supply of auxiliary energy at the storage tank will undoubtedly increase the temperature of fluid entering the collector, resulting in lower collector efficiency. When a water-based solar energy system is used in conjunction with a warm-air space heating system, the most economical means of auxiliary energy supply is by the use of a fossil fuel-fired boiler. In case of bad weather, the boiler can take over the entire heating load.

When a water-based solar energy system is used in conjunction with a water space heating system or to supply the heated water to an absorption air conditioning unit, the auxiliary heater can be located in the storage-load loop, either in series or in parallel with the storage, as illustrated in **Figure 4.3.**

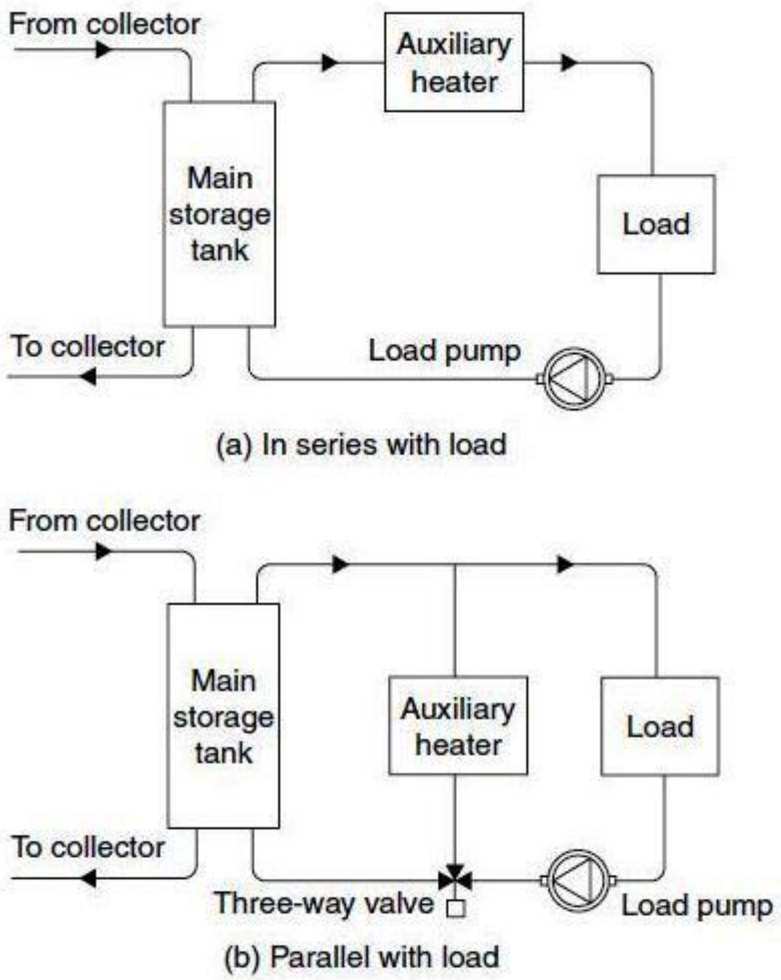


Figure 4.3 Auxiliary energy supply in water-based systems.

4.1.5 Heat pump systems

Active solar energy systems can also be combined with heat pumps for domestic water heating or space heating. In residential heating, the solar energy system can be used in parallel with a heat pump, which supplies auxiliary energy when the sun is not available. Additionally, for domestic water systems requiring high water temperatures, a heat pump can be placed in series with the solar storage tank.

A heat pump is a device that pumps heat from a low-temperature source to a higher-temperature sink. Heat pumps are usually vapor compression refrigeration machines, where the evaporator can take heat into the system at low temperatures and the condenser can reject heat from the system at high temperatures.

In the heating mode, a heat pump delivers thermal energy from the condenser for space heating and can be combined with solar heating. In the cooling mode, the evaporator extracts heat from the air to be conditioned and rejects heat from the condenser to the atmosphere, with solar energy not contributing to the energy for cooling.

Heat pumps have been used in combination with solar systems in residential and commercial applications. The additional complexity imposed by such a system and extra cost are offset by the high coefficient of performance and the lower operating temperature of the collector subsystem. A schematic of a common residential type heat pump system is shown in **Figure 4.4**. During favorable weather conditions, it is possible with this arrangement to have solar energy delivered directly to the forced air system while the heat pump is kept off.

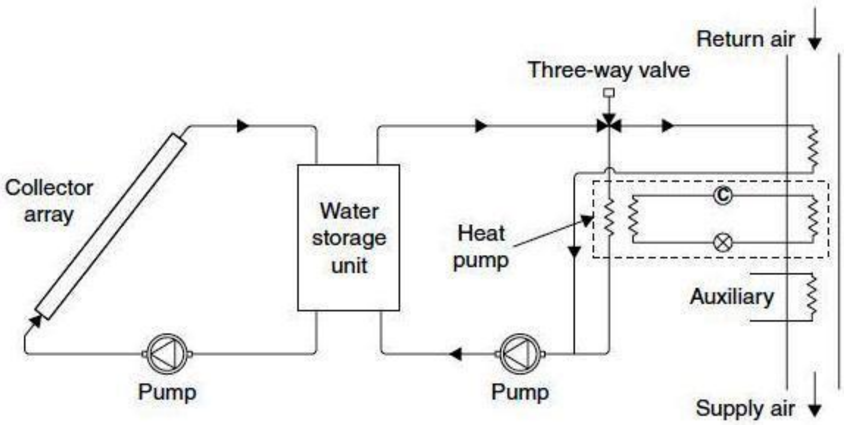


Figure 4.4 Schematic diagram of a domestic water-to-air heat pump system (series arrangement).

Chapter Five
Industrial Process Heat, Chemistry Applications, and Solar Dryers

7.1 industrial process heat: General design considerations

Beyond the low-temperature applications, there are several potential fields of application for solar thermal energy at a medium and medium-high temperature level (80–240°C). The most important of them is heat production for industrial processes, which represents a significant amount of heat. For example, industrial heat demand constitutes about 15% of the overall demand of final energy requirements in the southern European countries. The present energy demand in the EU for medium and medium-high temperatures is estimated to be about 300 TWh/a.

From a number of studies on industrial heat demand, several industrial sectors have been identified as having favorable conditions for the application of solar energy. The most important industrial processes using heat at a mean temperature level are sterilizing, pasteurizing, drying, hydrolyzing, distillation and evaporation, washing and cleaning, and polymerization. Some of the most important processes and the range of the temperatures required for each are shown in **Table 5.1.**

Large-scale solar applications for process heat benefit from the effect of scale. Therefore, the investment costs should be comparatively low, even if the costs for the collector are higher. One way to ensure economical terms is to design systems with no heat storage, i.e., the solar heat is fed directly into a suitable process (fuel saver). In this case, the maximum rate at which the solar energy system delivers energy must not be appreciably larger than the rate at which the process uses energy. This system, however, cannot be cost effective in cases where heat is needed at the early or late hours of the day or at nighttime, when the industry operates on a double-shift basis.

The usual types of industries that use most of the energy are the food industry and the manufacture of non-metallic mineral products. Particular types of food industries that can employ solar process heat are the milk (dairies) and cooked pork meats (sausage, salami, etc.) industries and breweries. Most of the process heat is used in the food and textile industries for such diverse applications as drying, cooking, cleaning, and extraction. Favorable conditions exist in the food industry because food treatment and storage are processes with high energy consumption and high running time. Temperatures for these applications may vary from near ambient to those corresponding to low-pressure steam, and energy can be provided either from flat-plate or low-concentration-ratio concentrating collectors.

Table 5.1 Temperature Ranges for Various Industrial Processes

Industry	Process	Temperature (°C)
Dairy	Pressurization	60–80
	Sterilization	100–120
	Drying	120–180
	Concentrates	60–80
	Boiler feedwater	60–90
Tinned food	Sterilization	110–120
	Pasteurization	60–80
	Cooking	60–90
	Bleaching	60–90
Textile	Bleaching, dyeing	60–90
	Drying, degreasing	100–130
	Dyeing	70–90
	Fixing	160–180
	Pressing	80–100
Paper	Cooking, drying	60–80
	Boiler feedwater	60–90
	Bleaching	130–150
Chemical	Soaps	200–260
	Synthetic rubber	150–200
	Processing heat	120–180
	Pre-heating water	60–90
Meat	Washing, sterilization	60–90
	Cooking	90–100
Beverages	Washing, sterilization	60–80
	Pasteurization	60–70
Flours and by-products	Sterilization	60–80
Timber by-products	Thermodifussion beams	80–100
	Drying	60–100
	Pre-heating water	60–90
	Preparation pulp	120–170
Bricks and blocks	Curing	60–140
Plastics	Preparation	120–140
	Distillation	140–150
	Separation	200–220
	Extension	140–160
	Drying	180–200
	Blending	120–140

5.1.1 Solar industrial air and water systems

The two types of applications employing solar air collectors are the open circuit and the recirculating applications. In the open circuit, heated ambient air is used in industrial applications where, because of contaminants, recirculation of air is not possible. Examples are paint spraying, drying, and supplying fresh air to hospitals.

It should be noted that heating outside air is an ideal operation for the collector because it operates very close to ambient temperature, thus more efficiently. In recirculating air systems, a mixture of recycled air from the dryer and ambient air is supplied to the solar collectors. Solar-heated air supplied to a drying chamber can be applied to a variety of materials, including lumber and food crops. In this case, adequate control of the rate of drying, which can be performed by controlling the temperature and humidity of the supply air, can improve product quality.

Similarly, the two types of applications employing solar water collectors are the once-through systems and the recirculating water heating applications.

Once-through systems are employed in cases where water is used for cleaning in food industries and recycling the used water is not practical because of the contaminants picked up by the water in the cleaning process.

A solar energy system may deliver energy to the load either in series or parallel with the auxiliary heater. In a series arrangement, shown in **Figure 5.1**, energy is used to pre-heat the load heat transfer fluid, which may be heated more, if necessary, by the auxiliary heater, to reach the required temperature. If the temperature of the fluid in the storage tank is higher than that required by the load, a three way valve, also called a tempering valve, is used to mix it with cooler make-up or returning fluid. The parallel configuration is shown in **Figure 5.2**. Since the energy cannot be delivered to the load at a temperature lower than that of the load temperature, the solar system must be able to produce the required temperature before energy can be delivered.

Therefore, a series configuration is preferred over the parallel one because it provides a lower average collector operating temperature, which leads to higher system efficiency. The parallel feed, however, is common in steam producing systems, as shown in **Figure 5.3**, and is explained in the next section.

One of the most important design characteristics to consider when designing a solar industrial process heat system is the time matching of the solar energy source to the load. As was seen in the previous chapter, heating and cooling loads vary from day to day. In industrial process heat systems, however, the loads are pretty much constant and small variations are due to the seasonal variation of the make-up water temperature.

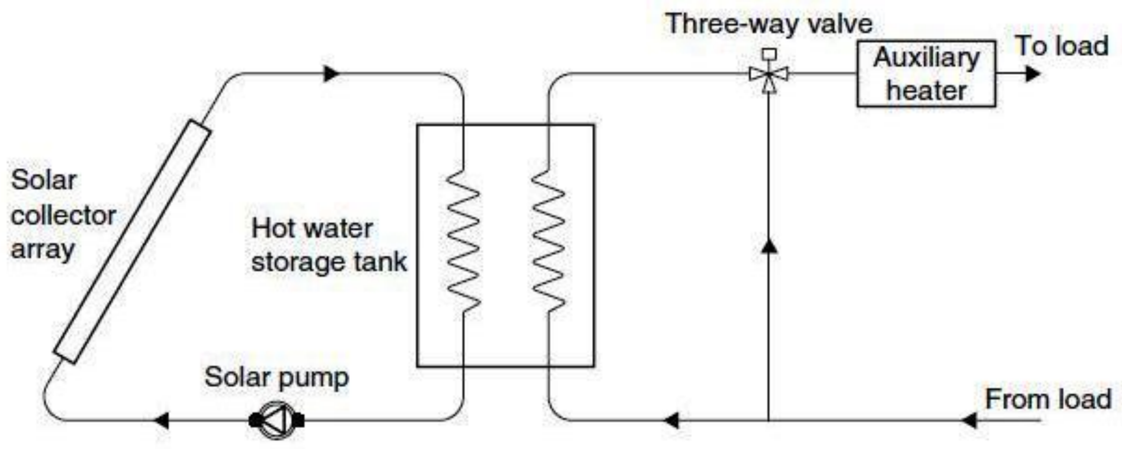


Figure 5.1 Simple industrial process heat system with a series configuration of auxiliary heater.

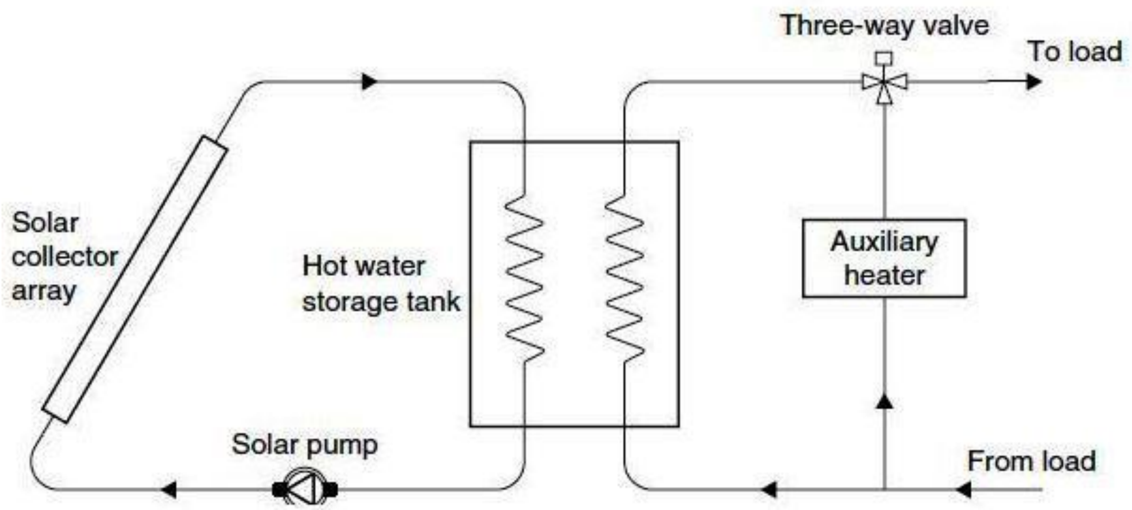


Figure 5.2 Simple industrial process heat system with a parallel configuration of auxiliary heater.

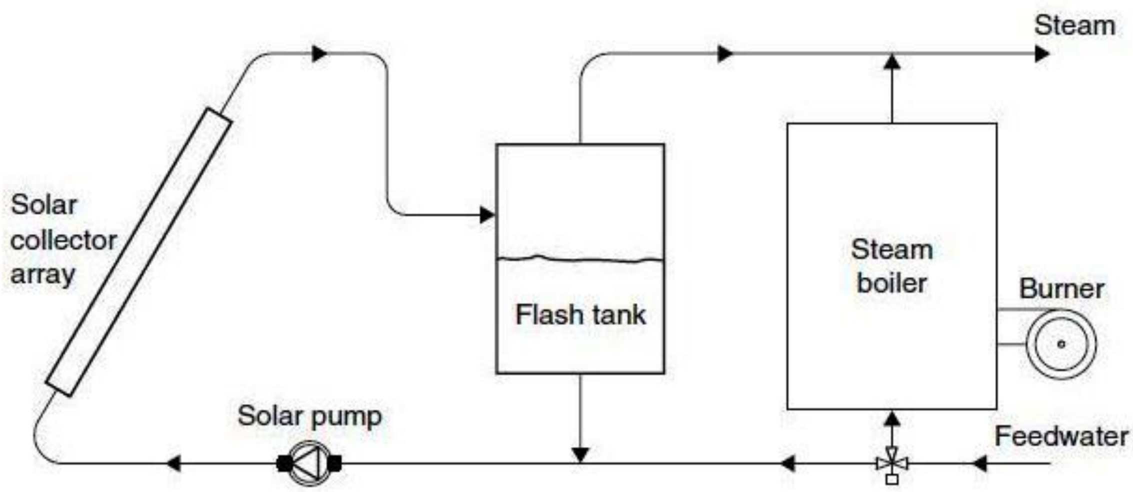


Figure 5.3 Simple industrial process heat steam system with a parallel configuration with an auxiliary steam boiler.

5.2 Solar steam generation systems

Parabolic trough collectors are frequently employed for solar steam generation because relatively high temperatures can be obtained without serious degradation in the collector efficiency. Low-temperature steam can be used in industrial applications, in sterilization, and for powering desalination evaporators.

Three methods have been employed to generate steam using parabolic trough collectors:

1. The steam-flash concept, in which pressurized water is heated in the collector and flashed to steam in a separate vessel.
2. The direct or in situ concept, in which two-phase flow is allowed in the collector receiver so that steam is generated directly.
3. The unfired boiler concept, in which a heat transfer fluid is circulated through the collector and steam is generated via heat exchange in an unfired boiler.

5.2.1 Steam Generation Methods

The steam-flash system is shown schematically in **Figure 5.4**. In this system, water, pressurized to prevent boiling, is circulated through the collector and flashed across a throttling valve into a flash vessel. Treated feedwater input maintains the level in the flash vessel and the sub cooled liquid is recirculated through the collector.

The in situ boiling concept, shown in **Figure 5.5**, uses a similar system configuration with no flash valve. Sub cooled water is heated to boiling and steam forms directly in the receiver tube. capital costs associated with direct steam and flash-steam systems are approximately the same.

A diagram of an unfired boiler system is shown in **Figure 5.6**. In this system, a heat transfer fluid is circulated through the collector, which is non-freezing and non-corrosive and in which system pressures are low and control is straightforward. These factors largely overcome the disadvantages of water systems and are the main reasons for the predominant use of heat transfer oil systems in current industrial steam-generating solar systems.

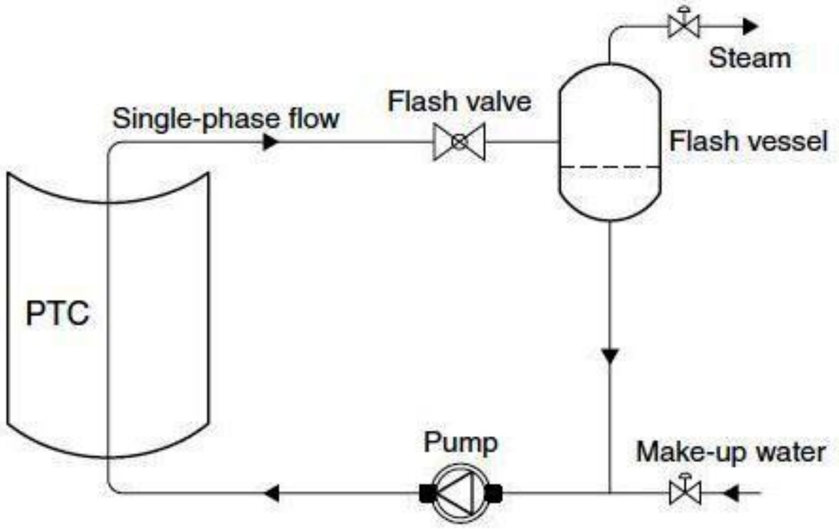


Figure 5.4 The steam-flash steam generation concept

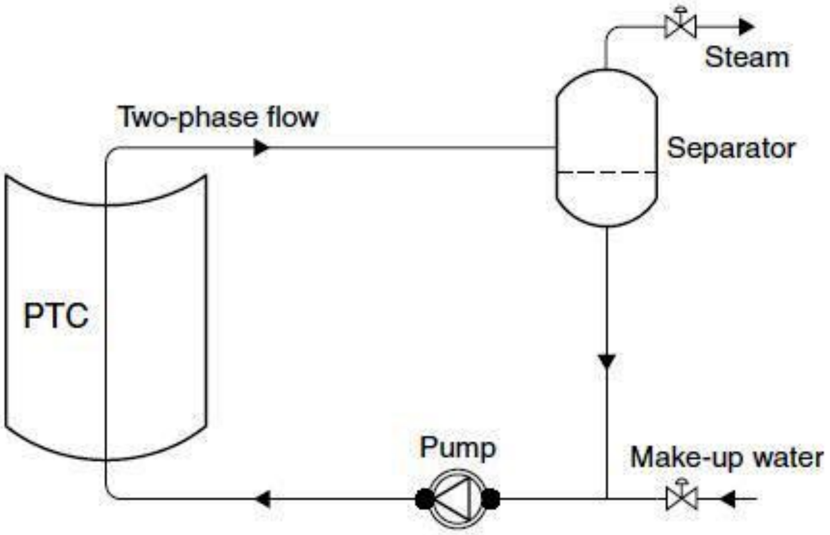


Figure 5.5 The direct steam generation concept.

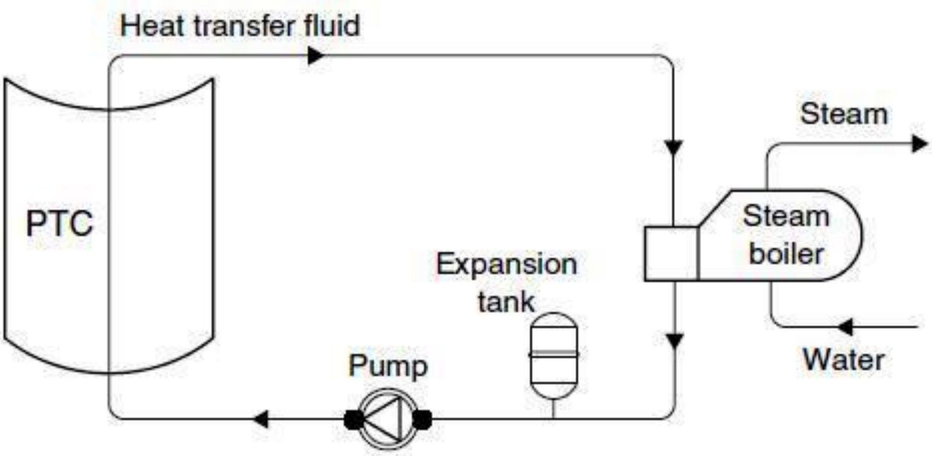


Figure 5.6 The unfired boiler steam generation concept.

5.2.2 Flash Vessel Design

To separate steam at lower pressure, a flash vessel is used. This is a vertical vessel, as shown in **Figure 5.7,** with the inlet of high-pressure, high-temperature water located at about one third of the way up its height. The standard design of flash vessels requires that the diameter of the vessel is chosen so that the steam flows toward the top outlet connection at no more than about 3 m/s. This should ensure that any water droplets could fall through the steam in a contraflow, to the bottom of the vessel. Adequate height above the inlet is necessary to ensure separation. The separation is also facilitated by having the inlet projecting downward into the vessel. The water connection is sized to minimize the pressure drop from the vessel to the pump inlet to avoid cavitation

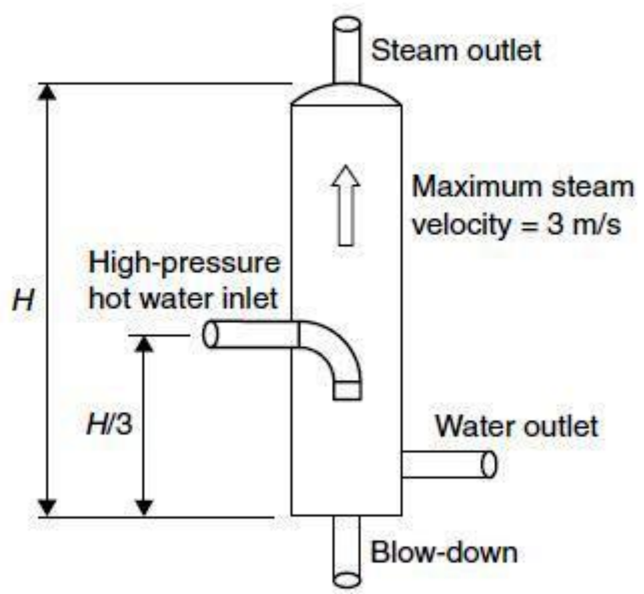


Figure 5.7 Flash vessel schematic diagram.

5.3 Solar chemistry applications

Solar chemistry applications include a variety of fields; the main ones are the production of energy carriers (e.g., hydrogen), also called *reforming of fuels*; fuel cells; materials processing

5.4 Solar dryers

Solar drying is another very important application of solar energy. Solar dryers use air collectors to collect solar energy. Solar dryers are used primarily by the agricultural industry. The purpose of drying an agricultural product is to reduce its moisture content to a level that prevents its deterioration. In drying, two processes take place: One is a heat transfer to the product using energy from the heating source, and the other is a mass transfer of moisture from the interior of the product to its surface and from the surface to the surrounding air.

The purpose of a dryer is to supply more heat to the product than that available naturally under ambient conditions, thus increasing sufficiently the vapor pressure of the crop moisture. Therefore, moisture migration from the crop is improved. The dryer also significantly decreases the relative humidity of the drying air, and by doing so, its moisture-carrying capability increases, thus ensuring a sufficiently low equilibrium moisture content.

5.4.1 Active Solar Energy Dryers

Distributed type

A typical distributed-type active solar dryer is shown in **Figure 5.8**. It comprises four components: a drying chamber, a solar energy air heater, a fan, and ducting to transfer the hot air from the collector to the dryer.

Integral type

Large-scale, commercial, forced-convection, greenhouse-type dryers are like transparent roof solar barns and are used for solar timber drying kilns **(see Figure 5.9).** Small-scale forced dryers are often equipped with auxiliary heating. Another variation of this type of dryer is the solar collector–roof/wall, in which the solar heat collector forms an integral part of the roof and/or wall of the drying chamber. A solar-roof dryer is shown in **Figure 5.10**. A collector-wall system is like a Trombe wall, where a black painted concrete block wall with outside glazing forms the solar collector and serves also as a thermal storage.

Mixed-mode type

The mixed-mode dryer is similar to the distributed type with the difference that the walls and roof of the dryer are made from glass, to allow solar energy to warm the products directly, as shown in **Figure 5.11**.

It should be noted that, because drying efficiency increases with temperature, in conventional dryers the maximum possible drying temperature that would not deteriorate the product quality is used. In solar dryers, however, the maximum drying temperature is determined by the solar collectors, because their efficiency decreases with higher operating temperatures and this may not yield an optimal dryer design.
Most air heaters use metal or wood absorbers, whereas black polythene absorbers have been used in a few designs in an attempt to minimize cost.

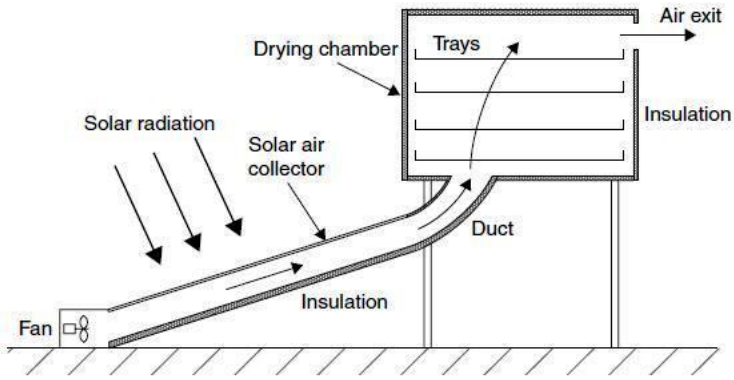


Figure 5.8 Schematic diagram of a distributed-type active solar dryer.

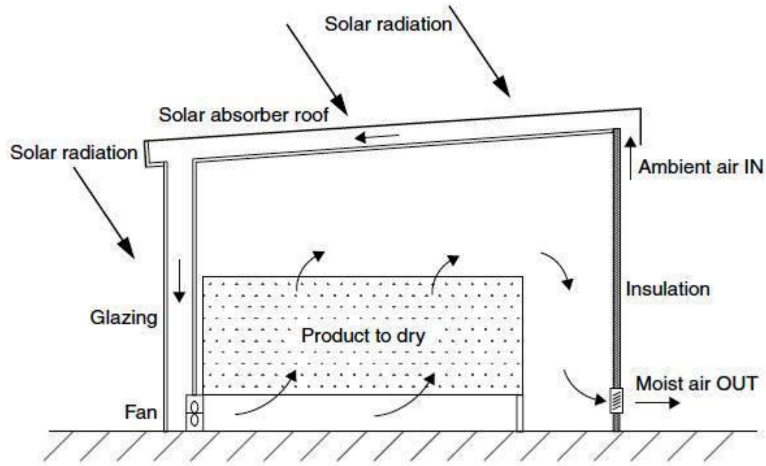


Figure 5.9 Schematic diagram of a forced-convection, transparent-roof solar barn.

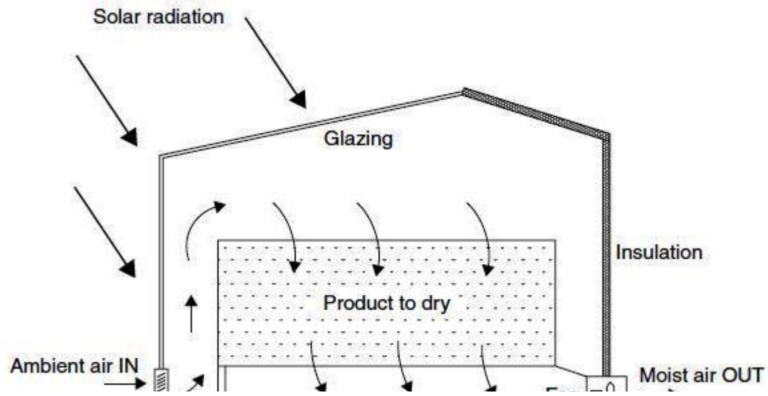


Figure 5.10 Schematic diagram of an active collector–roof solar energy storage dryer.

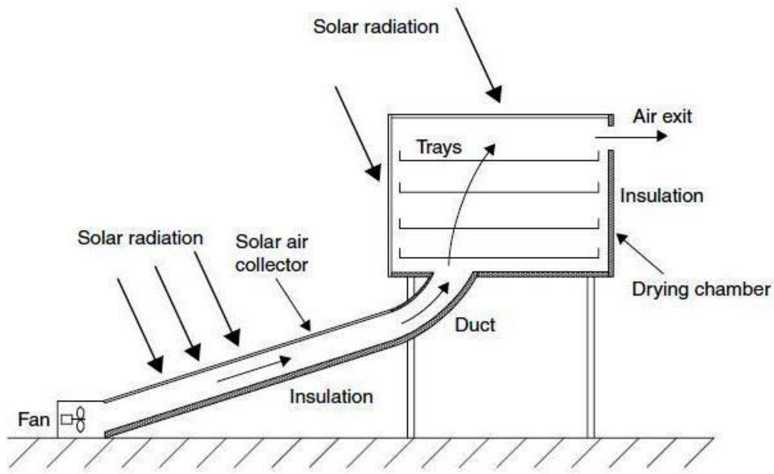


Figure 5.11 Schematic diagram of a mixed-mode-type active solar dryer.

5.4.2 Passive Solar Energy Dryers

Passive or natural circulation solar energy dryers operate by using entirely renewable sources of energy, such as solar and wind.

Distributed type

Distributed, natural circulation, solar energy dryers are also called *indirect passive dryers*. A typical distributed natural circulation solar energy dryer comprises an air heating solar energy collector, appropriate insulated ducting, a drying chamber, and a chimney, as shown in **Figure 5.12**. In this design, the crop is located on trays or shelves inside an opaque drying chamber, which does not allow the solar radiation to reach the product directly. Air, which is heated during its passage through an air solar collector, is ducted to the drying chamber to dry the product

Integral type

Integral-type, natural circulation, solar energy dryers are also called *direct passive solar energy dryers*. In this system, the crop is placed in a drying chamber, which is made with transparent walls; therefore, the necessary heat is obtained by the direct absorption of solar radiation at the product, from the internal surfaces of the chamber, and by convection from the heated air mass within the chamber. The heat removes the moisture from the product and, at the same time, lowers the relative humidity of the resident air mass, thus increasing its moisture-carrying capacity. The air in the chamber is also expanded because the density of the hot air is lower than the cold, thus generating natural circulation, which also helps in the removal of moisture, along with the warm air. Because heat is transferred to the crop by both convection and radiation, the rate of drying for direct dryers is greater than that for indirect dryers. Integral-type, natural circulation solar energy dryers can be of a very simple construction, as shown in **Figure 5.13,**

Mixed-mode type

Mixed-mode, natural circulation, solar energy dryers combine the features of the integral-type and the distributed-type natural circulation solar energy dryers. In this case, the combined action of solar radiation incident directly on the product to be dried and the air heated in a solar air collector provide the necessary heat required for the drying process. A mixed-mode, natural circulation solar energy dryer has the same structural characteristics as the distributed type, i.e., a solar air heater, a separate drying chamber, and a chimney; in addition, the drying chamber walls are glazed so that the solar radiation can reach the product directly as in the integral-type dryers, as shown in **Figure 5.14**.

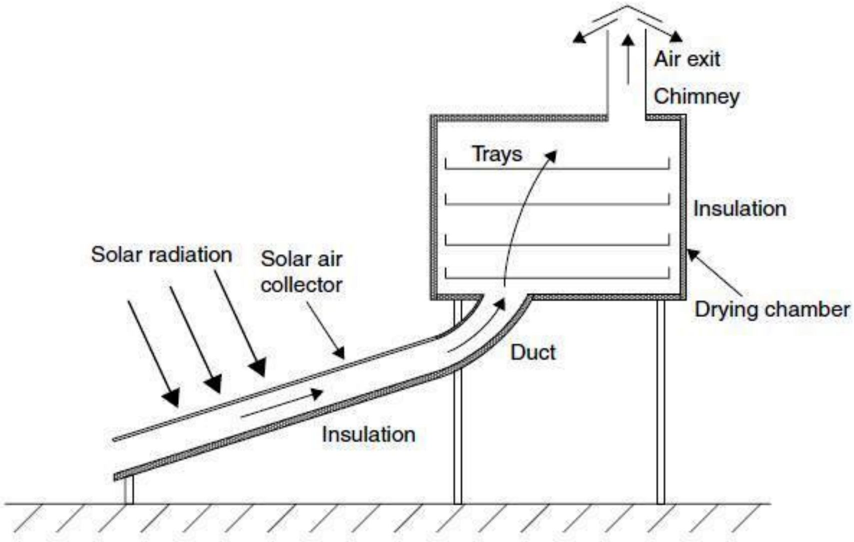


Figure 5.12 Schematic diagram of a distributed-type passive solar dryer.

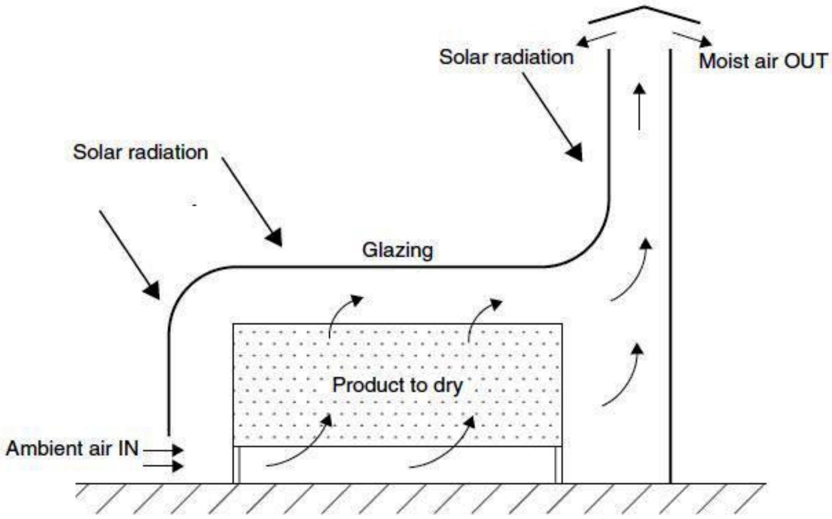


Figure 5.13 Schematic diagram of an integral-type passive solar dryer.

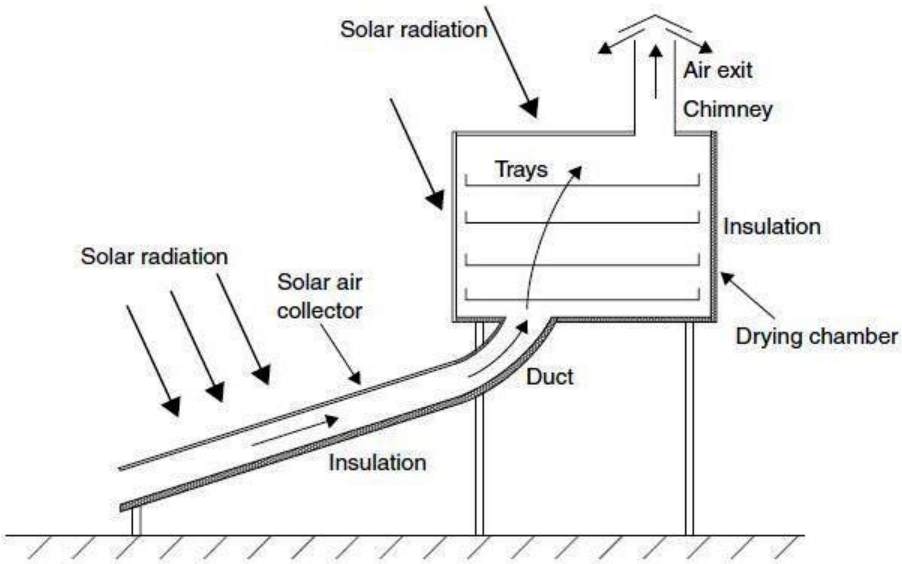


Figure 5.14 Schematic diagram of a natural circulation, mixed-mode solar energy dryer.

6. Solar Desalination Systems

6.1 Introduction

The provision of freshwater is becoming an increasingly important issue in many areas of the world. In arid areas, potable water is very scarce and the establishment of a human habitat in these areas strongly depends on how such water can be made available.

Water is essential to life. The importance of supplying potable water can hardly be overstressed. Water is one of the most abundant resources on earth, covering three fourths of the planet's surface. About 97% of the earth's water is saltwater in the oceans and 3% (about 36 million km3) is fresh water contained in the poles (in the form of ice), ground water, lakes, and rivers, which supply most human and animal needs. Nearly 70% from this tiny 3% of the worlds freshwater is frozen in glaciers, permanent snow cover, ice, and permafrost. Thirty percent of all freshwater is underground, most of it in deep, hard-to-reach aquifers. Lakes and rivers together contain just a little more than 0.25% of all freshwater; lakes contain most of it.

Of the total water consumption, about 70% is used by agriculture, 20% is used by the industry, and only 10% of the water consumed worldwide is used for household needs. It should be noted that, before considering the application of any desalination method, water conservation measures should be considered. For example, drip irrigation, using perforated plastic pipes to deliver water to crops, uses 30–70% less water than traditional methods and increases crop yield. This system was developed in the early 1960s, but today it is used in less than 1% of the irrigated land. In most places on the earth, governments heavily subsidize irrigation water and farmers have no incentive to invest in drip systems or any other water-saving methods.

8.1.3 Desalination and Energy

The only nearly inexhaustible sources of water are the oceans. Their main drawback, however, is their high salinity. Therefore, it would be attractive to tackle the water-shortage problem by desalinizing of this water. Desalinize, in general, means to remove salt from seawater or generally saline water.
According to the World Health Organization (WHO), the permissible limit of salinity in water is 500 parts per million (ppm) and for special cases up to 1000 ppm. Most of the water available on earth has salinity up to 10,000 ppm, and seawater normally has salinity in the range of 35,000–45,000 ppm in the form of total dissolved salts. Excess brackishness causes the problem of bad taste, stomach problems, and laxative effects. The purpose of a desalination system is to clean or purify brackish water or seawater and supply water with total dissolved solids within the permissible limit of 500 ppm or less. The installed capacity of desalinated water systems in the year 2000 was about 22 million m^3/d, which is expected to increase drastically in the next decades. The dramatic increase of desalinated water supply will create a series of problems, the most

significant of which are those related to energy consumption and environmental pollution caused by the use of fossil fuels. It has been estimated that the production of 22 million m^3/d requires about 20 million tons of oil per annum (about 8.5 EJ/a or 2.36 x 1012 kWh/a of fuel) Given the current concern about the environmental problems related to the use of fossil fuels, if oil were much more widely available, it is questionable whether we could afford to burn it on the scale needed to provide everyone with freshwater. Given current understanding of the greenhouse effect and the importance of CO_2 levels, this use of oil is debatable. Therefore, apart from satisfying the additional energy demand, environmental pollution would be a major concern. If desalination is accomplished by conventional technology, then it will require burning substantial quantities of fossil fuels. Given that conventional sources of energy are polluting, sources of energy that are not polluting must be developed. Fortunately, many parts of the world that are short of water have exploitable renewable sources of energy that could be used to drive desalination processes

8.2 Desalination processes

Desalination can be achieved using a number of techniques. Industrial desalination technologies either use phase change or involve semipermeable membranes to separate the solvent or some solutes. Therefore, desalination techniques may be classified into the following categories: phase change or thermal processes and membrane or single-phase processes

In **Table 8.1**, the most important technologies in use are listed. In the phase change or thermal processes, the distillation of seawater is achieved by utilizing a thermal energy source. The thermal energy may be obtained from a conventional fossil fuel source, nuclear energy, or a non-conventional solar energy source or geothermal energy. In the membrane processes, electricity is used for either driving high-pressure pumps or ionization of salts contained in the seawater.

Table 8.1 Desalination Processes

Phase change processes	Membrane processes
1. Multi-stage flash (MSF) **2.** Multiple effect boiling (MEB) **3.** Vapor compression (VC) **4.** Freezing **5.** Humidification-dehumidification **6.** Solar stills Conventional stills Special stills Cascaded-type solar stills Wick-type stills Multiple-wick-type stills	**1.** Reverse osmosis (RO) RO without energy recovery RO with energy recovery (ER-RO) **2.** Electrodialysis (ED)

Table 8.2 Renewable Energy System Desalination Combinations

RES technology	Feedwater salinity	Desalination technology
Solar thermal	Seawater Seawater	Multiple-effect boiling (MEB) Multi-stage flash (MSF)
Photovoltaics	Seawater Brackish water Brackish water	Reverse osmosis (RO) Reverse osmosis (RO) Electrodialysis (ED)
Wind energy	Seawater Brackish water Seawater	Reverse osmosis (RO) Reverse osmosis (RO) Mechanical vapor compression (MVC)
Geothermal	Seawater	Multiple-effect boiling (MEB)

8.3 Direct collection systems

Among the non-conventional methods to desalinate brackish water or seawater is solar distillation. this process requires a comparatively simple technology and can be operated by unskilled workers. Also, due to the low maintenance requirement, it can be used anywhere with a smaller number of problems. A representative example of the direct collection system is the typical solar still, which uses the greenhouse effect to evaporate salty water. It consists of a basin in which a constant amount of seawater is enclosed in an inverted V-shaped glass envelope **(see Figure 8.1).** The sun's rays pass though the glass roof and are absorbed by the blackened bottom of the basin.

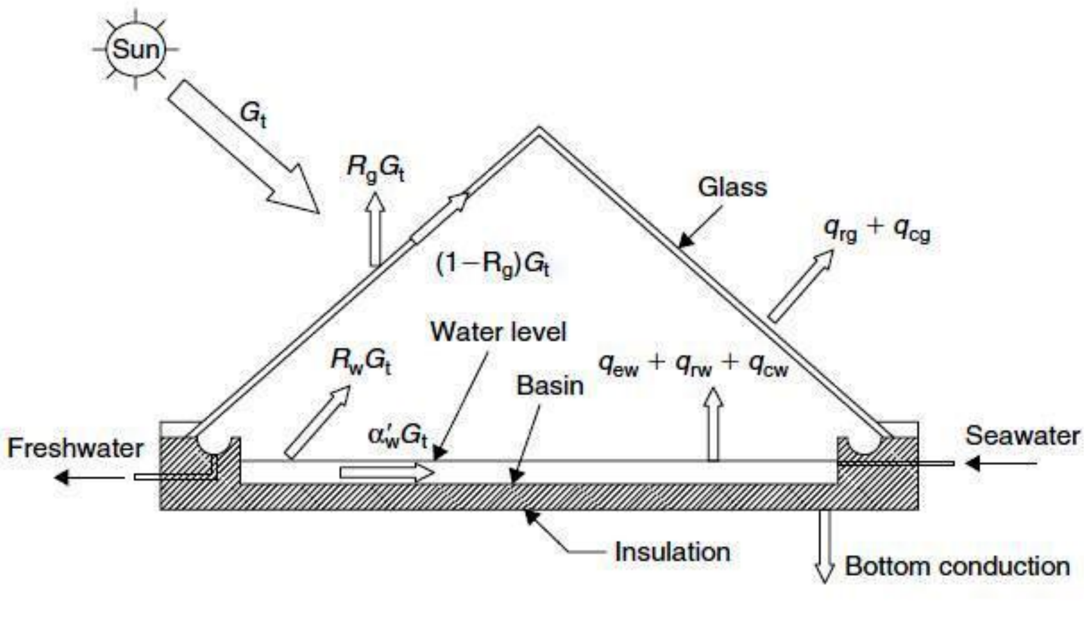


Figure 8.1 Schematic of a solar still.

As the water is heated, its vapor pressure is increased. The resultant water vapor is condensed on the underside of the roof and runs down into the troughs, which conduct the distilled water to the reservoir. The still acts as a heat trap because the roof is transparent to the incoming sunlight but opaque to the infrared radiation emitted by the hot water (greenhouse effect). The roof encloses the vapor, prevents losses, and keeps the wind from reaching and cooling the salty water.

8.3.1 Classification of Solar Distillation Systems

On the basis of various modifications and modes of operation introduced in conventional solar stills, solar distillation systems are classified as passive or active. In active solar stills, an extra-thermal energy by external equipment is fed into the basin of a passive solar still for faster evaporation. The external equipment may be a collector-concentrator panel, waste thermal energy from any industrial plant, or a conventional boiler. If no such external equipment is used, then that type of solar still is known as a *passive solar still*. Types of solar stills available in literature are conventional solar stills, a single-slope solar still with passive condenser, a double–condensing chamber solar still, a vertical solar still, a conical solar still, an inverted absorber solar still, and a multiple-effect solar still.

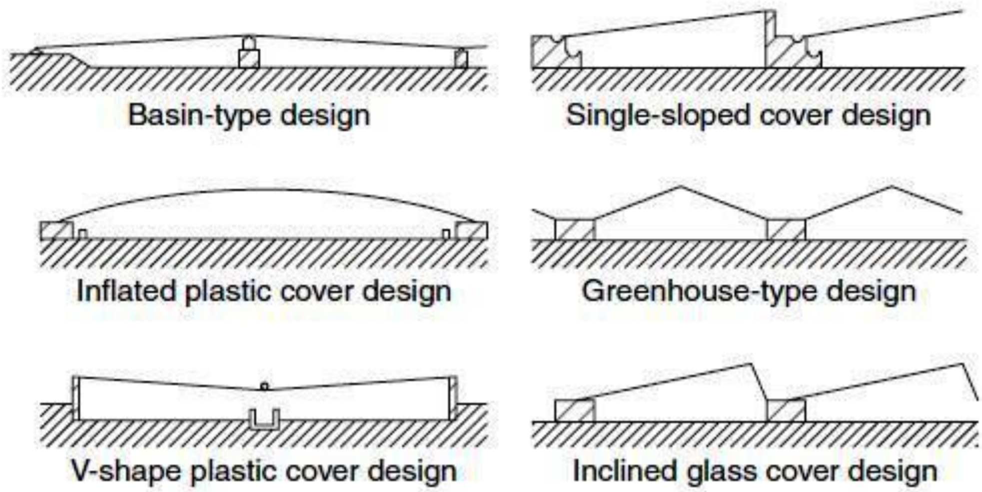


Figure 8.2 Common designs of solar stills.

8.3.2 Performance of Solar Stills

Solar stills are the most widely analyzed desalination systems. The performance of a conventional solar distillation system can be predicted by various methods, such as computer simulation, periodic and transient analysis, iteration methods, and numerical methods. In most of these methods, the basic internal heat and mass transfer relations,

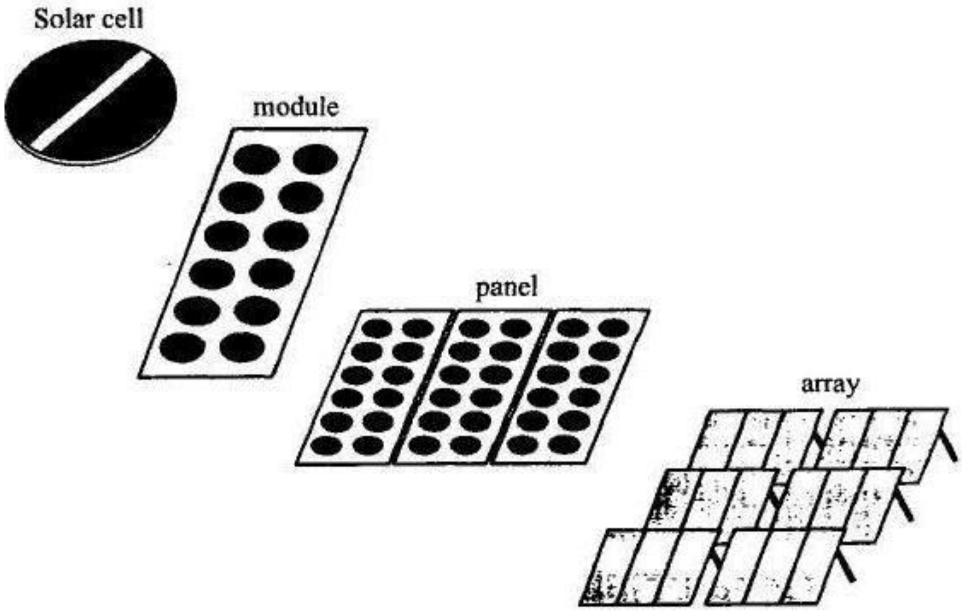
$$\eta = \frac{q_{ew}}{G_t} = \frac{h_{cw}(t_w - t_g)}{G_t}$$

Chapter Six

Solar Electricity

6.1The Photovoltaic PV

The term **photovoltaic** means the direct conversion of light into electrical energy using solar cells. Semiconductor materials such as silicon, gallium arsenide, cadmium telluride or copper indium diselenide are used in these solar cells. The crystalline solar cell is the most commonly used variety.



6.2 PV array systems and PV applications

Photovoltaic (PV) systems can be grouped into stand-alone systems and grid connected systems. In stand-alone systems the solar energy yield is matched to the energy demand. Since the solar energy yield often does not coincide in time with the energy demand from the connected loads, additional storage systems (batteries) are generally used. If the PV system is supported by an additional power source – for example, a wind or diesel generator - this is known as a photovoltaic hybrid system.

In grid-connected systems the public electricity grid functions as an energy store. In Germany, most PV systems are connected to the grid. Because of the premium feed-in tariff for solar electricity in Germany, all of the energy they generate is fed into the public electricity grid. The forecast for the next 40 years is that photovoltaics may provide up to one third of the power supply in Germany.

While more and more grid-connected PV systems will be installed in Europe and North America in the coming years, in the long term it is expected that ever-increasing numbers of stand-alone systems will be installed, especially in developing countries. Small individual power supplies for homes - known as solar home systems – can provide power for lights, radio, television, or a refrigerator or a pump. And, increasingly, villages are gaming their own power supplies with an alternating current circuit and outputs in the two-digit kilowatt range.

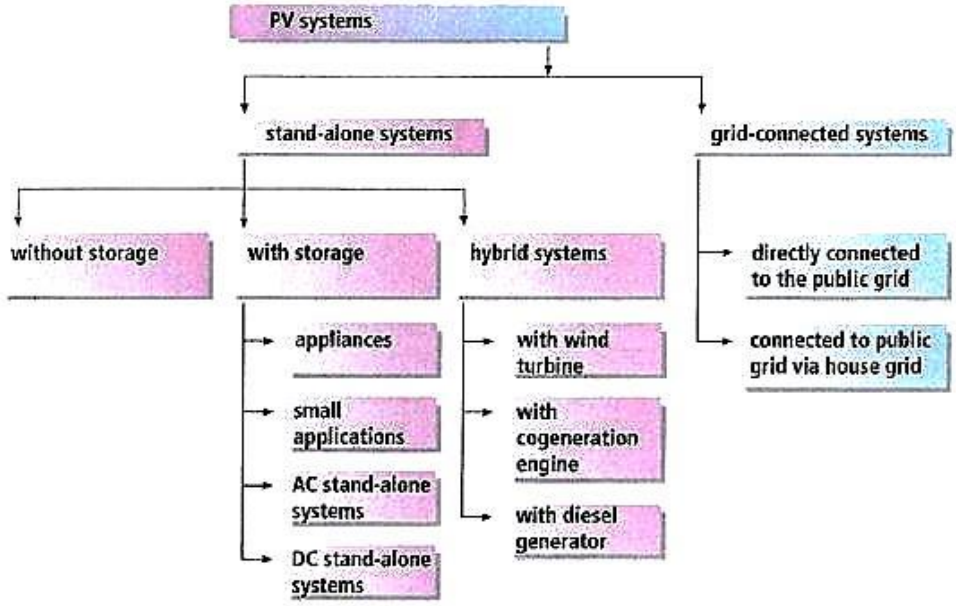


Figure 6.1 Types of PV systems.

6.2.1 Stand-alone systems

The first cost-effective applications for photovoltaics were stand-alone systems. Wherever it was not possible to install an electricity supply from the mains utility grid, or where this was not cost-effective or desirable, stand-alone photovoltaic systems could be installed. The range of applications is constantly growing. There is great potential for using stand-alone systems in developing countries where vast areas are still frequently not supplied by an electrical grid. But technological innovations and new lower-cost production methods are opening up potential in industrialized countries as well.

Solar power is also on the advance when it comes to mini-applications: pocket calculators, clocks, battery chargers, flashlights, solar radios, etc., are well known examples of the successful use of solar cells in stand-alone applications. Other typical applications for stand-alone systems:

- mobile systems on cars, camper vans, boats, etc.;
- remote mountain cabins, weekend and holiday homes and village electrification in developing countries;
- telephones, parking ticket machines, traffic signals and observation systems, communication stations, buoys and similar applications that are remote from the grid;
- applications in gardening and landscaping;
- solar pump systems for drinking water and irrigation, solar water disinfection and desalination.

Components of stand alone PV system

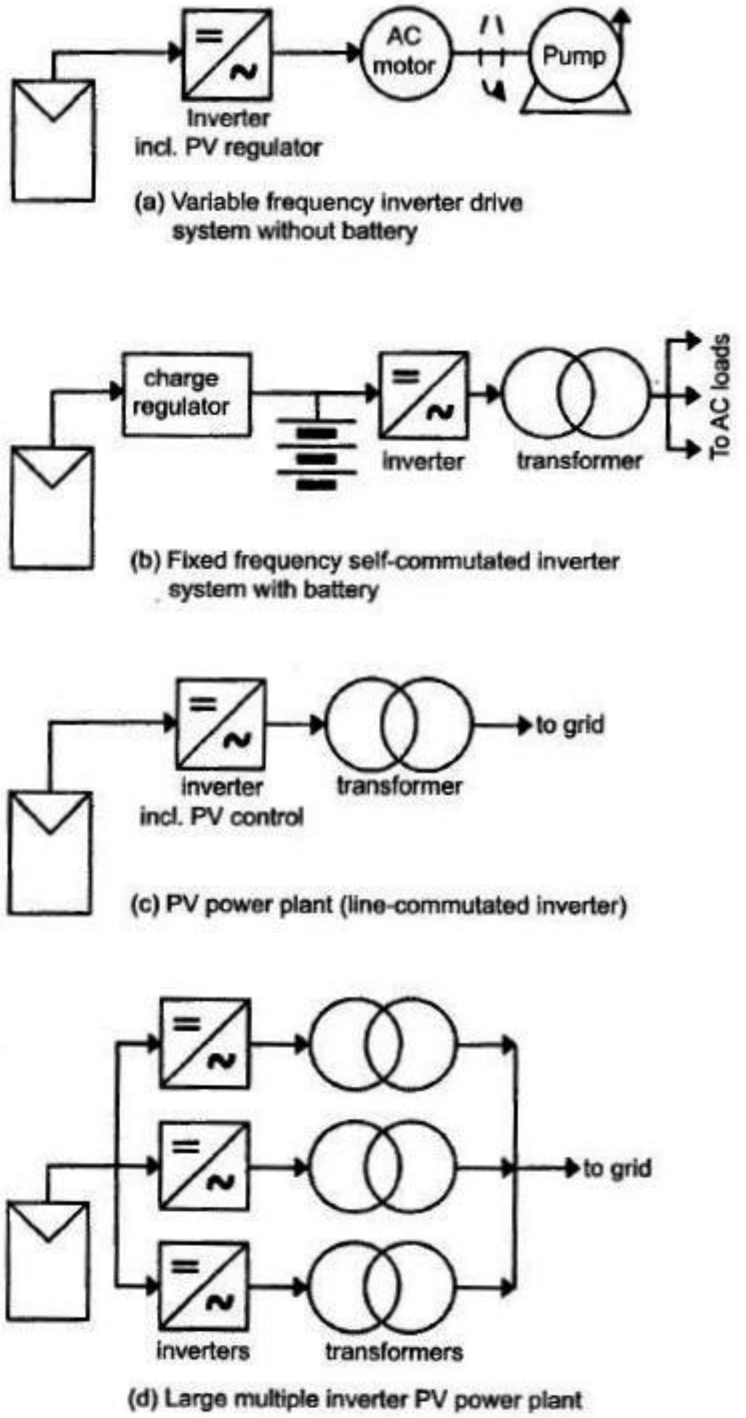
Stand-alone PV systems generally require an Energy storage system because the energy generated is not usually (or infrequently) required at the same time as it is generated (i.e. solar energy is available during the day, but the lights in a stand-alone solar lighting system are used at night). Rechargeable batteries are used to store the electricity. However, with batteries, in order to protect them and achieve higher availability and a longer service life it is essential that a suitable charge controller is also used as a power management unit. Hence, a typical stand-alone system comprises the following main components:

1- PV modules, usually connected in parallel or series-parallel;
2- charge controller;
3- battery or battery bank;
4- load;
5- inverter - in systems providing alternating current (AC) power

1.1.3 Grid-connected systems

A grid-connected PV system essentially comprises the following components:

1- PV modules/array (multiple PV modules connected in series or parallel with mounting frame);
2- PV array combiner/junction box (with protective equipment);
3- direct current (DC) cabling;
4- DC main disconnect/isolator switch;
5- inverter;
6- AC cabling;
7- meter cupboard with power distribution system, supply and feed meter, and electricity connection.



(a) Variable frequency inverter drive system without battery

(b) Fixed frequency self-commutated inverter system with battery

(c) PV power plant (line-commutated inverter)

(d) Large multiple inverter PV power plant

Various inverter configurations

Effects of radiation intensity on module output

Solar cell module output is very much governed by the intensity of the solar radiation on a module. Figure 3.5 shows that module output is directly proportional to the solar irradiance. Halving the intensity of solar radiation reduces the module output by half. Lower radiation also lowers the voltage at which current is produced. Look at the I-V curves in Figure 3.5: a 50 per cent drop in insolation causes a 50 per cent drop in current. Cloud cover reduces the power output of a module to a third or less of its sunny weather output. During cloudy weather, the voltage of a module is also reduced. In hot, cloudy weather modules charging 12V batteries should be selected so that they maintain a high voltage – make sure they have 36 cells.

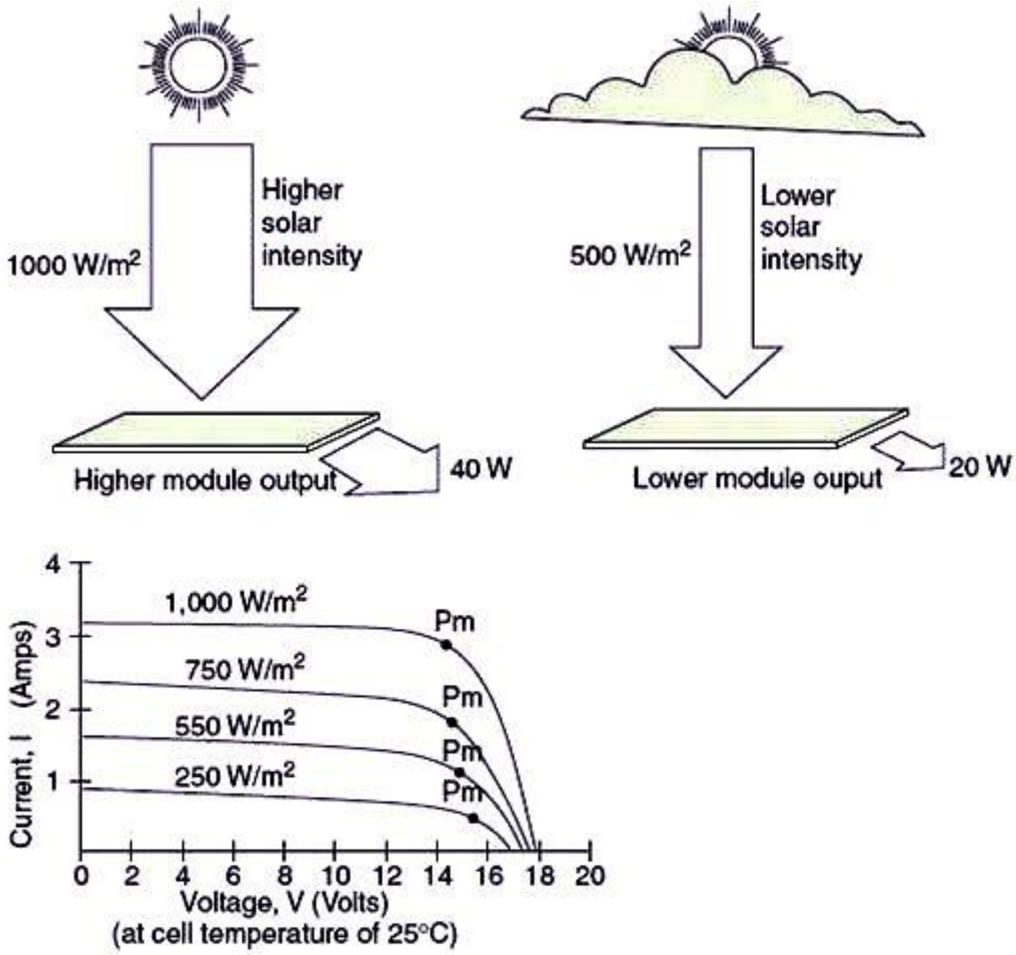


Figure 3.5 Effects of radiation intensity on module output

Effects of heat on module output

Unlike solar thermal devices, most solar PV modules produce less power as they get hotter. As the temperature increases, power output of monocrystalline solar cells falls by 0.5 per cent per degree centigrade (this is shown by the I-V curve in Figure 3.6). Thus, a 5°C (9°F) rise in temperature will cause a 2.5 per cent drop in power output. When mounted in the sun, solar cell modules are usually 20°C (36°F) warmer than the thermometer temperature. Note the differences in the I-V curves at various temperatures. At 60°C (140°F) the current 12V output of the module is much lower than at 10°C (50°F)!

This is important because the temperature on some rooftops can be higher than 60°C (140°F), reducing the output of the module by 20 per cent or more below its rated output. For this reason, installers are encouraged to mount modules on poles, on structures above the roof or in places where they are cooled by airflow to keep output as high as possible.

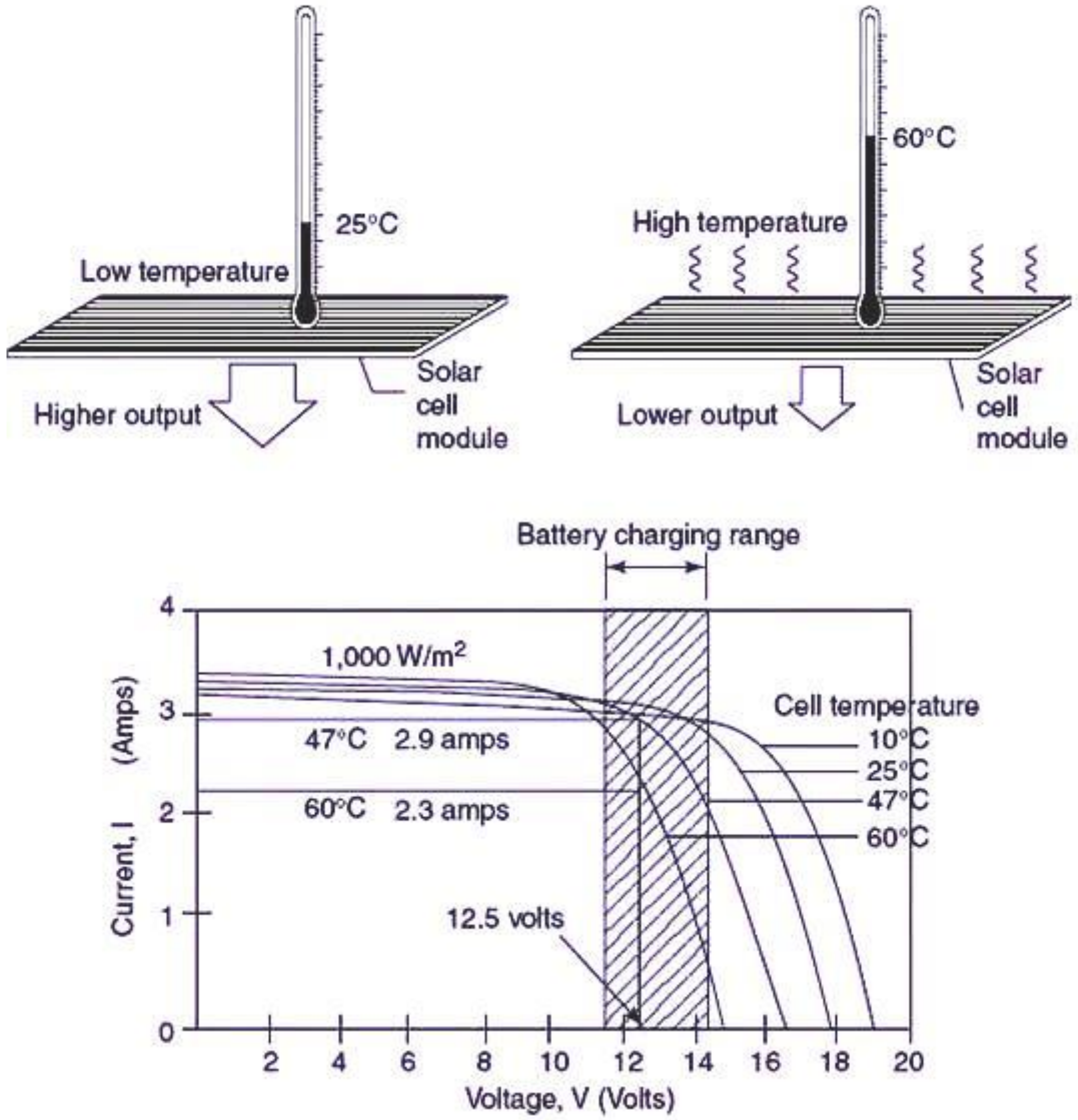


Figure 3.6 Effects of temperature on a typical monocrystalline module output

6.2 Performance of PV module

PV module is the electricity generator in PV system. PV module consists of a number of solar cells and these cells are connected in series and parallel circuits on a panel (module). The area of solar cell is order of few square inches and the area of the module is order of several square feet. The efficiency of the PV module is the important parameter in the module which represents the ratio between the PV power output and the global solar radiation input. Nowadays, PV modules with 18% efficiency are available in the market with reasonable cost.

For sample, a SANYO (HIP-215NHE5) PV module has efficiency 17.2%. This module has maximum power output about 215 W when the global radiation is 1000 W/m^2 and with area about 1.25 m^2.Table 1 shows the manufacturing specifications of the PV module which are under standard laboratory test conditions (Air mass 1.5, Irradiance = 1000 W/m^2, Cell temperature = 25°C).

The maximum power output (P_{max}) of the PV module under the site weather conditions can be estimated by the following equation [7]:

$$P_{max}(G, T_c) = I_{sc}(G) \times V_{oc}(T_c) \times FF \tag{1}$$

Where I_{sc} is short circuit current, V_{oc} is open circuit voltage, and *FF* is fill factor.

It is clear from the Eq. 1 that the short circuit current is proportional to the irradiance (*G*) and the open circuit voltage is proportional to the cell temperature (T_c). The practical short circuit current and practical open circuit voltage at the site are given as [7]:

$$I_{SC}(G) = I_{SC}(at\ 1kW/m^2) \times G\ (in\ kW/m^2) \tag{2}$$

$$V_{oc}(T_c) = V_{oc} - 0.0023 \times number\ of\ cells \times (T_c - 25) \tag{3}$$

The cell temperate (Tc) is determined by

$$T_c = T_a + \frac{NOCT - 20}{0.8} G(kW/m^2) \tag{4}$$

Where NOCT is normal operating cell temperature (usually between 42°C and 46°C), and T_a is ambient temperature [7].

Electrical and Mechanical Characteristics

HIP-215NHE5

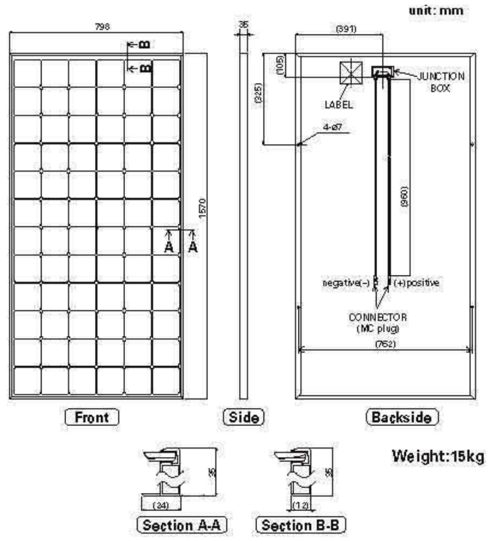
Electrical data

Maximum power (Pmax)	[W]	215
Max. power voltage (Vpm)	[V]	42.0
Max. power current (Ipm)	[A]	5.13
Open circuit voltage (Voc)	[V]	51.6
Short circuit current (Isc)	[A]	5.61
Warranted minimum power (Pmin)	[W]	204.25
Output tolerance	[%]	+10/-5
Maximum system voltage	[Vdc]	1000
Temperature coefficient of Pmax	[%/°C]	- 0.30
Voc	[V/°C]	- 0.129
Isc	[mA/°C]	1.68

Note 1: Standard test conditions: Air mass 1.5, Irradiance = 1000W/m², Cell temperature = 25°C

Note 2: The values in the above table are nominal.

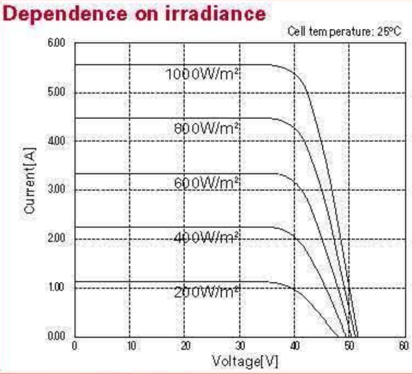
Dimensions and weight



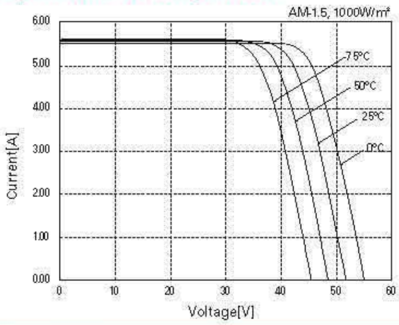
Warranty

Power output: 20 years (80% of minimum output power)
Product workmanship: 2 years
(Based on contract terms.)

Dependence on irradiance



Dependence on temperature



Certificates

IEC 61215

Electrical Protection Class II

Please consult your local dealer for more information.

Example

Determine the parameters of a module formed by 34 solar cells in series, under the operating conditions G=700 W/m^2, and T_a=34ºC. The manufacturers values under standard conditions are: I_{sc} = 3A; Voc = 20.4V; P_{max} = 45.9 W; NOCT = 43ºC.

Solution

1. Short-circuit current

   I_{sc} (700 W/m^2) =3 x 0.7 = 2.1 A.

2. Solar cell temperature
   T_c = 34 + 0.7 x (43-20)/80 = 54.12ºC

3. Open-circuit voltage
   V_{oc} (54.12ºC) = 20.4 – 0.0023 x 34 x (54.12 – 25) = 18.1 V

4. Maximum power point
   FF= 45.9/ (3 x 20.4) = 0.75
   P_{max} (G, T_c) = 2.1 x 18.1 x 0.75 = 28.5 W

Thus, noting the manufacturers value of Pmax we see that the module will operate at about 62% of its nominal rating.

Home Work

Determine the annual module power output of a SANYO (HIP-215NHE5) module in Baghdad, if the monthly average global radiation and ambient temperature are in below:

Month	Monthly average global radiation (kW h/m^2/day) (6 a.m. – 6 p.m.)	Monthly average ambient temperature (ºC) (6 a.m. – 6 p.m.)
Jan.	3.0	8.4
Feb.	3.8	14.7
Mar.	4.8	23.6
Apr.	5.7	28.0
May.	6.5	32.0
Jun.	7.3	36.6
Jul.	7.2	38.0
Aug.	6.6	40.0
Sep.	5.7	35.5
Oct.	4.4	27.3
Nov.	3.3	19.6
Dec.	2.7	13.4

6.3 PV Arrays

A PV array is a group of modules that are electrically connected either in series or in parallel. The electrical characteristics of the array are analogous to those of individual modules, with the power, current, and voltage modified according to the number of modules connected in series or parallel.

6.3.1 Increasing Voltage

PV modules are connected in series to obtain higher output voltages. Output voltage, Vo, of modules connected in series is given by the sum of the voltages generated by each module:

$$Vo = V1 + V2 + V3 + \ldots \quad (6.1)$$

An easy way to understand the concept of series-connected systems is through the analogy between a hydraulic system and an electrical system shown in Figure 6.4. As can be observed in the hydraulic system (left side), the water that falls from four times the 12 m height produces four times the pressure of water falling from the first level. This is analogous to the 48 V that the electrical system (right side) reaches after passing a current of 2 A through four modules connected in series. The current can be compared to the flow because both remain constant within their respective circuits, and the voltage is analogous to the role of pressure in the hydraulic system.

6.3.2 Increasing Current

PV modules are connected in parallel to obtain greater current. The voltage of the parallel-connected modules is the same as the voltage of a single module, but the output current, Io, is the sum of the currents from each unit connected in parallel:

$$Io = I1 + I2 + I3 + \ldots \quad (6.2)$$

In a manner similar to that of systems connected in series, systems connected in parallel can also be compared to a hydraulic system, like the one shown in Figure 6.5. In the hydraulic system (top), water that falls from the same height gives the same pressure as each individual pump, but the flow is equal to the total flow from all of the pumps. In the electrical system, then, the voltage remains constant and the output current of the four modules is added, producing 8 A of current and 12 V

Figure 6.6 provides an example of modules connected in both series and parallel. The positions of blocking and bypass diodes are also shown. Diode sizes should by determined taking into consideration the maximum current generated by the PV array under short-circuit conditions. The electrical code stipulation used internationally requires that the current value supported by the diode should be at least 1.56 times the short-circuit current value of the array.

Finally, the nominal power of the array is the sum of the nominal-power values of each module, irrespective of how the modules are wired in series or in parallel.

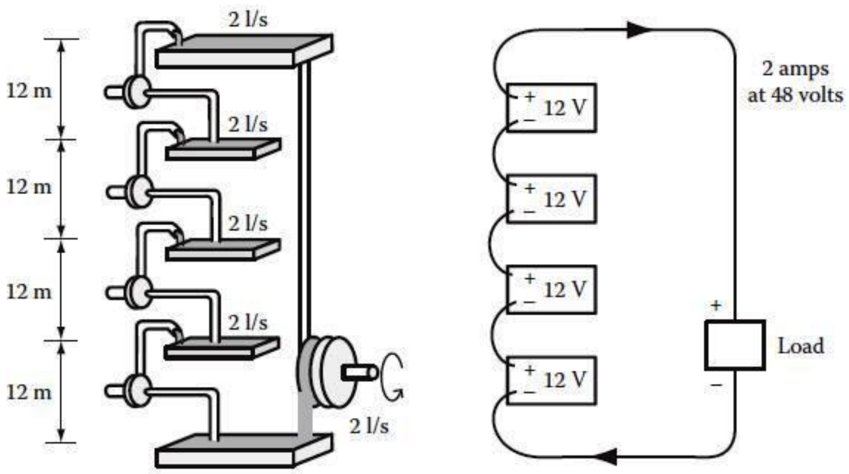


FIGURE 6.4 Analogy of a series connection using a hydraulic and an electrical system.

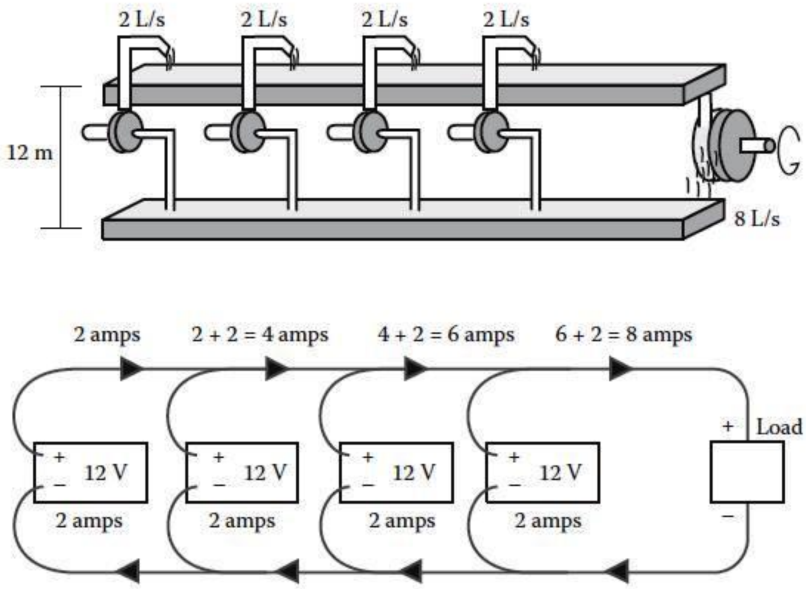


FIGURE 6.5 Hydraulic analogy of a parallel electrical connection, which is analogous to increasing flow of electrons.

PV-integrated Systems

1- PV Integrated with Air Collector
2- PV/T Water Heating

Solar Thermal Power Systems

The basic schematic of conversion of solar to mechanical energy is shown in **Figure 10.1**. In these systems, solar thermal energy, usually collected by concentrating solar collectors, is used to operate a heat engine. Some of these systems also incorporate heat storage, which allows them to operate during cloudy weather and nighttime. The main challenge in designing these systems is to select the correct operating temperature. This is because the efficiency of the heat engine rises as its operating temperature rises, whereas the efficiency of the solar collector reduces as its operating temperature rises. Concentrating solar collectors are used exclusively for such applications because the maximum operating temperature for flat-plate collectors is low relative to the desirable input temperature for heat engines, and therefore system efficiencies would be very low. Five system architectures have been used for such applications. The first four are high-temperature systems:

1- parabolic trough collector system,
2- linear Fresnel reflector,
3- power tower system,
4- dish system.
5- solar pond, which is a low-temperature system.

These, except the linear Fresnel reflector system, which has not yet reached industrial maturity.

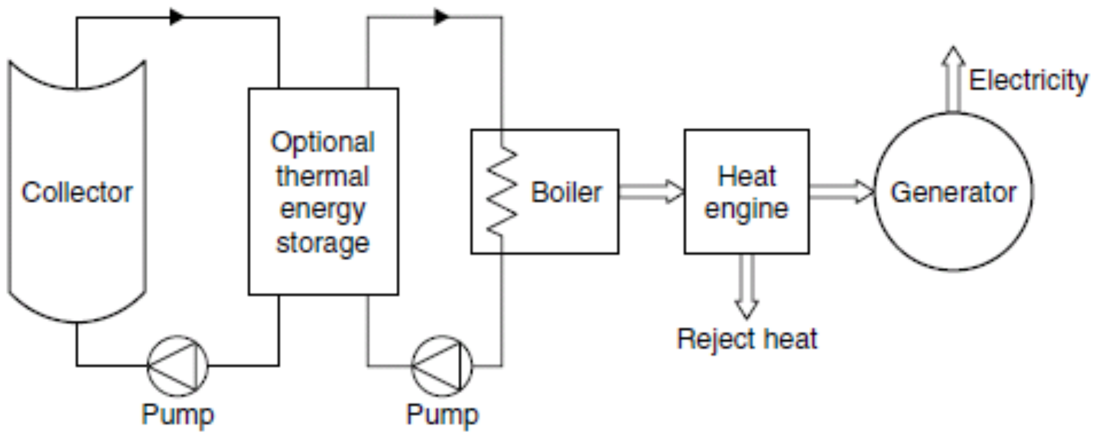


Figure 10.1 Schematic diagram of a solar-thermal energy conversion system.

1- Parabolic trough collector systems

parabolic trough collectors are the most mature solar technology to generate heat at temperatures up to 400°C for solar thermal electricity generation or process heat applications. The biggest application of this type of system is the nine southern California power plants known as solar electric generating systems (SEGS), which have a total installed capacity of 354 MWe. Details on these plants are given in **Table 10.2**. As can be seen, SEGS I is 13.8 MWe, SEGS II–VII are 30 MWe each, and SEGS VIII and IX are 80 MWe each. These have been designed, installed, and operated in the Mojave Desert of southern California, the first one since 1985 and the last one since 1991. These plants are based on large parabolic trough concentrators providing steam to Rankine power plants

Table 10.2 Characteristics of SEGS Plants

SEGS plant	Year operation began	Net output (MW_e)	Solar outlet temp. (°C)	Luz collector used	Solar field area (m^2)	Solar turbine efficiency (%)	Fossil turbine efficiency (%)	Annual output (MWh)
I	1985	13.8	307	LS-1	82,960	31.5	—	30,100
II	1986	30	316	LS-2	190,338	29.4	37.3	80,500
III	1987	30	349	LS-2	230,300	30.6	37.4	92,780
IV	1987	30	349	LS-2	230,300	30.6	37.4	92,780
V	1988	30	349	LS-2	250,500	30.6	37.4	91,820
VI	1989	30	390	LS-2	188,000	37.5	39.5	90,850
VII	1989	30	390	LS-2 + LS-3	194,280	37.5	39.5	92,646
VIII	1990	80	390	LS- 3	464,340	37.6	37.6	252,750
IX	1991	80	390	LS-3	483,960	37.6	37.6	256,125

Collector	LS-1	LS-2		LS-3	Eurotrough
Year	1984	1985	1988	1989	2004
Area (m^2)	128	235		545	545/817.5
Aperture (m)	2.5	5		5.7	5.77
Length (m)	50	48		99	99.5/148.5
Receiver diameter (m)	0.042	0.07		0.07	0.07
Concentration ratio	61	71		82	82
Optical efficiency	0.734	0.737	0.764	0.8	0.78
Receiver absorptance	0.94	0.94	0.99	0.96	0.95
Receiver emittance at (°C)	0.3 (300)	0.2 (300)	0.1 (350)	0.1 (350)	0.14 (400)
Mirror reflectance	0.94	0.94	0.94	0.94	0.94
Operating temperature (°C)	307	349	390	390	390

Description of the PTC Power Plants

In these plants, large fields of PTC collectors supply the thermal energy used to produce steam supplied to a Rankine steam turbine-generator cycle to produce electricity. Each collector has a linear parabolic reflector, which focuses the sun's direct beam radiation on a linear receiver located at the focus of the parabola. Figure 10.3 shows a process flow diagram, representative of the majority of plants operating today in California. The collector field consists of many large single-axis tracking PTC collectors, installed in parallel rows aligned on a north-south horizontal axis and tracking the sun from east to west during the day to ensure that the sun is continuously focused on the linear receiver. A heat transfer fluid is circulated through the receiver, where it is heated by solar energy and returns to a series of heat exchangers in the power block to generate high-pressure superheated steam and back to the solar field. This steam is used in a conventional reheat steam turbine-generator to produce electricity. As shown in Figure 10.3, the steam from the turbine is piped to a standard condenser and returns to the heat exchangers with pumps so as to be transformed again into steam. The type of condenser depends on whether a large source of water is available near the power station. Because all plants in California are installed in a desert, cooling is provided with a mechanical draft wet cooling towers.

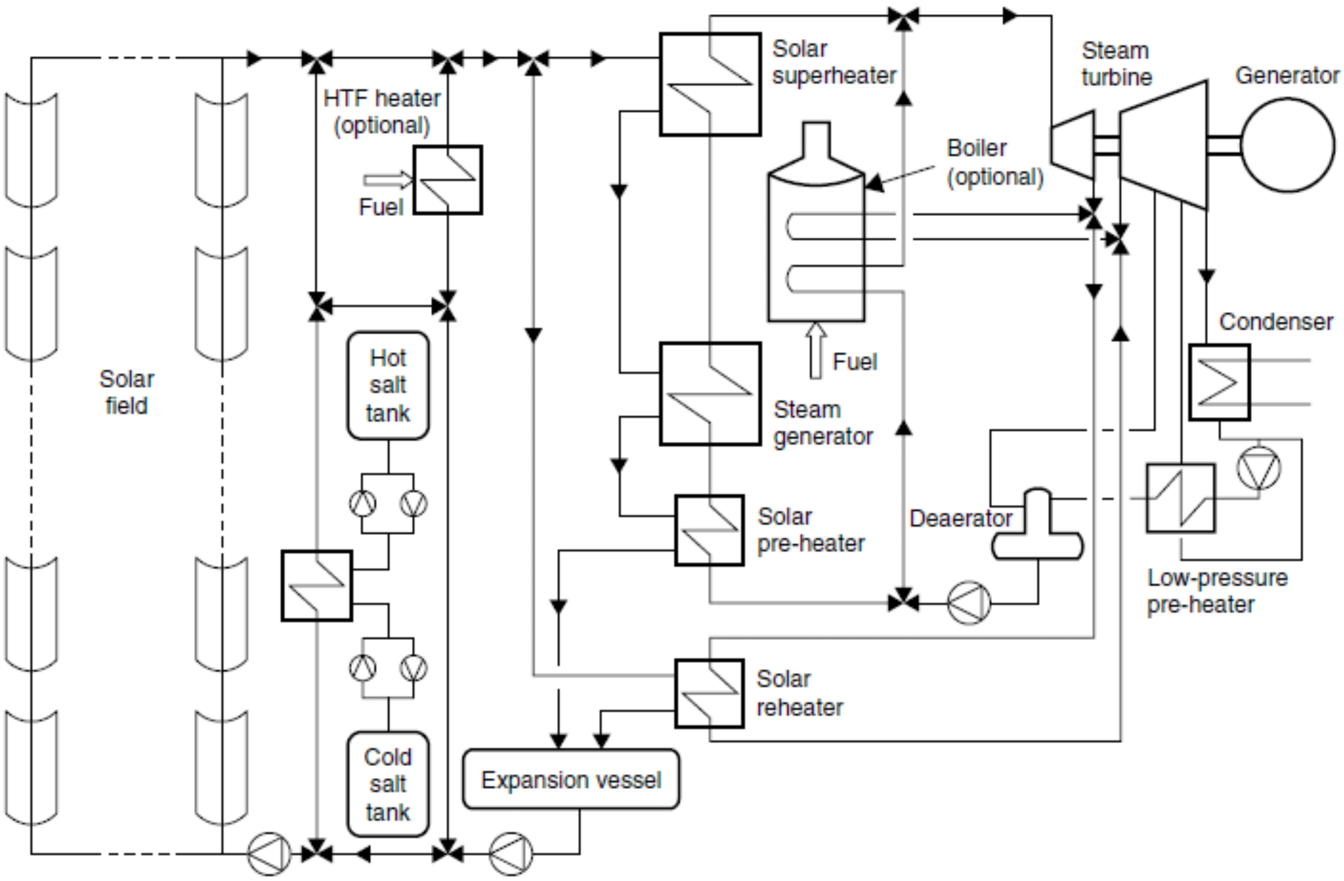


Figure 10.3 Schematic diagram of a solar Rankine parabolic trough system.

A new design concept, which integrates a parabolic trough plant with a gas turbine combined-cycle plant, called the ***integrated solar combined-cycle system*** (ISCCS), is shown schematically in Figure 10.4. Such a system offers a possibility to reduce cost and improve the overall solar-to-electricity efficiency As shown, the ISCCS uses solar heat to supplement the waste heat from a gas turbine to augment power in the steam Rankine bottoming cycle. In this system, solar energy is used to generate additional steam, and the gas turbine waste heat is used for pre-heating and steam superheating.
One of the most serious problems when working in a desert environment is cleaning dust from the parabolic mirrors. As a general rule, the reflectivity of glass mirrors can be returned to design levels with good washing. After considerable experience gained over the years, operating and maintenance procedures nowadays includes deluge washing and direct and pulsating high-pressure sprays, which use demineralized water for good effectiveness. Such operations are carried out during nighttime. Another measure that's applied is periodic monitoring of mirror reflectivity, which can be a valuable quality control tool to optimize mirror-washing frequency and the labor costs associated with this operation.

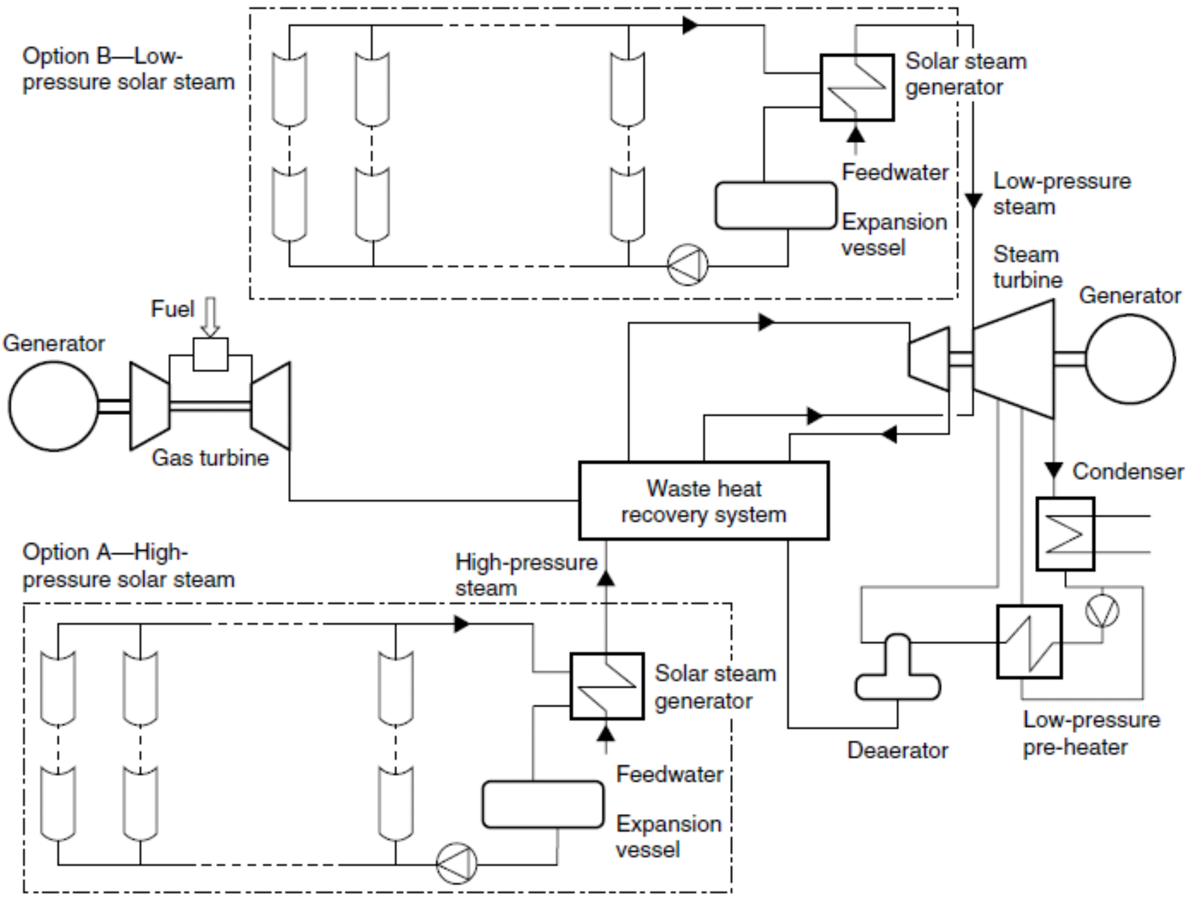


Figure 10.4 Schematic diagram of the integrated solar combined-cycle plant.

2- Linear Fresnel Plants

In the " youngest " of the technologies based on this principle – at least in terms of its implementation 17) – the parabolic trough is replaced by a number of parallel planar (or nearly planar) mirror elements, which are all mounted at the same height near the ground. They follow the position of the Sun by rotating around their long axes so that they point to a focus line at a height of 10 – 15 m, which remains fixed over time (Figures 3.6 and 3.7). Along this line, an absorber tube up to 1000 m long is mounted, and in it – similarly to the development for the parabolic trough – water is directly vaporized. The steam from many parallel absorber tubes can operate a large turbine.
In the Solarmundo concept, which is the basic variant of this principle, the radiation reflected from the mirror field is focused by a secondary reflector onto shadowing, its land - area requirements are, compared with parabolic troughs, modest: half the land area is required for a given mirror area, whereby, however, the above - mentioned performance reduction per unit of mirror area must be tolerated.

Figure 3.6 A linear Fresnel collector: in this foreground, the absorber pipe is visible; behind it is the piping with the secondary reflector (Photo DLR).

Figure 3.7 Here, one sees the support piping for the mirrors (Photo DLR).

3- Power tower systems

power towers or central receiver systems use thousands of individual sun-tracking mirrors, called ***heliostats***, to reflect solar energy onto a receiver located atop a tall tower. The receiver collects the sun's heat in a heat transfer fluid (molten salt) that flows through the receiver. This is then passed optionally to storage and finally to a power conversion system, which converts the thermal energy into electricity and supplies it to the grid. Therefore, a central receiver system is composed of five main components: heliostats, including their tracking system; receiver; heat transport and exchange; thermal storage; and controls. In many solar power studies, it has been observed that the collector represents the largest cost in the system; therefore, an efficient engine is justified to obtain maximum useful conversion of the collected energy. The power tower plants are quite large, generally 10 MWe or more, while the optimum sizes lie between 50–400 MW. It is estimated that power towers could generate electricity at around US$0.04/kWh by 2020. A schematic of the system is shown in Figure 10.5

The salt's heat energy is used to make steam to generate electricity in a conventional steam generator, located at the foot of the tower. The molten salt storage system retains heat efficiently, so it can be stored for hours or even days before being used to generate electricity

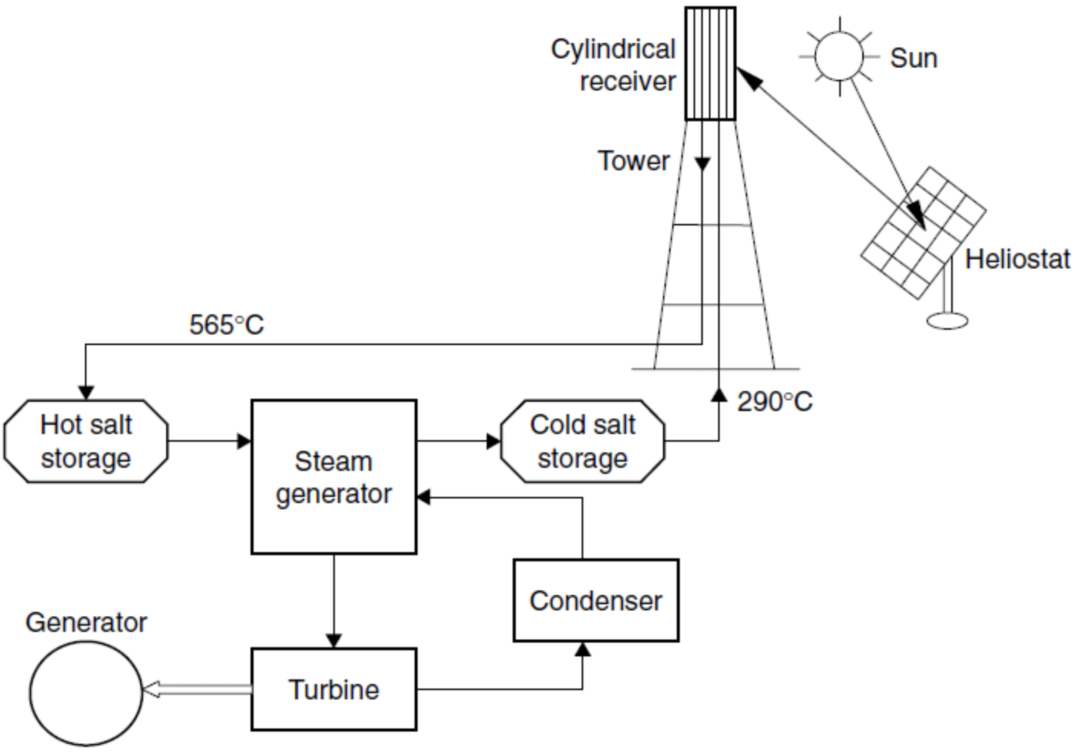


Figure 10.5 Schematic of the Solar Two plant

4- Dish systems

dish systems use dish-shaped parabolic mirrors as reflectors to concentrate and focus the sun's rays onto a receiver, which is mounted above the dish at the dish focal point. The receiver absorbs the energy and converts it into thermal energy. This can be used directly as heat or can support chemical processes, but its most common application is in power generation. The thermal energy can be either transported to a central generator for conversion or converted directly into electricity at a local generator coupled to the receiver.

A dish-engine system is a stand-alone unit composed primarily of a collector, a receiver, and an engine, as shown in **Figure 10.8.** It works by collecting and concentrating the sun's energy with a dish-shaped surface onto a receiver that absorbs the energy and transfers it to the engine. The heat is then converted in the engine to mechanical power, in a manner similar to conventional engines, by compressing the working fluid when it is cold, heating the compressed working fluid, and expanding it through a turbine or with a piston to produce mechanical power. An electric generator converts the mechanical power into electrical power.

Dish-engine systems use a dual-axis tracking system to follow the sun and so are the most efficient collector systems because they are always pointing at the sun. Concentration ratios usually range from 600 to 2000, and they can achieve temperatures in excess of 1500°C. While Rankine cycle engines, Brayton cycle engines, and sodium-heat engines have all been considered for systems using dish-mounted engines, greatest attention has been paid to Stirling-engine systems,

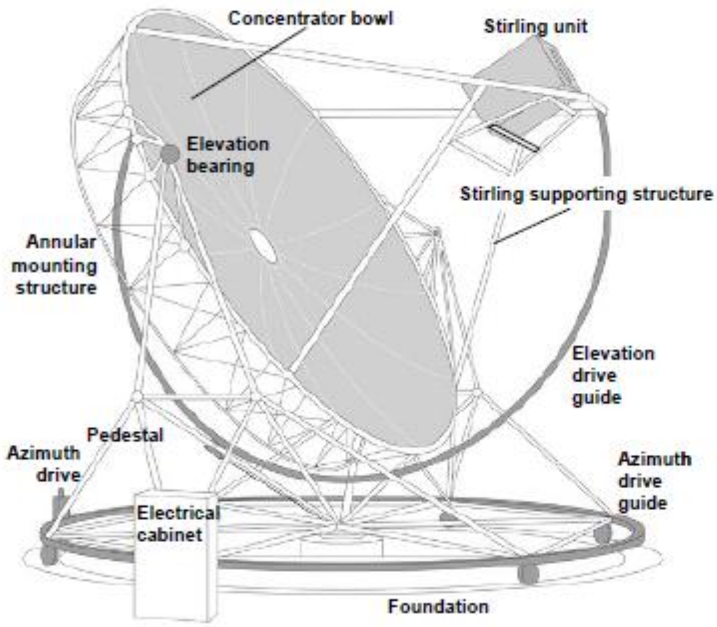


Fig. 10.8 Dish/Stirling systems

5- Solar ponds

Salt gradient lakes, which exhibit an increase in temperature with depth, occur naturally. A salt gradient solar pond is a body of saline water in which the salt concentration increases with depth, from a very low value at the surface to near saturation at the depth of usually 1–2 m. The density gradient inhibits free convection, and the result is that solar radiation is trapped in the lower region. Solar ponds are wide-surfaced collectors in which the basic concept is to heat a large pond or lake of water in such a way as to suppress the heat losses that would occur if less dense heated water is allowed to rise to the surface of the pond and lose energy to the environment by convection and radiatio. As shown in Figure 10.12, this objective can be accomplished if a stagnant, highly transparent insulating zone is created in the upper part of the pond to contain the hot fluid in the lower part of the pond. In a non-conventional solar pond, part of the incident insolation is absorbed and converted to heat, which is stored in the lower regions of the pond. Solar ponds are both solar energy collectors and heat stores. Salt gradient lakes, which exhibit an increase in temperature with depth, occur naturally. A salt-gradient non-convecting solar pond consists of three zones:

1. **Upper convecting zone** (UCZ). This is a zone, typically 0.3 m thick, of almost constant low salinity, which is at close to ambient temperature. The UCZ is the result of evaporation, wind-induced mixing, and surface flushing. Usually this layer is kept as thin as possible by the use of wave suppressing surface meshes or by placing wind-breaks near the pond.
2. **Non-convecting zone** (NCZ). In this zone, both salinity and temperature increase with depth. The vertical salt gradient in the NCZ inhibits convection and thus gives the thermal insulation effect. The temperature gradient is formed due to the absorption of solar insolation at the pond base.
3. **Lower convecting zone** (LCZ). This is a zone of almost constant, relatively high salinity (typically 20% by weight) at a high temperature. Heat is stored in the LCZ, which should be sized to supply energy continuously throughout the year. As the depth increases, the thermal capacity increases and annual variations of temperature decrease. Large depths, however, increase the require initial capital expenditure and exhibit longer start-up times.

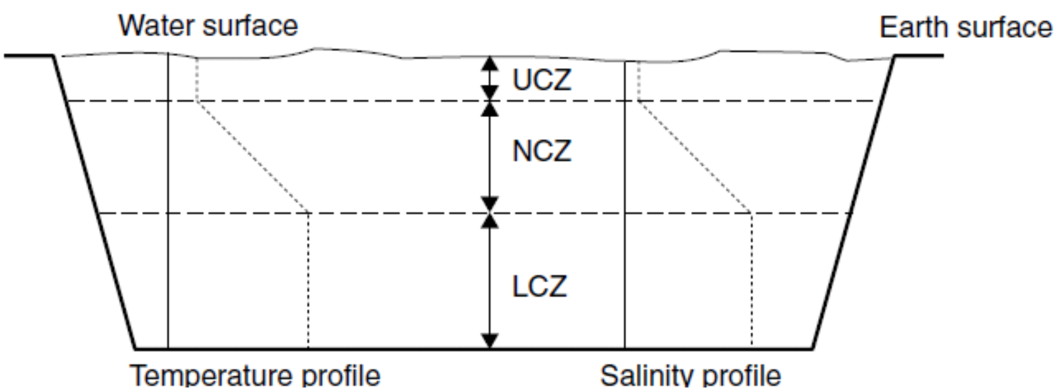


Figure 10.12 Schematic vertical section through a salt-gradient solar pond

Although many feasibility studies have been made for the generation of electric power from solar ponds, the only operational systems are in Israel. These include a 1500 m2 pond used to operate a 6 kW Rankine cycle turbine-generator and a 7000 m2 pond producing 150 kW peak power. Both of these ponds operate at about 90°C. A schematic of the power plant design, working with an organic fluid, is shown in **Figure 10.13.**

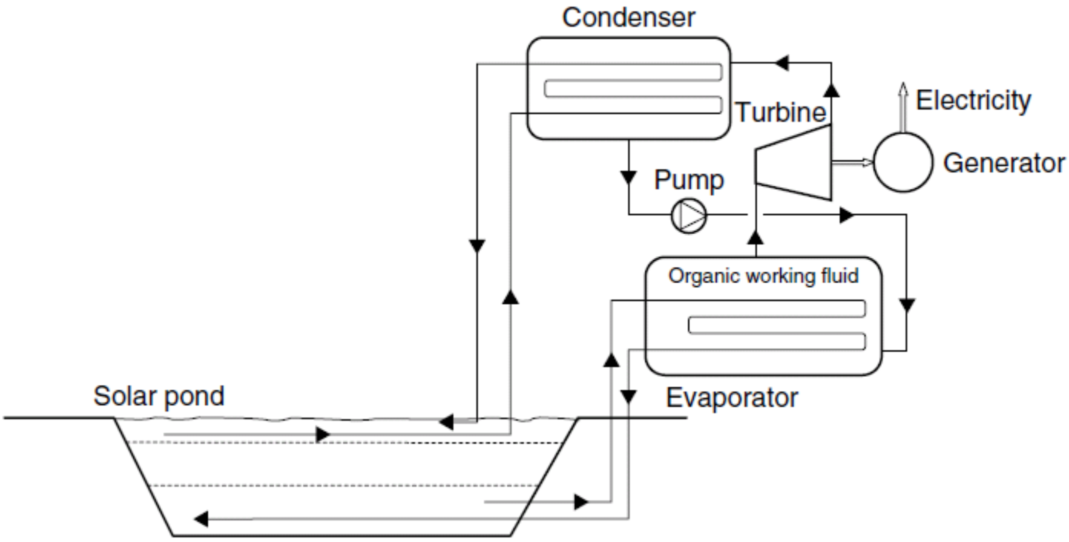


Figure 10.13 Schematic of a solar pond power generation system.

Chapter Seven

Wind Energy

7.1 Basics of wind energy conversion

Energy available in wind is basically the kinetic energy of large masses of air moving over the earth's surface. Blades of the wind turbine receive this kinetic energy, which is then transformed to mechanical or electrical forms, depending on our end use. The efficiency of converting wind to other useful energy forms greatly depends on the efficiency with which the rotor interacts with the wind stream.

7.2 Power available in the wind spectra

The kinetic energy of a stream of air with mass m and moving with a velocity V is given by

$$E = 0.5\, m\, V^2 \qquad (2.1)$$

Consider a wind rotor of cross sectional area A exposed to this wind stream as shown in Fig. 2.1. The kinetic energy of the air stream available for the turbine can be expressed as

$$E = 0.5\, \rho_a\, v\, V^2 \qquad (2.2)$$

where ρ_a is the density of air and v is the volume of air parcel available to the rotor. The air parcel interacting with the rotor per unit time has a cross-sectional area equal to that of the rotor (A_T) and thickness equal to the wind velocity (V). Hence energy per unit time, that is power, can be expressed as

$$\boldsymbol{P = 0.5\, \rho_a\, A\, V^3} \qquad (2.3)$$

From Eq. (2.3), we can see that the factors influencing the power available in the wind stream are the air density, area of the wind rotor and the wind velocity. Effect of the wind velocity is more prominent owing to its cubic relationship with the power.

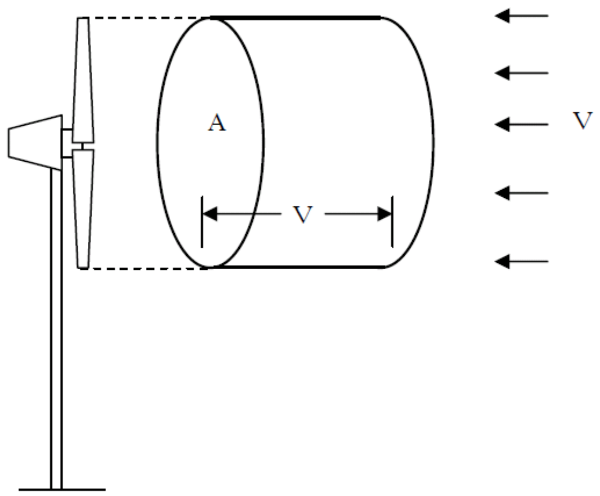


Fig. 2.1. An air parcel moving towards a wind turbine

Factors like temperature, atmospheric pressure, elevation and air constituents affect the density of air. Dry air can be considered as an ideal gas. According to the ideal gas law,

$$p\, V_G = n\, R\, T \tag{2.4}$$

where p is the pressure, V_G is the volume of the gas, n is the number of kilo moles of the gas, R is the universal gas constant and T is the temperature. Density of air, which is the ratio of the mass of 1 kilo mole of air to its volume, is given by

$$\rho_a = \frac{m}{V_G} \tag{2.5}$$

From Eqs. (2.4) and (2.5), density is given by

$$\rho_a = \frac{m\, p}{R\, T} \tag{2.6}$$

If we know the elevation Z and temperature T at a site, then the air density can be calculated by

$$\boldsymbol{\rho_a = \frac{353.049}{T} e^{\left(-0.034\frac{Z}{T}\right)}} \tag{2.7}$$

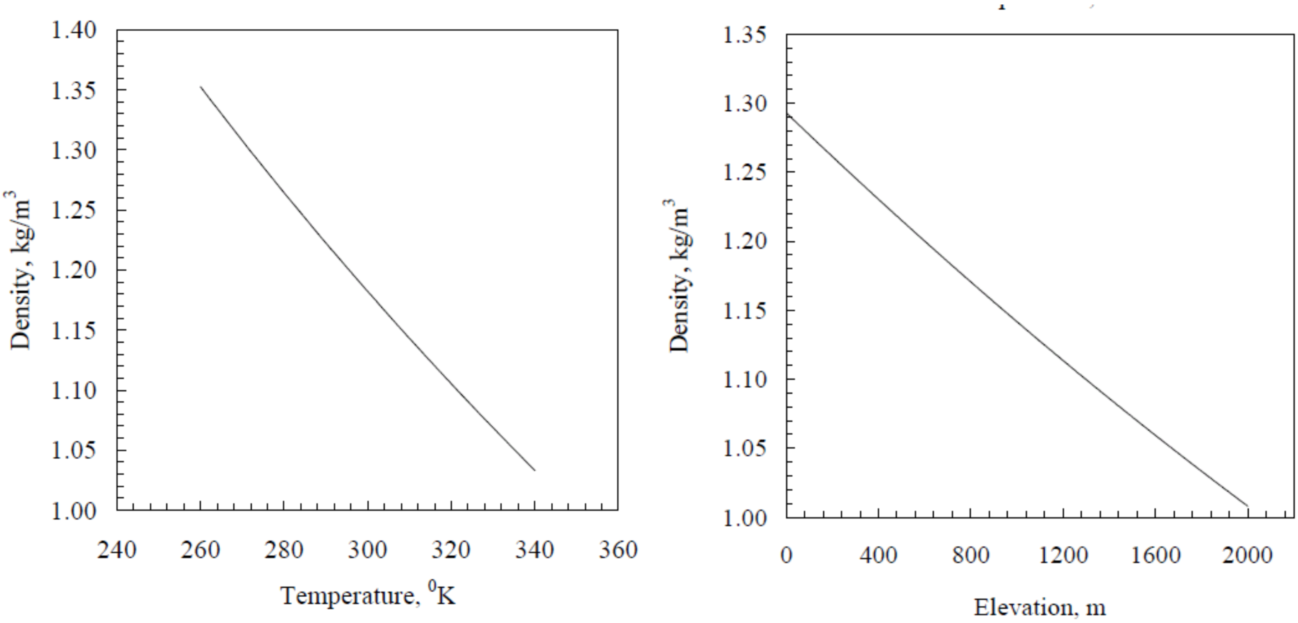


Fig. 2.2. Effect of elevation and temperature on air density

The density of air decreases with the increase in site elevation and temperature as illustrated in Fig. 2.2. The air density may be taken as **1.225** for most of the practical cases. Due to this relatively low density, wind is rather a diffused source of energy. Hence large sized systems are often required for substantial power production.

7.3 Wind turbine power and torque

Theoretical power available in a wind stream is given by Eq. (2.3). However, a turbine cannot extract this power completely from the wind. When the wind stream passes the turbine, a part of its kinetic energy is transferred to the rotor and the air leaving the turbine carries the rest away. Actual power produced by a rotor would thus be decided by the efficiency with which this energy transfer from wind to the rotor takes place. This efficiency is usually termed as the **power coefficient (Cp).** Thus, the power coefficient of the rotor can be defined as the ratio of actual power developed by the rotor to the theoretical power available in the wind. Hence,

$$C_P = \frac{P_T}{P_W} = \frac{2P_T}{\rho_a A_T V^3} \qquad (2.8)$$

where P_T is the power developed by the turbine. The power coefficient of a turbine depends on many factors such as the profile of the rotor blades, blade arrangement and setting etc. A designer would try to fix these parameters at its optimum level so as to attain maximum C_p at a wide range of wind velocities. The thrust force experienced by the rotor (F) can be expressed as

$$F = 0.5\, \rho_a\, A\, V^2 \qquad (2.9)$$

Hence we can represent the rotor torque (T) as

$$T = 0.5\, \rho_a\, A\, V^2 R \qquad (2.10)$$

where R is the radius of the rotor. This is the maximum theoretical torque and in practice the rotor shaft can develop only a fraction of this maximum limit. The ratio between the actual torque developed by the rotor and the theoretical torque is termed as the **torque coefficient (C_T)**. Thus, the torque coefficient is given by

$$C_T = \frac{2T_T}{\rho_a A_T V^2 R} \qquad (2.11)$$

where T_T is the actual torque developed by the rotor.

The power developed by a rotor at a certain wind speed greatly depends on the relative velocity between the rotor tip and the wind. For example, consider a situation in which the rotor is rotating at a very low speed and the wind is approaching the rotor with a very high velocity. Under this condition, as the blades are moving slow, a portion of the air stream approaching the rotor may pass through it without interacting with the blades and thus without energy transfer. Similarly if the rotor is rotating fast and the wind velocity is low, the wind stream may be deflected from the turbine and the energy may be lost due to turbulence and vortex shedding. In both the above cases, the interaction between the rotor and the wind stream is not efficient and thus would result in poor power coefficient.

The ratio between the velocity of the rotor tip and the wind velocity is termed as the **tip speed ratio (λ).** Thus,

$$\lambda = \frac{R\Omega}{V} = \frac{2\pi NR}{V} \tag{2.12}$$

where Ω is the angular velocity and N is the rotational speed of the rotor. The power coefficient and torque coefficient of a rotor vary with the tip speed ratio.

There is an optimum λ for a given rotor at which the energy transfer is most efficient and thus the power coefficient is the maximum ($C_{P\ max}$). Now, let us consider the relationship between the power coefficient and the tip speed ratio.

$$C_P = \frac{2P_T}{\rho_a A_T V^3} = \frac{2T_T\Omega}{\rho_a A_T V^3} \tag{2.13}$$

Dividing Eq. (2.13) by Eq. (2.11) we get

$$\frac{C_P}{C_T} = \frac{R\Omega}{V} = \lambda \tag{2.14}$$

Thus, the tip speed ratio is given by the ratio between the power coefficient and torque coefficient of the rotor.

Example

Consider a wind turbine with 5 m diameter rotor. Speed of the rotor at 10 m/s wind velocity is 130 r/min and its power coefficient at this point is 0.35. Calculate the tip speed ratio and torque coefficient of the turbine. What will be the torque available at the rotor shaft? Assume the density of air to be 1.24 kg/m^3.

Solution

Area of the rotor is

$$A_T = \frac{\pi}{4} \times 5^2 = 19.63\ m^2$$

As the speed of the rotor is 130 r/min, its angular velocity is

$$\Omega = \frac{2\times\pi\times130}{60} = 13.6\ rad/s$$

The tip speed ratio at this velocity is

$$\lambda = \frac{2.5\times13.6}{10} = 3.4$$

The torque coefficient is

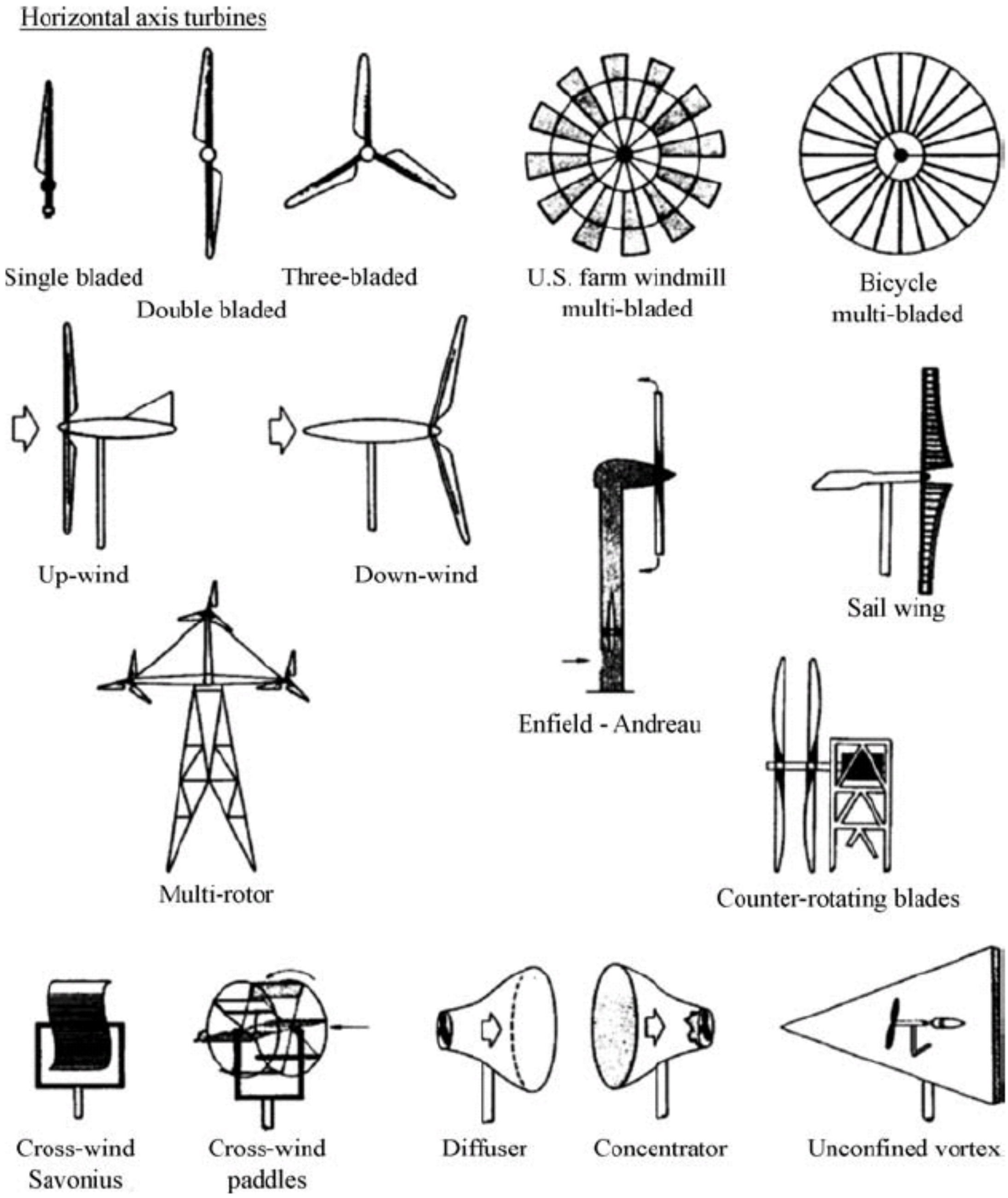
$$C_T = \frac{0.35}{3.4} = 0.103$$

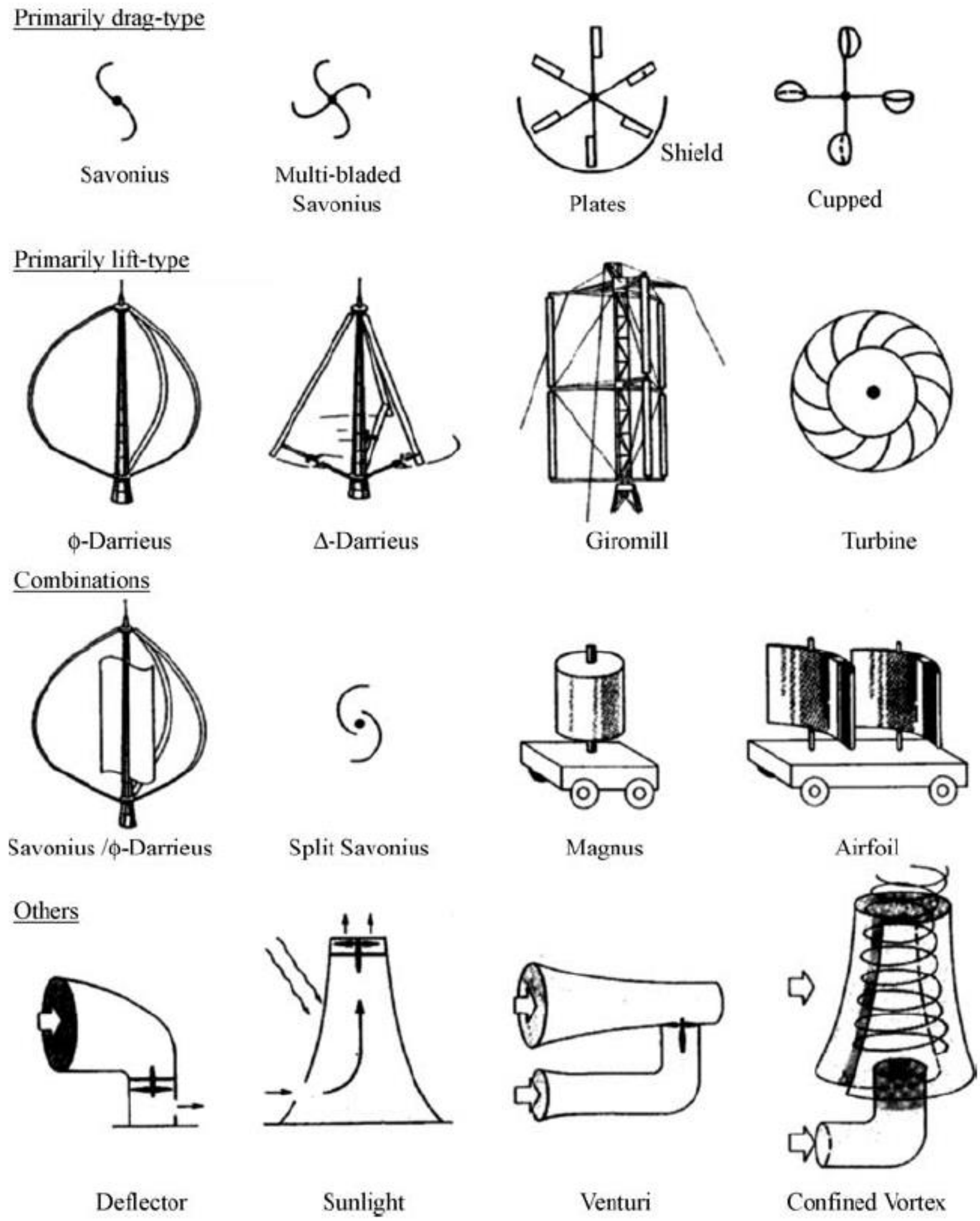
From this, torque developed can be calculated as

$$T_T = \frac{1}{2} \times 1.24 \times \frac{\pi}{4} \times 5^2 \times 10^2 \times 0.103 = 313.39\ NM$$

7.4 Classification of wind turbines

Since the inception of the wind energy technology, machines of several types and shapes were designed and developed around different parts of the world. Some of these are innovative designs which are not commercially accepted. Although there are several ways to categorize wind turbines, they are broadly classified into horizontal axis machines and vertical axis machines, based on their axis of rotation.




Primarily drag-type
Savonius
Multi-bladed Savonius
Shield
Plates
Cupped
Primarily lift-type
ϕ-Darrieus
Δ-Darrieus
Giromill
Turbine
Combinations
Savonius /ϕ-Darrieus
Split Savonius
Magnus
Airfoil
Others
Deflector
Sunlight
Venturi
Confined Vortex

2.5 Aerodynamics of wind turbines

Aerodynamics deals with the motion of air or other gaseous fluids and the forces acting on bodies moving through them. During the course of wind turbine development, several efforts were made to understand and interpret the aerodynamic principles governing wind energy conversion and to apply them in the successful system design. Earlier initiatives in this direction relied more on the aviation industry.

2.5.1 Airfoil

For the efficient energy extraction, blades of modern wind turbine are made with airfoil sections. Major features of such an airfoil are shown in Fig. 2.11. The airfoils used for the earlier day's wind turbines were the aviation air foils under the NACA (National Advisory Committee for Aeronautics) series. NACA specifies the features of the airfoil by numbers.

For example, in a four digit specification, the first number denotes the maximum camber of the airfoil at the chord line (in per cent of chord), the second number gives the location of the point of maximum camber from the leading edge (in tenth of the chord) and the third and fourth numbers indicate the maximum thickness (in per cent of the chord). Thus a NACA 2415 air foil have maximum camber of 2 per cent, located at 0.4 times the chord length from the leading edge and the maximum thickness is 15 per cent of the chord.

The five digit specification of airfoil is similar, but information on the lift characteristics are also included. In a five-numbered NACA airfoil, the design lift coefficient in tenth is given by 1.5 times of the first digit. One-half of the distance from the leading edge to the location of maximum camber (in per cent of the chord) is represented by the second and third digits. The fourth and fifth digits are the thickness of the airfoil (in per cent of the chord). Thus a NACA 23012 series airfoil will have a design lift coefficient of 0.3. The maximum camber of the airfoil is 0.15 times the chord and its thickness is 12 per cent. Blades with higher digit NACA numbers are also available.

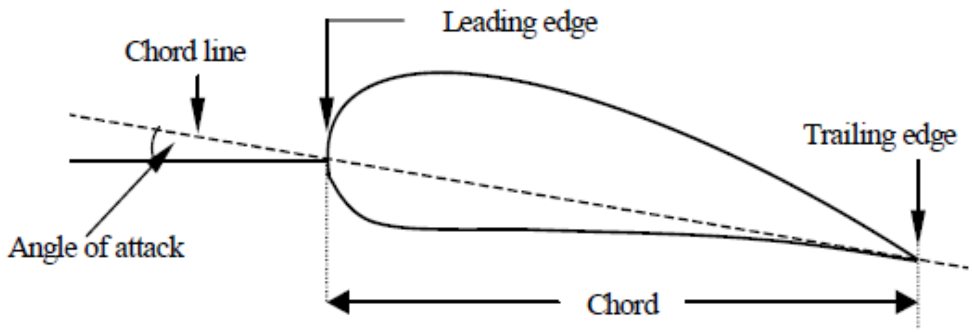


Fig 2.11. Important parameters of an airfoil

When an airfoil is placed in a wind stream, air passes through both upper and lower surfaces of the blade. Due to the typical curvature of the blade, air passing over the upper side has to travel more distance per unit time than that passing through the lower side. Thus the air particles at the upper layer move faster. According to the Bernoulli's theorem, this should create a low-pressure region at the top of the airfoil. This pressure difference between the upper and lower surfaces of the airfoil will result in a force F. The component of this force perpendicular to the direction of the undisturbed flow is called the lift force L (Fig. 2.12). The force in the direction of the undisturbed flow is called the drag force D. The lift force is given by

$$\boldsymbol{L = C_L \frac{1}{2} \rho_a A V^2} \qquad (2.15)$$

and the drag force (D) by

$$\boldsymbol{D = C_D \frac{1}{2} \rho_a A V^2} \qquad (2.16)$$

where C_L and C_D are the lift and drag coefficients respectively.

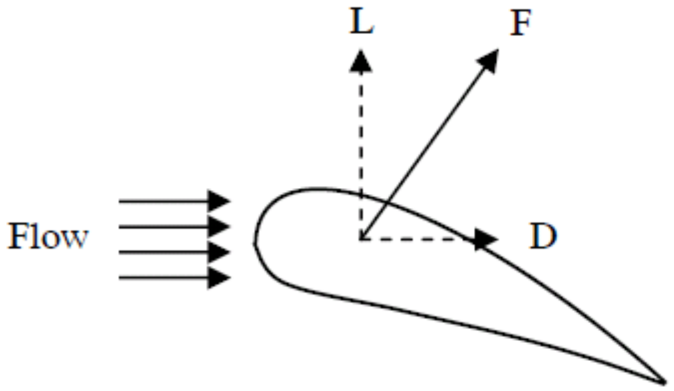


Fig. 2.12. Airfoil lift and drag

The angle between the undisturbed wind direction and the chord of the airfoil is known as the **angle of attack (α).**

C_D-C_L characteristics of an airfoil can be established under wind tunnel experiments. Airfoils are fixed at different angles of attack in the wind tunnel flow and the forces of lift and drag acting on the foil are measured using transducers placed in the vertical and horizontal planes. From this corresponding lift and drag coefficients are calculated using Eqs. (2.15) and (2.16). In case of a wind turbine, our objective is to maximise the lift force and minimise the drag. Hence, in a given flow, it is very important to place our airfoil at an optimum angle of attack so that the **C_D/C_L ratio is the minimum**.

2.5.2 Aerodynamic theories

Different theories are proposed to analyze the aerodynamics of wind turbines. These theories give an insight to the behavior of the rotor under varying operating conditions. Let us discuss some of the fundamental theories among them, applicable to HAWT.

Axial momentum theory

The conventional analysis of HAWT originates from the axial momentum concept introduced by Rankine, which was further improved by Froudes for marine propellers. Ideal flow conditions are considered for this analysis. The flow is assumed to be incompressible and homogeneous. The rotor is considered to be made up of infinite number of blades. Static pressures far in front and behind the rotor are considered to be equal to the atmospheric pressure. Frictional drag over the blades and wake behind the rotor are neglected.

Consider a wind turbine with rotor of area A_T, placed in a wind stream as shown in Fig. 2.15. Let A and A' be the areas of the sections 1-1, and 2-2 and V and V' are the respective wind velocities at these sections.

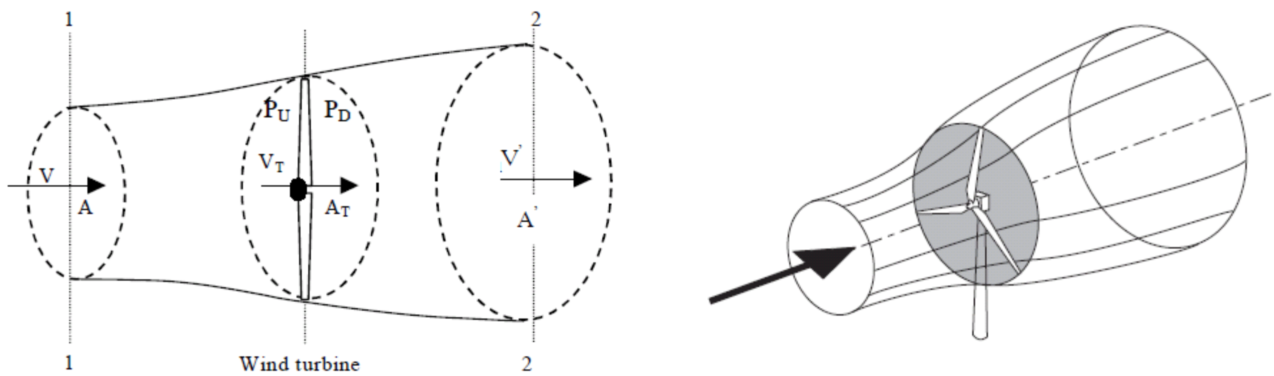


Fig. 2.15. The axial stream tube model

V_T is the velocity at the turbine section. According to the law of conservation of mass, the mass of air flowing through these sections is equal. Thus:

$$\boldsymbol{\rho_a A\, V = \rho_a\, A_T\, V_T = \rho_a\, \acute{A}\, \acute{V}} \quad (2.18)$$

The thrust force experienced by the rotor is due to the difference in momentum of the incoming and outgoing wind, which is given by

$$\boldsymbol{F = \rho_a\, A\, V^2 - \rho_a\, \acute{A}\, \acute{V}^2} \quad (2.19)$$

As AV =A′V′= $A_T V_T$ from (2.18), the thrust can be expressed as

$$\boldsymbol{F = \rho_a A_T V_T \left(V - \acute{V}\right)} \quad (2.20)$$

The

thrust can also be represented as the pressure difference in the upstream and down stream sides of the rotor. Let p_U and p_D be the pressure at the upstream and down stream side of the rotor respectively. Hence:

$$\boldsymbol{F = (p_U - P_D)A_T}$$

Applying the Bernoulli's equation at the sections and considering the assumption that the static pressures at sections 1-1 and 2-2 are equal to the atmospheric pressure *p*, we get

$$\boldsymbol{p + \frac{\rho_a V^2}{2} = p_U + \frac{\rho_a V_T^2}{2}} \tag{2.22}$$

And

$$\boldsymbol{p + \frac{\rho_a \acute{V}^2}{2} = p_D + \frac{\rho_a V_T^2}{2}} \tag{2.23}$$

From Eqs. (2.22) and (2.23),

$$\boldsymbol{p_U - p_D = \frac{\rho_a(V^2 - \acute{V}^2)}{2}} \tag{2.24}$$

Substituting the above expression for ($p_U - p_D$) in Eq. (2.21),

$$\boldsymbol{F = \frac{\rho_a A_T(V^2 - \acute{V}^2)}{2}} \tag{2.25}$$

Comparing Eqs. (2.20) and (2.25) we get

$$\boldsymbol{V_T = \frac{(V - \acute{V})}{2}} \tag{2.26}$$

Thus the velocity of the wind stream at the rotor section is the average of the velocities at its upstream and downstream sides.

At this stage, we introduce a parameter, termed as the axial induction factor into our analysis. The **axial induction** factor a indicates the degree with which the wind velocity at the upstream of the rotor is slowed down by the turbine. Thus

$$\boldsymbol{a = \frac{V - V_T}{V}} \tag{2.27}$$

From Eqs. (2.26) and (2.27),

$$\boldsymbol{V_T = V(1 - a)} \tag{2.28}$$

and

$$\boldsymbol{\acute{V} = V(1 - 2a)} \tag{2.29}$$

As we have seen earlier, the power imparted to the wind turbine is due to the transfer of kinetic energy from the air to the rotor. The mass flow through the rotor over a unit time is

$$\boldsymbol{m = \rho\, A_T V_T} \tag{2.30}$$

Hence the power developed by the turbine due to this transfer of kinetic energy is

$$\boldsymbol{P_T = \frac{1}{2}\rho_a A_T V_T\left(V^2 - \acute{V}^2\right)} \tag{2.31}$$

Substituting for V_T and V´ from Eqs. (2.28) and (2.29), we get

$$\boldsymbol{P_T = \frac{1}{2}\rho_a A_T V^3 4a(1-a)^2} \tag{2.32}$$

Comparing Eq. (2.32) with the expression for power coefficient in Eq. (2.8), we can see that

$$\boldsymbol{C_P = 4a(1-a)^2} \tag{2.33}$$

For Cp to be maximum,

$$\boldsymbol{\frac{dC_P}{da} = 0} \tag{2.34}$$

Thus differentiating Eq. (2.33), equating it to zero and solving, we get a=1/3. Substituting for a in Eq. (2.33), the maximum theoretical power coefficient of a horizontal axis wind turbine is 16/27 and the maximum power produced is

$$\boldsymbol{P_{T\,MAX} = \frac{1}{2}\rho_a A_T V^3 \frac{16}{27}} \tag{2.35}$$

This limit for the power coefficient is known as the **Betz limit**.

2.6 Rotor design

Designing a wind energy conversion system is a complex process. The environmental conditions to which the turbine is exposed can be severe and unpredictable. Principles of aerodynamics, structural dynamics, material science and economics are to be applied to develop machines which are reliable, efficient and cost effective. In this section, a simple procedure for an approximate design of a wind rotor is discussed, based on the fundamental aerodynamic theories. Following input parameters are to be identified for such a design.

1. Radius of the rotor (R)
2. Number of blades (B)
3. Tip speed ratio of the rotor at the design point (λ_D)
4. Design lift coefficient of the airfoil (C_{LD})
5. Angle of attack of the airfoil lift (α)

The radius of the rotor primarily depends on the power expected from the turbine and the strength of the wind regime in which it operates. Various losses involved in the energy conversion process are also to be considered. If the power expected from the turbine (P_D) at its design point is known, with the relationship

$$P_D = \frac{1}{2} C_{PD}\, \eta_d \eta_g\, \rho_a\, A_T\, V_D^{\,3} \tag{2.64}$$

the radius of the rotor can be estimated as

$$R = \left[\frac{2\, P_D}{C_{PD}\, \eta_d \eta_g\, \rho_a\, \pi\, V_D^{\,3}} \right]^{\frac{1}{2}} \tag{2.65}$$

where

C_{PD} : is the design power coefficient of the rotor,

λ_d : is the drive train efficiency,

λ_g: is the generator efficiency

V_D is the design wind velocity.

For a well designed system, the design power coefficient (C_{PD}) may be in the range of 0.4 to 0.45 and the combined efficiency of the drive train and generator may be taken as 0.9. If the design is to be based on the energy required for a specific application (E_A), the rotor radius can be calculated by

$$R = \left[\frac{2\, E_A}{\eta_S\, \rho_a\, \pi\, {V_M}^3\, T} \right]^{\frac{1}{2}} \qquad (2.66)$$

where
η_S :is the overall system efficiency,
V_M :is the mean wind velocity over a period and
T :is the number of hours in that period.
For example, if our design is based on the daily energy demand, then V_M is the daily mean wind velocity and T= 24. For applications like water pumping, it is reasonable to take η_S in the range of 0.12 to 0.15. For wind electric generation, η_S may vary from 0.25 to 0.35, depending on the design features of the system.

Example
Design the rotor for an aero generator to develop 100 W at a wind speed of 7 m/s. NACA 4412 airfoil may be used for the rotor.

Solution
Let us take the design power coefficient as 0.4 and the combined drive train and generator efficiency 0.9. Taking the air density as 1.224 kg/m^3, from Eq. (2.65), the rotor radius is

$$R = \left[\frac{2 \times 100}{0.4 \times\ 0.9 \times 1.224 \times \pi \times 7^3} \right]^{\frac{1}{2}} = 0.65\, m$$

Wind energy conversion systems
4.1 Wind electric generators

Electricity generation is the most important application of wind energy today. The major components of a commercial wind turbine are:

1. Tower
2. Rotor
3. High speed and low speed shafts
4. Gear box
5. Generator
6. Sensors and yaw drive
7. Power regulation and controlling units
8. Safety systems

The major components of the turbine are shown in Fig. 4.1

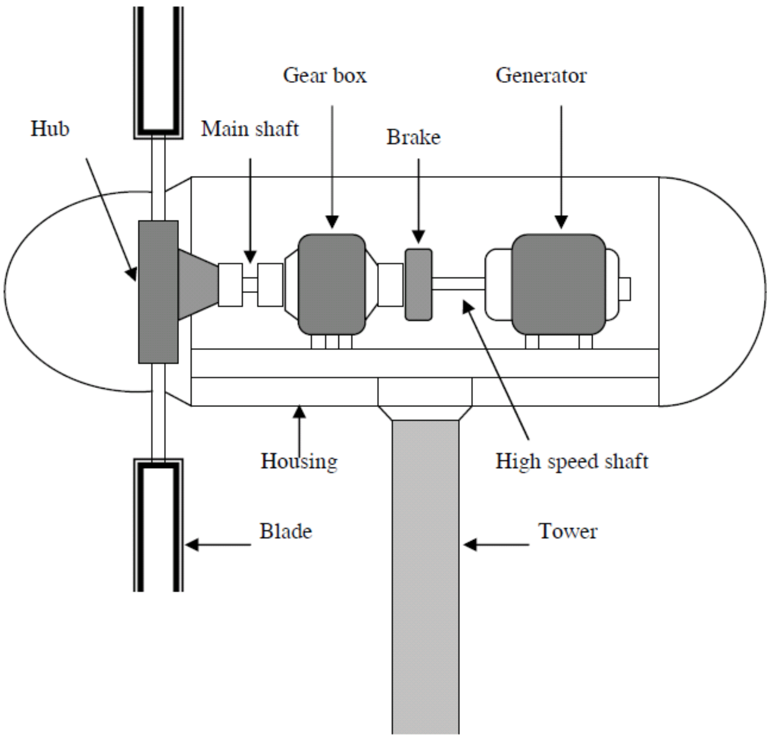


Fig. 4.1. Components of a wind electric generator

4.2 Wind farms

Wind turbines of various sizes are available commercially. Small machines are often used for stand alone applications like domestic or small scale industrial needs. When we have to generate large quantities of power, several wind turbines are clubbed together and installed in clusters, forming a wind farm or wind park. There are several advantages in clustering wind machines. The installation, operation and maintenance of such plants are easier than managing several scattered units, delivering the same power. Moreover, the power transmission can be more efficient as the electricity may be transformed to a higher voltage.

Types of wind farms

1- On shore wind farm (A land based wind farm)
2- Offshore wind farms

4.4Wind pumps

One of the classical applications of wind energy is water pumping. Several thousands of wind pumps are still in use in interior areas of America and Australia, catering to the water needs of crops and livestock. Tremendous scope for such machines do exist in many parts of the developing world, where grid connected power supply is not readily extendable due to technical and economic constraints. Gasoline, diesel or kerosene

engines are being used to energize water pumps in these areas. Wind pumps are found economically competitive with these options, even at areas of moderate wind. Hence, with proper improvement in the technology and right policy initiatives, use of wind pumps is expected to continue in the coming years.
According to historians, the first machines utilising wind energy were operated in the orient. As early as 1,700 B.C., it is mentioned that Hammurabi used windmills for irrigation in the plains of Mesopotamia.

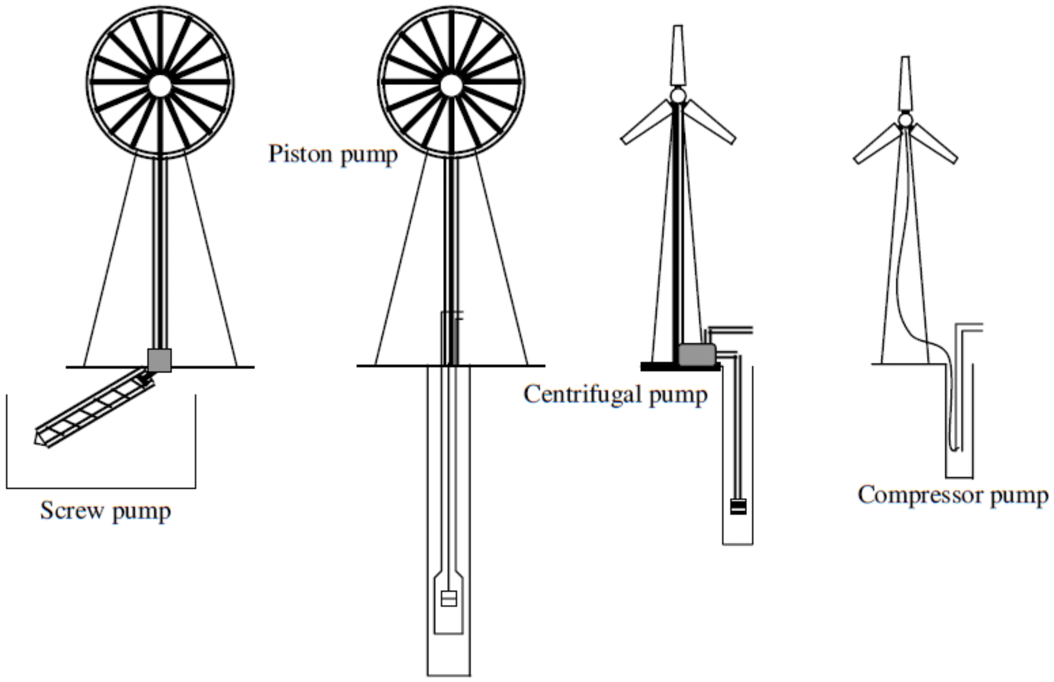


Fig. 4.2.8. Different pumps coupled mechanically to wind rotors

Performance of wind energy conversion systems

5.1 Power curve of the wind turbine

Fig. 5.1 shows the typical power curve of a pitch controlled wind turbine. The rated power of the turbine is 1 MW. The given curve is a theoretical one and in practice we may observe the velocity power variation in a rather scattered pattern. We can see that the important characteristic speeds of the turbine are its cut-in velocity (V_I), rated velocity (V_R) and the cut-out velocity (V_O). The cut-in velocity of a turbine is the minimum wind velocity at which the system begins to produce power. It should not be confused with the start-up speed at which the rotor starts its rotation. The cut-in velocity varies from turbine to turbine, depending on its design features. However, in general, most of the commercial wind turbines cut-in at velocities between 3 to 5 m/s.
Due to technical and economical reasons, the wind turbine is designed to produce constant power - termed as the rated power (P_R) - beyond its rated velocity. Thus, the

rated velocity of a turbine is the lowest wind velocity corresponding to its rated power. Usually the system efficiency is maximum at V_R. From V_I, to V_R, the power generated by the turbine increases with the wind velocity. Between V_R and V_O, the turbine is restricted to produce constant power P_R corresponding to V_R, irrespective of the changes in velocity. This power regulation
is for better system control and safety. Hence P_R is the theoretical maximum power expected from the turbine. At wind velocities higher than V_O, the machine is completely shut down to protect the rotor and drive trains from damage due to excessive loading. Some times V_O is also termed as the furling velocity, as in the earlier sail type machines the canvas was rolled upto protect the mill from strong winds.

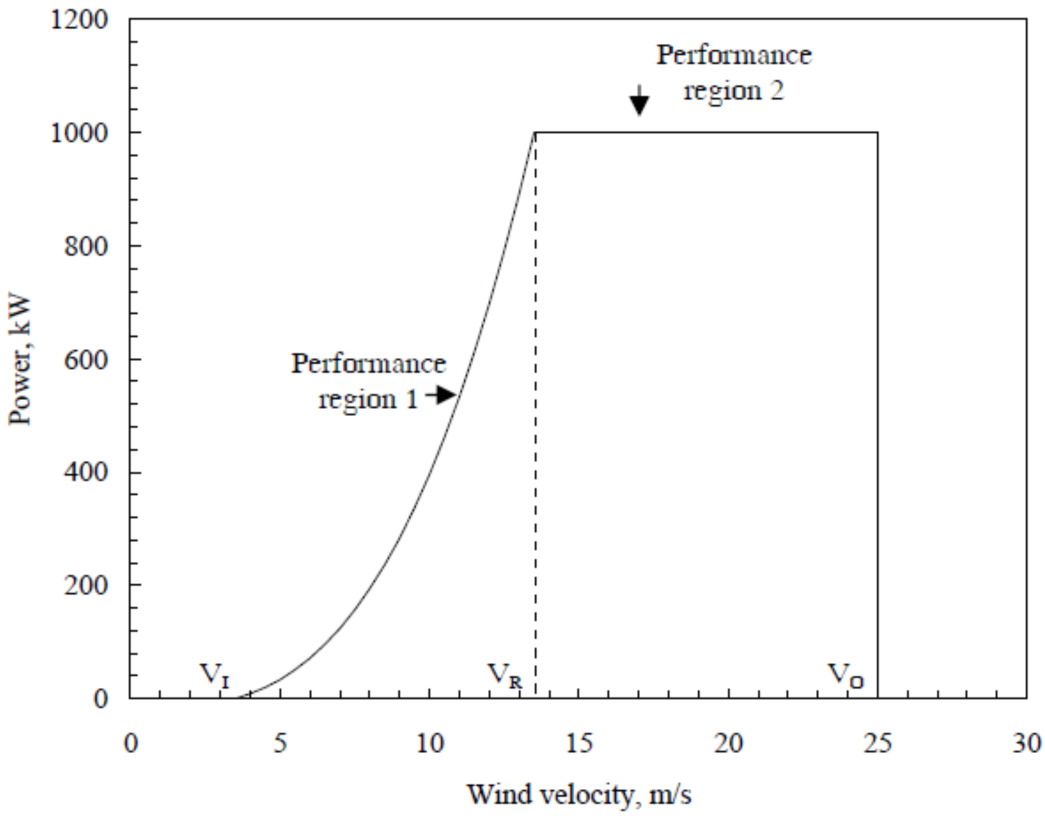


Fig. 5.1. Ideal power curve of a pitch controlled wind turbine

Table 5.1. Performance regions of a wind turbine

Velocity range	Power
0 to V_I	No power as the system is idle
V_I to V_R	Power increases with V
V_R to V_O	Constant power P_R
Greater than V_O	No power as the system is shut down

Chapter Eight

Water energy

Water Cycle

The color of our planet is blue when seen from space. The reason is that 71% of the earth's surface consists of water. However, without the sun our blue planet would not be blue. Water, which gives the earth its characteristic appearance, would be completely solidified into ice. Because of the heat of the sun, 98% of water is fluid. Altogether there are around 1.4 billion cubic kilometers of water on earth. of this amount, 97.5% is salt water in the oceans and only 2.6% is fresh water. Almost three - quarters of the fresh water is bound in polar ice, ocean ice and glaciers; the rest is mainly in the groundwater and the soil moisture. Only 0.02% of the water on earth is in rivers and lakes.

Due to the influence of the sun, on average 980 liters of water evaporate from each square meter of the earth's surface and come down again somewhere else in the form of precipitation. Altogether about 500 000 cubic kilometers of water collect in this way each year. This gigantic water cycle converts around 22% of all the solar energy radiated onto earth (Figure 9.2).

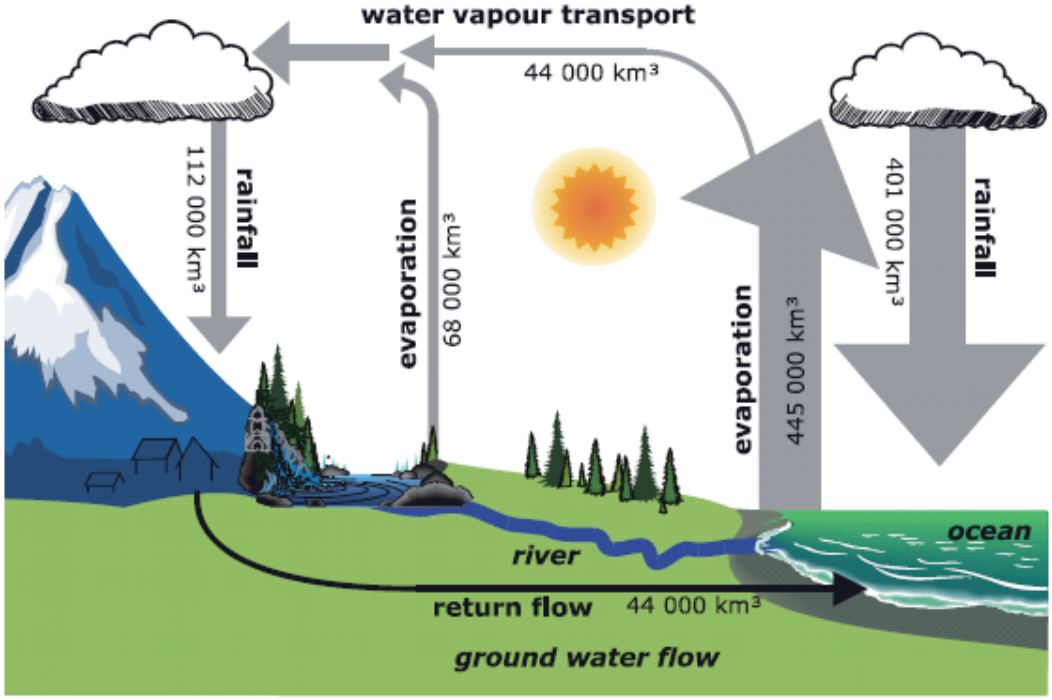


Figure 9.2 Earth's water cycle.

Hydroelectric Power Generation

8.1 Principles

Hydropower plants harness the potential energy within falling water and use classical mechanics to convert that energy into electricity. The theoretical water power $P_{Wa,th}$ between two specific points on a river can be calculated according to Equation (8.1) (see Chapter 2.4.1).

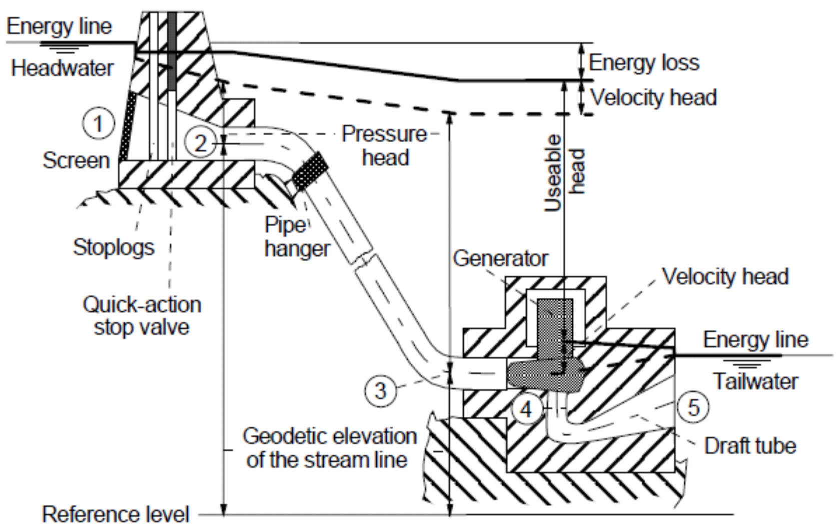


Fig. 8.1 Physical correlations in a hydroelectric power station

$$P_{Wa,th} = \rho_{Wa}\, g\, \dot{q}_{Wa} (h$$

ρ_{Wa} is the water

density, g the gravitational constant, and q_{Wa} the volumetric flow rate through the hydroelectric power station. h_{HW} und h_{TW} describe the geodetic level of head and tailwater. System setup. A hydroelectric power station, depending on scale, normally consists of a dam or weir, and the system components intake works, penstock, in some cases a headrace, plus the powerhouse and tailrace (Fig. 8.1). The flow is led to the turbine via the intake structure, the headrace and penstock. Afterwards it streams through the draft tube into the tailrace. In Fig. 8.1 the lines enable the graphic representation of the Bernoulli equation. The dotted line represents the geodetic level of the water flowing through the hydroelectric power station. The so-called energy line is at the top left corner of the diagram. It shows the locations and respective energy losses. The distance to the broken line below the energy line corresponds with the kinetic energy of the water. This becomes apparent at the intake structure, where the water flow increases due to the narrowing of the cross-section and the kinetic energy therefore increases at the same time. The difference between the geodetic level and the broken line is the pressure energy level.

Water Turbines

Water turbines form the core of water - powered systems and extract the energy from water. Modern water turbines have very little in common with the rotating wheels of traditional watermills. Depending on the head of the water and the water flow, turbines optimized for the respective operating area are used (Figure 9.3). These turbines reach a power of over 700 megawatts.

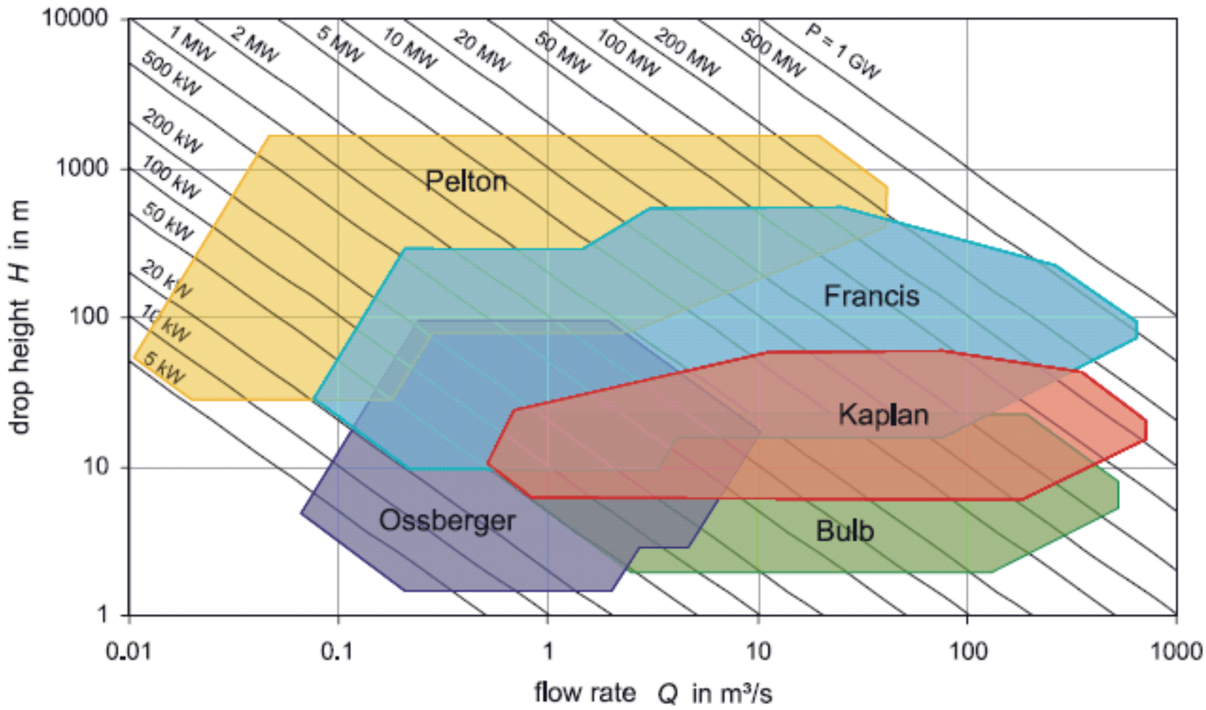


Figure 9.3 Operating areas for different water-powered turbines.

1- The Kaplan turbine, developed by the Austrian engineer Viktor Kaplan in 1912, is usually the first choice for low heads – for instance, for power plants on rivers (Figure 9.4). This turbine uses the pressure of the water at the different elevations of barrages. It has three to eight adjustable blades and looks like a large ship screw (propeller) that powers the fl owing water. The efficiency of Kaplan turbines reaches values between 80 and 95%.
2- The bulb turbine (Figure 9.5) is similar to the Kaplan turbine, except that it has a horizontal axle and, as a result, is suitable for even smaller heads. The generator is placed in a bulb - shaped workroom behind the turbine, which explains why it is also referred to as a bulb turbine.
3- The Francis turbine, which was developed by the Briton James Bicheno Francis in 1848, is used for larger heads of up to 700 m. This turbine also uses the pressure difference of water and reaches efficiencies of over 90%. In principle, the Francis turbine can also be used as a pump and is therefore suitable as a pump turbine for pumped - storage plants (Figure 9.6)
4- In 1880 the American Lester Allen Pelton developed the Pelton turbine. It is mainly designed for large heads and, consequently, for use in high mountains. This turbine can reach very high efficiencies of 90 to 95%. The water is supplied to the turbine over a penstock. The water then flows through a nozzle at very high velocity to spoon - shaped buckets (Figure 9.7).

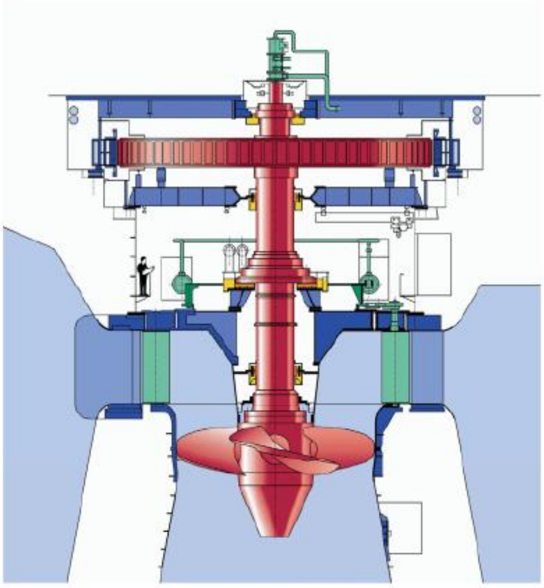


Figure 9.4 Drawing showing a Kaplan turbine with a generator (left) and a photo of a Kaplan turbine (right). Source: Voith Hydro.

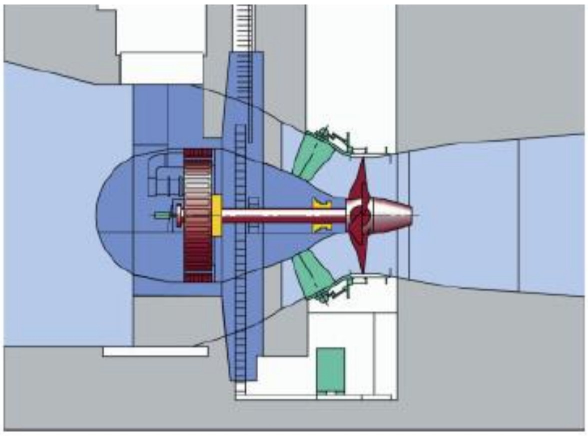
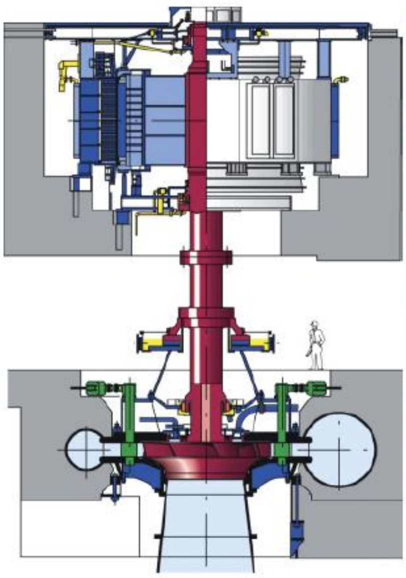


Figure 9.5 Bulb turbine with generator. Source: Voith Hydro.



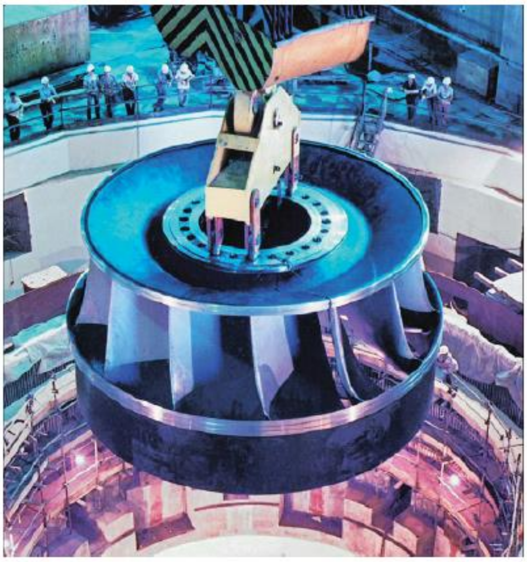


Figure 9.6 Francis pump turbine at Goldisthal pumped-storage plant (left) and a Francis turbine at the Itaipu plant (right). Source: Voith Hydro.

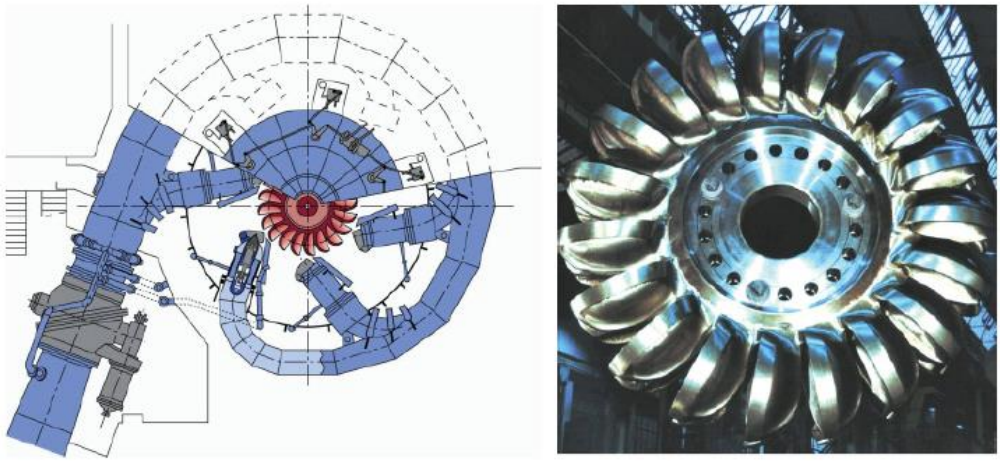


Figure 9.7 Drawing of a 6-nozzle Pelton turbine (left) and photo of a Pelton turbine (right). Source: Voith Hydro.

Hydropower Plants

The energy that can be exploited from water essentially depends on two parameters: runoff volume and the head of the water. Almost all hydropower plants utilize natural elevation differences using technical equipment

The types of hydropower plants are:

1- Run - of - River Power Plants
2- Storage Power Plants
3- Pumped - Storage Power Plants

9.3.1 Run - of - River Power Plants

The natural course of a river itself concentrates large quantities of water. A run - of - river power plant can be built anywhere on a river where a sufficient difference in elevation exists (Figure 9.8). The weir then backs up the water. This creates a difference in elevation in the water's surface above and below the plant. At the top the water flows through a turbine that powers an electric generator. Grating at the turbine intake prevents rubbish and flotsam washed along by the river from blocking up the turbine. A transformer then converts the voltage of the generator into the desired mains voltage.

Large hydropower plants are usually constructed so that multiple turbines can run in parallel. If the water flow drops during the dry periods of the year, some of the turbines can be shut down. The remaining turbines then still receive almost the full amount of water they need. This prevents the turbines from working in partial – load mode with poor efficiency. If, on the other hand, there is flooding and a river carries more water

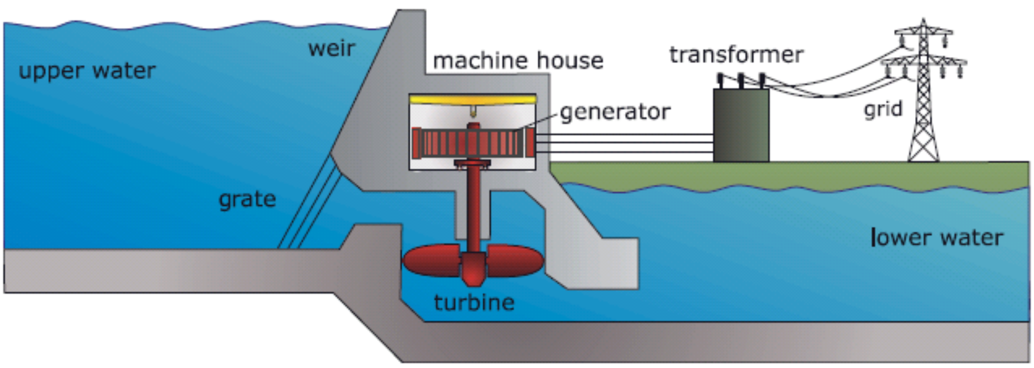


Figure 9.8 Principle of a run-of-river power plant.

with it than the turbines can process, the surplus water has to be let out unused over a weir.

9.3.2 Storage Power Plants

Storage power plants produce high levels of power output. Dams store huge masses of water at geographically optimal locations. This type of dam makes it possible for storage power plants to be built in the mountains (Figure 9.10). A high – pressure pipeline pumps the water into a machine house, where, due to the large head, enormous water pressure of up to 200 bars is created. In the machine house water powers the turbines that produce energy over an electric generator.
It is not unusual to find dams over 100 m high. The highest dams on earth are over 300 m high. Reservoirs are often also used to store drinking water and to control flooding. Storage power plants that are designed primarily to generate electricity have very high power output. Power plants that produce several hundred or even thousand megawatts are not unusual (Table 9.1).

Figure 9.10 Storage power plants with reservoirs: Malta (left), Kaprun in Austria (right). Source: www.verbund.at.

Table 9.1 The largest hydroelectric power plants in the world.

Power plant	Country	River	Completed	Power output in MW	Dam length in m	Dam height in m
Three Gorges Dam	China	Yangtse	2009	18 200	2310	180
Itaipú	Brazil/ Paraguay	Paraná	1983	14 000	7760	196
Guri	Venezuela	Rio Caroni	1986	10 300	1300	162
Tucuruí	Brazil	Rio Tocantins	1984	7 960	6900	78
Grand Coulee	USA	Columbia River	1942	6 495	1592	168

9.3.3 Pumped - Storage Power Plants

Pumped - storage power plants need very specific geographical conditions. To be built, they need two basins with a major difference in altitude between them. Some pumped - storage plants have a natural inflow where a river flows into the higher basin. Pumped - storage plants without a natural inflow are purely storage plants.
When electric power is needed, the water of the higher basin is pumped over an intake mechanism through a pressure pipe to the turbine, which drives an electric machine as the generator. Once the turbine has extracted the energy from the water, the water flows into the lower basin. A transformer there converts the voltage of the generator to mains voltage (Figure 9.11).

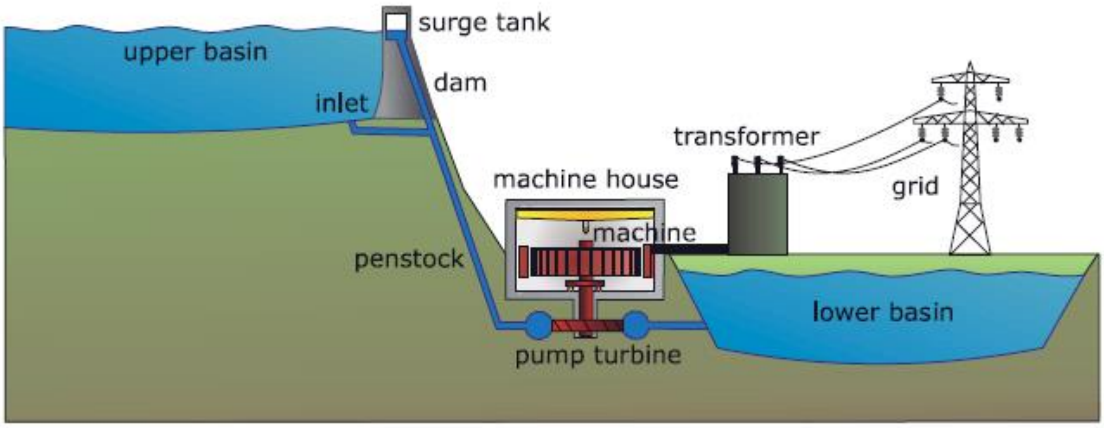


Figure 9.11 Principle of a pumped-storage power plant.

Ocean Current Power Plants

Ocean current power plants have a structure similar to wind power plants, except that the rotors rotate below the water surface. A built - in hub mechanism raises the rotor to the water surface for maintenance. The first prototype was successfully installed in 2003 off the North Devon coast in England. (Figure 9.14).

Figure 9.14 Left: Prototype system in Project Seaflow off the west coast of England. Photo: ISET.
Right: Maintenance ship in a planned ocean current power plant park. Graphics: MCT.

Wave Power Plants

For decades high hopes have been pinned on the development of wave power plants. A study of the potential of wave energy indicates that large amounts of energy could be generated. However, only coastal regions with low water depths are appropriate for the use of wave energy. Due to the comparatively small useable sea areas available in many countries, this technology has relatively low potential. Basically, a distinction is made between the following functions:

1- Float ball systems
3- Chamber systems
4- Tapchan systems

1. Float ball systems use the energy potential of waves. A float ball follows the movement of waves. Part of the installation is anchored to the ground. The movement of the float ball can be used by a piston or a turbine.
2. Chamber systems, a chamber locks in air. The waves cause the water level to fluctuate in the chamber. The oscillating water level compresses the air. The displaced air escapes through an opening and powers a turbine and a generator. When the water column falls, the air flows back through the turbine into the chamber (Figure 9.13).
3. Tapchan is an abbreviation for 'tapered channel' . In these systems, waves in coastal areas or on a floating object feed into a tapered and rising channel. An upper basin captures the waves. When the water flows back into the ocean, it powers a turbine.

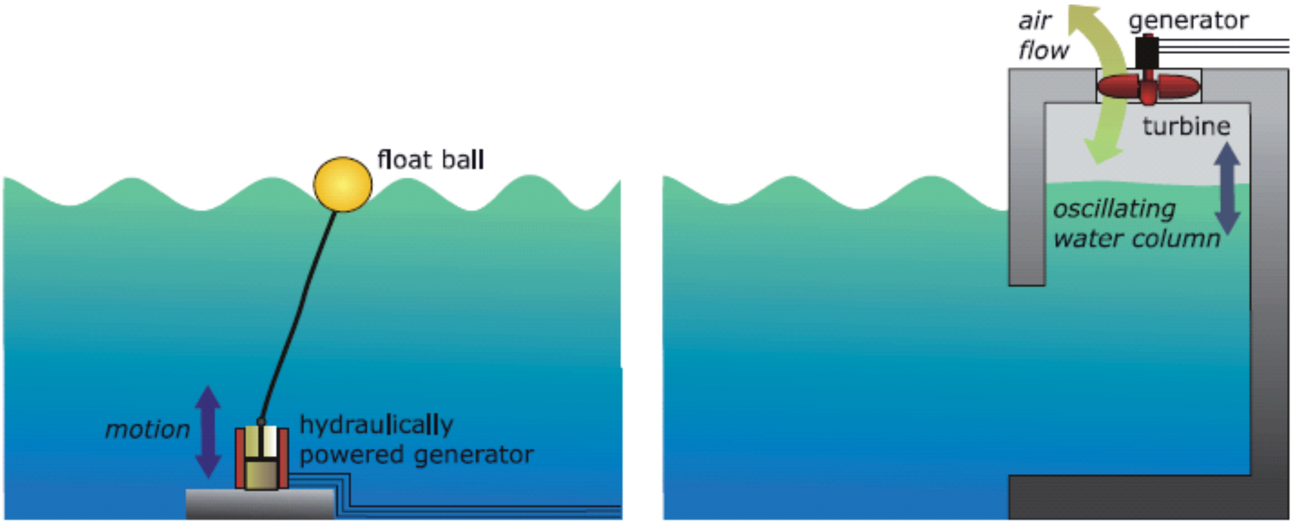


Figure 9.13 Principle of wave power plants. Left: Float ball system. Right: Chamber system.

Tides Energy

Tides are due to the gravitational attraction of the moon and the sun at the surface of the Earth. The effect of the moon on the Earth in terms of tides is larger than the effect of the sun; even through the gravitational force of the sun is larger. To find how the gravitational force of the moon distorts any volume of the material body of the Earth, the gradient of the gravitational force of the moon on that volume must be found (a gradient is how force changes with distance; in calculus, it is the differentiation with respect to length). The tidal effects (Figure 12.14) are superimposed on the near-spherical Earth, and there will be two tides per day due to the spin of Earth. When the tidal effects of the sun and moon are aligned, the tides are higher, spring tides. When the continents are added, the ocean bulges reflect from shorelines, which causes currents, resonant motions, and standing waves, so there are some places in the oceans where the tidal variations are nearly zero. In other locations, the coastal topography can intensify water heights with respect to the land. The largest tidal ranges in the world are the Bay of Fundy (11.7 m), Ungava Bay (9.75 m), Bristol Channel (9.6 m), and the Turnagain Arm of Cook Inlet, Alaska (9.2 m)..

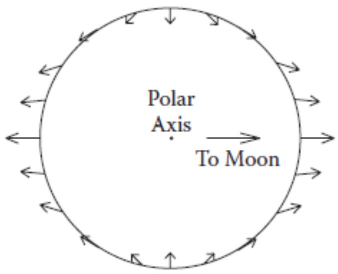
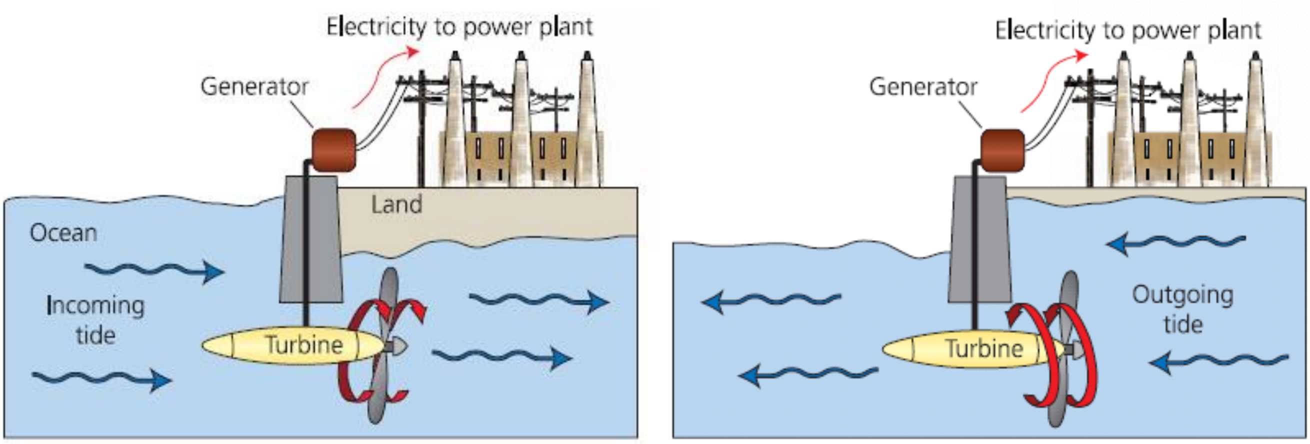


FIGURE 12.14 Tidal forces on the Earth due to the moon.



Tidal energy uses the motion of the incoming and outgoing tides to turn turbines and generate electricity. Underwater turbines will be more expensive to install than wind farm turbines, and the turbine blades might injure aquatic species. If those problems can be corrected, tidal energy and related wave energy offer a long-term renewable form of energy.

Chapter Nine

Geothermal Energy

Geothermal energy is energy that comes from deep inside of Earth. The word geothermal comes from the Greek words ***geo*** (meaning "earth" and ***therme*** (meaning "heat".

Earth's Heat

Earth itself is made up of concentric (Figure 10.2) bands comprising the core, the mantle and the crust. The earth's core has a diameter of around 6900 km (4290 miles). A differentiation is made between the outer, liquid core and the inner core, which is made of solid matter. Maximum temperatures in the earth's core reach 6500 ° C, which is hotter than the surface of the sun.

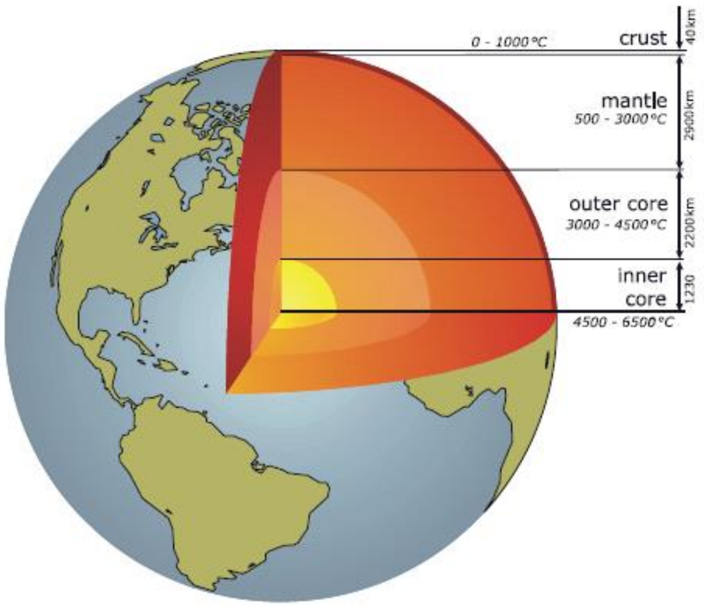


Figure 10.2 The structure of the earth.

Use of Geothermal Energy Today

1- Geothermal energy is used directly Direct use means that heat energy straight from Earth is used to heat a house or other building. People can use geothermal energy directly only in areas where the energy naturally reaches the surface. In the United States, most direct use of geothermal energy is in the western states.
2- Geothermal energy is used to generate electricity. The world's biggest users of such electricity are the United States, the Philippines, Indonesia, Mexico, Italy, Japan, New Zealand, and Iceland. The United States produces more geothermal energy than any other country—30 percent of the world's total.

10.2 Geothermal Heat and Power Plants

10.2.1 Geothermal Heat Plants

If boreholes already exist in a thermal water area, it is comparatively easy to develop a geothermal heat supply. In geothermal heat plants a feed pump fetches hot thermal water from a production well to the surface (Figure 10.6). As thermal water often has a high salt content, along with certain natural radioactive impurities, it cannot be used directly to provide heat. A heat exchanger extracts the heat from the thermal water and transfers it to a district heating grid. A reinjection well injects the cooled thermal water back into the earth.
Relatively low temperatures of 100 ° C or less are sufficient for heating purposes. Deep drilling depths are therefore not necessary. A central heat system controls the amount of output depending on the heat requirement. If heat requirements are particularly high, a peak - load boiler can cover the heat peaks. A backup boiler is also helpful to guarantee reliable heat supply in case problems occur with the extraction pump or the well.

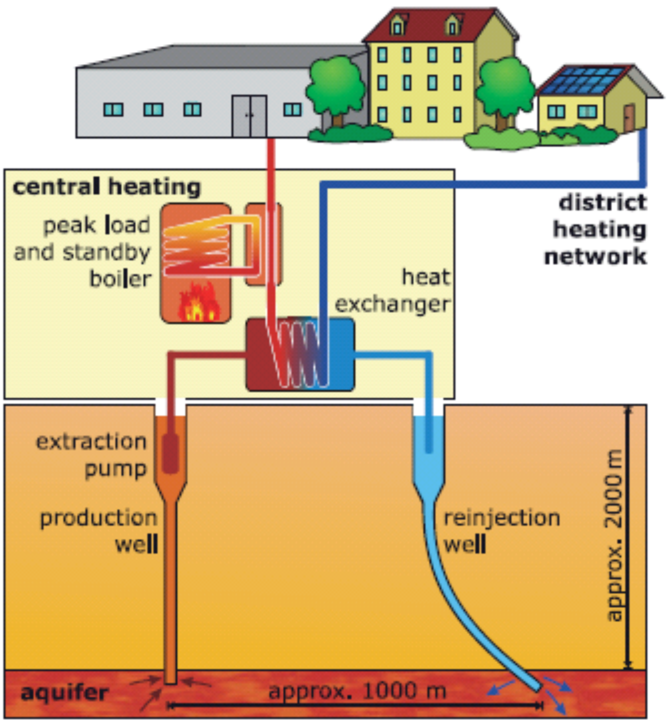


Figure 10.6 Principle of a geothermal heat plant.

10.2.2 Geothermal Power Plants

Using geothermal energy to generate electricity is somewhat more complex than providing thermal heat. Normal steam turbine systems can be used in geothermally optimal locations with temperatures between 200 ° C and 300 ° C. If hot steam deposits exist underground, they can be used directly to drive the turbines.

If hot thermal water is under pressure, it can be evaporated through an expansion stage. The steam from the water that is still hot can in turn be transferred directly to a steam turbine. This technique is called a fl ash process.

At temperatures of 100 ° C or less geothermal water is not hot enough to vaporize water. A normal steam turbine using water as the work medium is not suitable in this case. An ORC (Organic Rankine Cycle) system is used instead (Figure 10.7).

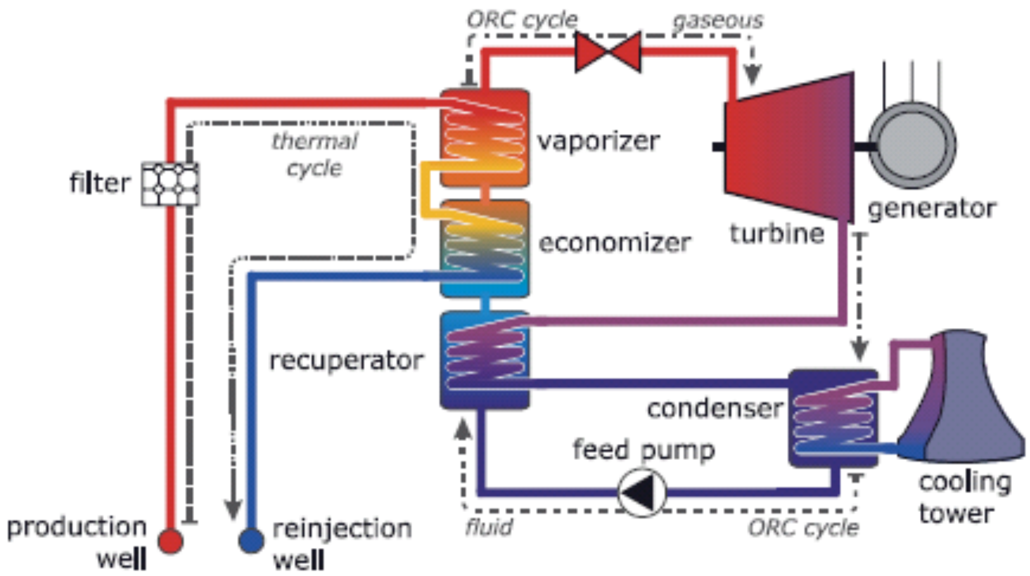


Figure 10.7 Principle of a geothermal ORC system.

10.2.3 Geothermal Heat Pumps

Geothermal heat pumps use the thermal properties of the ground in a way that is very different from those of geothermal generating stations or direct-use technologies. The problem with the direct-piped hot-water applications and with geothermal power stations is that both depend on ready access to concentrated deposits of thermal energy. By contrast, given enough land, geothermal heat pumps, which can heat and cool buildings, can be successfully installed almost anywhere.

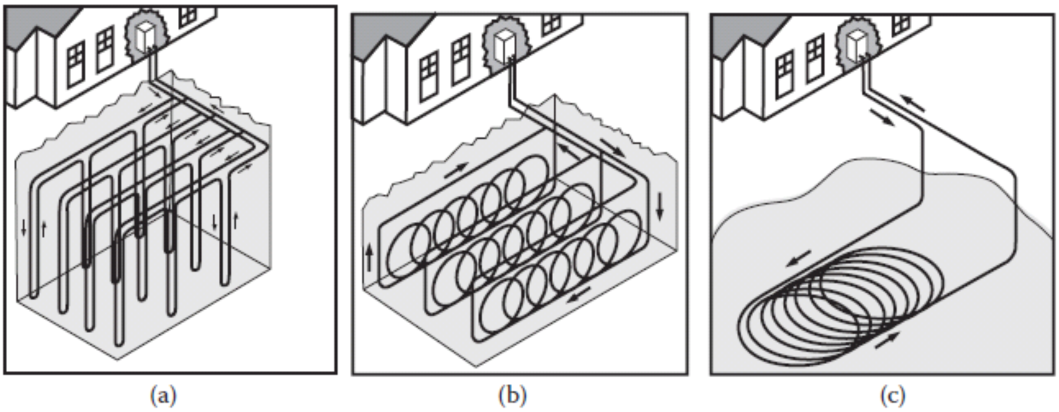


FIGURE 11.9 Geothermal heat pump, closed-loop systems; (a) borehole, (b) lateral, and (c) pond/lake.

Ground heat exchanger

Chapter Ten

Bioenergy

The conversion of solar energy by the fundamental process of photosynthesis is the basis for almost all life. Life that is not dependent on photosynthesis has been found in vents in the deep oceans, a significant scientific discovery; however, it is of no significant importance for the production and consumption of bioenergy. of course, humans are also dependent on biomass for food, fiber, and energy. In terms of the mass of the Earth, the thin layer of biomass is inconsequential, but it is significant in the regulation of the atmosphere and temperature of the Earth. There are three aspects for biomass: overall biomass (which is essentially steady state; growth, storage, decay), food and fiber, and bioenergy. In general, around 30% of the primary energy of the world is bioenergy, and in some developing countries, it can be 70–90%. Even in developed countries, the contribution from bioenergy can reach 20% due to a large forest industry, and in some of the developed countries, the contribution of bioenergy has been increasing. It is difficult to estimate the percentage of biomass for food, fiber, and bioenergy in the world, as in the developing world food, fiber, and sources of bioenergy are grown and traded locally.

Types of Bioenergy Source

1 Solid bioenergy sources: The largest group of solid bioenergy sources is products made from **wood**.These are obtained when firewood is taken from forests and when waste is utilized from the industrial processing of wood products. In many places by-products from agriculture, such as straw, are also used for generating energy from biomass

2 Liquid bioenergy sources: Mobility is central to our modern industrialized society. Apart from a few exceptions, the transport of people and goods is sustained by liquid fuels. Today there are already various technically equivalent liquid bioenergy sources available that can take over these tasks. **Ethanol** from alcoholic fermentation and **methanol** from lignocelluloses biomass such as wood are biogenic fuels. By far the most widespread energy crops, however, are **rape** and **sunflower**, the **oil** from which is used either in its naturally occurring form or as **biodiesel**.

3 Gaseous bioenergy sources: Gaseous bioenergy sources are the result of converting natural biomass. They can be produced by microbiological processes, such as anaerobic methane fermentation, but they can also arise through the thermochemical conversion of solid biomass in gasification processes. Biogas is created in the fermentation of vegetable and animal biomass without the action of oxygen. Here a symbiosis of bacteria groups brings about the breakdown of carbon compounds into the gaseous end-products **methane (CH_4)** and carbon dioxide (CO_2). In practice, this happens in agricultural biogas installations or in landfill bodies for example

Biomass Heating

Wood as a Fuel

Wood is by far the main fuel used for biomass heating. It is available in different processed forms (Figure 12.5). As the first step, felled trees are cut to a common length to produce round wood. High - quality woods are not used as fuel but are processed further by the timber industry.

Figure 12.5 Different processed forms of wood. From top left to bottom right: round wood, firewood, wood briquettes, wood pellets.

Wood heating systems are:

1- **Fireplaces and Closed Woodburning Stoves**

The classic biomass heating system is the fireplace. For centuries open fireplaces have been used to heat individual rooms. Yet this is a relatively inefficient use of firewood. Open fireplaces usually only reach 20 to 30% efficiency. This means that 70 to 80% of the firewood's energy escapes unused through a chimney. As romantic as old castles and palaces may seem, the use of open fires to achieve consistently pleasant room temperatures in draughty castle halls was an almost hopeless task. With 70 to 85% efficiency, enclosed fireplaces and closed woodburning stoves are considerably more effective than open fireplaces (Figure 12.7).

Figure 12.7 Enclosed fireplace and closed woodburning stove. Source: BBT Thermotechnik GmbH.

2 Firewood Boilers

The firewood boiler (Figure 12.8) is an option for those who want to heat with reasonably priced firewood and without the bother of a fireplace or stove. As these boilers are usually installed in a cellar, they do not have aesthetic merits of a fireplace. They have large containers for wood supplies that need to be stocked manually, and they can burn for several hours on a single load of wood. Firewood boilers are available in different performance classes and reach maximum efficiencies of more than 90%. The efficiency of smaller boilers is usually somewhat less.

Figure 12.8 Solid fuel boiler for heating with firewood. Source: BBT Thermotechnik GmbH.

3 Wood Pellet Heating

Wood pellet heating systems offer by far the greatest ease of operation. The fuel is kept in a special pellet store, and an automated feed mechanism using either a feeding screw or a suction device transports the pellets directly to the burner. A screw conveys the pellets from the bottom part of the store. With a suction device similar to a big vacuum cleaner the pellets are also sucked up from below. The suction hoses are very flexible and even enable the bridging of large distances between the store and the burner. As the suctioning of the pellets can be noisy, modern pellet boilers have a small hopper from which the pellets are conveyed to the burner through gravity or a small feeding screw. The hopper is then filled from the store via an automatic timer switch so that the pellet feeding system does not disturb anyone at night.

Figure 12.9 Wood pellet heating with pellet store. Source: BBT Thermotechnik GmbH.

Biomass Heat and Power Plants

In addition to being burnt in stoves and boilers for heating systems in single homes and apartment blocks, biomass can also be used in large heat plants. A central heat plant consists of a high - performance boiler and a fuel store. The fuel store is usually big enough to ensure that independent operation can be guaranteed for several days or even weeks. A district heating grid then transports the heat to the consumers connected to the grid.

With centralized heat plants, individual consumers no longer have to worry about fuel procurement and system maintenance. These tasks are handled by the operator of the heat plant. The efficiency of large heat plants is often somewhat higher than that of small non - central systems. On the other hand, heat losses are higher because of the long pipes in the district heating grid. However, large heat plants fare considerably better when it comes to the emission of harmful substances. Compared to heating systems in single - family homes, large plants use more modern filtering techniques and have stricter conditions on emissions. This ensures that combustion gases emit fewer harmful substances.

Numerous new biomass power plants have recently been built all over the world. One example is the Königs Wusterhausen plant near Berlin, Germany (Figure 12.12). This power plant has an output of 20 megawatts and with 160 million kilowatt hours per year can cover the energy demands of around 50 000 households. For fuel it uses 120 000 tons of waste and wood residues from the Berlin region annually. The efficiency of this biomass plant is around 35%.

Figure 12.12 The Königs Wusterhausen biomass power plant in Germany (left) and a wheel loader for biomass fuel transport (right). Source: MVV-press photo.