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Solar energy in progress and future research trends

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Abstract

Extensive fossil fuel consumption in almost all human activities led to some undesirable phenomena such as atmospheric and environmental pollutions, which have not been experienced before in known human history. Consequently, global warming, greenhouse affect, climate change, ozone layer depletion and acid rain terminologies started to appear in the literature frequently. Since 1970, it has been understood scientifically by experiments and researches that these phenomena are closely related to fossil fuel uses because they emit greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) which hinder the long wave terrestrial radiation to escape into space, and consequently, the earth troposphere becomes warmer. In order to avoid further impacts of these phenomena, the two concentrative alternatives are either to improve the fossil fuel quality with reductions in their harmful emissions into the atmosphere or more significantly to replace fossil fuel usage as much as possible with environmentally friendly, clean and renewable energy sources. Among these sources, solar energy comes at the top of the list due to its abundance, and more evenly distribution in nature than any other renewable energy types such as wind, geothermal, hydro, wave and tidal energies. It must be the main and common purpose of humanity to sustain environment for the betterment of future generations with sustainable energy developments. On the other hand, the known limits of fossil fuels compel the societies of the world in the long run to work jointly for their gradual replacement by renewable energy alternatives rather than the quality improvement of fossil sources.

Solar radiation is an integral part of different renewable energy resources. It is the main and continuous input variable from practically inexhaustible sun. Solar energy is expected to play a very significant role in the future especially in developing countries, but it has also potential prospects for developed countries. The material presented in this paper is chosen to provide a comprehensive account of solar energy sources and conversion methods. For this purpose, explanatory background material has been introduced with the intention that engineers and scientists can have introductory preliminaries on the subject both from application and research points of view. Applications of solar energy in terms of low and high temperature collectors are given with future research directions. Furthermore, photovoltaic devices are discussed for future electric energy generations based on solar power site-exploitation and transmission by different means over long distances such as fiber-optic cables. Another future perspective use of solar energy is its combination with water and as a consequent electrolysis analysis generation of hydrogen gas, which is expected to be another form of clean energy sources. Combination of solar energy and water for hydrogen gas production is called solar-hydrogen energy. Necessary research potentials and application possibilities are presented with sufficient background. Possible future new methodologies are mentioned and finally recommendations and suggestions for future research and application directions are presented with relevant literature review.

Keywords: Climate; Fossil fuel; Global warming; Hydrogen; Model; Photovoltaic; Radiation; Solar thermal; Technology

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1. Introduction

Fresh water and energy are the two major commodities that furnish the fundamentals of every human activity for reasonable and good life quality. These two resources are intricately related to each other. In fact, during the early civilizations, water power has been employed as the major energy source. Solar energy is the most ancient source, and it is the root material for almost all fossil and renewable types. Special devices have been used for benefiting from the solar energy since time immemorial and such applications actually date back to before Christ. Energy is a continuous driving power for the social and technological prospective developments. Energy sources are vital and essential ingredients for all human transactions and without them human activities of all kinds will not be progressive at all. On one hand, the energy sources are limited and on the other hand, the population growth at present average rate of 2% inserts extra pressure on additional energy demands.

The oil crises of the 1970s led to a surge in research and development efforts that are dedicated to the development of solar energy alternatives. These efforts were strongly correlated with the fluctuating market price of energy, and suffered a serious setback as this price later plunged.

Nomenclature

a	linear model coefficient
b	linear model coefficient
a'	restrictive model parameter
b'	restrictive model parameter
c	light velocity
c_1	linear model coefficient
c_2	linear model coefficient
c_3	linear model coefficient
c_4	linear model coefficient
c_5	linear model coefficient
C	constant
$d_{i,j}$	distances
$D_{i,j}$	half-squared differences
E	electric field
E_0	eccentricity correction factor
f_{clear}	sunshine fraction
$f(R)$	astronomical factor
h_g	geographical elevation
h	Plank constant (6.626×10^{-34} J s) or geographical elevation
H	daily global radiation on a horizontal surface
H_f	heat flow per unit area of cross-section
H_b	daily direct (beam) radiation
$\bar{H}_{bc}$	monthly-averaged potential daily clear-sky beam irradiation on a horizontal surface
H_{cg}	cloudless global irradiation H_{cg}
H_d	daily diffuse radiation on a horizontal surface
H_m	magnetic field
H_0	maximum daily radiation
$\bar{H}_0$	extraterrestrial irradiation on a horizontal plane
$\bar{H}_{b,\text{clean}}$	monthly average of daily clear sky horizontal surface beam radiation
$\bar{H}_d$	the monthly mean daily horizontal surface diffuse radiation
I	global radiation
I_b	direct (beam) radiation
I_d	diffuse radiation
I_h	horizontal surface radiation
I_n	normal radiation
I_{sc}	solar constant (1360 W/m^2)
k	thermal conductivity
$\bar{K}$	monthly mean daily clearness index
$\bar{K}_{\text{clear}}$	monthly average clear sky clearness index
n	the number of hours of bright sunshine per month
N	total number of daylight hours in the month
N_d	day number of the year
P	radiation power
$Q(R)$	radiation flux per unit area
r	radius of the earth
r_{hs}	cross-correlation coefficient between global solar irradiation
R	distance from the sun
R_f	photosphere radius
R_M	maximum distance
S	sunshine duration
S_i	measured solar irradiation value
S_s	total solar radiation
S_E	solar irradiance estimation at a site S'_0
$\bar{S}_c$	correction for the irradiance threshold of sunshine recorders
$\bar{S}_c$	monthly-averaged day length
$\bar{S}_0$	maximum possible sunshine duration
T	temperature
T_s	surface temperature
T_f	fluid temperature
V_E	estimation variance
V_M	cumulative semivariogram value corresponding to R_M
Var( )	variance of the argument
w_i	weighting factors
x	distance along x direction
Z	the angle between the normal to the surface and the direction of the beam
δ	solar declination angle
Γ	day angle
$\gamma(d_{i,j})$	cumulative semivariogram
λ	wavelength
$\lambda_{\max}$	maximum wavelength
ν	frequency
ϕ	latitude angle
σ	Stefan's constant (5.67×10^{-8} W/m^2 K^4)
θ_z	zenith angle
ω_s	sunset hour angle

The missing ingredient in such a process was a long-term perspective that hindered the research and development policies within the wider context of fossil and solar energy tradeoffs rather than reactions to temporary price fluctuations. The same events also gave rise to a rich literature on the optimal exploitation of natural resources, desirable rate of research and development efforts to promote competitive backstop technologies [139]. There is also vast literature on energy management in the light of atmospheric pollution and global warming processes [19,36,37,59,88,89,90,91,138,139,143].

Since the energy crisis in 1973, air pollution from combustion processes has caused serious damage and danger on the forests, monuments, human health as has been documented by official studies and yearly statistics. Many environmental damages including acid rains, and their forest damaging consequences, incurred economical losses in short, and especially, long-term durations. Hence, seemingly cheap energy inflicted comparatively very high expenses on the society. Fig. 1 shows three partners in such a social problem including material beneficiary, heat beneficiary and in between the third

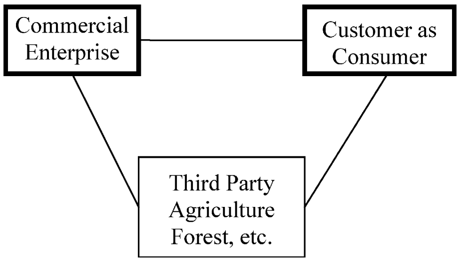


Fig. 1. Energy usage partners.

party who has nothing to do with these two major actors.

The climate change due to use of chloroflorocarbons (CFCs) is a major cause of imbalance and natural absorption of CO_2 is another example as possible social costs from the energy use which are handed over to the future generations by today's energy consumers. Again the major source of climate change is the combustion of bad quality fossil fuels.

Today, the development scale of any country is measured by few parameters among which per capita energy consumption holds the most significant rank. In fact, most industrialized countries require a reliable, efficient and readily available energy for effective transportation, industrial, domestic and military systems. This is particularly true for developing countries especially those that do not possess reliable and sufficient energy sources. Importation of energy from other countries is expected to be one of the main items in the national budgets of many countries in an increasing manner in the future. However, recently many countries have launched projects to optimize, update and search for their internal energy resources, whatever are the availabilities.

Non-renewable energy resources are limited to cover all the foreseeable future energy consumptions of the world. As a whole electricity production based on fossil or nuclear fuels induce substantial social and environmental costs, whereas it would appear that the use of renewable energy sources involves far less and lower costs. There are a number of different energy cost categories born by third parties, which ought to be taken into consideration in the comparison of different energy resources and technologies. Hohmeyer [60] has given the following seven effective categories for consideration.

1. Impact on human health:
    - 1.1 short-term impacts like injuries,
    - 1.2 long-term impacts like cancer, and
    - 1.3 intergenerational impacts due to genetic damage.
2. Environmental damage on:
    - 2.1 crops and forests like flora,
    - 2.2 cattle and fish like fauna,
    - 2.3 global climate, and
    - 2.4 materials.
3. Long-term cost of resource depletion:
    - 3.1 Structural macro-economic impacts like employment effects.
4. Subsidies for:
    - 4.1 research and development,
    - 4.2 operation costs,
    - 4.3 infrastructure, and
    - 4.4 evacuation in cases of accidents.
5. Cost of an increased probability of wars due to:
    - 5.1 securing energy resources (like gulf war), and
    - 5.2 proliferation of nuclear weapons.
6. Cost of radioactive contamination of production equipment and dwellings after major nuclear accidents.
7. Psycho-social cost of:
    - 7.1 serious illness and death, and
    - 7.2 relocation of population due to construction or accidents.

Economic growth and prosperity rely heavily on adequate energy supply at reasonably low costs [20]. Unfortunately, energy is the main source of pollution in any country on its way of development. It is well known, by now, that the SO_2 emission from the fossil fuels is the main cause of acid rain as a result of which more than half the forests in the Northern Europe have already been damaged. On the global scale, increase in the emission rates of greenhouse gases and in particular CO_2 represents colossal treat to the world's climate. Various theories and calculations in the atmospheric research circulations have already indicated that over the last half century, there appeared a continuously increasing trend in the average temperature value up to 0.5 °C. If this trend continues in the future, it is expected that in some areas of the world, there will appear extreme events such as excessive rainfall and consequent floods, droughts and also local imbalances in the natural climatic behaviors giving rise to unusual local heat and cold. Such events will also affect the world food production rates. In order to decrease degradation effects on the environment and atmosphere, technological developments are sought since 1973 oil crisis. It has been recently realized that renewable energy sources and systems can have a beneficial impact on the following essential technical, environmental, and political issues of the world. These are:

1. major environmental problems such as acid rain, stratospheric ozone depletion, greenhouse effect and smog,
2. environmental degradation,
3. depletion of the world's non-renewable conventional sources such as coal, oil, natural gas,
4. increasing energy use in the developing countries, and
5. world population increase.

The use of conventional energy resources will not be able to offset the energy demand in the next decades but steady increase will continue with undesirable environmental consequences. However, newly emerging renewable alternative energy resources are expected to take increasing role in the energy scenarios of the future energy consumptions.

Oil rich countries do not have energy shortages as long as the fossil fuel resources are economic and available within the country. The net return from industrial material produced in a country is the reflection of energy consumption in an efficient way. Otherwise, burning fossil fuels without economic industrial return may damage any country in the long run, especially, with the appearance of renewable energy resources that are expected to be more economical, and exploitable in the long run. Fossil fuel reservoir availability steadily decreases at an unprecedented rate and hence, there are future non-sustainability alarms on the energy source. It is, therefore, necessary to reduce consumption rates even starting from today by partial replacements through the sustainable alternatives, such as solar energy. Solar energy is practically unlimited, environmentally clean and friendly. Unfortunately, for the time being large-scale fossil energy production is cheaper than the available solar alternatives as stated by Chakravorty et al. [18]. Parallel to the fossil energy exploitation and consumption technological advancements, solar energy consumption has also developed but to the level that for today such developments are marginal. Abundance and cheap exploitation of fossil fuels leave room only for technological developments, in order to reduce the environmental pollution. Researches and technological developments are concentrated on clean coal and oil technology rather than improving fossil fuel conversion efficiencies. There is hardly any study towards the reduction of fossil energy cost, but studies are directed rather to energy demand mitigation. Solar energy, on the other hand, has many prospects of future developments and technological renewals that are appropriate for research and development.

Especially, the oil crises in 1973s have led to a surge in solar energy research and development efforts. The rate of these developments is dependent on the fluctuating oil prices. Perhaps, the most significant side view was the individual and rivalry developments in fossil and solar alternatives rather than their joint exploitations.

Although an adequate supply of energy is a prerequisite of any modern society for economic growth, on the other hand, energy is also the main source of environmental pollution, particularly in industrialized countries. In an indirect way, it is also known that acid rains as a result of sulfur dioxide emission from fossil fuel plants have already damaged plant and forest life, which are observable especially in the developed countries. Additionally, on the global scale, increasing emissions of air pollutions are main causes of greenhouse gases. If the increasing trend of carbon dioxide continues at the present rate, then major climatic disruptions and local imbalances in the hydrological as well as atmospheric cycles will be the consequences leading to excessive rainfall or drought, excessive heat and cold. Such changes are already experienced by those who are at their 1950s and will also affect the world's potential for food production which is the major survival supply for the human life. The continual use of conventional energy resources is expected to affect adversely the natural environmental conditions, and consequently, social energy related problems are expected to increase in the future. A new factor, however, which may alleviate the environmental and social problems of future energy policies, or even solve them, is the emerging new forms of renewable energies such as solar, wind, biomass, small hydro, ocean and geothermal energies as well as the solar hydrogen energy possibilities. Up to now, the renewable sources have been completely discriminated from the conventional alternatives due to economic reasons. However, the trend in recent years steadily favors the renewable energies in many cases over the conventional sources.

Today consumption of fossil fuel quantities is so high that even minor imbalances between supply and demand may cause considerable societal disruptions. In order to get rid of such disruptions at least for the time being, each country imports coal, and especially, oil to cover the energy imbalances. Oil embargo, by Organization of Petroleum Exporting Countries (OPEC) in 1973, gave the first serious warning and alarm to even industrialized countries that energy self-sufficiency is an essential part of the country concerned for her economic, social and even cultural survival. In fact, the technological and industrial developments in the last 150 years rendered many countries to energy dependable status.

Worldwide use of energy for several decades appeared to be increasing dramatically, but in the last decade, it has leveled off, and even dropped to a certain extent as shown in Fig. 2. In this graph all forms of energy uses are represented in terms of the amount of coal that would provide the equivalent energy. Around 1970s most of the predictions foresaw that energy demand would continue to accelerate causing expected severe energy shortages. However, just an opposite situation developed, and today, there is energy surplus on the worldwide market that has resulted from economic downturn coupled with many-fold increase in the oil prices during the last 20 years.

Fossil fuel reserves in the form of oil and natural gas are still considerable at present consumptive rates for the next 50 years. However, with increasing amounts of renewable sources and discoveries of new reservoirs, this span of time is expected to extend for almost a century from now onwards.

With the unprecedented increase in the population, the industrial products and the technologic developments, the human beings started to search for new and alternative ways of using more energy without harming or perhaps even destroying the natural environment. This is one of the greatest unsolved problem facing mankind in the near future. There is an unending debate that key atmospheric energy source, solar radiation should be harnessed more

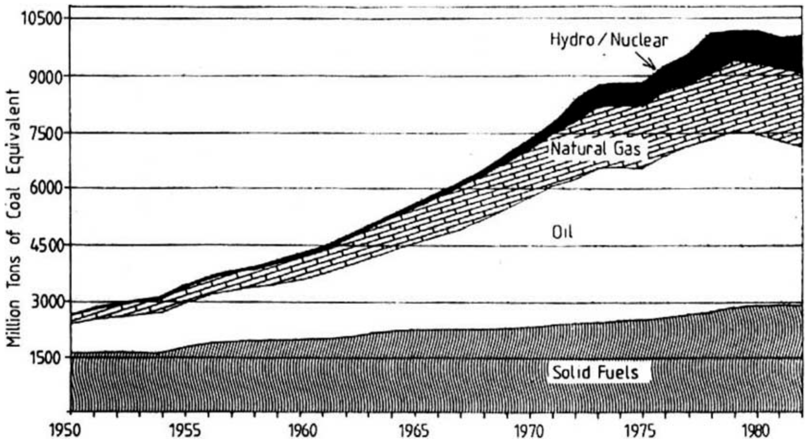


Fig. 2. Changes in annual energy consumption in the world [35].

effectively and turned directly into heat energy to meet the growing demand for cheaper power supplies.

The main purpose of this paper is to discuss the potential of solar energy for future uses as the major alternative among the renewable sources in addition to its environmentally friendly clean characteristics. An extensive literature review on recent and future directions are also presented for solar energy prediction models. The practical uses of solar energy in the forms of low and high temperature collectors and photovoltaic possibilities are also given with future potential research directions.

2. Natural energy sources

All types of energy, renewable or non-renewable, can be traced back to either atmospheric activities in the past or to the present and future activities within the atmosphere. The renewable energy sources are regarded as related to present atmospheric movements, but non-renewable sources have been deposited in the depths of the earth. The latter types are also referred to as the fossil fuels. By burning the fossil fuels the stored energy of the past atmospheric activities is added to the present energy demand. Consequently, their burning leads to the altering of the weather in the short, and climate in the long terms in an unusual manner.

So far as the nuclear power plants are concerned, they are relatively conservative. However, nuclear energy prospects are affected by several important questions, such as increasing production costs, their unsuitability for the large rural areas of the world, risks of nuclear weapon proliferations and from a market point of view, the potential prohibitive cost of commercial insurance against accidents and waste disposal [96]. Although, nuclear energy stands as an unlimited alternative, but its public alertness on serious risks and controversial waste disposal problems remain as major hindrance for worldwide use. There is also national and international political arena for its choice as an alternative among the energy sources. Nuclear energy is often mentioned as a viable alternative, but the nuclear reactor industry has seen serious setbacks due to public awareness of the risks involved, and the controversial waste disposal practices. For this reason, future progress in the nuclear energy option depends on considerations that belong mainly to the political arena and decisions, which lie outside the scope of the present paper.

After the industrial revolution in the middle of the 18th century, human beings started to require more energy for consumption. Hence, non-renewable energy sources in the form of coal, oil and wood began to deplete with time. Their limited reserves and environmental pollution potentials led to search for alternative and renewable energy sources.

All the renewable energy sources have their origin in the sun. The sun's rays that reach the outer atmosphere are subjected to absorption, reflection and transmission processes before reaching the earth surface. On the other hand, the solar radiation shows different appearances depending on the earth surface topography as explained by Neuwith [87].

The renewable energy sources are primary energy alternatives, which are parts of the everyday weather elements such as sunshine and the wind. Extraterrestrial sources of energy are the solar radiation and moon's gravitation that appears in the form of tides. The terrestrial sources are the earth's heat through conduction and earth's gravitation and rotation. These external and internal sources are constant energy supplies to the atmosphere. Apart from balancing each other, they both contain thermal and mechanical forms depending on heat and mass, respectively. The solar radiation is the main source of heat energy, and earth's motion and gravitation exert influence on the masses. The atmosphere is fed by continuous flux of radiation from the sun. In general, there are six different heat and mass exchanges within the atmosphere. These exchanges play the main role in the energy distribution throughout the whole system. The major energy source is radiation between the atmosphere and space as one of the external sources.

This source initiates the movement of heat and mass energy from the oceans (seas) into the air and over the land surfaces. The next important heat energy transfer occurs between the free surface water bodies (oceans, seas, rivers, reservoirs) and the atmosphere. Thus water moisture as a result of evaporation is carried at heights towards the inlands by wind effect having the kinetic energy. Such a rise gives the water vapor potential energy. After the condensation by cooling, the water vapor appears in the form of precipitation and falls at high surface elevations forming the surface runoff, which due to gravity flows to the seas. The energy cycle along with the hydrological cycle is presented by Şen [126]. During its travel toward the earth's surface, raindrop loses its potential energy with the increase in its kinetic energy. Water is the intermediator in such a dynamic system. Finally, the water is returned to the seas via streams and rivers, because the gravity ultimately takes over the movement of masses. The energy cycle explained herein, appears as an integral part of the water (hydrological) cycle. During this cycle, no extra energy is produced within the atmosphere. Such movements result from the fine balance that has existed for so long between the output of radiation from the sun and the overall effects of earth's gravitation.

3. Energy units

In general, energy is defined as the ability to perform work. According to the first law of thermodynamics, the total sum of all energy forms in a closed system is constant. It is also referred to as the principal of energy conservation. In order to discuss quantitatively and comparatively various energy alternatives, it is necessary to bring them into a common footing in terms of measurement units.

The basic and physical unit of energy is Joule (J) which is based on the classical definition of work as the multiplication of force by distance. Hence, one Joule is equivalent to the multiplication of one Newton (N) of force by 1 m distance, and this definition gives $J = N\,m$. The joule is named after the 19th century scientist, James Prescott Joule who demonstrated by experiments the equivalence of heat and work. Unfortunately, the Joule is far too small a unit to be convenient for describing different resources of world energy supplies. It is, therefore, necessary to define its greater versions as mega-Joule (MJ) as 10^6 joule and giga-Joule (GJ) equivalent to 10^9 joule and tera-Joule (TJ) as 10^{12} J.

Another difficulty in practice with Joule is that oil producers measure the output of a well by barrels and coal producers by tons. Such different units require unification of the energy units by a common base. For instance, the coal equivalent ton (cet) is a basic unit which has been adopted by United Nations. A commonly used value for the cet is 38.6×10^6 kJ. Likewise, it is also possible to define oil equivalent ton (oet) which is equal to 51×10^6 kJ.

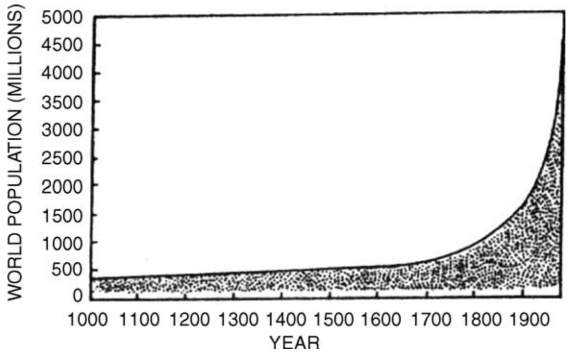


Fig. 3. World population.

In general, electrical energy is expressed, in terms of kilowatt hours (kW h). It is, therefore, necessary to know the energy conversion factors between different energy units [92].

4. Energy and population

The two major reasons for the increase in the energy consumption at all times are the steady population increase and strive for better social and economical developments. The world population is expected to double in the next 50 years. Such an increment in the population will take place mostly in the developing countries, because the developed countries are not expected to show any significant population increase.

The energy demand growth is linked to population growth and individual development achievements. The demand and production of energy on world scale are certain to increase in the foreseeable future. Of course, growth will definitely be greater in the developing countries than the industrialized ones. Fig. 3 shows the world population increase for the last 1000 years. Such a trend indicates exponential growth with increasing rates in recent years. In other words, values double with every passage of a fixed time duration. The recent rise in population is even more dramatic when one realizes that per capita consumption of energy is also raising compounding the effects.

Economic growth and the population increase are the two major forces which will continue to cause increase on energy demand during the coming decades. The future energy demand is shown in Table 1 for the next 30 years

Table 1
Future energy demand

1000 Moet	1990	2020	Increase (%)
Industrialized countries	4.1	4.6	12
Central and eastern Europe	1.7	1.8	5
Developing countries	2.9	6.9	137
World	8.7	13.3	52

[96]. In this table, Moet means million oil equivalent ton as energy unit.

The energy use of a country distinguishes its development scale compared to other countries. A poor citizen in a less-developed country must rely on human and beast powers. In contrast, developed countries consume large quantities of energy for transportation and industrial uses as well as heating and cooling of building spaces.

5. Renewable alternatives

The sun is the primary source for new and renewable energy alternatives. Unfortunately, this source is not consumed sufficiently at its full extent everywhere in the world. This is due to the fact that all the portions of earth surface do not receive usable amounts of solar energy. For instance, places far away from the equatorial belt do not have enough irradiation intensity because annual clear and sunny days number is too small. On the contrary, zones close to the equator in the north and south have high potentials. Hence, there are unbalances in the receipt of solar energy generateable irradiation amounts.

The long-term sought energy sources are expected to have the following important points for a safer and pleasant environment in the future:

1. diversity of various alternative energy resources (conventional, non-renewable and renewable) with steadily increasing trend in the renewable source consumptions but steadily decreasing trend by time in the non-renewable resources usage,
2. quantities must be abundant and sustainable for the long future,
3. acceptable cost limits and compatible prices with strong economic growth,
4. energy supply options must be politically reliable,
5. friendly energy resources for the environment and climate changes,
6. renewable sources are domestic resources that help to reduce the important energy alternatives, and finally,
7. they can support small to medium scale local industries.

The renewable energies are expected to play an active role in the future energy share because they satisfy the following prerequisites:

1. they are environmentally clean, friendly and do not produce greenhouse gases,
2. they should have sufficient resources for larger scale utilization. For instance, the solar energy resources are almost evenly distributed all over the world with maximum possible generateable amounts increasing towards the equator,
3. intermittent nature of solar and wind energy should be alleviated by improving the storage possibilities, and finally
4. cost effectiveness of the renewable sources is one of the most important issues that must be tackled in a reduction direction. However, new renewable energies are now, by and large, becoming cost competitive with conventional forms of energy.

Hydropower is an already established technological way of renewable energy generation. In the industrial and surface water rich countries, the full scale developments of hydroelectric energy generation by turbines at large scale dams are already exploited to the full limitations, and consequently, smaller hydro systems are of interest in order to gain access to the marginal resources. The world's total annual rainfall is, on the average, 108.4×10^{12} l/y of which 12×10^{12} t recharges the groundwater resources in the aquifers, 25.13×10^{12} t appears as surface runoff, 71.27×10^{12} t evaporates into atmosphere. If the above rainfall amount falls from a height of 1000 m above the earth surface, then the kinetic energy of 1.062×10^{15} kJ/y is imparted to the earth every year [92]. Some of this huge energy is stored in dams, which confine the potential energy so that one can utilize it to generate hydroelectric power.

Wind power, by now is reliable and established technology, which is able to produce electricity at cost competitive with coal and nuclear energy alternatives. Although the amount of wind energy is economically insignificant for the time being in many parts of the world, mankind took the advantage of its utilization since early years whenever he/she found the chance to provide power for various tasks. Among these early utilizations are the hauling of water from a lower to a higher elevation, grinding grains in mills by water and other mechanical power applications for many centuries. It is still possible to see at some parts of the world these type of marginal benefits from the wind speed. Perhaps, the windmills in Holland exemplify the most publicized application of wind power. All of the previous activities have been technological and the scientific investigation of wind power formulations and accordingly development of modern technology appeared after the turn of 20th century. In recent decades the significance of wind energy originates from its friendly behavior to the environment so far as the air pollution is concerned although there are to some extent noise and pollution appearance in the modern wind-farms. Due to its cleanness, wind power is sought wherever possible for conversion to the electricity with the hope that the air pollution as a result of fossil fuel burning will be reduced. In some parts of USA, up to 20% of electrical power is generated from wind energy. In fact, after the economic crises in 1973 its importance increased by forcing the economic limitations and today there are wind-farms in many western European countries [135].

Biomass is important in world energy terms since it covers almost 15% of the present world energy supply. Especially, in developing countries biomass is the major component of the national energy supply. Although biomass sources are widely available but they have low conversion efficiencies. This energy source is used especially for cooking and comfort and by burning it provides heat. The sun radiation that conveys energy is exploited by the plants through the photosynthesis, and consequently, even the remnants of plants are potential energy sources because they conserve historical sun energy until they parish either naturally after very long time spans or artificially by human beings or occasionally by forest fires. Only 0.1% of the solar incident energy is used by photosynthesis process but even this amount is 10 times greater than the present day world energy consumption. Currently, living plants or remnants from the past are reservoirs of biomass that is a major source of energy for humanity in the future. However, biomass energy returns its energy to the atmosphere partly by respiration of the living plants and by oxidation of the carbon fixed by photosynthesis is used to form fossil sediments which eventually transform to the fossil fuel types such as coal, oil and natural gas. This argument shows that the living plants are the recipient media of incident solar radiation and they give rise to various types of fossil fuels.

On the other hand, solar energy applications in buildings are of interest for heating, cooling and day lighting. Furthermore, solar electricity production from photovoltaic has already made great advancements since the beginning of 1980s. The emergence of interest in solar energy utilization took place since 1970 principally due to then rising cost of energy from conventional sources. Solar radiation is the world's most abundant and permanent energy source. The amount of solar energy received by the surface of the earth per minute is greater than the energy utilization by the entire population in one year. For the time being, solar energy, being available everywhere, is attractive for stand-alone systems particularly in the rural parts of developing nations. Occurrences of solar energy dynamically all over the world in the forms of wind, wave and hydropower through the hydrological cycle provide abilities to ponder about their utilization, if possible instantly or in the form of reservations by various conversion facilities and technologies. It is also possible that in the very long, the human beings might search for the conversion of ocean currents and temperature differences into appreciable energy quantities so that the very end product of solar radiation in the earth will be useful for sustainable development.

The comprehensive design and assessment of solar energy systems depend, largely, on adequate information on the solar energy characteristics of the region in which the systems are to be located. The best information is obtained by measurements of radiation at any site with time. However, due to the high cost of setting up and maintaining a large number of stations for conducting such measurements, various satisfactory methods have been suggested and used in practical applications for the estimation of the radiation component. A significant group of estimation models is empirical whereby meteorological data are used in conjunction with the regression techniques [108,110]. Detailed account of solar energy prediction model alternatives will be explained in Section 10.

Design of many technical apparatus such as coolers, heaters, solar energy electric generators in form of photovoltaic requires terrestrial irradiation data at the study area. Especially, among the use of clean energy resources, the solar energy utilization gained intensive interest since 1970, principally due to the then rising cost of energy from conventional sources. Scientific and technological studies in the last three decades tried to convert the continuity of solar energy into sustainability for the human comfort. Accurate estimations of global solar irradiation need meteorological, geographical and astronomical data, and especially, many estimation models are based on the easily measurable sunshine duration at a set of meteorology stations.

6. Solar energy alternatives

The nuclear fusion reactions in the sun yield a huge amount of energy, which is estimated at 3.47×10^{24} kJ per unit time. Only a small part of about 5×10^{-11} of this huge energy is irradiated onto the earth's surface. The incident solar energy is distributed into many branches as shown in Fig. 4. Solar energy is both clean, inexhaustive and harmless to living organisms on the earth because the harmful short wavelength ultra-violet rays are absorbed before reaching the troposphere by the stratospheric ozone layers and weakened by the air composition and moisture in the troposphere. Solar energy activates the atmosphere thus generates climatic phenomena, but the balance of the energy is absorbed by molecules of the materials on the earth and converted into heat at low temperatures. This is an example of the entropy increasing process of nature. It is, therefore, necessary to plan actively to utilize sun's photon and high temperature heat-energies before they decay to produce entropy. The artificial utilization of solar energy is also shown in Fig. 4. Two classifications are apparent from this figure and the photon energy has better quality and quantity, which are much higher than that of heat.

The most advanced photon utilization technology is the solar cell to which the photovoltaic effects of semiconductors are applied. They are the standard bearer of new energy technologies because they have a bright future to match these high technologies. Their fruitful development is dependent on cost reduction of power generating systems, which include solar cells.

In fact, all energy sources with the exception of atomic energy have solar energy origin. A sweeping statement yet true to the extent that even coal, oil and natural gas are forms

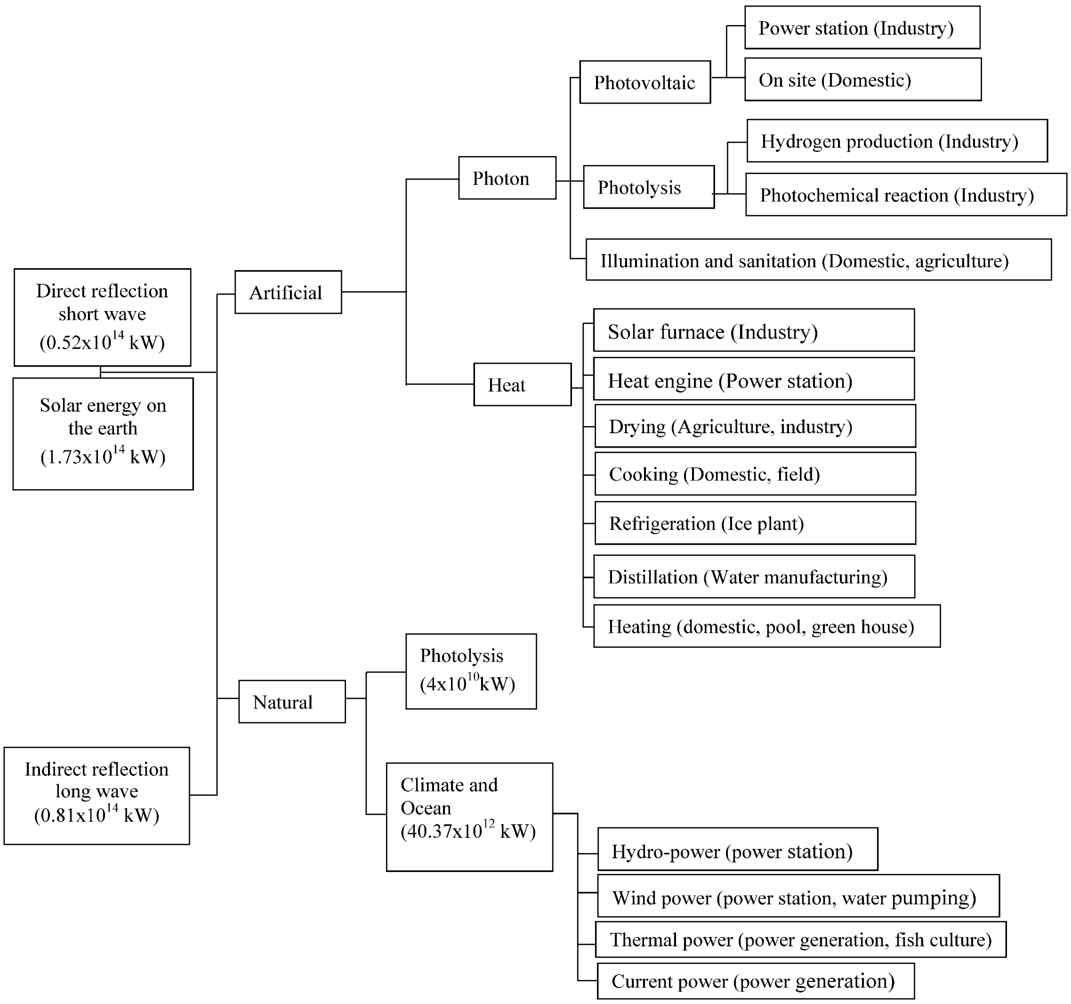


Fig. 4. Solar energy distribution and utilization [92].

of solar energy. In order to separate the various forms of solar energy the following three categories are adopted:

1. heat from the sun's rays which is possible when there is little or no cloud cover. This type of energy is dependent on heat from the sun's rays and dominated by the multiplicity of methods designed to heat water,
2. power from the sun's light, any time except at night, cloudy or clear, and finally,
3. power from air or water movement, any time day or night, cloudy or clear.

7. Sun radiation

Earth receives virtually all of its energy from space in the form of solar electromagnetic radiation. Its total heat content does not change significantly with time, indicating a close overall balance between absorbed solar radiation and the diffuse stream of low-temperature thermal radiation emitted by the planet. The radiance at the mean solar distance—the solar constant—is about 1360 W/m^2 [86]. The solar radiation varies according to the orbital variations. If S_s is the total solar radiation output from the sun in all frequencies then at a distance R from the sun-center, the flux of the radiation will be the same assuming that the radiation is equal in all directions. If the radiation flux per unit area at a distance R is represented by $Q(R)$, then the total radiation is equal to $4\pi R^2 Q(R)$. Hence, it is possible to write that

$$S_s = 4\pi R^2 Q(R) \tag{1}$$

or

$$Q(R) = S_s/4\pi R^2 \tag{2}$$

The earth is approximately 150×10^6 km away from the sun. Hence, Eq. (2) yields approximately that the total solar output is about 3.8×10^{26} W. Of course, the radiation incident on a spherical planet is not equal to the solar constant of that planet. The earth intercepts a disk of radiation from the sun with area πr^2, where r is the radius of the earth. Since, the surface area of the earth is $4\pi r^2$, the amount of solar radiation per unit area on a spherical planet becomes as

$$\pi R^2 Q(R)/4\pi r^2 = Q(R)/4 \quad (3)$$

Consequently, the average radiation on the earth's surface can be calculated as $1360/4 = 340\ \mathrm{W/m^2}$. All these calculations assume that the earth is perfectly spherical without any atmosphere and revolves on a circular orbit. Of course, these simplifications must be released in practical applications.

The driving force for the atmosphere is the absorption of solar energy at the earth's surface. Over time scales long compared to those controlling the redistribution of energy, the earth–atmosphere system is in the thermal equilibrium. The absorption of solar radiation, at visible wavelengths as short-wave (SW) radiation, must be balanced by the emission to space of infrared or long-wave (LW) radiation by the planet's surface and atmosphere. A simple balance of SW and LW radiations leads to equivalent blackbody temperature for earth at $T = 255$ K. This is some 30 K colder than the global-mean surface temperature $T_s \approx 288$ K. The difference between these two temperatures follows from the greenhouse effect, which results from the different ways the atmosphere processes SW and LW radiations. Although transparent to SW radiation (wavelength $\approx 1\ \mu$m), the same atmosphere is almost opaque to LW radiation (wavelength $\approx 10\ \mu$m) reemitted by the planet's surface. By trapping radiant energy that must eventually be rejected to space, the atmosphere's capacity elevates the surface temperature over what it would be in the absence of an atmosphere. From the time it is absorbed at the surface until it is eventually emitted to space, energy assumes a variety of forms.

The oscillating field plane of electric and magnetic waves are perpendicular to each other, i.e. when the electric field E, and magnetic field H_m are in the yz-plane, respectively, the propagation direction is along the x-axis. Solar radiation electromagnetic waves travel with the speed of light and cover the distance between the sun and the earth at about 8 min. The wavelength λ of the wave is related to the frequency ν through the light velocity, c, as

$$c = \lambda\nu \quad (4)$$

Solar energy spectrum contains wave lengths, which are too long to be seen by naked eye (the infra-red), and also wave lengths, which are too short to be visible (the ultra-violet). The spectral distribution of the solar radiation in $\mathrm{W/m^2}$ per micrometer of wavelength; that is, it gives the power per unit area between the wavelength range of λ and $\lambda + 1$, where λ is measured in micrometers. The solar spectrum is roughly equivalent to a perfect black body at a temperature of 5800 K. After the combined effects of water

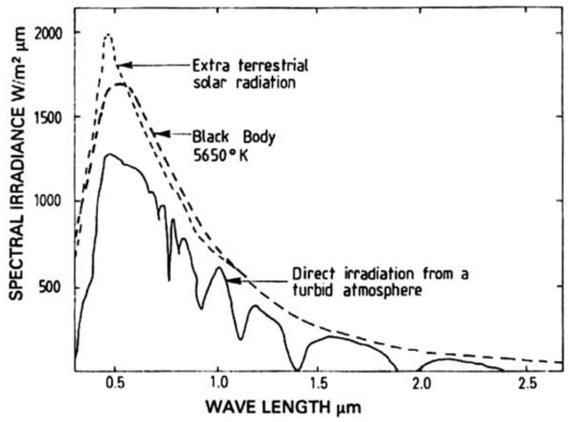


Fig. 5. Solar spectrum [35] (Dunn, page 37).

vapor, dust, and adsorption by various molecules in the air, certain frequencies are strongly absorbed and as a result the spectrum received by the earth's surface is modified as shown in Fig. 5. The area under the curve gives the total power per square meter radiated by a surface at the specified temperature. The earth receives its radiation from the sun at short wavelength around a peak of $0.5\ \mu$m, whereas it radiates to space at a much lower wavelength around a peak value of $10\ \mu$m, which is well into the infrared. The relationship between the wavelength λ_{max}, which is the power radiated is a maximum, and its relationship with the body temperature is given as Wien's law which reads as [21,40]

$$\lambda_{max} T = 3 \times 10^{-3}\ \mathrm{mK} \quad (5)$$

Electromagnetic waves show particle properties as photons, and in particular, they behave as if they were made up of energy packets, having an energy E, which is related to frequency ν as,

$$E = h\nu \quad (6)$$

where h is the universal Plank constant, $h = 6.626 \times 10^{-34}$ J s.

It is well known by now that the planets, dusts, and gases of the solar system orbit around the enormous central sun contains 99.9% of the mass of the system and provides the gravitational attraction that holds it together. The average density of the sun is slightly greater than of water as $1.4\ \mathrm{g/cm^3}$. One of the reasons for sun's low density is that it is composed predominantly of hydrogen, which is the slightest element. Its massive interior is made up of matter held in gaseous state by enormously high temperatures. Consequently, in smaller quantities gases would rapidly expand and dissipate at such extreme temperatures. The emitted energy of the sun is 3.8×10^{26} W and it arises from the thermonuclear fusion of hydrogen into helium at temperatures around 1.5×10^6 K in the core of the sun which is given by the following chemical equation

$$4\,{}^1_1\mathrm{H} \rightarrow {}_3\,{}^4\mathrm{He} + 2\beta + \mathrm{energy}(26.7\ \mathrm{MeV})$$

In the sun's core, the dominant element is helium (65% by mass) and the hydrogen content is reduced to 35% by mass as a direct result of its consumption in the fusion reactions. It is estimated that the remaining hydrogen in the sun's core is sufficient to maintain the sun at its present luminosity and size for another 4×10^9 years. There is a high-pressure gradient between the core of the sun and its perimeter, which is balanced by the gravitational attraction of the mass of the sun. The energy released by the thermonuclear reaction is transported by energetic photons, but because of the strong adsorption by the peripheral gases most of these photons do not penetrate the surface. In all regions of the electromagnetic spectrum the outer layers of the sun continuously lose energy by radiation emission into space in all directions. Consequently, a large temperature gradient exists between the core and the outer parts of the sun.

Until the rise of modern nuclear physics, there was no known source for the sun's energy, but it is now clear that the solar interior is a nuclear furnace that releases energy in much the same way as do man-made thermonuclear-explosions. It is by now obvious through spectroscopic measurements of sunlight reaching the earth from the photosphere layer of the sun that the solar mass is composed predominantly of the two lightest elements—hydrogen, which makes up about 70%, and helium about 27%, and the remaining 3% of solar matter is made up of all the other 90-odd elements [84]. The origin of solar irradiation that is received on the earth is the conversion of hydrogen into helium through solar fusion. Theoretical considerations show that at the temperatures and pressures of the solar interior, helium is steadily being produced from lighter hydrogen as four nuclei unite to form one nucleus of helium as presented in Fig. 6. During such a conversion single hydrogen nuclei (proton) made unstable by heat and pressure first combine to form double hydrogen nuclei which then unite with a third hydrogen nucleus to form helium-3, with a release of electromagnetic energy. The helium nucleus formed in this fusion possesses weights slightly less than the combined weight of the four hydrogen atoms, which gave rise to it. This small excess of matter is converted directly to electromagnetic radiation and is the unlimited source of solar energy.

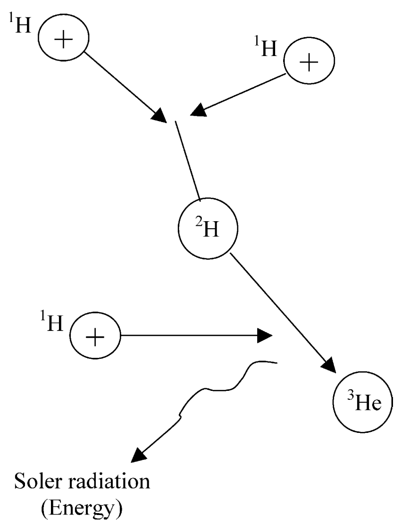


Fig. 6. Hydrogen 'burning' in the sun [84].

The source of all renewable energy is the enormous fusion reactor in the sun, which converts hydrogen into helium at the rate of 4×10^6 tonnes/s. Sun's surface temperature is approximately 6000 °C and it radiates electromagnetic energy in terms of photons, which are light particles. Almost one-third of this incident energy on the earth is reflected back, but then the rest is absorbed, and eventually retransmitted to deep space in terms of long-wave infrared radiation. Today, the earth radiates just as much energy as it receives and sits in a stable energy balance at a temperature suitable for life on the earth. In fact, solar radiation is in the form of white light and it spreads over a wider spectrum of wavelengths from the short-wave infrared to ultraviolet. The wavelength distribution is directly dependent on the temperature of the sun's surface.

As the solar radiation reaches the upper boundary of earth's atmosphere, the light starts to scatter depending on the cloud cover and the atmospheric composition [56]. A proportion of the scattered light comes to earth as diffuse radiation. The term 'sunshine' implies not the diffuse but direct solar radiation that comes straight from the sun. On a clear day, direct radiation can approach a power density of 1 kW/m^2, which is known as solar power density for the solar collector testing purpose (Section 11).

All solid, liquid and gaseous matters are no more than a vibrating cosmic dance of energy, which can be perceived by human in three-dimensional form, structure, density, color and sound. Density makes the matter as solid, liquid or gaseous in addition to the movement of its atoms, molecules also give rise to the sensations of heat and cold. The interaction of matter with the area of the electromagnetic spectrum, which is known as light gives it color, which is perceived through the eyes. However, if one takes a step inwards it can be observed that matter is composed of large and small scale molecules. Each atom until the advent of modern physics was considered to consist of a nucleus of positively charged protons and zero-charged neutrons, with a number of 'shells' of orbiting negatively charged electrons. With these particles the hydrogen and helium atoms are shown in Fig. 7. In modern physics the subatomic particles are considered as wave packets as electromagnetic force fields and as energy relationships. They have 'spin' and they rotate about the axis of their movement. They have no 'oscillation', like an ultra-high-speed-pendulum. Whilst spinning and oscillating they move around relative to each other in three dimensions. They also have an 'electrical charge' and a 'magnetic moment' and therefore, an 'electromagnetic field'.

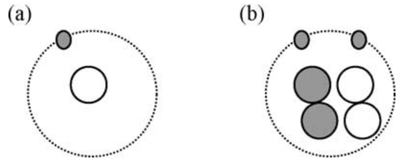


Fig. 7. (a) Hydrogen, (b) helium atoms.

Radiation consists of atomic or subatomic particles as electrons and/or electromagnetic energy waves such as heat, light, radio and television signals, infrared, X-rays, gamma rays, etc. Sun plays dominant role since geological time scale immemorial for different natural activities in the universe at large, and in the earth at particular, and especially in the formation of fossil or renewable energy sources. It will remain to do so until the end of the earth's remaining life, which is predicted as about 5 billion years. Deposited fossil fuels that are used through the combustion are expected to last circa for the next 300 years at the most in the form of coal, but then onwards the human beings are confronted to remain with the renewable energy resources only.

An account of the earth's energy sources and demand cannot be regarded as complete without a discussion of the sun, the solar system and the place of the earth within this system. In general, the sun supplies the energy absorbed in short terms by the earth's atmosphere and oceans, but in the long terms by the lithosphere where the fossil fuels are embedded. Conversion of some of the sun's energy into thermal energy derives the general atmospheric circulation [14]. A small portion of this energy in the atmosphere appears in the form of kinetic energy of the winds, which in turn derive the ocean circulation. Some of the intercepted solar energy by the plants is transformed virtually by photosynthesis into biomass. In turn, a large portion of this is ultimately converted into heat energy by chemical oxidation within the bodies of animals and by the decomposition and burning of vegetable matter. On the other hand, a very small proportion of the photosynthetic process produces organic sediments, which may eventually be transformed into fossil fuels. It is estimated that the solar radiation intercepted by the earth in 10 days is equivalent to the heat which would be released by the combustion of all known reserves of fossil fuels on earth.

The total power that is incident on the earth's surface from the sun every year is 1.73×10^{14} kW and this is equivalent to 1.5×10^{18} kW h annually, which is equivalent to 1.9×10^{14} cet. Compared to the annual world consumption of almost 10^{10} cet, this is a very huge and unappreciable amount. This is approximately about 10,000 times greater than what is consumed on the earth annually. By engineering considerations this energy is considered as uniformly spread all over the world's surface, and hence the amount that falls on 1 m^2 at noon is about 1 kW in the tropical regions. This solar power density varies with latitude, elevation and season of the year in addition to time in a particular day. Most of the developing countries lie within the tropical belt of the world where there are high solar power densities, and consequently, they want to exploit this source in the most beneficial ways. On the other hand, about 80% of the world's population lives between latitudes 35°N and 35°S. These regions receive sun radiation for almost 3000–4000 h per year. In solar power density terms, this is equivalent to around 2000 kW h/yr again cet as 0.25. Additionally, in these low latitude regions seasonal sunlight hour changes are not significant. This means that these areas receive sun radiation almost uniformly throughout the whole year.

Apart from the solar radiation the sunlight also carries energy. It is possible to split the light into three overlapping groups as:

1. photovoltaic group: produces electricity direct from the sun's light,
2. photochemical group: produces electricity, or, light and gaseous fuels by means of non-living chemical processes, and finally,
3. photobiological group: produces food (animal and human fuel) and gaseous fuels by means of living organisms or plants.

The last two groups also share the term 'photosynthesis' This means literally the building (synthesizing) by light.

8. Environmental prospects

It has been stated by Dunn [35] that several problems have arisen from the increased use of energy. For example, oil spillages result from the tanker transportations. Burning of various energy resources has caused global scale carbon dioxide rise due to especially fossil fuels. If the necessary precautions are not considered in the long run, this gas in the atmosphere could exceed the natural levels and may lead to climate change. Another problem is big scale air pollution in large cities, especially, during cold seasons. Use of fossil fuels in automobiles causes exhaust gases that give rise to another sort of air pollution as well as the surface ozone concentration increases, which are dangerous for human health and environment. Air pollution leads to acid rains that cause pollution of surface and groundwater resources, which are the major water supply reservoirs for big cities.

In order to reduce all these unwanted and damagefull effects, it is consciously desirable to shift towards the use of environmentally friendly, clean and renewable energy resources, especially, the solar energy alternatives. It seems that for the next few decades, the use of conventional energy resources such as oil, coal and natural gas will continue, perhaps at reduced rates with the replacement of renewable sources to a certain increasing rate. It is necessary to take the necessary measures and developments toward more exploitation of solar and other renewable energy alternatives by the advancement in the research and technological progress. Efforts will also be needed in conversion and moving towards a less energy demanding way of life.

Use of energy is not without penalty in that energy exploitation causes many undesirable degradation effects in the environmental surrounding and life. It is, therefore, necessary to reduce the environmental impacts down to a minimum level with the best energy usage. If the energy consumption goes at present level with present energy sources which are mainly of fossil types, then the future prospective cannot be expected as sustainable or without negative impacts. It has been understood by all the nations since about 1970s that the energy usage and types must be changed towards cleaner and environmentally friendly sources so as to reduce both environmental and atmospheric pollutions. Sustainable future development depends in a major scale on the energy sources pollution potential. The criterion of sustainable development can be defined as the development, which meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable development within a society demands a sustainable supply of energy in addition to an effective and efficient utilization of energy resources. In this regard, solar energy provides a very potential alternative for future prospective development.

The major environmental problems are classified by Dincer [28] as follows:

1. major environmental accidents,
2. water pollution,
3. maritime pollution,
4. land use and sitting impact,
5. radiation and radioactivity,
6. solid waste disposal,
7. hazardous air pollution,
8. ambiant air quality,
9. acid rain,
10. stratospheric ozone depletion, and finally,
11. global climate change leading to greenhouse effect.

The last three items are the most widely discussed issues all over the world. The main gaseous pollutants and their impacts on the environment are presented in Table 2. Herein, plus and minus signs indicate proportional and inversely proportional effects, whereas ± implies either effects depending on circumstances.

At present, large-scale fossil energy production is cheaper than the available solar energy generation alternatives [18]. However, conventional energy generation technologies based on fossil fuel have reached maturity leaving little room for significant cost reduction. Indeed, current research on these technologies is mainly concerned with pollution abatement (e.g. clean coal technologies or the use of hydrogen) rather than with improving fossil fuel conversion efficiencies, which are nearing their theoretical limits. Similarly, the important progress in energy conservation serves mainly to mitigate the rapid increase in energy demand, but does not contribute directly to reduce the production costs of fossil energy. In contrast, solar technologies still have large potential for improvement, pending appropriate research and development studies. Moreover, the true price of fossil energy must include scarcity and pollution components to allow a valid evaluation of social costs and benefits of alternative energy options.

9. Solar irradiation calculation

After the solar radiation enters the earth's atmosphere, it is partially scattered and partially absorbed. The scattered portion is also called as the diffuse radiation, which goes partially back to space and the remaining part reaches the ground. On the other hand, the radiation arriving on the ground directly in line from the sun is called direct or beam radiation. Only measurement and knowledge of direct radiation are necessary in designing many solar collector devices. Absorbed, diffused and direct radiation types are

Table 2
Main gaseous pollutants

Gaseous pollutants	Greenhouse effects	Stratospheric ozone depletion	Acid precipitation	Smog
Carbon monoxide (CO)	+	±		
Carbon dioxide (CO_2)	+	±		
Methane (CH_4)	+	±		
Nitric oxide (NO) and nitrogen dioxide (NO_2)		±	+	+
Nitrous oxide (N_2O)	+	±		
Sulfur dioxide (SO_2)	-	+		
CFCs	+	+		
Ozone (O_3)	+	+		

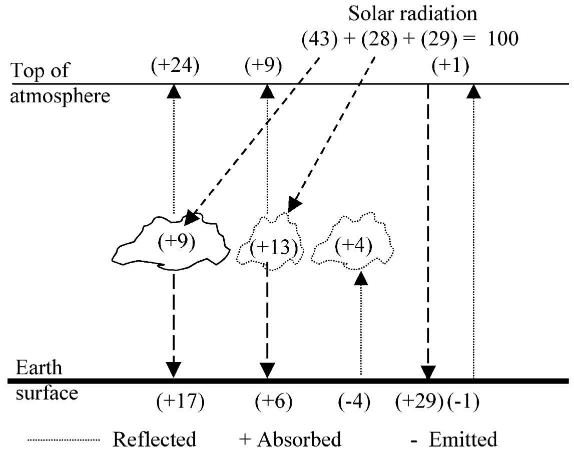


Fig. 8. Direct, diffuse and absorbed radiation.

presented in Fig. 8, where the solar radiation from the sun at the top of atmosphere is assumed as 100 units. When the solar radiation in the form of electromagnetic wave hits a particle, a part of the incident energy is scattered in all directions as diffuse radiation. All small or large particles in nature scatter radiation. If the particles are spherical and much smaller than the wavelength of incident radiation, it is referred to as the Rayleigh scattering where the scattering process is identical in forward and backward directions with a minimum scattering in between. When the particle size is of the order of incident radiation wavelength, the solution of the wave equation becomes formidable. In this case, the scattering is called Mie's scattering and more energy is scattered in a forward than in backward direction.

Global radiation is measured by pyranometer, which measures all radiation incident on it within the solid angle of 2π. A representative trace of such an instrument is presented in Fig. 9 for clear and partially cloudy days. The global radiation I_g is the quantity collected during an hour, which is given by the shaded area. Radiation data are measured

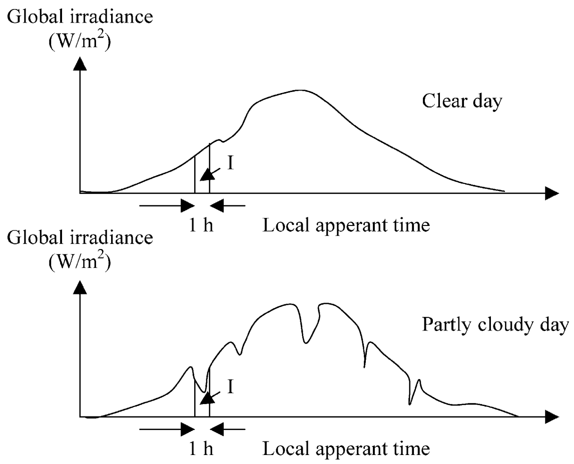


Fig. 9. Diurnal variation of the radiation flux.

usually on hourly basis. Diffusion radiation is measured by a pyranometer fitted with a device that occults the direct radiation from the sun. In meteorology and astronomy 'occult' means a device for hiding a planet or a star from our eyesight. The total amount of diffuse radiation received during a period of an hour is denoted by I_d [64].

The measurement of direct (beam) radiation, I_b is possible by a pyrheliometer, an instrument with a small conical aperture slightly wider than the solid angle subtended by the solar disk [144]. Once the direct normal irradiance, I_n on the ground is known then direct irradiance on a horizontal surface I_h can be calculated as

$$I_h = I_n \cos \theta_z \tag{7}$$

where θ_z is the zenith angle. Hourly direct radiation is obtained by integrating this quantity over 1 h period as

$$I_b = \int_0^{1\text{ h}} I_n \cos \theta_z \tag{8}$$

In indirect measurement of direct radiation two pyranometer readings are necessary, one with and the other without an occulting device. The hourly beam radiation on a horizontal surface is deduced from the difference between these readings. Thus

$$I_b = I - I_d \tag{9}$$

If the global, I, and direct radiation, I_d, amounts are measured, then the diffuse radiation can be obtained as

$$I_d = I - I_b \tag{10}$$

The daily global radiation on a horizontal surface can be calculated by integration as

$$H = \int^{\text{day}} I \, dt \tag{11}$$

Similarly, daily diffuse radiation on a horizontal surface is

$$H_d = \int^{\text{day}} I_d \, dt \tag{12}$$

Hence, daily direct radiation is the difference between these two quantities and can be written as

$$H_b = H - H_d \tag{13}$$

The monthly average daily values of the extraterrestrial irradiation on a horizontal plane $\bar{H}_0$ and the maximum possible sunshine duration $\bar{S}_0$ are two important parameters that are frequently needed in solar energy applications. Values of $\bar{H}_0$ are tabulated for latitude intervals at 5° [34,64]. Most of the solar irradiation researchers make their own calculations for these parameters. For reducing the amount of calculations, short-cut methods of using the middle day of each month or a single recommended day for each month, have often been employed [73]. The values of

H_0 for a given day can be computed by

$$H_0 = \frac{24 \times 3600}{\pi} I_{sc} \times E_0 \left(\cos \Phi \cos \delta \sin \varpi + \frac{2\pi \varpi_s}{360} \sin \Phi \sin \delta \right) \quad (14)$$

where ϕ is the latitude, δ is the declination angle and ω_s is the sunset hour angle. The following accurate expressions are considered for declination angle δ (in radiant) and the eccentricity correction factor of the earth's orbit E_0 [114]

$$\delta = 0.006918 - 0.399912 \cos \Gamma + 0.07257 \sin \Gamma - 0.006758 \cos 2\Gamma + 0.000907 \sin \Gamma - 0.002697 \cos 3\Gamma + 0.00148 \sin 3\Gamma \quad (15)$$

and

$$E_0 = 1.00011 + 0.034221 \cos \Gamma + 0.001280 \sin \Gamma + 0.000719 \cos 2\Gamma + 0.000077 \sin 2\Gamma \quad (16)$$

where day angle, Γ in radian is given by

$$\Gamma = \frac{2\pi(N_d - 1)}{365} \quad (17)$$

Herein, N_d is the day number of the year ranging from 1 on 1st January to 365 on 31st December. As stated by Jain [65], Eq. (15) estimates δ with a maximum error of $3'$ and Eq. (16) estimates E_0 with a maximum error of 0.0001. The monthly averages of H_0 for each month can be calculated for the ϕ values from 90°N to 90°S at 1° interval. The number of days in February is taken as 28. The best value of the solar constant available at present is $I_{sc} = 1360\ \mathrm{W\ m^{-2}}$ [40].

On the other hand, values of monthly average daily maximum possible sunshine duration, S_0 for a given day and latitude value can be obtained from

$$S_0 = (2/15)\cos^{-1}(-\tan \phi \tan \delta) \quad (18)$$

and the monthly averages, S_0', can be taken for all the ϕ values. The values of S_0' can be computed from the following expression

$$S_0' = (2/15)\cos^{-1}[(\cos 85° - \sin \phi \sin \delta)/\cos \phi \cos \delta] \quad (19)$$

It is also possible to consider the following expressions for the approximate calculations of δ and E_0 as [64]

$$\delta = 23.45 \sin[360(284 + N_d)/365)] \quad (20)$$

and

$$E_0 = 1 + 0.033 \cos(2\pi N_d/365) \quad (21)$$

respectively. The use of Eq. (16) instead of Eq. (21) does not make appreciable difference, but the use of Eq. (15) instead of Eq. (20) can indeed lead to substantial differences in the values of H_0 up to 10% or even more. Different solar radiation calculations have been given in tabulated form by ASHRAE [8].

Long-term average values of the instantaneous (or hourly) global and diffuse irradiation on a horizontal surface are needed in many applications of solar energy designs. The measured values of these parameters are available at only a very few places and at others no measurements exist where the usual practice is to estimate them from theoretical models which have been developed on the basis of measured values. The first attempt to analyze the hourly radiation data is due to Hoyt [61] who employed the data of widely separated localities to obtain the curves or the ratio (hourly/daily) for the observed global radiation versus the sunset hour angle for each hour from 9 a.m. to 3 p.m. Liu and Jordan [69] extended the day length of these curves.

The knowledge of solar radiation amount falling on a surface of the earth is of prime importance to engineers and scientists involved in the design of solar energy systems. In particular, many design methods for thermal and photovoltaic systems require monthly average daily radiation on a horizontal surface as an input, in order to predict the energy production of the system on a monthly basis [13,33,80,134].

9.1. Meteorological effects

In the past, there has been claims that all weather and climate changes are caused by variations in the solar irradiance countered at other times by the assertion that these variations are irrelevant as far as the lower atmosphere is concerned [76].

The existence of atmosphere gives rise to many atmospheric and meteorological events. Atmospheric composition has changed significantly since pre-industrial times, and the carbon dioxide (CO_2) concentration has risen from 280 parts per million (ppm) to around 370 ppm today. On the other hand, methane (CH_4) concentration was about 700 parts per billion (ppb) but reached to 1700 ppb today, and nitrogen (N_2O) has increased from 270 to over 310 ppb. However, halocarbon did not exist at all, but after 1950s, it became in appreciable amounts causing noticeable greenhouse effects. These concentration increments in the atmosphere since 1800s are entirely due almost to anthropogenic activities.

The amount of the solar radiation incident on the earth is partially reflected again into the earth's atmosphere and then onwards into the space. The reflected amount is referred to as the planetary albedo, which is the ratio of the reflected (scattered) solar radiation to the incident solar radiation measured above the atmosphere. The amount of solar radiation absorbed by the atmospheric system plays the dominant role in the creation of meteorological events within the lower atmosphere (troposphere). For the assessment of meteorological events the accurate determination of planetary albedo is very important. On the basis of different studies, today the average global albedo is at about 30% with maximum change of satellite measurement at $\pm 2\%$. This change is due to both seasonal and inter-annual time scales. Furthermore, the maximum and minimum albedo values appear in January and July, respectively. The annual variations are as a result of different cloud and surface distributions in the two hemispheres. For instance, comparatively more extensive snow surfaces are available in the northern European and Asian landmasses in addition to more dynamic seasonal cycle of clouds in these areas than the southern polar region.

Other causes in the albedo variation are the sun elevation, the distribution and type of clouds, and finally, the surface albedo. The absorbed solar energy has maximum values of 300 W/m^2 in low latitudes. The planetary radiation is dominated by emission from the lower troposphere and shows a decrease with latitude. Such a decrease is at a slower rate than the decrease in the absorbed solar radiation energy. At latitudes less than 30° the planetary albedo is relatively constant at 25%, and consequently, there are large amounts of solar radiation for solar energy activities and benefits in these regions of the earth. However, the solar absorption exceeds the planetary emission between 40°N and 40°S, and therefore, there is a net excess in low latitudes and a net deficit in high latitudes. Consequently, such an imbalance in the solar radiation energy implies heat transfer from low to high latitudes by the circulations within the atmosphere. Accordingly, the solar energy decreases steadily from the equator towards the polar region. It is possible to state that the natural atmospheric circulations in planetary scales are due to solar energy input into the planetary atmosphere. In order to appreciate the heat transfer by atmosphere, the difference between the absorbed and emitted planetary solar radiation amounts can be integrated from one pole to other, which give rise to radiation change as in Fig. 10. It can be noted that maximum transfer of heat occurs between 30° and 40° of latitude and is approximately equal to 4×10^{15} W. The regional change of net solar radiation budget is shown in Fig. 11, which indicates substantial seasonal variation as a result of seasonal solar distribution.

9.1.1. Clouds

For many reasons, clouds are critical ingredients of climate and many renewable energy resources availability at a location on the world [86]. At any instant about half of the earth is covered by clouds. The clouds are highly dynamic in relation to atmospheric circulation. Especially, the irradiative properties of clouds make them a key component of the earth's energy budget and hence solar energy.

It is an unfortunate characteristic of solar energy that it arrives in a quite random manner depending on the meteorological conditions. It does not arrive all times that suit our needs. Since, the time of usage does not match with the time of availability, it is necessary to store the solar energy at times of availability so as to use it at later times of need.

Cloud particles interact strongly with SW and LW radiations. The scattering efficiency of cloud particles makes them highly reflective to visible radiation.

9.2. Topographic effects

Topography is the expression of the earth's surface directional vision, height and surface features Although the surface albedo is different than the planetary albedo it makes an important contribution to the planetary albedo. The cloud distribution is the major dominant influence on the earth surface incident solar energy. Since the albedo is a dominant factor in different meteorological and atmospheric events,

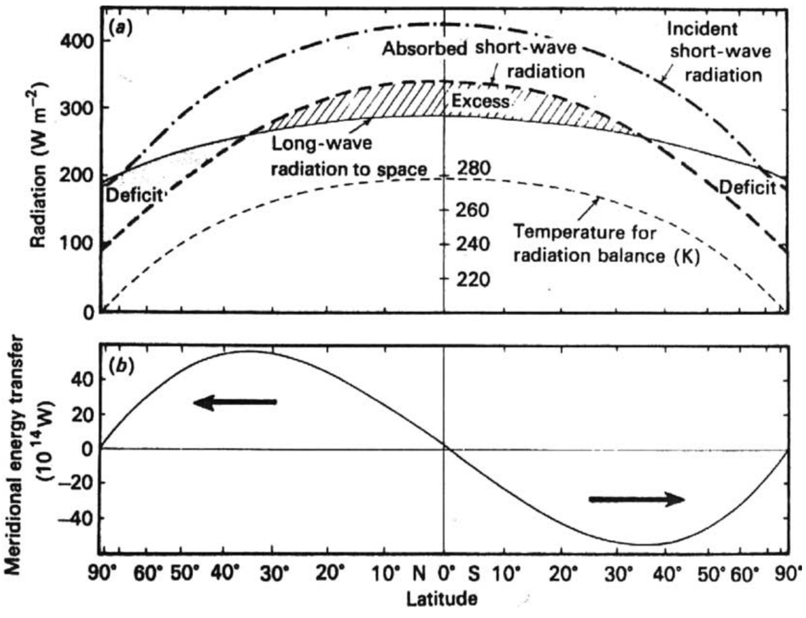


Fig. 10. Latitudinal radiation balance change of the earth.

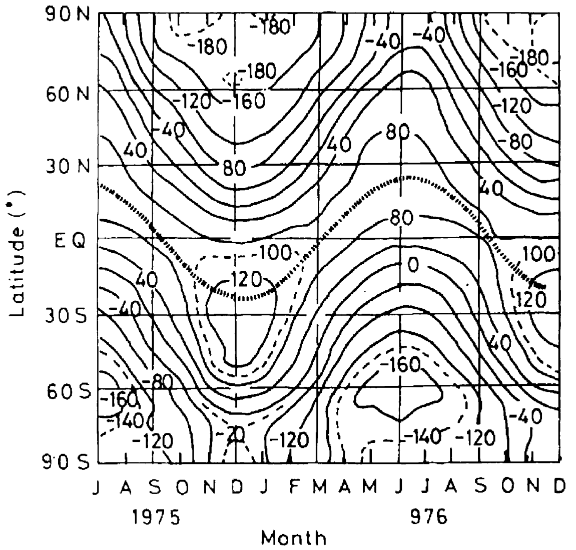


Fig. 11. Seasonal net solar radiation variations.

its influence on the availability of solar radiation has an unquestionable significance. Hence, the calculation of solar energy potential at a location is directly related to albedo events, and therefore, the characteristics of surface features become important. In general, the albedo and hence the solar radiation energy potential at any location is dependent on the following topographic and morphologic factors.

1. the type of surface,
2. the solar elevation and the geometry of the surface relative to the sun, and
3. the spectral distribution of the solar radiation and the spectral reflection.

Table 3 indicates different surface albedo values with the least value for calm sea surface as 2%, and the maximum at the fresh snow surface reaching up to 80% albedo value. In general, forests and wet surfaces have low, but snow-covered surfaces and deserts have high albedo values. On the other hand, the surface albedo is also a function of the spectral reflectivity of the surface.

Table 3
Percentages of solar radiation reflected by different surfaces (Albedo)

Surface	Albedo (%)
New snow	85
Old snow	70
Clayey desert	29–31
Green grass	8–27
Pine forest	6–19
Granite	12–18
Water (depending on angle of incidence)	2–78
High-level cloud	21
Middle-level cloud (between 3 and 6 km)	48
Low-level cloud sheets	69
Cumulus clouds	70

In all the above discussions, the earth is assumed to have a perfect spherical shape, but in reality, it is slightly distorted by rotation and the distortion amount is approximately 0.3% of the earth's mean radius with the equatorial radius being greater than the polar radius. Additionally, the earth surface is also rough with heights and lows. The mean sea surface level has been obtained by long-term observations at coastal stations around the world. With reference to the mean sea level, the surface of the continents has a mean altitude of 840 m, whilst the mean depth of the ocean is 3800 m, which implies that the average height of the earth's crust is 2440 m below sea level. The most extensive topographic feature is the continental slope or escarpment. Only 11% of the land area is above 2000 m elevation.

9.3. Astronomic effects

Sun releases energy continuously by a fusion reaction that produces 3.94×10^{23} kW of power. This is the main source astronomically available in the sun, but it has to cover about 150×10^6 km for the sun radiation to reach the earth. Besides, only a very small fraction of this energy becomes incident on the earth's surface. The amount of power received by the earth is 1.73×10^{14} kW, which yields to 340 W/m^2 if considered uniformly distributed over the earth's surface.

There are three astronomical effects in the forms of geometrical factors, which determine the seasonal variation of solar radiation incident on the earth and these are shown in Fig. 12. The earth revolves around the sun in an elliptical orbit being closest to the sun, i.e. at perihelion, about 3rd January and farthest from the sun, i.e. aphelion, on July 5. The eccentricity of the present-day orbit is $E_0 = 0.017$.

Sun radiation is subject to many absorbing, diffusing and reflecting effects within the earth's atmosphere with about 10 km average thickness, and therefore, it is necessary to

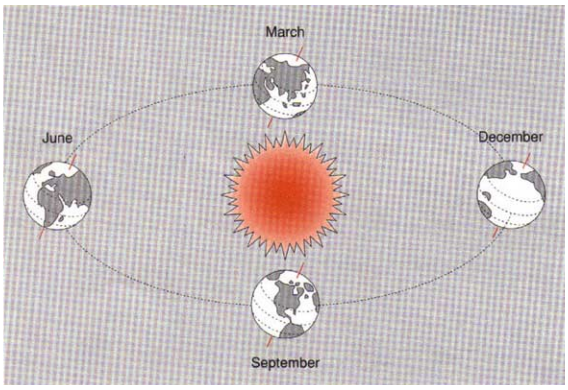


Fig. 12. Geometry of the earth–sun system.

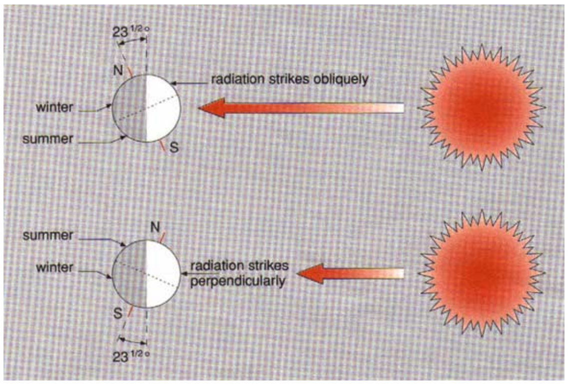


Fig. 13. Incident solar radiation on earth's surface.

know the power density, i.e. Watt per meter per minute on the earth's outer atmosphere and at right angle to the incident radiation. The density defined in this manner is referred to as the solar constant.

In order to appreciate the coming of solar irradiation on the earth's surface, it is very helpful to simplify the situation as shown in Fig. 13 where the earth is represented as a sphere. This implies that at the equator a horizontal surface at that point immediately under the sun would receive 1360 W/m^2. Along the same longitude but at different latitudes the horizontal surface receives smaller solar radiation from the equator towards the polar region. If the earth rotates around the vertical axis to the earth–sun plane, then any point on the earth surface receives the same amount of radiation throughout the year. However, earth rotates around an axis which is inclined with the earth–sun plane, and therefore, the same point receives different amounts of solar irradiation in different days and times in a day throughout the year. Hence, seasons start to play role in the incident solar radiation variation. Additionally, diurnal variations are also effective due to day and night succession. As a result of earth's rotation around an inclined axis surprisingly polar region receives more radiation in the summer than at the equator. An important feature is the absence of seasons at the tropics and the extremes of six-month summer and six-month winter at the poles [35]. The theoretical and natural occurrence aspects of the solar radiation and its energy have already been explained in the previous sections. However, the practical applications and beneficial use of the solar radiation require consideration of practical and engineering aspects. Here, the efficient and sustainable use of the solar energy comes into view. For instance, in any design of solar energy powered device, it is necessary to know how the power density will vary during the day, from season to season, and also the effect of tilting a collector surface at some angle to the horizontal. From the practical applications point of view, for most purposes solar energy applications can be divided into two components, namely, direct (beam) radiation, and scattered or diffuse radiation.

Direct radiation as the name implies is the amount of solar radiation received at any place on the earth directly from the sun without any disturbances. In practical terms, this is the radiation, which creates sharp shadows of the subjects. There is no interference of dust, gas and cloud or any other intermediate material on the direct solar radiation. However, diffuse radiation is first intercepted by the constituents of the air like water vapor, carbon dioxide, dust, aerosols, clouds, etc., and then released as a scattered radiation in many directions. In other words, direct radiation is practically adsorbed by some inter-mediator, which radiates electromagnetic waves similar to the main source, which is the sun. This is the main reason why diffuse radiation scatters in all directions and close to the earth's surface as a source does not give rise to sharp shadows. It is obvious than that the relative proportions of direct to diffuse radiation depends on the location, season of the year, elevation from the mean sea level and time of day. On a clear day, the diffuse component will be about 10–20% of the total radiation, but during an overcast day it may reach up to 100%. This point implies practically that in the solar radiation and energy calculations, weather and meteorological conditions must be taken into consideration in addition to the astronomical situation. On the other hand, throughout the year the diffuse solar radiation amount is smaller in the equatorial and tropical regions than the sub-polar and polar regions of the world. The instantaneous total radiation can vary considerably throughout the day as shown in Fig. 14.

10. Solar radiation and heat models

Long-term surface solar radiation records have been kept at only a few sites worldwide [98]. Solar radiation is conceptually simple and its attenuation through the atmosphere can be modeled with a fair degree of accuracy. The greatest uncertainty in estimating surface solar radiation is due to the effect of overlying clouds. Satellite observations of reflected solar radiation help to remove this uncertainty, and with the aid of radiation model or correlative relationships they are used to estimate the global distribution of surface radiation.

In general, modeling the solar radiation arriving at the top of atmosphere can simply be considered as the product of the solar constant S_{cs} and the astronomical factor, $f(R)$, of annual average 1.0, proportional to R^{-2}, where R is the distance of the earth from the sun. Passing through the atmosphere, the solar beam undergoes wavelength and direction dependent adsorption and scattering by atmospheric gases, aerosols, and cloud droplets. The scattered radiation reaching the earth's surface is referred to as diffuse radiation. On any clear day, the diffuse component from the Rayleigh and aerosol scattering is about 10–30% of the total incident radiation, whereas when the solar beam passes through a cloud essentially all the surface radiation is of

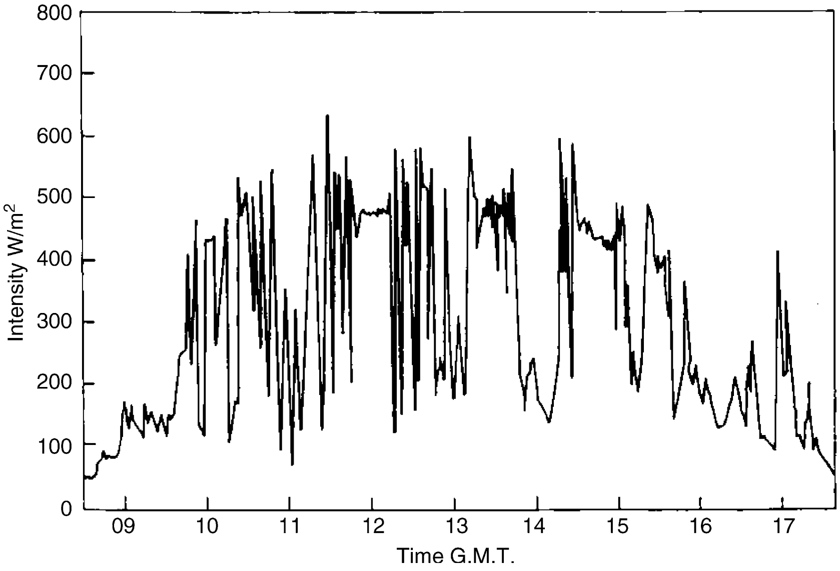


Fig. 14. Global solar radiation variation on a cloudy day.

diffuse type. This radiation consists of solar photons arriving from all directions of the sky with intensities depending on the incoming direction.

However, for the modeling of solar radiation at the earth's land surfaces, it is usually adequate to assume that the diffuse radiation is isotropic (has the same intensity in all directions from the sky). If I_g is the intensity of radiation arriving at the surface from a given direction, then the amount incident per unit surface area is $I_g \cos Z$, where Z is the angle between the normal to the surface and the direction of the beam (Fig. 15). In the simplest modeling efforts, land is assumed to be horizontal. However, in hilly and mountainous terrains the distribution of slopes has major effects on surface climate and radiation amounts. Surface radiation may change widely according to the frequency and optical thickness of clouds. Modeling these cloud properties successfully is important for the treatment of surface energy balance.

Solar irradiation on the earth surface has many implications in hydrology, climatology, agriculture, heat engineering and many other human activities. Hence, it is an essential task to estimate by some simple and practical means the natural variation of solar irradiation at the earth's surface depending on the locations in terms of longitudes and latitudes, in addition to the atmospheric effects on the extraterrestrial irradiation arrival through the troposphere at any desired location. Among the effective atmospheric agents on the irradiation are the aerosols and particulate matter concentrations as well as the humidity, temperature, cloud cover and sunshine duration. Theoretically, one can express in an implicit mathematical manner the amount of incident solar irradiation in terms of these agents. However, in practical studies more preferable is the relevance of simply applicable formulations. Estimation of solar irradiation has direct uses in the solar energy received at the earth surface, which represents a fundamental parameter in various disciplines, like climatology, agriculture, building agriculture and solar systems. Unfortunately, measurement networks do not provide solar radiation data with sufficient spatial and temporal resolutions. For this reason, it is necessary to develop models that are needed to fill spatial and temporal gaps for various regions in the world. Furthermore, model estimations are also necessary for on-site solar irradiation amounts on the basis of measured agents. Starting with the original contribution of Angström [5] up to date, there appeared many models for the estimation of the solar irradiation data from various geographical, meteorological and climatologic variables such as sunshine duration, cloud cover, humidity, temperature, pressure, altitude, etc. A critical review of recent solar irradiation methods has been provided by Gueymard et al. [52]. Apart from the linear Angström method others have been developed with various modifications by

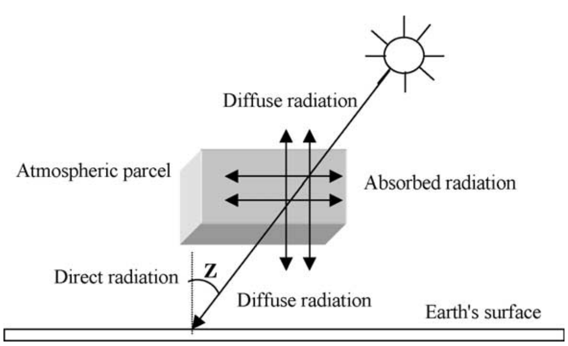


Fig. 15. Surface solar radiation.

different researches. Several major studies are performed by different researchers [30,31,47,93,104,107,113,120,130]. However, after the critical assessments by Guemard et al. [52], few new models are presented into the literature [70,94,121,126,131–133].

Monthly average daily radiation on a horizontal surface is summed from daily measurements for many sites in the world. However, there are a large number of areas particularly in developing countries, where there are no measurements or the measurements are available only for limited periods of time. It is, therefore, of practical interest whenever possible to calculate monthly average daily radiation from other meteorological variables. For both historical and practical reasons, the most significant basic meteorological variables must be used in modeling the solar irradiation. This variable, as the number of sunshine hours per month, is indeed a natural choice, since both radiation and sunshine depend on earth–sun geometry and on the condition of the atmosphere [25]. Solar radiation information is needed for numerous applications including agriculture, water resources, day lighting and architectural design, solar thermal and photovoltaic devices, and climate change studies. Since irradiation data are scarce, many different models have been suggested and used to estimate irradiation from sunshine duration records the latter is more readily available.

10.1. Linear models

The most widely used equation relating radiation to sunshine duration is the Angström–Prescott relationship, which can be expressed as [5,116]:

$$\frac{\bar{H}}{\bar{H}_0} = a + b\frac{n}{N} \tag{22}$$

where $\bar{H}$ is the monthly average daily radiation on a horizontal surface, $\bar{H}_0$ is the monthly mean daily horizontal extraterrestrial radiation, n is the number of bright sunshine hours per month, N is the total number of daylight hours in the month, and finally, a and b are model constants. These constants are determined empirically from a given data set and they assume a wide range of values depending on the location considered [5,6,52,78, 121,142]. If it is not possible to estimate these parameters from measured data for a specific location, they can be inferred from correlations established at neighboring locations [97,131].

The empirical determination of a and b is undoubtedly the greatest shortcoming of the Angström–Prescott relationship and it limits the usefulness of the formula. The Suehrcke [116,118] derivation is presented here briefly. For a given month with a number n of hours of bright sunshine, the sunshine fraction f_{clear} is defined as

$$F_{\text{clear}} = \frac{n}{N} \tag{23}$$

where N is the total number of daylight hours in the month. Suehrcke equates this approximately to

$$\frac{\bar{H}_{\text{b}}}{\bar{H}_{\text{b,clean}}} \tag{24}$$

where $\bar{H}_{\text{b}}$ is the monthly average of daily horizontal surface beam (direct) radiation and $\bar{H}_{\text{b,clean}}$ is the monthly average of daily clear sky horizontal surface beam radiation. In order to relate $\bar{H}_{\text{b}}$ to monthly mean daily horizontal surface radiation $\bar{H}$ Suehrcke uses Page [95] diffuse fraction relationship as

$$\frac{\bar{H}_{\text{d}}}{\bar{H}} = 1 - C\bar{K} \tag{25}$$

where $\bar{H}_{\text{d}}$ is the monthly mean daily horizontal surface diffuse radiation, C is a constant, and $\bar{K}$ is the monthly mean daily clearness index, defined as

$$\bar{K} = \frac{\bar{H}}{\bar{H}_0} \tag{26}$$

with $\bar{H}_0$ the monthly mean daily horizontal extraterrestrial radiation. Given that by definition

$$\bar{H} = \bar{H}_{\text{b}} + \bar{H}_{\text{d}} \tag{27}$$

Eqs. (23) and (26) lead to

$$\bar{H}_{\text{b}} = C\bar{H}_0\bar{K}^2 \tag{28}$$

The same relationship holds for $\bar{H}_{\text{b,clean}}$

$$\bar{H}_{\text{b,clear}} = C\bar{H}_0\bar{K}^2_{\text{clear}} \tag{29}$$

with $\bar{K}_{\text{clear}}$ as the monthly average clear sky clearness index defined as

$$\bar{K}_{\text{clear}} = \frac{\bar{H}_{\text{clear}}}{\bar{H}_0} \tag{30}$$

where $\bar{H}_{\text{clear}}$ is the monthly mean daily horizontal surface clear sky radiation. Combination of Eqs. (28) and (29) leads to elimination of the constant C and hence Suehrcke's relationship becomes

$$\bar{f}_{\text{clear}} = \left(\frac{\bar{K}}{\bar{K}_{\text{clear}}}\right)^2 \tag{31}$$

In this relation $\bar{K}_{\text{clear}}$ is the only semi-empirical constant, which is a measurable quantity, and it depends on the local atmospheric conditions and according to Suehrcke [116], it has values typically between 0.65 and 0.75.

On the other hand, by definition bright sunshine duration s is the number of hours per day that the sunshine intensity exceeds some predetermined threshold of brightness. Angström [5,6] proposed a linear relationship between the ratio of monthly-averaged global radiation $\bar{H}$ to cloudless global irradiation H_{cg} and monthly-averaged sunshine duration, $\bar{s}$. It is given as

$$\frac{\bar{H}}{H_{\text{cg}}} = c_1 + (1 - c_1)\frac{\bar{s}}{\bar{S}} \tag{32}$$

where $c_1 = 0.25$ and $\bar{S}$ is the monthly-averaged astronomical day duration (day length). Angström [5] determined the value of c_1 from Stockholm data, but it was not until more than 30 years later that he (Angström [7]) stated that Eq. (32) was obtained from mean monthly data and should not be used with daily data.

In order to eliminate $\bar{H}$ from sunshine records, Angström's model required measurements of global radiation on completely clear days, H_{cg}. The limitation prompted Prescott [102] to develop a model that was a fraction of the extraterrestrial radiation on a horizontal surface $\bar{H}_0$ rather than H_{cg}, because $\bar{H}_0$ can be calculated easily. Hence, the modified Angström model referred to as the Angström–Prescott formula is [52,83]

$$\frac{\bar{H}}{\bar{H}_0} = c_2 + c_3\frac{\bar{s}}{\bar{S}} \tag{33}$$

where the over-bars denote monthly average values, and $c_2 = 0.22$ and $c_3 = 0.54$, are determined empirically by Prescott [102]. Since then many empirical models have been developed that estimate global, direct and diffuse radiation amounts from the number of bright sunshine hours [3,53,54, 63,79,104,122]. All these models utilize coefficients that are site specific and/or dependent on the averaging period considered. This limits their application to stations where the values of the coefficients were actually determined or at best to localities of similar climate, and for the same average period.

Hay [54] lessened the spatial and temporal dependence coefficients by incorporating the effects of multiple-reflection but his technique requires surface and cloud albedo data. More recently, Suehrcke [116] has argued that the relationship between global radiation and sunshine duration is approximately quadratic and thus the linear models as given in Eqs. (32) and (33) have wrong functional forms. Few authors have considered the relationships between the sunshine duration, observed irradiation, and potential daily clear-sky beam radiation. Suehrcke and McCormick [117] first proposed the following relationship

$$\frac{\bar{H}_b}{\bar{H}_{bc}} = \frac{\bar{s}}{\bar{S}} \tag{34}$$

where $\bar{H}_{bc}$ is the monthly-averaged potential daily clear-sky beam irradiation on a horizontal surface. The same relationship is subsequently used to predict the performance of a solar hot water system. Hinrichsen [58] employed Eq. (34) to assign physical meaning to coefficients c_2 and c_3 in Eq. (33), while Suehrcke [116] used Eq. (34) to derive his non-linear relationship between global radiation and sunshine duration.

The physical arguments suggest that the same relationship exists for irradiation at normal incidence. Indeed, Gueymard [51] proposed that

$$\frac{\bar{H}_{bn}}{\bar{H}_{bnc}} = \frac{\bar{s}}{\bar{S}_c} \tag{35}$$

where $\bar{H}_{bn}$ is the monthly-averaged daily beam irradiation at normal incidence, $\bar{H}_{bnc}$ is the monthly-averaged potential daily clear-sky beam irradiation at normal incidence, and $\bar{S}_c$ is the monthly-averaged day-length modified to account for when the sun is above a critical solar elevation angle. The ratio $\bar{s}/\bar{S}_c$ is similar to $\bar{s}/\bar{S}$ in Eqs. (32)–(34), except $\bar{S}_c$ corrects for the irradiation threshold of sunshine recorders. The basis of Eqs. (34) and (35) implies that for a given day, the beam radiation incident at the surface (H_b or H_{bn}) is a fraction, s/S, of what would have been incident, if the sky had been clear all day [101]. In the absence of clouds, H_{bc} and H_{bnc} are functions of atmospheric scattering and absorption processes. The appeal of Eqs. (34) and (35) is twofold. On the one hand they provide a means of estimating the potential beam irradiation, and on the other they do not contain empirically derived coefficients. However, a minimum averaging period is recommended when using these equations to estimate potential beam irradiation, which has been suggested as month [51]. The time averaging is necessary since s is simply the total number of sunshine hours per day and provides no information about when the sky was cloudless during any given day. There are several other assumptions in Eqs. (34) and (35). Turbidity and precipitable water are the same during cloudless and partly cloudy days, measurements of s are accurate, and the sunshine recorder threshold irradiance is constant and known.

Different global terrestrial solar irradiation estimation models on the earth's surface are proposed which use the sunshine duration data as the major predictor at a location. Some others include additional meteorological factors as the temperature and humidity, but all the model parameter estimations are based on the least squares technique and mostly linear regression equation is employed for the relevant relationship between the terrestrial solar irradiation and the predictor factors.

Angström [5] provided the first global solar irradiation estimation model from the sunshine duration data. This model expresses the ratio of the average global terrestrial irradiation, $\bar{H}$ to extraterrestrial irradiation which is the cloudless irradiation, H_0, to the ratio of average sunshine duration, $\bar{S}$ to the cloudless sunshine duration S_0 as

$$\frac{\bar{H}}{H_0} = a + b\frac{\bar{S}}{S_0} \tag{36}$$

with $a = 0.25$ and $b = 0.75$ for Stockholm, Sweden. According to historical records in 1919, Kimball [72] suggested the same idea and proposed $a = 0.22$ with $b = 78$. Later, Prescott [102] modified this equation in such a manner that the summation $(a + b)$ is not equal to 1.0. He suggested that $a = 0.22$ and $b = 0.54$ and hence, more realistic estimations are obtained. Physically, in Eq. (36) a corresponds to relative diffuse irradiation on an overcast meteorological situation, whereas $(a + b)$ corresponds to the relative cloudless-sky condition global irradiation. An implied assumption in the structure of this linear model is the superposition principle of two extreme cloud states, which are reflected in $a + b$ summation. However, in actual situations superposition is not possible with respect to all possible combinations of atmospheric variables other than the cloud cover. This is the first indication why the summation, $a + b$, did not equal to 1.0 as suggested by Prescott [102].

In practical applications various nonlinear estimation models are also proposed in order to relieve the assumption of superposition. Another physical fact that the solar irradiation models should include nonlinear effects is that atmospheric turbidity and turbulence in the planetary boundary do not necessarily vary linearly with total cloud cover. There are numerous studies and proposals as alternatives of the linear model in the solar energy literature and with the expectations of more studies in the future, but Gueymard et al. [51] state that the studies related to solar irradiation should now be more fully scrutinized. In particular, it is understood that the mere use of Angström's equation to estimate global irradiation from local sunshine data would generally be judged as not publishable unless a new vision in the model structure is documented. All these explanations indicate that linear models are very restrictive, and therefore, many researchers have tried to propose nonlinear models for better refinements in the solar terrestrial irradiation estimations.

10.2. Non-linear models

Different versions of Angström linear models are in use extensively in the solar energy studies for estimation of the global terrestrial solar irradiation amounts from the sunshine duration data. However, atmospheric turbidity and transmissivity, planetary boundary layer turbulence, cloud thickness temporal and spatial variations cause embedding of nonlinear elements in the solar radiation phenomena. Hence, the use of simple linear models cannot be justified physically except statistically without pondering to obtain the model parameter estimations. In the literature, most often the Angström equation is either modified with the addition of extra terms with the hope to explain the nonlinear features or adjustment of the linear model parameters by relating them to geographical, meteorological and other model parameters.

Most of the sunshine based solar irradiation estimation nonlinear models are modifications of the Angström expression in Eq. (36). Some authors have suggested change of the model parameters, a and b, seasonally, for arriving at better estimations. Different authors have expressed the global irradiation in terms of the sunshine duration and the geographical location [1,11,104,119,136]. Hay [54], on the other hand, related clouds and the atmospheric conditions to the solar irradiation estimation. He proposed the use of Eq. (36) with a modified day-length instead of $\bar{S}$ and solar irradiation that first hits the ground instead of $\bar{H}$. In search for the nonlinearity effects, it is suggested to make modification of the Angström equation with two six-month seasons, namely, October–March and April–September periods leading to two different linear models as

$$\frac{\bar{H}}{H_0} = 0.18 + 0.60\frac{\bar{S}}{S_0} \tag{37}$$

and

$$\frac{\bar{H}}{H_0} = 0.24 + 0.53\frac{\bar{S}}{S_0} \tag{38}$$

respectively. It is to be noticed that although the summations of $(a + b)$ in these two models are the same, but a and b values have different distributions in two seasons. In some way use of these two linear models is dividing the overall linear variation domain between $\bar{H}/H_0$ and $\bar{S}/S_0$ into two nonparallel linear estimation models.

Gopinathan [47] has related the Angström parameters, a and b, to geographical elevation, h, and the ratio of sunshine duration as follows

$$a = 0.265 + 0.07h - 0.135\frac{\bar{S}}{S_0} \tag{39}$$

and

$$b = 0.265 - 0.07h - 0.325\frac{\bar{S}}{S_0} \tag{40}$$

Substitution of these parameters into Eq. (36) leads to a nonlinear global solar irradiation estimation model. Hence, the nonlinearity features are sought indirectly through the parameters relationship to the sunshine duration ratio.

On the other hand, Ögelman et al. [93] added a nonlinear term to the basic Angström equation and suggested, in general, a quadratic expression as

$$\frac{\bar{H}}{H_0} = a + b\frac{\bar{S}}{S_0} + c\left(\frac{\bar{S}}{S_0}\right)^2 \tag{41}$$

Through this quadratic equation, Akinoğlu and Ecevit [4] have founded that it is superior to other models in terms of global applicability. They have applied it to some Turkish data, and finally, obtained a suitable model better than the linear Angström approach as

$$\frac{\bar{H}}{H_0} = 0.195 + 0.676\frac{\bar{S}}{S_0} - 0.142\left(\frac{\bar{S}}{S_0}\right)^2 \tag{42}$$

Fig. 16 shows the results obtained from this quadratic model. Higher order polynomial type of nonlinear models are also proposed into the solar energy literature, and especially, Zabara [145] correlated the Angström parameters to third power of the sunshine duration ratio as

$$a = 0.395 - 1.247\frac{\bar{S}}{S_0} + 2.680\left(\frac{\bar{S}}{S_0}\right)^2 - 1.674\left(\frac{\bar{S}}{S_0}\right)^3 \tag{43}$$

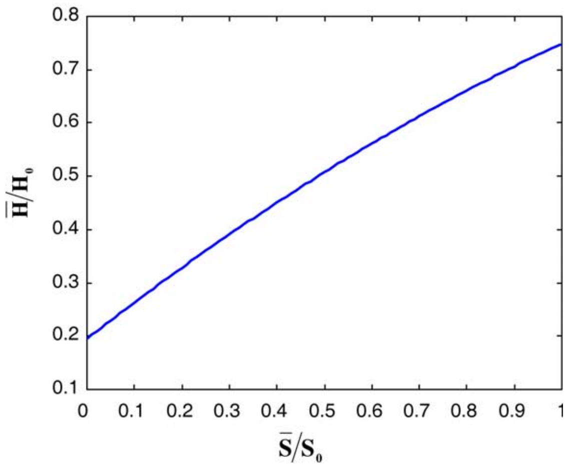


Fig. 16. Akınoğlu and Ecevit [4] quadratic model.

and

$$b = 0.395 + 1.384\frac{\bar{S}}{S_0} - 3.248\left(\frac{\bar{S}}{S_0}\right)^2 + 2.055\left(\frac{\bar{S}}{S_0}\right)^3 \quad (44)$$

After the substitution of these parameters into the basic Eq. (36), the Zabara model for Greece appears as in Fig. 17.

Akınoğlu and Ecevit [4] found a global relationship between the Angström parameters by using the published a and b values for 100 locations from all over the world and the relationship is suggested in the following quadratic form

$$a = 0.783 - 1.509b + 0.892b^2 \quad (45)$$

Given b this expression provides value of **a** and its substitution into Eq. (40) leads to a nonlinear model.

10.3. Unrestricted model

An alternative unrestricted method (UM) is proposed by Şen [128] for preserving the means and variances of the global irradiation and the sunshine duration data.

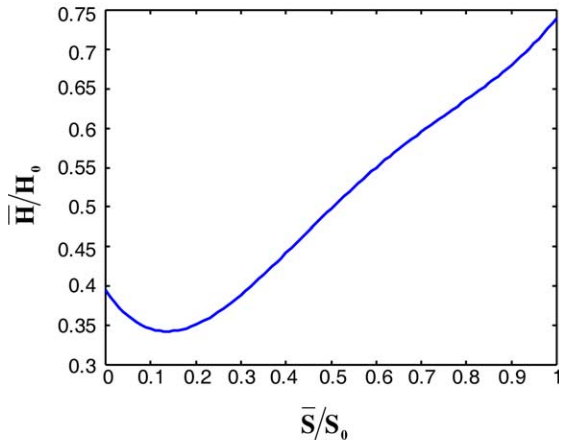


Fig. 17. Zabara [145] model.

In the restrictive regression approach (Angström equation), the cross-correlation coefficient represents only linear relationships. By not considering this coefficient in the UM, some nonlinearity features in the solar irradiation–sunshine duration relationship are taken into account. Especially, when the scatter diagram of solar irradiation versus sunshine duration does not show any distinguishable pattern such as a straight-line or a curve, then the use of UM is recommended for parameter estimations.

All the aforementioned equations are based on the classical least squares estimation, which has hidden restrictive assumptions of the linearity, normality, homoscadascity, correlation coefficient and error free data measurements [15]. Nonlinear models (Eqs. (41)–(44)) are based on nonlinear regression technique, which impose further assumptions on the parameter estimations. Hence, it is expected that all these models are affected by a set of assumptions, the validity of which are almost not checked in any practical study. It is therefore, necessary to provide a simple model, which will not require the restrictive assumptions.

In practice, the estimation of model parameters is achieved most often by the least squares method and regression technique using procedural assumptions and restrictions in the parameter estimations. Such restrictions, however, are unnecessary because procedural restrictions might lead to unreliable biases in the parameter estimations. One critical assumption for the success of the regression equation is that the variables considered over certain time intervals are distributed normally, i.e. according to Gaussian probability distribution function. As the time interval becomes smaller, the deviations from the Gaussian (normal) distribution become greater. For example, the relative frequency distribution of daily solar irradiation or sunshine duration is more skewed compared to the monthly or annual distributions. On the other hand, the application of the regression technique to Eq. (36) imposes linearity by the cross-correlation coefficient between the solar irradiation and sunshine duration data. However, the averages and variances of the solar irradiation and sunshine duration data play predominant role in many calculations and the conservation of these parameters becomes more important than the cross-correlation coefficient in any prediction model. In Gordon and Reddy [48], it is stated that a simple functional form for the stationary relative frequency distribution for daily solar irradiation requires knowledge of the mean and variance only. Unfortunately, in almost any estimate of solar irradiation by means of computer software, the parameter estimations are achieved without caring about the theoretical restrictions in the regression approach. This is a very common practice in the use of the Angström equation.

The application of the regression technique to Eq. (36) for estimating the model parameters from the available data leads to [16]

$$b = r_{hs}\sqrt{\frac{\mathrm{Var}(\overline{H/H_0})}{\mathrm{Var}(\overline{S/S_0})}} \tag{46}$$

and

$$a = \overline{\left(\frac{H}{H_0}\right)} - r_{hs}\sqrt{\frac{\mathrm{Var}(\overline{H/H_0})}{\mathrm{Var}(\overline{S/S_0})}}\overline{\left(\frac{S}{S_0}\right)} \tag{47}$$

where r_{hs} is the cross-correlation coefficient between global solar irradiation and sunshine duration data, Var( ) is the variance of the argument; and the overbars, (–) indicate arithmetic averages during a basic time interval. Most often in solar engineering, the time interval is taken as a month or a day and in rare cases as a season or a year. As a result of the classical regression technique, the variance of predictand, given the value of predictor is

$$\mathrm{Var}[\overline{(H/H_0)}/\overline{(S/S_0)} = S/S_0] = (1 - r_{rs}^2)\mathrm{Var}\overline{(H/H_0)} \tag{48}$$

This expression provides the mathematical basis for interpreting r_{rs}^2 as the proportion of variability in $\overline{(H/H_0)}$ that can be explained by knowing $\overline{(S/S_0)}$. From Eq. (48), one can obtain after arrangements

$$r_{rs}^2 = \frac{\mathrm{Var}(\overline{H/H_0}) - \mathrm{Var}[\overline{(H/H_0)}/\overline{(S/S_0)} = S/S_0]}{\mathrm{Var}(\overline{H/H_0})} \tag{49}$$

If, in this expression the second term in the numerator is equal to 0, then the regression coefficient will be equal to 1. This is tantamount to saying that by knowing $\overline{S/S_0}$, there is no variability in $(\overline{H/H_0})$. Similarly, if it is assumed that $\mathrm{Var}[\overline{(H/H_0)}/\overline{(S/S_0)} = (S/S_0)] = \mathrm{Var}(\overline{H/H_0})$, then the regression coefficient will be 0. This means that by knowing (*OVERLINEMATHMODEONLYS*/*S*0), the variability in $(\overline{H/H_0})$ does not change. In this manner, r_{rs}^2 can be interpreted as the proportion of variability in $\overline{(H/H_0)}$, that is explained by knowing $\overline{(S/S_0)}$. In all these restrictive interpretations, one should keep in mind that the cross-correlation coefficient is defined for joint Gaussian (normal) distribution of the global solar irradiation and sunshine duration data. The requirement of normality is not valid, especially if the period for taking averages is less than one year. Since, daily or monthly data are used in most practical applications, it is over-simplification to expect marginal or joint distributions to abide with Gaussian (normal) function. There are six restrictive assumptions in the regression equation parameter estimations such as used in the Angström equation that should be taken into consideration prior to any application [66]. These six restrictions in the solar irradiation estimation are normality, linearity, conditional distribution means, homoscedascity (variance constancy), autocorrelation and lack of measurement error [128].

The unrestricted parameter estimations require two simultaneous equations since there are two parameters to be determined. The average and the variance of both sides in Eq. (36) lead without any procedural restrictive assumptions to the following equations

$$\overline{\left(\frac{H}{H_0}\right)} = a' + b'\overline{\left(\frac{S}{S_0}\right)} \tag{50}$$

and

$$\mathrm{Var}(\overline{H/H_0}) = b'2\ \mathrm{Var}(\overline{S/S_0}) \tag{51}$$

where for distinction the unrestrictive model parameters are shown as a' and b', respectively. These two equations are the basis for the conservation of the arithmetic mean and variances of global solar irradiation and sunshine duration data. The basic Angström equation remains unchanged whether the restrictive or unrestrictive model is used. Eq. (50) implies that in both models the centroid, i.e. averages of the solar irradiation and sunshine duration data are equally preserved. Furthermore, another implication from this statement is that both models yield close estimations around the centroid. The deviations between the two model estimations appear at solar irradiation and sunshine duration data values away from the arithmetic averages. The simultaneous solution of Eqs. (50) and (55) yields parameter estimates as

$$b' = \sqrt{\frac{\mathrm{Var}(\overline{H/H_0})}{\mathrm{Var}(\overline{S/S_0})}} \tag{52}$$

and

$$a' = \frac{\bar{H}}{H_0} - \sqrt{\frac{\mathrm{Var}(\overline{H/H_0})}{\mathrm{Var}(\overline{S/S_0})}}\overline{\left(\frac{S}{S_0}\right)} \tag{53}$$

Physically, variations in the solar irradiation data are always smaller than the sunshine duration data, and consequently, $\mathrm{Var}(\overline{S/S_0}) \geq \mathrm{Var}(\overline{H/H_0})$ For Eq. (52) this means that always $0 \leq b' \leq 1$. Furthermore, Eq. (52) is a special case of Eq. (46) when $r_{hs} = 1$. The same is valid between Eqs. (47) and (53). In fact, from these explanations it is clear that all of the bias effects from the restrictive assumptions are represented globally in r_{hs}, which does not appear in the unrestrictive model parameter estimations.

The second term in Eq. (53) is always smaller than the first one, and hence a' is always positive. The following relationships are valid between the restrictive and unrestrictive model parameters

$$b' = \frac{b}{r_{hs}} \tag{54}$$

and

$$a' = \frac{a}{r_{hs}} + \left(1 - \frac{1}{r_{hs}}\right)\left(\frac{\bar{H}}{H_0}\right) \tag{55}$$

These theoretical relationships between the parameters of the two models imply that b and b' are the slopes of the restrictive models and the slope of the restricted (Angström) equation is larger than the unrestricted approach ($b' > b$) according to Eq. (54) since always $0 \leq r_{hs} \leq 1$ for global solar irradiation and sunshine duration data scatter

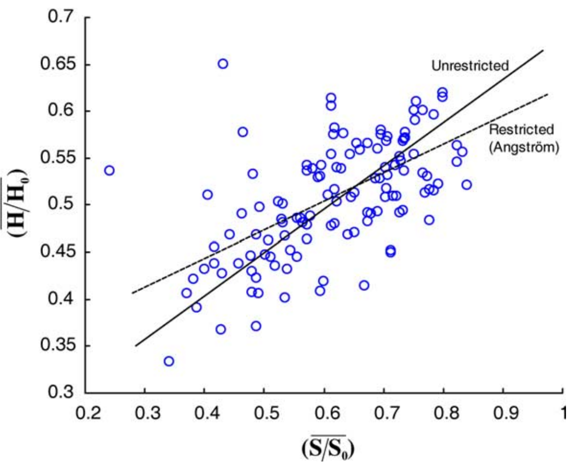


Fig. 18. Restricted and unrestricted models.

on a Cartesian coordinate system (Fig. 18). As mentioned previously two methods almost coincide practically around the centroid (averages of global solar irradiation and sunshine duration data). This further indicates that under the light of the previous statement, the unrestricted model overestimates compared to the Angström estimations for sunshine duration data greater than the average value and underestimates the solar irradiation for sunshine duration data smaller than the average. On the other hand, Eq. (55) shows that $a' < a$. Furthermore, the summation of model parameters is

$$a' + b' = \frac{a+b}{r_{hs}} + \left(1 - \frac{1}{r_{hs}}\right)\overline{\left(\frac{H}{H_0}\right)} \tag{56}$$

These last expressions indicate that the two approaches are completely equivalent to each other for $r_{hs} = 1$. The new model is essentially described by Eqs. (50), (54) and (55). Its application supposes that the restricted model is first used to obtain a', b' and r. If r is close to 1, then the classical Angström equation coefficients estimation with restrictions is almost equivalent to a' and b'. Otherwise, the new model results should be considered for application as in Eq. (50).

Through the unrestricted model, it has been observed that in the classical regression technique, requirements of normality in the frequency distribution function and of linearity and the use of the cross-correlation coefficient are imbedded unnecessarily in the parameter estimations. Assumptions in the restrictive (Angström) model cause overestimations in the solar irradiance amounts as suggested by Angström for small (smaller than the arithmetic average) sunshine duration and underestimations for large sunshine duration values. Around the average values solar irradiation and sunshine duration values are close to each other for both models, however, the unrestricted approach alleviates these biased-estimation situations. Additionally, the suggested unrestricted model includes some features of non-linearity in the solar energy data scatter diagram by ignoring consideration of cross-correlation coefficient.

10.4. Power solar radiation model

As explained above, there are many effects, which render the relationship between the solar terrestrial irradiation and the sunshine duration data into a nonlinear character This physical basis poses questions about the validity of basic Angström model in Eq. (36) for all the practical cases in the world. It is a physical fact that whatever the possibilities of nonlinear characters, these are reflected either in the sunshine duration or terrestrial solar irradiation measurements. Hence, it may not be physically plausible to suggest nonlinear models by adding integer valued power terms other than 1 as in Eqs. (41)–(44). However, the following type of power model is suggested first time in this paper

$$\frac{\bar{H}}{H_0} = a + b\left(\frac{\bar{S}}{S_0}\right)^c \tag{57}$$

where the exponent c reflects all the possible atmospheric non-linearity effects in the relationship between the global solar terrestrial irradiation and sunshine duration data. It is not necessary that c should have integer value. In fact, in natural occurrences, it should have non-integer values. In Eq. (57), a and b have the same physical interpretations as in for the classical Angström approach (Eq. (36)). It is known that a corresponds to the relative diffuse radiation on any overcast day and the summation of a and b represents the relative cloudless-sky global irradiation. This means that a and b parameters are reflections of extreme states which are full overcast, and completely cloudless cases. Hence, the power model as defined in Eq. (57) does not change the physical meanings of a and b. The extreme cases in the Angström formulation are also preserved in this a model. The power c provides the whole expected dynamism from the modeling. It is a parameter that represents the most occasional situations between the two extreme cases. It is obvious mathematically that power model reduces to Angström equation, if $c = 1$. Any nonlinear effect due to the atmospheric composition, the joint behaviors of irradiation and sunshine duration phenomena are reflected in this power value. Depending on the values of c different non-linearity trends are accounted in the power model in Fig. 19. There are two ways of determining the three model parameters in Eq. (57) from the available global solar irradiation and sunshine duration data at a given site.

The first approach benefits from the features of the classical Angström model. As already explained in Section 10.1, since the two parameters, namely, a and b, are equivalent to Angström coefficients at extreme cases, one will expect that these parameters will have the same values at the two boundary cases, i.e. for very low ($S \cong 0$) and high ($S \cong S_0$), values. It is, therefore, necessary to determine the Angström coefficient values through any available technique in the literature by using Eq. (40). The regression technique is the most commonly used tool in practice for estimating Angström coefficients. Hence, a and b values will be known. Subsequently, the substitution of these values

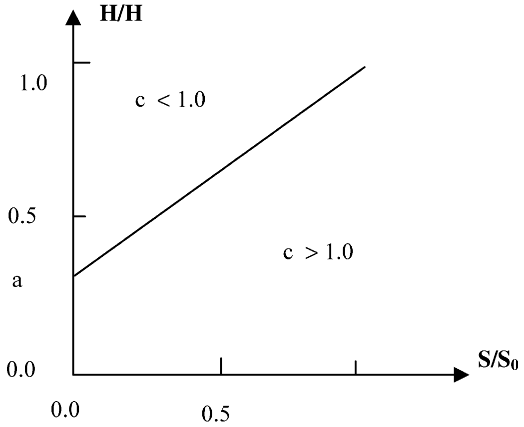


Fig. 19. Power model alternatives.

into Eq. (57) leaves one unknown, which is the power. Angström parameters are substituted into Eq. (57) and then by taking the logarithms on both sides the global estimate of c can be calculated as

$$c = \log\left(\frac{\bar{S}}{S_0}\right) \Big/ \left[\log\left(\frac{\bar{H}}{H_0} - a\right) - \log b\right] \tag{58}$$

This is the mathematical formulation way of determining the power value.

Another way of finding power model parameters is through trial-and-error method where the Angström model parameter estimations (a and b) are not known. For this purpose, a set of plausible a and b values are taken as initial parameter values and subsequently $\overline{(S/S_0)}_i$ data are plotted versus $[\overline{(H/H_0)}_i - a]/b$ values on a double logarithmic paper. Of course, the scatter of points might not yield to a straight-line on the double logarithmic paper, and accordingly, the values of a and b are adjusted to have another scatter diagram with the improvement towards a better straight-line. The repetition of this procedure with different a and b values is continued until the best straight-line is obtained. The one that appears as the best straight-line on the double logarithmic paper provides automatically the estimates of a and b in addition to c value which is equal to the straight-line slope.

10.5. Solar irradiation polygon model

Classical approaches based on Angström equation for expressing the solar global irradiation in terms of sunshine durations are abundant in the literature. As already explained above, all of them include linear and to a lesser extent nonlinear relationships between these variables. The parameters in these relationships are determined invariably by the least squares technique leading to regression lines or curves as models. None of these models provides within year variations in the parameters, and they are all very rigid in the application yielding to a single solar global irradiation estimate for a given sunshine duration value. Şen and Şahin [131] have presented a solar irradiance polygon (SIP) concept for evaluating both qualitatively and quantitatively within the year variations in the solar energy variables. On the basis of monthly, seasonal and annual SIPs parameters of the classical Angström approach are calculated by considering nonlinear features.

Both solar irradiation and sunshine duration records depend on combined effects of astronomical and meteorological events. The astronomic effects on the solar energy variables are deterministically calculable by mathematical expressions depending on the average distance of the sun, longitude, latitude, declination angle at different locations and seasons of the year (Section 9). Hence, they show definite periodicities without random behaviors. Besides, solar energy related meteorological events are measured for each day as for the sunshine duration and surface global variation. The meteorological events are unpredictable and their direct effects on the solar energy calculations introduce random behaviors. For these reasons meteorological solar irradiation and sunshine duration variables have randomness in their temporal and spatial evolutions. In fact, the meteorological variability reflects itself in the astronomical extraterrestrial irradiation $\bar{H}_0$ and sunshine duration $\bar{S}_0$, i.e. length of the day in two ways.

1. The astronomical extraterrestrial irradiation, and sunshine duration are shortened due to meteorological and atmospheric events which are measured at a solar station as meteorological solar irradiation $\bar{H}$ and sunshine duration $\bar{S}$. In other words, $\bar{S} < \bar{S}_0$ and $\bar{H} < \bar{H}_0$.
2. The shortening effect is not definite but might be in the form of different and random amounts during a day or month depending on the climate and weather conditions.

Consequently, ratios of meteorological solar energy variables to astronomical counterparts as $\bar{H}/\bar{H}_0$ and $\bar{S}/\bar{S}_0$ assume values between 0 and 1 in a random manner depending on the cloud cover percentage of the period concerned. Furthermore, it is logically obvious that these two ratios are directly proportional to each other. In practice, the measurements of $\bar{S}$ is comparatively easier and economical than $\bar{H}_0$ and therefore, many researches have proposed various statistical expressions in order to estimate the latter from the former.

So far in the literature Angström linear model parameters, a and b, are considered constant for the time period used in the application of Eq. (36). For instance, if daily values are used than a straight-line passing through the scatter of solar irradiation versus sunshine duration plots is matched which minimizes the deviation squares summation from this line, i.e. least squares technique.

Angström's linear model relates the global radiation to the sunshine duration only by ignoring the other meteorological factors such as the relative humidity, maximum temperature, air quality, latitude, elevation above mean sea level, etc. Each one of these factors contribute to the relationship between the $\bar{H}/\bar{H}_0$ and $\bar{S}/\bar{S}_0$ and their ignorance causes some errors in the model prediction and even in the linear model adaptation. For instance, the model in Eq. (36) assumes that if all the other meteorological factors are constant, then the global horizontal radiation is proportional to the sunshine duration only. The effects of other meteorological variables appear as deviations from the straight-line fit on a scatter diagram. In order to cover these error terms to a certain extent, it is necessary to assume that the model coefficients are not constant but random variables that change with time [121]. On the other hand, many researchers have considered additional meteorological factors to Eq. (36) for the purpose of increasing the accuracy in the coefficients estimate [31,47,104,107,113,120]. Although each one of these studies refined the coefficient estimates, but they all depend on the average parameter values obtained by the least squares method, and therefore, there are still remaining errors although smaller than the Angström's model. On the other hand, Ögelman et al. [94] have adopted the incorporation of the standard deviation of the sunshine duration for a better estimation of the model parameters, namely, a and b. Soler [113] has shown that monthly variations of $(a+b)$ are meteorologically sound and similar for different locations. However, he has not provided the monthly variations of a and b separately which can be obtained by SIP model.

The view taken herein, is that the linear regression technique which yields the average coefficient values is not sufficient to represent the whole variability in the meteorological factors, and still better interpretations within year variations should be considered from the scatter diagram. In order to achieve such a goal, the scatter of monthly average of $\bar{H}/\bar{H}_0$ versus $\bar{S}/\bar{S}_0$ ratios is considered with successive connections of months which appear in the form of irregular polygon. Hence, simple SIP concept is proposed for identifying numerically the linear variation parameters between successive months and to make useful interpretations from the appearances of SIPs. Since, the SIPs are closed polygons, non-linearity in within-year changes is also accounted in the solar irradiation data processing.

In search for relationship between past solar irradiance and sunshine duration data, classically a Cartesian coordinate system is used for the scatter of points, and then according to the appearance of these points, linear or nonlinear expressions are suggested, and subsequently, by the least squares technique the model parameters are estimated.

By considering time sequence, the points on the scatter diagram are connected successively. If this is done, say, on monthly basis, one cannot appreciate the pattern as shown in Fig. 20. No doubt, there should be a certain pattern due to at least the astronomic effects such as month to month periodic effects. A close inspection indicates that there emerges a polygon with 12 sides and vertices in a monthly sequential order which is referred to as the SIP. Features such as width,

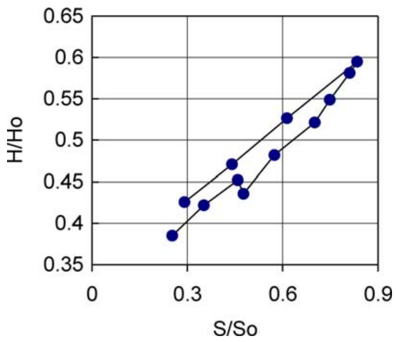


Fig. 20. Monthly solar irradiation polygon.

peripheral length, side lengths, aerial extent change depending on the geomorphologic characteristic of the station site, its altitude and longitude but more significant changes depending on the weather conditions. Hence, apart from the scatter of points SIPs provide the time variations. Since, it is known physically that surface global solar irradiation is positively related to the sunshine data, all the SIPs exhibit that high (low) values of extraterrestrial solar irradiation follow high (low) values of the sunshine data. In general, these diagrams provide the following benefits over the classical models.

1. they are closed polygons which indicate that the global solar irradiation and sunshine duration processes evolve periodically within a year. However, on the top of such a periodicity, there are also the effects of the local meteorological conditions. The reason of having different SIPs at different sites is due to differences in the weather and climate conditions, in addition to longitude, latitude and altitude values;
2. each side of the polygon shows transition, i.e. variation of the solar global irradiation amount with the sunshine duration between two successive months;
3. similar to the regression straight-line concept where the slope is related to parameter b, it is possible to calculate the slope between the two successive months, say i and $i-1$ as

$$b_i = \frac{\left(\frac{\bar{S}}{\bar{S}_0}\right)_i - \left(\frac{\bar{S}}{\bar{S}_0}\right)_{i-1}}{\left(\frac{\bar{H}}{\bar{H}_0}\right)_i - \left(\frac{\bar{H}}{\bar{H}_0}\right)_{i-1}}, \qquad i = 2, 3, \ldots, 12 \tag{59}$$

Herein, this coefficient is referred to as the monthly global solar irradiation change (MGSIC) with the sunshine duration. Şahin and Şen [121] have employed this equation in their study for the statistical analysis of the Angström parameter assessments. In fact, it is equivalent to the derivation of the global solar irradiance with respect to the sunshine duration. The smaller the time interval the closer this ratio to the mentioned derivation. It is to be noticed that such an interpretation cannot be attached to Angström parameter b, the estimation of which is based on the classical regression equation;

4. another detailed information that can be deduced from SIPs is the direction in the $\bar{H}/\bar{H}_0$ versus $\bar{S}/\bar{S}_0$ variation. Since, as stated above, these polygons are close, it is, therefore, necessary that there are two possible revolution directions either clockwise or anti-clockwise. Hence, in some monthly durations the MGSIC values become negative, in the sense that the global solar irradiation and the sunshine duration start to decrease with time. This is contrary to what can be deduced from the classical regression Angström coefficient b which does not provide any information about the direction of the change;
5. the lengths of polygon sides give way to weather astronomical change interpretations from one month to another. For instance, short lengths show that the changes are not significant. This is especially true if the weather conditions have remained almost the same during the transition between two successive months. For instance, one type of clear, hazy, overcast, partly cloudy and cloudy sky conditions during such a transition cause these lengths to be short;
6. comparison of two successive sides also provides information about the change of solar irradiation rate from one month to other. If the angle between the two sides is negligibly small, it is then possible to infer that the weather conditions have remained rather uniform;
7. the more the contribution of diffuse solar irradiation on the global irradiation the wider will be the SIP;
8. depending to the closeness of each side to vertical or horizontal directions, there are different interpretations. For instance, in the case of nearly horizontal side, there is no change in the global solar irradiance which means that the effect of weather has been such that it remained almost stable;
9. each polygon has rising and falling limbs, hence, showing two complementary periodic cycles. However, the number of months in each limb might not be equal to each other, depending on the meteorological effects and the station location;
10. the SIPs provide two values for a given constant $\bar{H}/\bar{H}_0$ (or $\bar{S}/\bar{S}_0$) each of which lies on a different limb as referred to in the previous step. Hence, the difference between these two values yields the domain of change for the given constant value;
11. For comparison purposes one can plot two or more SIPs according to latitudes, longitudes or altitudes.

10.6. Triple solar irradiation estimation model

In the triple solar irradiation estimation (TSIE) procedure the vertical Cartesian axis is allocated for sunshine duration ratio and the horizontal axis is for the relative humidity. The contour lines are then drawn for the solar irradiation ratios as dependent variable. Both solar irradiation and sunshine duration ratios vary between 0 and 1, because they are expressed as ratios to astronomical solar irradiation amounts during cloudless and without atmospheric chemical components, i.e. with clear and ideal atmosphere situations. It is known that astronomical solar irradiation and sunshine duration values are the maximum ideal quantities ever possible, but the natural counterparts are smaller than these values. In a way, all the TSIE graphs are dimensionless and rather standard with solar irradiation variable values confined to 0–1 interval. The contour lines of solar irradiation might be drawn at each 0.2 intervals. A representative TSIE graph is presented in Fig. 21. The following general interpretations can be drawn from such a graph.

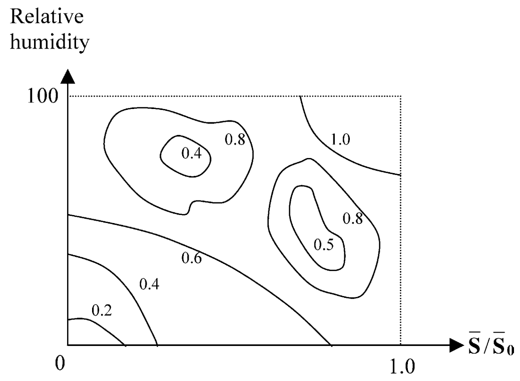


Fig. 21. Triple solar radiation estimation.

1. variation of solar irradiation with joint variation of sunshine duration and humidity,
2. solar irradiation variation with sunshine duration for any given level of relative humidity,
3. solar irradiation variation with relative humidity for any given level of sunshine duration value,
4. solar irradiation maximal occurrences at relative humidity and sunshine duration values,
5. variation of solar irradiation for any combination of sunshine and relative humidity combination,
6. nearly clear weather condition depiction based on sunshine duration and relative humidity values,
7. nearly overcast weather condition depiction based on sunshine duration and relative humidity values,
8. average and standard deviation values of solar irradiation for given ranges of relative humidity and sunshine duration, and hence, it is possible to obtain the arithmetical average and standard deviation variations of solar irradiation by sunshine duration and relative humidity values. This is very helpful in deciding the error limitations concerning upper and lower boundaries in any solar irradiation estimation, and
9. by making use of the previous step one can obtain estimation of solar irradiation for a given pair of sunshine duration and relative humidity value.

The TSIE graphs may be prepared for different time periods such as hourly, daily, weekly and monthly. Comparison of two or more TSIE graphs at different locations help to identify climatic features. On the other hand, it is possible to extend the concept of TSIE graphs by considering other meteorological variables instead of relative humidity such as temperature or pressure. Hence, it is possible to assess whole the available meteorological variable effects and to derive necessary interpretations for the solar irradiation characteristics at a site.

The TSIE graphs are distinct from the restrictive set of assumptions and readily available for linguistic interpretations prior to any quantitative estimation procedure. These graphs help to make preliminary fuzzy logic rule bases.

10.7. Fuzzy-genetic solar irradiation models

Terrestrial solar irradiation estimations are obtained mostly from the sunshine duration measurements through almost linear models such as the classical Angström formulation (Eq. (36)). The parameters of such models are estimated through the least squares or other technique in practical studies as explained above. In this section, a more efficient model based on the fuzzy system concept is proposed for the architecture of solar irradiation estimation from the sunshine duration measurements. Especially, partial fuzzy modeling accounts for the possible local nonlinear features in the form of piecewise linearizations. The parameters estimation of such a fuzzy model is achieved through the application of genetic algorithm technique. The fuzzy part of the model provides treatment of vague information about the sunshine duration data, whereas the genetic part furnishes an objective and optimum estimation procedure. It must be stated at this stage that the use of modern techniques such as fuzzy logic, artificial neural networks and genetic algorithms are very new in the solar radiation estimation studies [46,49,50,106,111,127,128].

Herein, the only effective agent on the terrestrial solar irradiation is assumed as the sunshine duration similar to the basic Angström approach in Eq. (36), but rather than a global regression line fitting, a piecewise linear model is proposed on the basis of fuzzification of the sunshine duration variable. The model parameters are estimated by using the genetic algorithm methodology.

The pioneering work by Zadeh [138–148] on the concept of fuzzy sets, logic and systems led many researches in different disciplines to consider vague variables in their modeling with imprecise measurements. Consequently, fuzzy concept of any variable provides a basis for the linguistic categorization of the variable in an uncertain manner. The uncertainty type is not quantitative but rather qualitative, and vague in terms of linguistic atomic words such as small, medium, big, hot, deep, high, etc. A detailed account of the fuzzy sets and logic is given by Ross [105] and Şen [129] for the solar irradiation estimation. Herein, fuzzy logical propositions are used in the forms of *IF–THEN* statements. Among a multitude of propositions, two of them are given below for the sake of argument.

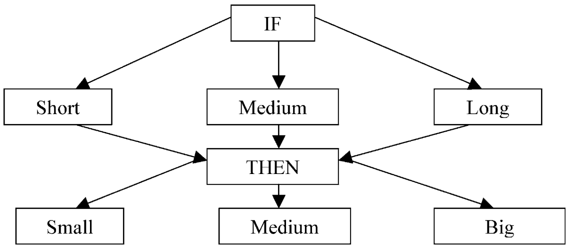


Fig. 22. Crisp boundary linguistic words and relationships.

> *IF* sunshine duration is long *THEN* the solar irradiation amount is high, or
> *IF* sunshine duration is short *THEN* the solar irradiation amount is small.

In these two solar energy propositions sunshine duration and solar irradiation are described in terms of linguistic variables such as long, high, short and small. Indeed, these two propositions are satisfied logically by simple Angström formulations. These linguistic variables explain only certain sub-parts of the whole variability domain. It can be understood from this argument that a set of relationship is sought between two variables as in Fig. 22, which shows the architecture of two-variable fuzzy proposition collection. For our purpose, the first three boxes on the same line represent sunshine duration linguistic words with the second line three words for the solar irradiation. Hence, it is possible to infer $3 \times 3 = 9$ different *IF–THEN* propositions from this figure. The question that still remains is whether the boundaries between the linguistic words in each line are distinct from each other or there may be some overlaps. Logically, it is not possible to draw crisp boundaries between subsequent words. For this purpose, Fig. 22 can be rendered into a more realistically valid architectural form as shown in Fig. 23 where there are interferences (shaded areas) between the sunshine duration (solar irradiation) linguistic words on the same line. The overlapping areas between the atomic words indicate fuzzy regions. It is also logical to think that as the linguistic word domain gets away

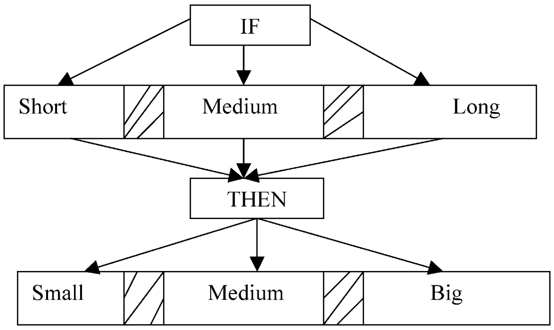


Fig. 23. Fuzzy boundary linguistic words and relationships.

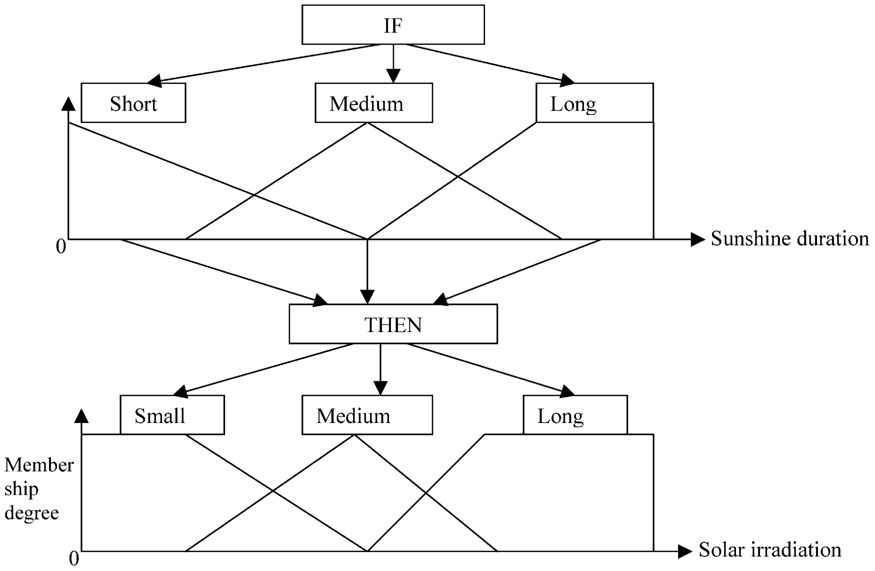
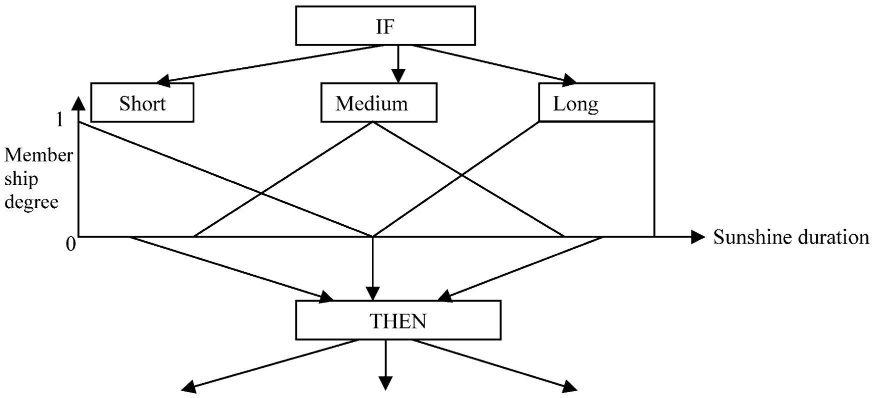


Fig. 24. Fuzzy sets and relationships.

from the interference locations, they represent more of the linguistic word meanings. For instance, medium sunshine duration linguistic word has two interference regions, and therefore, one can assume comfortably that the middle locations in the medium word domain are more genuine mediums. This last statement reflects a triangular type of medium belongingness to the medium region. On the contrary, the words that are located on both sides of the line, such as short and long or small and big, have only one interference region. This means that the belongingness into these words will increase as one moves away from the interference region. Likewise, this gives again the impression of a triangular belongingness, but with its greatest belonging at the far edges from the interference regions. Such belongingness is attached with certain numbers that vary between 0 and 1 [140]. In such a terminology, zero represents non-belongingness to the word concerned, whereas one corresponds to full belongingness. These belongingness numbers, between 0 and 1, are referred to as the membership degree in the fuzzy sets theory. Hence, it becomes evident that the new architecture of the logical prepositions will appear as in Fig. 24. Solutions with the architectural form in Fig. 24 are already presented by Şen [127,129] for solar irradiation estimation. In such an approach, there is no mathematical equation involved. However, in engineering applications, most often equations, although simple and linear, are sought for rapid calculations. For this purpose, the architecture in Fig. 24 can be changed into the one in Fig. 25 with crisps mathematical forms after the *THEN* part of the logical propositions. In the fuzzy logic terminology, the premises of the productions are vague in terms of fuzzy subsets, whereas the consequent



$$\frac{H}{H_0} = a_1 + b_1 \frac{S}{S_0} \qquad \frac{H}{H_0} = a_2 + b_2 \frac{S}{S_0} \qquad \frac{H}{H_0} = a_3 + b_3 \frac{S}{S_0}$$

Fig. 25. Mathematical relationships of the consequent part.

parts are adopted in the form of the simplest linear partial mathematical equations.

10.8. Spatial solar radiation estimation

In the previous sections, the modeling of solar radiation is discussed on a given site. However, in practical solar energy assessment studies, it is also necessary to have spatial (multiple sites) solar energy estimation procedures. The main purpose of this section is to develop a regional procedure for estimating the solar irradiation value at any point from sites where measurements of solar global irradiation already exist. The spatial weights are deduced through the regionalized variables theory [67,81], semivariogram (SV) and the cumulative SV (CSV) approach [124]. The SV and CSV help to find the change of spatial variability with distance from a set of given solar irradiation data. It is then employed in the estimation of solar irradiation value at any desired site through a weighted average procedure, which takes into account a certain number of adjacent sites with the least error. The validity of the methodology is first checked with the cross-validation technique and then applied for the spatial irradiation estimations.

Spatial variability is the main feature of regionalized variables, which are very common in the physical sciences [22]. In practice, the spatial variation rates of the phenomenon concerned are of great significance in fields such as solar engineering, agriculture, remote sensing and other earth and planetary sciences. A set of measurement stations during a fixed time interval (hour, day, month, etc.) provides records of the regionalized variable at irregular sites, and there are few methodologies to deal with this type of geographically scattered data. There are various difficulties in making spatial estimations due to not only the regionalized random behavior of the solar irradiation, but also from the irregular site configuration. Hence, the basic questions are

1. how to transfer the influence of each neighboring measurement station to the estimation point, and
2. how to combine them in order to make reliable regional estimations of solar irradiation.

Based on empirical work by Krige [75] to estimate ore grades in gold mines, the regionalized variable theory was developed by Matheron [82]. It is also known as geostatistics, which has been used to quantify the spatial variability through the Kriging technique. The basic idea in geostatistics is that for many natural phenomena, such as solar irradiation, close samples have higher probability of being similar in magnitude than samples further apart. This implies spatial correlation structure in the phenomena. Especially, in earth sciences, considerable effort has been directed towards the application of the statistical techniques leading to convenient regional interpolation and extrapolation methodologies [26,85].

The spatial solar irradiation estimation problem has been addressed by Dooley and Hay [32], and Hay [57]. They tried to evaluate the errors using solar irradiance data at a number of sites in Canada. The basis of their approach was the optimal interpolation techniques as suggested by Gandin [44] in the meteorology literature. The main interest was to estimate the long-term average of all the sites considered for each month irrespective of any particular year. Systematic interpolation evaluations have been carried out in solar irradiation networks by different authors [55,149,150].

It is possible to prepare solar irradiation maps of a region based on a set of measurements at different sites by using basic geostatistical techniques such as SVs and then the Kriging methodology [67]. The success of Kriging maps is dependent on the suitability of the theoretical SV with the data at hand. In fact, SVs are the fundamental ingredients in Kriging procedures, because they represent the spatial correlation structure of any phenomenon. There are however, practical difficulties in the identification of SVs from available data [124,125]. Empirical CSVs are adopted as spatial correlation structure representatives of irradiation data. They are transformed into standard weighting functions (SWFs), which show the change of weighting factor with dimensionless distance values. As the dimensionless distance value increases the effect of weighting decreases.

10.8.1. Linear interpolation

The essence of the spatial interpolation is to transfer available information in the form of data from a number of adjacent irregular sites to the estimation site through a function that represents the spatial weights according to the distances between the sites. Generally, changes in the measurement site number, or especially, the location of the estimation site will cause changes in the weightings due to change in the distances. In the linear interpolation technique, as presented by Gandin [43], the value at an uninstrumented site is assumed to be the linear combination of the records at the adjacent sites which can be expressed as

$$S_{\mathrm{E}} = \sum_{i=1}^{n} w_i S_i \tag{60}$$

where S_{E} is the solar irradiance estimation, n is the number of the measurement sites, and w_i is the weighting factor which shows the contribution from the ith site with its measured solar irradiation value, S_i. Unbiased estimation requires that the summation of all weights is equal to 1 as a restriction. Of course, such an estimation will give rise to an error, E, defined as the difference between the solar irradiance estimation, S_E, and the measured values S_i $(i = 1, 2, \ldots, n)$. The error estimation variance V_{E}, can be written as,

$$V_{\mathrm{E}} = \frac{1}{n} \sum_{i=1}^{n} (S_{\mathrm{E}} - S_{\mathrm{i}})^2 \tag{61}$$

The same estimation variance may be used for cross-validation, whereby any measured solar irradiation at site i is assumed as not existing. The analytical derivation of weightings for the data is found in Ref. [22]. The Kriging approach calculates the best linear unbiased estimate for the interpolation at hand. It is based on the linear estimator as in Eq. (60) and minimization of the estimation variance in Eq. (61). The Kriging technique has been applied for the first time in the earth sciences for ore body recovery in mining, but it has had also several applications in the atmospheric and hydrologic sciences [29,41,42,100,103,115,123,141].

In the following, the CSV as suggested by Şen [122] will be applied for the representation of spatial dependence structure of solar irradiation data, and then for finding a SWF.

10.8.2. Classical weighting functions

In any optimum estimation technique, the main idea is that the estimation at any point is considered as a weighted average of the measured values at irregular sites. Hence, if there are $i = 1, 2, \ldots, n$ measurement sites with records S_i then the solar irradiation estimation, S_E, can be calculated as

$$S_E = \frac{\sum_{i=1}^{n} W(r_{i,E}) S_i}{\sum_{i=1}^{n} W(r_{i,E})} \tag{62}$$

where $W(r_{i,E})$ is the weighting function between the ith site and the estimation site, and $r_{i,E}$ is the distance between the ith solar irradiation measurement station and the estimation site. In fact, Eq. (62) is identical to Eq. (60), since $W(r_{i,E})/\sum_{i=1}^{n} W(r_{i,E}) = w_i$. However, Eq. (62) is most commonly used in different disciplines because of its explicit expression as the weighted average. For instance, in the application of inverse distance and inverse square distance methods, $W(r_{i,E})$ is considered simply to be equal to $1/r_{i,E}$ and $1/r_{i,E}^2$, respectively. Additional, weighting functions that are proposed by Cressman [23], Gandin [43] and Barnes [12] also appear as sole functions of the distances between the sites. Unfortunately, none of the aforementioned weighting functions are event dependent, but they are suggested on the basis of the logical and geometrical conceptualizations of site configuration. These weighting functions have the following major drawbacks.

1. they do not take into consideration the natural regional variability features of solar radiation. For instance, in meteorology, Cressman [23] weightings are given as

$$W(r_{i,E}) = \begin{cases} \dfrac{R^2 - r_{i,E}^2}{R^2 + r_{i,E}^2} & \text{for } r_{i,E} \le R \\ 0 & \text{for } r_{i,E} \ge R \end{cases} \tag{63}$$

   where R is the radius of influence and is determined subjectively depending on personal experience.
2. although weighting functions are considered universally applicable all over the world, they may show unreliable variability for small areas. For instance, within the same study area, neighboring sites may have quite different weighting functions, and
3. geometric weighting functions cannot reflect the regional variability of the phenomenon, but they can be considered as practical first approximation tools only.

A generalized form of the Cressman model with an extra exponent parameter α is suggested as

$$W(r_{i,E}) = \begin{cases} \left(\dfrac{R^2 - r_{i,E}^2}{R^2 + r_{i,E}^2}\right)^{\alpha} & \text{for } r_{i,E} \le R \\ 0 & \text{for } r_{i,E} \ge R \end{cases} \tag{64}$$

The inclusion of α has alleviated some of the aforesaid drawbacks to some extent, but its determination still presents difficulties in practical applications. Another form of geometrical weighting function was proposed by Sasaki [109] and Barnes [12] as

$$W(r_{i,E}) = \exp\left[-4\left(\frac{r_{i,E}}{R}\right)^2\right] \tag{65}$$

In reality, it is expected that weighting functions should reflect the spatial dependence of the phenomenon. To this end, regional covariance and SV functions are among the early alternatives for the weighting functions that take into account the spatial correlation of the phenomenon considered. The former method requires a set of assumptions such as the Gaussian distribution of the regionalized variable. The latter technique, SV, does not always yield a clear pattern of regional correlation structure. Hence, in this paper the CSV technique is used which does not suffer from these drawbacks. It is a graph that shows the variation of successive half-squared difference summations with distance. Hence, CSV is a non-decreasing function of distance, which exhibits various significant clues about the regional behavior of the meteorological factors. It can be obtained from a given set of solar irradiation data by execution of the following steps:

1. calculate the distance $d_{i,j}$ $(i \ne j = 1, 2, \ldots, m)$ between every possible pair of measurement sites. For instance, if the number of sample sites is n, then there are $m = n(n-1)/2$ distance values,
2. for each distance, $d_{i,j}$ calculate the corresponding half-squared differences, $D_{i,j}$, of the solar irradiation data. For instance, if the solar irradiation variable has values of S_i and S_j at two distinct sites then the half-squared difference is

$$D_{i,j} = \frac{1}{2}(S_i - S_j)^2 \tag{66}$$

3. take the successive summation of the half-squared differences starting from the smallest distance rank to

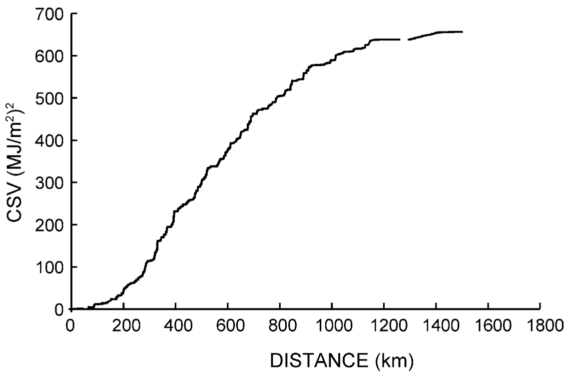


Fig. 26. Representative CSV.

the biggest. This procedure yields a non-decreasing function as

$$\gamma(d_{i,j}) = \sum_{i=1}^{m} \sum_{i=1}^{m} D_{i,j} \quad (67)$$

where $\gamma(d_{i,j})$ represents CSV value at distance $d_{i,j}$, and finally,

4. plotting of $\gamma(d_{i,j})$ versus the corresponding distance $d_{i,j}$ appears similar as a representative CSV functions in Fig. 26. The sample CSV functions are free of subjectivity because no a priori selection of distance classes is involved in contrast to the analysis as suggested by Perrie and Toulany [99] in which the distance axis is divided into subjective intervals, and subsequently, average is taken within each interval as the representative value.

10.8.3. Standard weighting function

It is said in the previous subsection that all the classical weighting functions appear as a non-increasing function with distance. It is, therefore, logical to execute the following steps in order to transform a given CSV into a SWF.

1. find the maximum distance, R_M, and corresponding sample CSV value, V_M. R_M corresponds to the distance between the two farthest station locations in any study area,
2. divide all the distances (CSV values) by R_M (by V_M) and the result appears as a dimensionless form of the given CSV confined within 0 and 1 on both axis.
3. subtract the dimensionless CSV values from one and hence the result appears as a non-increasing function as shown in Fig. 27. This has similar pattern to all the classical weighting functions explained in the previous section. This function is referred to as the SWF.

Now a regional estimation procedure can be proposed for determining the regional solar irradiation variations through an interpolation technique by using SWF. In order to show the validity of the estimation methodology

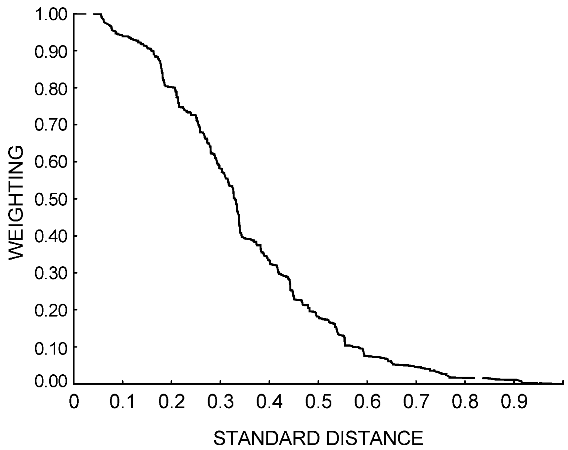


Fig. 27. A representative SWF.

a cross-validation procedure is applied with actual solar irradiation measurements at a given set of sites. There are two different spatial estimation procedures. The first one takes into consideration all the available measurement sites and the second alternative is restricted with a certain number of adjacent sites such that the spatial estimation error becomes the minimum. In the application of the latter methodology, each site has different number of adjacent sites for consideration in the spatial solar irradiation estimation. Its application has been presented by Şen and Şahin [132].

11. Solar radiation devices and collectors

The solar radiation can be used principally as a source of heat, particularly in the forms of domestic hot water consumption, crop dying, power heat engines, power for refrigerators and air conditioners, and ate photovoltaic cells operation for direct electricity production.

Solar energy is expected to be the foundation of a sustainable energy economy, because sunlight is the most abundant renewable energy resource. Additionally, solar energy can be harnessed in an almost infinite variety of ways, from simple solar cookers now used in different parts of the world. There is a vast literature about the solar energy concerning the engineering and architectural design procedures and projects [77]. It is not possible to present all these studies herein, but the proper references with brief description will be provided so that the reader can depend on himself for further information on the topic.

Most of the low-temperature solar heating systems depend on the use of glazing, because it has the ability to transmit visible light, but to block infrared radiation. High-temperature solar collectors employ mirrors and lenses. In order to gather radiation directly by devices, house roofs are constructed as discrete solar collectors. Solar thermal engines are extensions of active solar heating which help to produce high temperatures to drive steam turbines to produce electric power. On the other hand, solar ponds and even ocean thermal energy conversion devices that operate on the solar-induced temperature difference between the top and the bottom of the world's oceans may cover many hectares.

Another way of benefiting from solar radiation is by passive solar heating devices, which have different meanings. For instance, in the narrow sense, it means the absorption of solar energy directly into a building to reduce the energy required for heating the habitable space. Passive solar heating systems are integral parts of the building, and mostly use air to circulate the collected energy without pumps or fans. In the broad sense, passive solar heating means low-energy building design, which is effective in reducing the heat demand to the point where small passive solar gains make a significant contribution in winter.

Careful building design makes the best use of natural daylight. In order to make the best use of solar energy, it is necessary to understand the climate of the region. Inappropriate buildings to local climate cause energy wastages [62].

It is possible to consider a south-facing window as a kind of passive solar heating element. Solar radiation will enter during daylight hours, and if the building's internal temperature is higher than that outside, heat will be conducted and convected back out. Here, the main question is whether more heat flows in that out, so that the window provides a net energy benefit. The answer depends on the following several points. These are:

1. internal building temperature,
2. the average external air temperature,
3. the available solar energy amount,
4. the transmitting characteristics, orientation and shading of the window, and finally,
5. the *U*-value (Section 15.3) of the window whether it is single or double glazed.

The total amount of heat needed for supply over the year can be called as the gross heating demand. Such a demand may have three supply sources.

1. the body heat of people, heat from cooking, washing, lighting and appliances are together named as 'free heat gains' in a house or apartment. They are not significant individually, but collectively they may amount to 15 kW h per day. Free heat gains help for reductions in space heat loading,
2. passive solar gains occur mainly through the windows, and,
3. Fossil fuel energy exploitation from the normal heating system.

11.1. Flat plate collectors

In order to design a solar energy powered device, it is necessary to know how the power density will vary during the day at the site concerned seasonally. It is also important to consider the tilting of the collector surface with the horizontal. As has already been explained earlier, it is possible to consider the solar radiation in two parts. Namely, direct radiation and scattered or diffuse radiation. In practical terms, direct radiation gives rise to sharp shadows, and it is the amount of radiation directly received from the sun without disturbance. Diffuse radiation, however, is disturbed after entering the troposphere by clouds, aerosols, dust and some gasses. Direct radiation has one direction but the diffuse radiation does not show up sharp shadows and comes from every direction. The intensity of diffuse radiation is much less than the direct radiation. In the solar engineering device designs, most often the direct radiation amounts are significant. The relative proportions of direct to diffuse radiation depend on the day of the year, meteorological conditions and the surrounding site. The diffuse component on a clear day is not more than 20% depending on the circumstances. On an overcast day this proportionality may become almost 100%.

The flat plate collectors are based on two important principles. First, the black base absorbs the solar radiation better than any other color. Second, in Fig. 28 the glass lid for heat keeping shows the cross-section of the commonly used flat plate collectors. Its surface should be located perpendicularly to the solar radiation direction for the maximum solar energy gain. Herein, sun's ray goes through the glass cover and the air layer to warm up the black metal plate. The black metal plate warms the water layer.

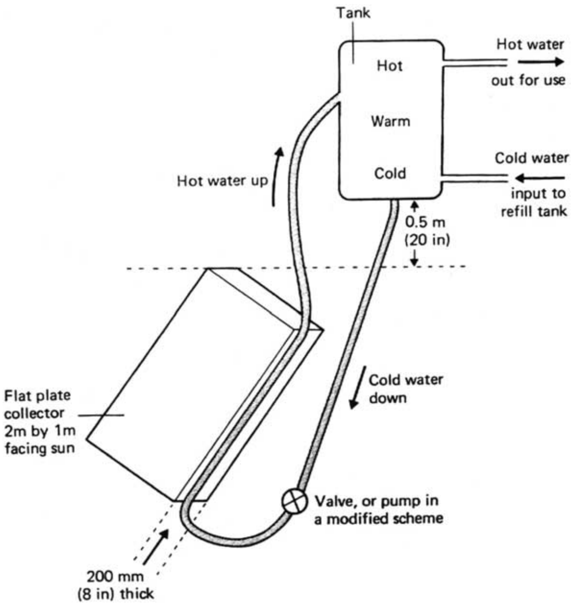


Fig. 28. Flat plate collector cross-section [62].

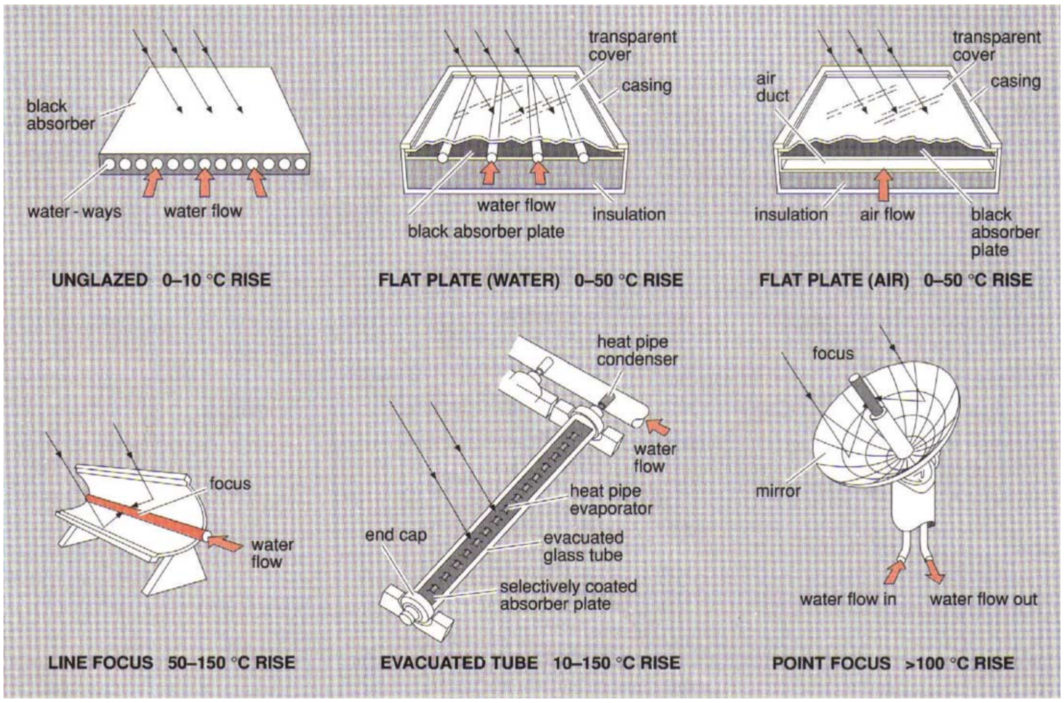


Fig. 29. Various types of collectors.

Unfortunately, the ordinary metal plate is also warmed up. The heat insulation lagging keeps most of the heat inside the sandwich. Thus, with the warm in the water, it has now to be moved to where good use can be made of it. The simplest method for achieving this water movement is shown in Fig. 29 as the 'thermo-siphon' system. Its operation is based on one of the simple facts that hot water will rise to settle above a quantity of cooler water. As the collector heats up the water rises out at the upper pipe and pushes its way into the top of the tank. This hot water then displaces some of the cold in the tank, pushing it down and out of the bottom. This heat-induced circulation is completed as the water, being pushed down the pipe, comes round the bottom and back into the collector.

In practice, different types of solar collectors are given and the most primitive are the unglazed panels which are the most suitable for swimming pool heating where it is not necessary for the collectors to rise more than a few degrees above ambient air temperature, so heat losses are relatively unimportant. On the other hand, flat plate collectors are the main apparatus for domestic solar water heating. These usually have single glaze in addition to the second glazing layer, if necessary. The more elaborate the glazing system, the higher the temperature difference that can be sustained between the absorber and the external wall. It is necessary that the absorber plate should usually have a black surface with high absorption. In general, most black paints reflect approximately 10% of the incident radiation. On the other hand, flat plate air collectors are mainly used for space heating only. These types of collectors are connected with photovoltaic panel for producing both heat and electricity. Evacuated tube collectors in Fig. 29 are in the form of a set of modular tubes similar to fluorescent lamps. The absorber plate is a metal strip down the center of each tube. Vacuum in the tube suppresses convective heat losses.

Flat plate collectors are usually roof mounted and their tracking of the sun is not possible. They are subject to many external events such as frost, wind, sea-spray, acid rain, and hail stones. They must also be resistant against the corrosion and significant temperature changes. Low-temperature flat plate collectors are able to rise the water temperature up to boiling point in summer seasons, provided that they have double-glaze and the water circulation is not fast enough to carry away the heat quickly. These may have only few square meters of area. In order to collect enough solar energy to supply the winter demand, the collectors would have very large areas, but in such a case, its solar energy production during the summer seasons will not be totally exploited. This means wastage of the capital expenditure. On the other hand, if the house is insulated properly, it is not necessary to have large areal collectors, because the energy need will be small. Here lies the key problem in active solar space heating as either to isolate the house to have less energy demand or to built poorly insulated houses and try to implement solar energy for space heating.

In order to collect the maximum solar radiation through a device such as the collectors, it is necessary to direct the collector's surface at right angles to the solar radiation rays.

Sun's apparent motion changes this angle continuously during the day, and accordingly the collector must be moved for collecting the maximum solar energy. For this purpose, tackling collectors are produced and they collect theoretically about $\pi/2$ times more energy per day than the fixed ones. Of course, much of this advantage is lost if a large fraction of the total radiation is diffuse.

In practice, most often the collectors do not move, and therefore, they must be located such that during one day the maximum of the solar radiation can be converted into solar energy. For this reason, fixed collectors are located to face south (north) in the northern (southern) hemisphere. Hence, for a given latitude there is a certain angle, which yields the maximum solar energy over the year. As a practical rule for low latitudes the angle of the collector is almost equivalent to the angle of latitude, but increases by 10° at 40°N and 40°S latitudes. All these arrangements are for flat surfaced collectors. Typical temperatures that can be achieved by flat plate collectors vary between 40 and 80 °C depending on the astronomic, topographic and meteorological conditions. In a flat plate collector, the energy incident on the surface cannot be increased and all that can be done is to ensure that surface absorbs as much as possible of the incident radiation, and that the losses from this surface are reduced as far as possible. Fig. 30 shows a flat plate collector. Some of the incident radiation is lost by reflection but for a blackened surface about 95% of the radiation is absorbed. The heat losses from flat plate collectors are shown in the same figure. In these collectors the lower surface has usually insulating layer of material such as several centimeters of glass wool. The heat can be lost through the following mechanisms,

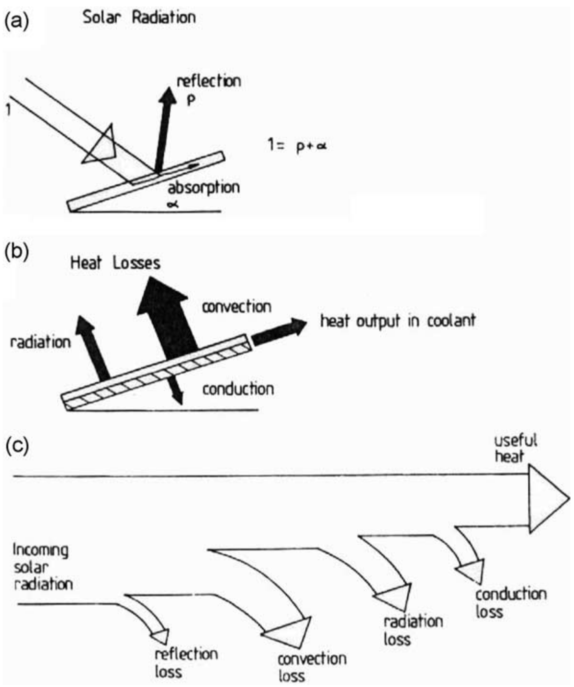


Fig. 30. Flat plate solar collectors [35].

Table 4
Collector surface tilting to the south at 53°N latitude near London

Tilt (°)	Annual total radiation (kW h/m^2)	June total radiation (kW h/m^2)	December total radiation (kW h/m^2)
0-Horizontal	944	155	16
30	1068	153	25
45	1053	143	29
60	990	126	30
90-Vertical	745	82	29

1. conduction,
2. convection, and
3. radiation.

These heat lost mechanisms will be explained later in this paper. On the other hand, it is necessary to have tilted surfaces for the maximum solar energy collection. The tilt angle is dependent both on the latitude and the day of the year. If the tilt angle is equal to the latitude then the sun's rays will be perpendicular to the collector surface at midday in March and September. For the maximization of solar collection in the summer, it is convenient to tilt the surface a little more towards the horizontal. However, for the maximization in the winter, the surface is tilted more to the vertical. Fortunately, the effects of tilt and orientation are not particularly critical. Table 4 presents totals of energy incident on various tilted surfaces in London region.

Instead of flat plate collectors, solar ponds are used for thermal electricity production. They are similar to large salty lakes as shown in Fig. 31. In such a pond, salty water is at the bottom with fresh water at the top. The *n* salt concentration difference creates a gradient. The incident solar radiation is absorbed directly from the sun radiation in the bottom of the pond. The hot and salty water cannot rise, because it is heavier from the fresh water at the top layer.

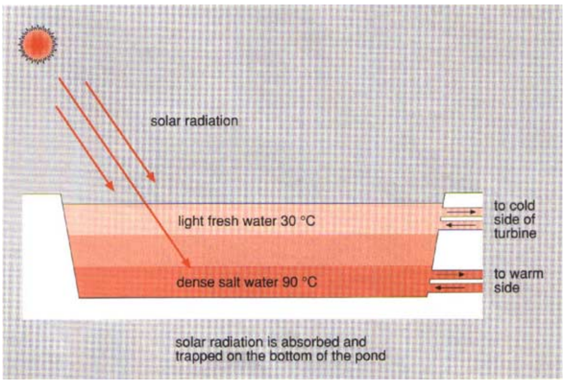


Fig. 31. Solar pond.

Hence, the upper fresh water layer acts as an insulating blanket and the temperature at the bottom of the lake can reach 90 °C.

The thermodynamic limitations of the relatively low solar-to-electricity conversion efficiencies are typically less than 2%. One of the main advantages of the solar pond system is that the large thermal mass of the pond acts as a heat store, and electricity generation can go on day or night, as required. However, large amounts of fresh water are needed to keep the solar pond running with proper salt gradient.

11.2. Concentrating (focusing) collectors

Logically, in order to collect the maximum radiation for each unit surface area of the collector, it is necessary to direct its surface at right angles to direct radiation direction continuation of maximum benefit by the collector during a day is possible by keeping the collector surface perpendicular to the incident solar radiation throughout the daylight. It is theoretically simple to show that a moving collector compared to the horizontal ones at the same site can collect $\pi/2$ times more energy per day. However, in practice this factor is around 1.5 times. Of course, the more the direct radiation, the better is the energy generation from the sun radiation.

If high temperatures are needed then the collector surface is manufactured as a curve for concentrating (focusing) the solar radiation at certain points by mirror or lens. Mirrors are cheaper to construct than lenses. The mirror collectors may have spherical or linear parabolic shapes as shown in Fig. 32. In a parabolic mirror solar radiation is concentrated at a point, and therefore, the concentration ratio is approximately 40,000. The concentration of one-dimensional linear parabolic system is around 200. So far as the lenses are concerned there are single surface or equivalent Fresnel types as shown in Fig. 33. Although in flat plate collectors diffuse solar radiation also makes contribution in the radiation collection, but the concentrating collectors focus the incident sunlight on the collector surface, leaving the contribution of diffuse radiation a side. Another disadvantage of the concentrating collectors is that they must track the sun in order to obtain the optimal benefit. Concentrating collectors cause temperature rises in the heater up to 300–6000 °C. These collectors must be aligned with sufficient accuracy to ensure that the focus coincides with the collector surface. The greater the degree of concentration, the more accurate is the alignment required. Typical uses of solar radiation collectors can be grouped into four different categories depending on the purpose.

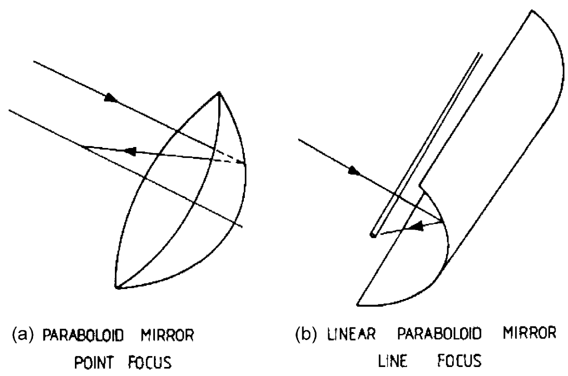


Fig. 32. Paraboloid mirror concentrator of solar radiation [35].

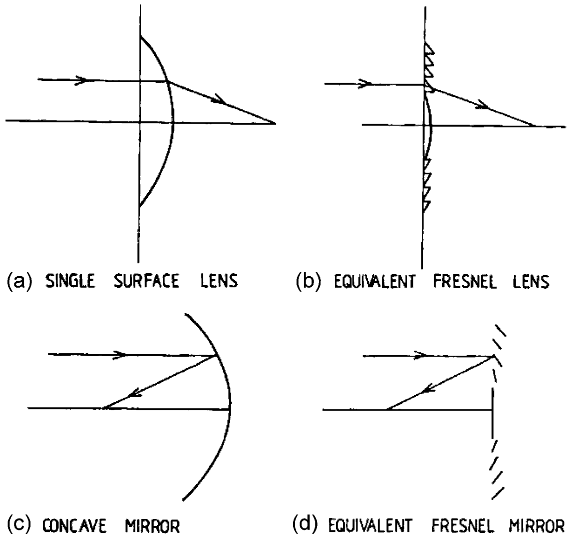


Fig. 33. Single surface and equivalent fresnel lenses [35].

1. as a heat source for low temperatures, which may be used for domestic hot water or crop drying purposes,
2. in order to power heat engines, relatively high heat collectors can be used,
3. depending on the climate, the collectors can be used as high temperature heat to power refrigerators and air conditioners, and finally,
4. in the photovoltaic cells operation for direct electricity production.

Although the flat collectors make use of diffuse solar radiation also, but this is not possible with the concentrators where the temperatures can reach to 300–600 °C. In a concentrator collector the position must be aligned such that sufficient accuracy is ensured by directing the focus with the collector surface.

Most low-temperature solar collectors are dependent on the properties of glass which is transparent to visible light and short-wave infrared, but opaque to long wave infrared reradiated from a solar collector or building behind it. In order to benefit from daylight, and especially solar radiation as energy source, manufacturers strive for making glass as transparent as possible, by keeping the iron content down.

Table 5
Optical properties of commonly used glazing materials

Material infrared	Thickness (mm)	Solar transmittance	Long-wave transmittance
Float glass (normal window glass)	3.9	0.83	0.02
Low-iron glass	3.2	0.90	0.02
Perspex	3.1	0.82	0.02
Polyvinylfluoride (tedlar)	0.1	0.92	0.02
Polyester (mylar)	0.1	0.89	0.18

In Table 5, the optical properties of some commonly used glazing materials are indicated.

Line focus collectors focus the solar radiation on to a pipe running down the center of a trough which is mainly used for generating steam for electricity. To get the maximum benefit, it is necessary that the trough is pivoted to track the sun's movement in any direction.

Point focus collectors as shown in Fig. 28 also track the sun but in two dimensions and these also generate steam for electricity. If the solar radiation is concentrated trough mirrors or lenses then over boiling temperatures may be reached for water. It is possible to use such high temperature trough in steam production for mechanical work, for instance, for water pumping or electricity generation. These are already named as high-temperature collectors. Most often parabolic mirrors are used for solar radiation concentrations. As shown in Fig. 34, all sun's rays directed parallel to the axis of such a mirror are reflected to one point. It is necessary that the mirror tracts the sun, otherwise slightly off-axis solar beams will make inconvenient reflections, and the intensity of radiation concentration onto a point or line will be weakened. In the line focus form the sun radiation can be concentrated on a small region running along the length of the mirror. For the maximum focusing of the sun radiation, it is necessary to tract the sun in elevation only that is up and down. However, in the point focus form, the sun radiation is reflected on a boiler in the mirror center. For optimum performance, the axis must be pointed directly at the sun all times, so it needs to tract the sun both in elevation and in azimuth.

On the other hand, another technology of centralized electricity generation is solar–thermal power. In order to reflect the sun's rays onto an oil-filled tube this is produced by using large mirror troughs, which in turn superheats water to produce the steam that drives an electricity-generating turbine. Since mid-1980s, about 350 MW of solar systems are installed across 3 mile^2 of southern California desert, which is enough to electrify 170,000 homes. Especially, in areas of extensive pollution control, solar–thermal electricity substitution is required for the pollution protection. In order to have sufficiency and success, solar–thermal electricity production is practical in areas where there are intense and direct sunlight conditions such as the arid regions of the world.

12. Photo-voltaic

The term 'photovoltaic' is derived by combining the Greek word for light, *photos*, with *volt*, the name of the unit of electromotive force. The discovery of the photovoltaic effect is generally credited to the French physicist, Edmond Becquerel who in 1939 published a paper describing the experiments with a 'wet cell' battery, in the course of which he found that the battery voltage increased when its silver plates were exposed to sunlight.

Photovoltaic cells consist of a junction between two thin layers of dissimilar semi-conducting materials. These two parts are known as positive-type '*p*' and negative-type '*n*' semiconductors [92]. These are usually manufactured from silicon although other materials can also be used. *n*-Typed semiconductors are made of crystalline silicon that has been 'doped' with tiny quantities on an impurity (usually phosphorous) in such a way that the doped material possesses a surplus of free electron. On the other hand,

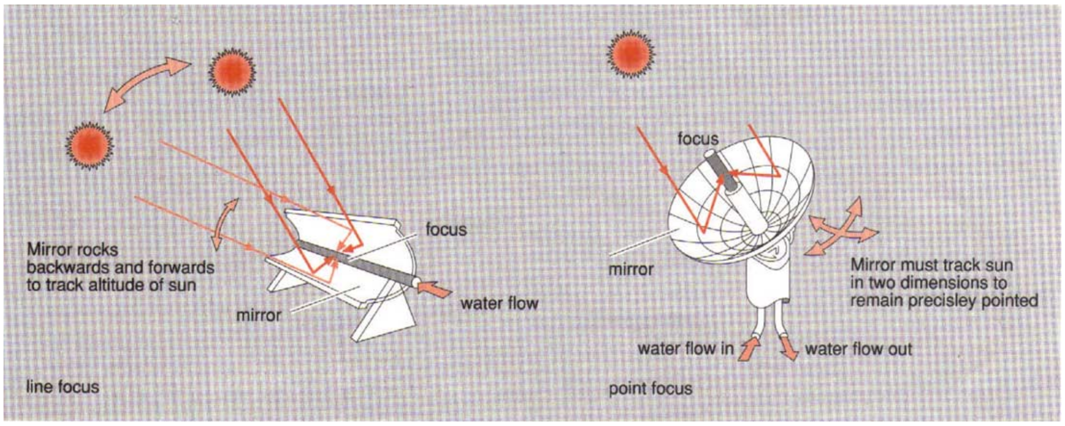


Fig. 34. Line and point focus by mowing mirrors.

p-type semiconductors are also made from crystalline silicon, but they are doped with very small amounts of a different impurity (usually boron) which causes the material to have a deficit of free electrons. These missing electrons are called holes. By combining these two dissimilar semiconductors, one can produce $n-p$ junction. This sets up an electric field in the region of the junction. Such a set up will cause negatively charged particles to move in one direction, and positively charged particles to move in the opposite direction.

Light is composed of a steam of tiny energy particles called photons. If photons of a suitable wavelength fall within the $p-n$ junction, then they can transfer their energy to some of the electrons in the material so prompting them to a higher energy level. When the $p-n$ junction is formed, some of the electrons in the immediate vicinity of the junction are attracted from the *n*-side to combine with holes on the nearby *p*-side. Similarly, holes on the *p*-side near the junction are attracted to combine with electrons on the nearby *n*-sides. Hence, the net effect of this is to set up around the junction a layer on the *n*-side that is more positively charged than it would otherwise be. In effect, this means that a reverse electric field set up around junction such that negative on the *p*-side and positive on the *n*-side. Since, the region around the junction is also depleted of charge carriers (electrons and holes), it is therefore, called as the depletion region.

Photovoltaic are much more effective in hazy or partly cloudy conditions and they can be installed even on small residential rooftops.

In recent years, power generation from renewable resources has been counted upon to bridge the gap between global demand and supply of power. The direct conversion technology based on solar photovoltaic has several positive attributes and seems to be most promising. Extensive research activities over the past 25 years have led to significant cost reduction and efficiency amelioration [27,71]. Relatively less attention seems to have been paid to factors related to system reliability [2,17,18,74,77,105]. In this context, stand-alone solar photovoltaic systems consisting of photovoltaic array, electrical interface and the energy storage facilities have often been of interest to researchers. The reliability has not been studies in detail as an important statistical parameter to assess the operational lifetime of the photovoltaic array [45].

Generation of electricity from sunlight has been a dream of scientists, planners and energy experts since 1950s, when practically the first photovoltaic cell was invented. It is a device that converts the solar radiation directly into electric current via complex photoelectric process. Photovoltaic technology has advanced during the last five decades, making it possible to convert a larger share of sunlight into electricity which has reached as much as 14% in the most advanced prototype systems. They are now widely used, for example, to power electronic calculators, remote telecommunication equipments, electric lights and water pumps. The 50 MW worth of cells produced in 1990 are only sufficient to power about 15,000 European and Japanese homes [38]. Although the cost of photovoltaic has fallen drastically during the last decades, but still it is four to six times the cost of power generation from fossil fuels. So further reductions are needed for solar power to be competitive with grid electricity. However, photovoltaics are already the most economical way of delivering power to homes far from utility lines. It is expected that this technology will become an economical way of providing supplementary utility power in rural areas, where the distance from plants tends to cause a voltage reduction that is otherwise costly to remedy. As they become more versatile and compact, photovoltaic panels could be used as roofing material on individual homes, bringing about the ultimate decentralization of power generation. In fact, the desert areas are the most attractive and rich regions of the world for the solar irradiation conversion into electric power. Large solar power plants could appear in the world's deserts, providing centralized power in the same way to today's coal and nuclear plants.

13. Photo-optical collection and transmission of solar energy

The need for new and renewable energy alternatives due to the depletion of conservative energy sources brought along also the studies on the efficient usage and transmission of available energies. As is well known, the major criticism against these energy alternatives is the problem of the energy storage [137]. Especially, unevenly distributed solar energy potential on the world causes unbalance in their production among various regions, some of which are relatively richer then the others. Such unbalances can be avoided only through an efficient energy transportation system.

If the storage or transmission of solar energy can be achieved then the coal, fuel oil and natural gas purchase of any country will reduce significantly. Such a solar energy transmission system will provide benefits for great trade centers, factories, and especially its application to photo-optical plants will lead reduction in the fossil energy consumption to a possible minimum level, and provide continuity (sustainability) in the renewable energy alternatives. Among the photo-optical transmission methods, Çinar [24] has considered the collection of radiation by focus-collectors. On the other hand, Baojun et al. [9,10] have investigated the solar energy relationships with fiber-optic radiation.

The most advanced recent technologies of solar energy collection as well as transmission are the fiber-optic applications. Collection of energy directly as light by concentrator collectors causes almost no energy loss in the transmission. Besides, since the collected solar radiation is

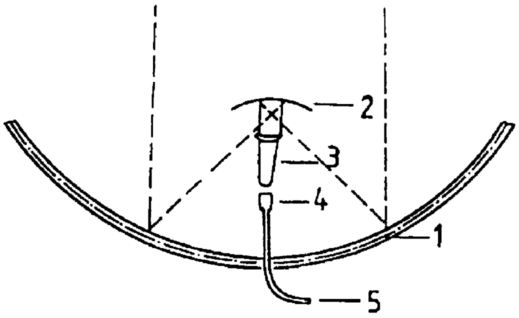


Fig. 35. Fiber optical collector system.

in the form of light, it can be consumed directly in the lighting problems. However, it can also be used in the heating and converted into electrical energy, if desired.

After the collection of the solar energy through focusing, it is refined by means of a lens system and finally, directed towards a fiber-optic glass transmission cable. The transmission is affected without any further loss to desired area in far distances as shown in Fig. 35. It is obvious that large diameter convex collectors collect the incoming radiation, and then lead it to another small diameter convex reflector. This small dish reflects the incoming radiation to the refining lens system, which refines the radiation twice after the focusing. The light ray that is refined down to the size of a needle, goes through a collector which includes a set of lenses that render the radiation into a parallel beams. Such a condensed solar ray enters without any loss into fiber-optical cable, which has a high transmission capability. The following items are used for the description of collector system in Fig. 35.

1. large diameter convex collector,
2. small diameter convex reflector,
3. refining lens system,
4. lens system that renders the solar rays into parallel form, and finally,
5. fiber-optic glass transmission cable.

Through the aforementioned system, the transmission of solar energy will be possible without losses from solar radiation rich regions of the world to poor regions. For this purpose, a regional energy transmission network must be constructed. In this manner, the solar energy can be transmitted to consuming countries where the solar radiation possibilities are rather poor. In the case of central European and Arabian conditions, because of the low solar potential of the central Europe, the solar energy transmission from Arabian deserts is possible. Fig. 35 includes the fiber-optic glass cable transmission system among the selected regions of Arabia and northern Africa desert regions to European countries. The significance of this topic can be appreciated from the solar energy figures presented in Table 6 concerning the central Europe and Arabian Rub-Al-Khali desert. It covers about 660,000 km^2 and from its each square meter it is possible to generate 1 kW/h solar energy. Solar energy collection area is about $360 \times 10^9\ m^2$, and hence, $360 \times 10^9\ m^2 \times 1$ kW/h $= 360 \times 10^9$ kW/h $= 360 \times 10^9$ MW/h solar energy can be harvested which is equal to 1.440×10^9 MW/year. By considering about 6 m^2 of surface area for each collector, it is possible to find the number of necessary collectors as $360 \times 10^9/6 = 60 \times 10^9$.

Due to the location and planning of some housing complex the lighting problems might exist and such undesirable situations can be avoided with fiber-optic system in the architectural designs. This system may even provide facilities for multi-story greenhouse activities. On the other hand, by leading the solar radiation over the fruits, vegetables and flowers in multi-story buildings, a covered agricultural production area may be established, and consequently, cheap and healthy food productions may become available in the market.

The application of fiber-optic electric energy production plants in the future may minimize the demand on the fossil energy, and may provide sustainability in the renewable energy availability, especially by exploiting abundantly existing solar radiation potential in the world. The collection of solar energy through fiber-optic glass and lens systems causes no losses, and additionally, transmission takes place instantaneously.

Especially the transmission of solar radiation to regions with very little variation will give opportunity for its direct use as light in heating, electric energy and hydrogen gas generation purposes. Photo-optical energy plants help to use the most significant renewable energy source of solar irradiation at low costs, and hence the demand on fossil fuels such as coal, petroleum and natural gas is expected to decrease leading to clean atmospheric environment. The solar energy obtained in this manner may also be used for electrolysis of water into hydrogen and oxygen elements

Table 6
Average solar energy per square kilometer in central Europe and Arabia

Region	Total annual sunshine duration (h)	Radiation (kcal/h)	Radiation (kcal/yr)	Energy (kW/h)	Energy (kW/yr)
Central Europe	1200	172	206,200	0.2	240
Northeast Turkey	1825	344	627,800	0.4	730
Arabian deserts	4000	860	3,440,000	1.0	4000

with the purpose of hydrogen energy production. This will increase the efficiency of solar-hydrogen energy prospects and future usages.

14. Solar-hydrogen power

The world energy demand depends mainly on fossil fuels with respective shares of petroleum, coal and natural gas at 38, 30 and 20%, respectively. The remaining 12% are filled by the non-conventional energy alternatives, which are 7% hydropower and 5% nuclear energy shares. It is expected that the world oil and natural gas reserves will last for about several decades, but the coal will sustain the energy requirements for few centuries. This means that the fossil fuel amount is currently limited and even though new reserves might be explored in the future, they will still remain limited and the rate of energy demand increased will require exploitation of other renewable alternatives at ever increasing rates. The desire to use renewable energy sources is not only due to their availability in many parts of the world, but more empathetically as a result of the fossil fuel damage to environmental and atmospheric cleanness issues. The search for new alternative energy systems has increased vigorously in the last few decades because of the following reasons:

1. the extra demand on energy within the next five decades is expected to continue and increase in such a manner that the use of fossil fuels will not be sufficient. Therefore, the deficit in the energy supply will be covered by additional energy productions and discoveries,
2. fossil fuels are not available in each country because they are unevenly distributed over the world, but renewable sources, and especially, the solar radiation is more evenly distributed, and consequently, each country can make the best to search and develop her own energy harvest, and finally,
3. fossil fuel combustion leads to some undesirable effects such as the atmospheric pollution because of the CO_2 emissions and environmental problems including the air pollution, acid rains, greenhouse effect, climate changes, oil spills, etc. It is understood by now that even with refined precautions and present technology level, these undesirable effects cannot be avoided completely but minimized. One way of such minimization is to substitute at least some important part of the fossil fuel usage by solar energy.

The world wide environmental problems resulting from the use of fossil fuels are the most compelling reasons for the present vigorous search for future alternative energy options that are renewable and environmentally friendly. The renewable sources have also some disadvantages as being available intermittently as in the case of solar and wind sources or fixed to certain locations including hydropower, geothermal and biomass alternatives. Another shortcoming, for the time being, is their transportation directly as a fuel. These shortcomings point to the need for an intermediate energy systems to form the link between their production sites and the consumer locations. If, for example, heat and electricity from solar power plants are to be made available at all times to meet the demand profile for useful energy, then an energy carrier is necessary with storage capabilities over long periods of time for use when solar radiation is not available [140].

The solar radiation is abundant and becoming more economical, it is not harvested on large scales. This is due to the fact that it is difficult to store and move energy from ephemeral and intermittent sources such as the sun. However, fossil fuels can be transported easily from remote areas to consumption sites. For the transportation of electric power it is necessary to invest and currently spend money in large amounts. Under these circumstances of economic limitations, it is more rational to convert solar power to a gaseous form than is far cheaper to transport and easy to store. For this purpose, hydrogen is an almost completely clean-burning gas that can be used in place of petroleum, coal or natural gas. It does not release the carbon compounds that lead to global warming. In order to produce hydrogen, it is possible to run an electric current through water and this conversion process is known as electrolysis. After the production of hydrogen it can be transported to any distance with virtually no energy loss. Transportation of gases such as hydrogen is less risky than any other form of energy such as oil which is frequently spilled in tanker accidents, or during routine handling [112].

On the other hand, storage of hydrogen is much easier than electricity, especially in pressurized tanks or in metal hydrides, metal powders that naturally absorb gaseous hydrogen and release it when heated. Moreover, hydrogen can provide the concentrated energy needed by factories and homes. It can be used instead of natural gas in many human activities, such as restaurants, heat warehouses, and a wide range of industrial processes. It is also possible to develop appliances as hydrogen-powered furnaces, stove burners, water heaters, etc. Hydrogen can be used to run automobiles through either an internal combustion engine or more efficiently a fuel cell [39].

In all countries, automobiles consume petroleum as a chief fuel that causes air and atmospheric pollution in many cities. For sustainable energy future, non-polluting solar (renewable) energy sources are essential to power transportation systems. Prototype electric automobiles are now available which do not consume air-polluting fossil fuels. These environmentally friendly automobile developments and wide uses are restricted due to the size of their batteries, and the need for frequent recharging. Tightening air quality standards led many companies to produce electric cars and vans during the 1990s.

Automakers now consider vehicles fueled with hydrogen. It is the cleanest burning fuel, which produces only water vapor and small amounts of nitrogen oxides. Minor modifications are needed to make a gasoline-powered engine run on hydrogen although storing hydrogen remains a problem.

The ideal intermediary energy carrier should be storable, transportable, pollution-free, independent of primary resources, renewable and applicable in many ways. These properties may be met by hydrogen when produced electrolytically using solar radiation, and hence, such a combination is referred to as the solar-hydrogen. This is to say that transformation to hydrogen is one of the most promising methods of storing and transporting solar energy in large quantities and over long distances.

Water can be split electrolytically into its components, hydrogen and oxygen by using thermal and/or photovoltaic electricity from solar power plants. Hydrogen can then be used similar to natural gas for heating and as gasoline fuel for transportation. If electrochemical fuel cell conversions are used then hydrogen can be converted directly for electricity production. Among the many renewable energy alternatives, the solar-hydrogen energy is regarded as the most ideal energy resource that can be exploited in the foreseeable future in large quantities. On the other hand, where conventional fuel sources are not available, especially in rural areas, solar energy can be used directly or indirectly by its transformation into hydrogen gas. The most important property of hydrogen is that, it is the cleanest fuel, non-toxic with virtually no environmental problems during its production, storage and transportation. Combustion of hydrogen with oxygen produces absolutely no pollution, except its combustion in air produces small amounts of nitrogen oxides. Solar-hydrogen energy through the use of hydrogen does not give rise to acid rains, greenhouse effects, ozone layer depletions, leaks or spillages. It is possible to regard hydrogen after the treatment of water by solar energy as a synthetic fuel. Hydrogen can be produced by steam reforming of natural gas or coal gasification. In order to benefit from the unique properties of hydrogen, it must be produced by the use of a renewable source so that there will not be any limitation or environmental pollution in the long run.

Different methods help to produce hydrogen from direct or indirect forms of solar energy. These methods can be viewed under four different processes, namely, direct thermal decomposition or thermolysis, thermochemical processes, electrolysis and photolysis. Big scale hydrogen production has been obtained so far from the water electrolysis method which can be used effectively in combination with photovoltaic cells. Hydrogen can be extracted directly from water by photolysis using solar radiation. Photolysis can be accomplished by photobiological systems, photochemical assemblies or photo-electrochemical cells.

14.1. Hydrogen storage and transport

Any discrepancy between the energy supply and demand can be offset by hydrogen storage, and its use at the time of need as a source of energy. Hydrogen can be stored at large scale in the aquifers as underground storages, in depleted petroleum or natural gas reservoirs, and artificial caverns as a result of mining activities. The latter method is the most commonly used alternative in some countries. Hydrogen can be transported to consumption places from the production plants through underground pipelines in gaseous form and by supertankers in liquid form. Hydrogen can be stored in stationary or mobile storage systems at the consumer site depending on the end use. It can be stored either as a pressurized gas or as a liquid, or using some of its unique physical and chemical properties in metal hydrides and in activated carbon. Hydrogen can be used instead of fossil fuels virtually for all purposes. As a fuel for surface and air transportation heat production and production of electricity directly (in fuel cells) or indirectly (through gas and steam turbine driven generators) [140].

Hydrogen can be converted to electricity electrochemically in fuel cells with high efficiencies. It is not subject to Carnot cycle limitation, which is the case with the present day thermal power plants whether they burn fossil or nuclear fuels. It has been stated by Veziroğlu [140] that Tokyo Electric Utility started experimenting with a 4.5 MW United Technologies fuel cell years ago. Now, they have another 11 MW fuel cell on line.

Another unique property of hydrogen is that it will combine with certain metals and alloys easily in large amounts forming hydrides in exothermic chemical reactions. Hydrogen is released when hydrides are heated. The temperature and pressure characteristics vary for different metals and alloys. Many household appliances working with hydrogen do not need chlorofluorocarbons and hence, they will not damage the ozone layer.

On the other hand, hydrogen has further property that it is flameless or the catalytic combustion in the presence of small amounts of catalysts, such as platinum or palladium. Catalytic combustion appliances are safer and have higher second thermodynamic law efficiencies and environmental compatibility.

14.2. Research and development needs

Industrial countries consider hydrogen as environmentally clean energy source hydrogen. In order to make further developments in the environmentally friendly solar-hydrogen energy source enhancement and research, the following main points must be considered.

1. it is necessary to invest on the research and development of hydrogen energy technologies,
2. make widely known the transfer of these technologies,

3. establishment of appropriate industries, and
4. initiation of a durable and environmentally compatible energy system based-on solar-hydrogen.

Veziroğlu [140] has suggested the following research points in the future for better solar-hydrogen energy prospects.

1. hydrogen production techniques coupled with solar and wind energy sources,
2. hydrogen transportation facilities through pipelines,
3. establishment and maintenance of hydrogen storage techniques,
4. development of hydrogen fuelled vehicles as buses, trucks, cars, etc.
5. fuel cell applications for decentralized power generation and vehicles,
6. research and development on hydrogen hydrides for hydrogen storage and air conditioning,
7. infrastructure development for solar-hydrogen energy,
8. economical considerations in any mass production, and finally,
9. environmental protection studies.

On the other hand, possible demonstrations and/or pilot projects include the following alternatives,

1. photovoltaic hydrogen production facility,
2. hydrogen production plants by wind-farms,
3. hydro power plant with hydrogen off-peak generators,
4. hydrogen community,
5. hydrogen house, and
6. hydrogen powered vehicles.

In order to achieve these goals, preliminary prerequisites are to have a data bank on hydrogen energy industry and on the production specifications and also prices are to be set-up. Another important and future promising technology for applying solar photon energy is the decomposition of water. This use is referred to as the 'Solar-Hydrogen Energy System' by Ohta [92] and Justi [68].

Photolysis does not mean water decomposition technically only by photon energy, but also any photochemical reaction used to obtain the desired products.

15. Heat transfer and losses

As explained earlier the easiest way of solar radiation collection is for low temperature heating purposes. It is well known that black surfaces absorb solar radiation more than any other color, and therefore, when a surface is blackened it will absorb most of the incident solar radiation. Continuous pour of solar radiation on such a surface will increase its temperature. This will continue until the heat gain from the solar radiation will be in equilibrium with the heat loss from the collector. There are two types of heat losses, namely, natural unavoidable losses and losses due to human uses. The heat can be transmitted to consumption site through pipes soldered to the metal plate, which is heated due to solar radiation exposition. The heat balance of collector will have three components in general as follows [8,35].

Absorbed heat − lost heat = removed heat by coolant

It is possible to define the coefficient of efficiency for the collector as

Efficiency coefficient

= (absorbed heat − lost heat)/incident solar radiation

In practice, the collectors must be designed in such a manner, that the efficiency becomes high. In order to achieve such a goal there are two methods either to reduce the heat losses or to increase the incident solar radiation, and hence, the heat absorbed per unit area. For low temperature collectors, heat loss reduction methodology is suitable. It is possible to reduce heat loss by using transparent cover plates specially treated absorber surfaces, and by evacuating the space between the cover plate and the absorber surface. For high temperature solar collectors, the efficiency must be increased by increasing the incident radiation through the concentrators. For this purpose only the direct radiation is considered.

It is necessary in any solar radiation collector efficient work to reduce the heat losses or to minimize them. As a material is heated by solar radiation it seeks to reach equilibrium with its surrounding by conduction, convection and radiation processes. Let us examine these processes one by one in more detail.

15.1. Conduction

It is the heat transfer within a solid body where there are at least two different heat areas, i.e. temperature difference. Such a heat transfer is possible by means of vibrations of the atomic lattice, which forms the body of the material. The heat is also carried away by electrons, and this contribution is much greater than that due to lattice vibration. During conduction there is no mass transfer. Atoms move randomly under thermal stress in liquids and gases, and they also lead to heat conduction. The heat transfer is proportional with the temperature difference along a distance (temperature gradient) and hence the heat flow by conduction can be expressed by the following mathematical equation

$$H_f = -k(dT/dx) \quad (68)$$

where H_f is the heat flow per unit area of cross section (W/m^2), T is the temperature (°C), x is the direction and distance (m), and k is the thermal conductivity of the material (W/m °C). Thermal conductivity is special for

Table 7
Thermal conductivity of some materials

Material	k (W/m °C)
Metals	
Cooper	385
Aluminum	205
Steel	50
Non-metals	
Glass	0.8
Concrete	0.8
Wood	0.14
Sawdust	0.06
Rock wool	0.04
Polystyrene (expanded)	0.03
Glass fiber	0.03
Liquids	
Water	0.61
Gases	
Hydrogen	0.142
Helium	0.142
Air	0.0239

each material and its value is given for various materials in Table 7.

As solar radiation absorbed by opaque materials, the energy redistributes itself because it is conducted between adjacent molecules. Such redistribution is dependent on temperature difference and the thermal conductivity of the material. Metals, in general, have big conductivities and consequently can transmit large amounts of energy under small temperature differences (temperature gradients). In insulators the reverse situation is valid where under large temperature gradients only a small amount of heat is conducted. It is known that the air is a very good insulator. Hence, most of the practical insulators rely on very small pockets of air traps between the panels of glazing as bubbles in a plastic medium or between the fibers of mineral wools.

15.2. Convection

This is a process by which heat from the hot surfaces is carried away by a fluid such as water flowing fluid across the surface is heated and then the heated volume is removed due to fluid flow with replacements of new and cold fluid. This heat transfer is referred to as convective cooling or heating. The rate of heat removal depends on both the temperature difference between the surface and the bulk fluid temperature and also on the velocity and characteristics of the fluid. Another sort of convective heat transfer can be considered for a horizontal hot plate in still air, where the air adjacent to the top surface will become hotter than the bulk of air temperature. As a result of hot air expansion and density decrease, hot air is replaced by cooler air. In solar energy conversion both forced and natural convections may be accompanied by phase changes. Hence, the convective heat transfer can be expressed by the following relation

$$H_f = h(T_s - T_f) = h\,\Delta T \quad (69)$$

where H_f is the heat flow per unit area (W/m^2), h is the convective heat transfer coefficient (W/m^2 °C), T_s is the surface temperature (°C), T_f is the fluid temperature (°C), and $\Delta T = T_s - T_f$. The actual calculation of h is somewhat complicated, because it is dependent on both the nature of the fluid and also on its flow velocity. Approximate convective heat transfer coefficients are given for flat plate collector in Table 8.

This refers to the transference of heat to a fluid (gas or liquid). Energy is transferred to molecules of the fluid, which then physically move away taking the energy with them. A warmed fluid expands and rises creating a fluid known as natural convection, which is one of the principle processes of heat transfer through windows. It occurs between the air and glass. It is possible to reduce the convection losses through double-glazing windows by filling space between the double-glazing with heavier, less mobile gas molecules, such as argon or carbon dioxide. On the other hand, since the convection currents cannot flow in a vacuum, the space between the double-glazing may be evacuated.

15.3. Radiation

A hot body may lose heat by radiation through emission of electromagnetic waves The maximum power which can be radiated from a body at a given temperature is called the black body radiation corresponding to that temperature. The radiation power, P, from a black body increases as the fourth power of the absolute temperature, T, of the same body and it is given by Stefan's law as

$$P = \sigma T^4 \quad (70)$$

where $\sigma = 5.67 \times 10^{-8}$ W/m^2 K^4 is the Stefan's constant. Heat flux in the case of radiation from a black body is presented in Table 9 for different absolute temperatures.

Similar to sun's radiation heat can be radiated from the surfaces of heated materials. The amount of radiation is first dependent on the temperature of the radiating body and then on the destination of the radiation. In low-heat solar collectors on the roofs energy radiates to the atmosphere.

Table 8
Convective heat transfer coefficient [35]

System configuration	h (W/m^{2}C)
Heat transfer between parallel plates (separation 2.5–10 cm) with air at atmospheric pressure	3
Heat transfer from surface of cover plate where v is the wind velocity at surface of plate in meters per second	$2.3 + 3.8v$

Table 9
Black body radiation

Surface temperature (K)	Heat flux (W/m^2)
6000	73.5×10^6
3000	4.6×10^6
2000	9.1×10^5
1073	75.0×10^3
873	32.9×10^3
673	11.6×10^3
473	2.84×10^3
353	1.10×10^3
333	880
300	459

Radiation amount is also dependent on the surface material emission. Most materials used in the building construction have high emissions of approximately 0.9, which means that they radiate 90% of the theoretical maximum for a given temperature. Usually, the total heat loss from combined effects of conduction, convection and radiation is referred to as the *U*-value. Its unit is the amount of loss per area per centigrade degree. Typical *U*-values are provided in Table 10.

16. Future expectations

In general, there are two distinctive reasons for future energy researches. First, as a result of global warming, atmospheric and environmental pollutions due to energy consumption, present day energy pattern, dominantly fossil fuels, must be either improved in quality or more significantly they must be substituted with more environmentally reliable clean and renewable energy sources. The second reason for the future researches on energy progress is the appreciation that the fossil fuel reserves are limited and bound to be exhausted sooner or later. If the necessary precautions are not taken from now on by radical innovations in energy systems and their technologies, then the future human generations on the earth might face extremely precarious positions. Additionally, population increase places extra pressure on the energy resources and the energy consumption per capita per day in developing countries which is about 10 oil-equivalent-liter and it is below one-tenth of that in industrial countries. In order to produce new energy sources independent of fossil and nuclear fuels the following points must be taken into future research programs.

Table 10
U-values of different types of window construction

Window type	*U*-value (W/m^2/°C)
Single-glazed window	6
Double-glazed window	3
With 'low-E' coating	1.8
With heavy gas filling	1.5
Experimental evacuated double-glazed window with transparent insulation spacers	0.5
For comparison: 10 cm opaque fiberglass insulation	0.4

1. the solar beam collector with a Fresnel lens or concave mirror,
2. electric charge separation by solar radiation, and,
3. other natural processes that reduce entropy such as the functions of a membrane, catalyst, biological organ, other chemical phenomena, etc.

In the long run, full consideration must be given to the amount of energy that is required to produce more energy. One of the constant research areas is the storage and the two most promising new devices are, 'silica gel beds' and 'two vessel storages'. Silica gel beds try to improve the efficiency of pebble storages. It is possible to obtain the same performance with a volume of 15 times less. The silica gel beds are relatively unaffected by thermal losses, there is also a saving on insulation [92].

On the other hand, the two-vessel store introduces a fresh storage technique. As Howell [62] explained the idea relies on the chemical reaction that when acid and water are mixed then heat is released. Hence, for heat storage it can be used to drive water and acid into separate vessels where they can remain for years as stored energy. By allowing the acid back into the water the stored heat is released.

With the world's second hydrogen conference held in 1978, the possibility of hydrogen based energy concept started to draw perceptibly nearer. Whilst they are eminently suited to solar energy they are low in efficiency and the future works should concentrate on raising that efficiency.

It is necessary all over the world to reduce the cost of solar collectors although this may appear in the guise of increased efficiency at the same cost. This is tantamount to saying that as production increases and the days of handmade collectors pass, the labor content of the product will reduce to a minimum. As the only other major production cost is the cost of material, the other move must be towards cheaper materials.

As collector material although copper and aluminum make excellent devices to heat water, one must not forget that they are only intermediaries. The objective is to heat fluid not metal. It is, therefore, sought in the future researches on solar collectors to use, especially, plastics, and many more might follow with combined advantages of suitability, mass production, cheap raw materials, and long life insurance. Replacement of glass with a layer of clear fluorescent tubes reduces the cost almost fivefold.

It is expected that within the next two decades solar energy whether transmitted through electrical lines or used to produce hydrogen will become the cornerstone in the global energy policy. In the future, wherever solar energy is abundant hydrogen can be produced without pollution and shipped to distant markets. For this purpose, the Saharan Desert in Africa can be regarded as the solar-hydrogen production area from where the hydrogen can be transmitted to consumption centers in Europe. Germany leads the afford to develop solar-hydrogen systems. There are demonstration electrolysis projects powered by photovoltaic cells already operating in Germany and solar energy rich deserts of the Kingdom of Saudi Arabia. Germany spends some $25 million annually on hydrogen research projects.

Invention of optical fibers let to extensive studies on the traditional methods of illumination and sterilization using the sun's radiation. Optic fibers provide a pathway to transmit solar beams almost anywhere. Çınar [24] has explained such transmission of solar energy from sunshine rich desert areas to consumption centers. The solar radiation incident on the Fresnel lens is focused at a point where the entropy of the system is greatly reduced. If the temperature of the focused place is 300 °C and the ambient temperature is 27 °C, then the entropy of the focus is reduced by about half. Searching for similar entropy reducing natural phenomena is an important task in energy science. The application fields of solar energy are well known and rather traditional but new technology is having an impact and will eventually put into practical use.

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