Part I

Polymeric Materials for Solar Thermal Applications, First Edition. M. Köhl, M.G. Meir, P. Papillon,
G.M. Wallner, and S. Saile

1 Principles

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1.1 Introduction

Apart from fossil and nuclear energy sources, so-called renewable energy is available. The already located and predicted resources of fossil fuels and fissile materials evidently underline that in a limited system like the earth only renewable energy can assure a long-lasting existence. Three categories of renewable energies, based on different primary sources, are available:

- solar energy: thermonuclear (fusion) processes in the sun;
- geothermal energy: residual heat from the genesis of earth and decay of isotopes inside the earth;
- tidal energy: gravity caused by planetary (orbs) motion.

Within the ability and experience of humankind only these energy sources are inexhaustible.

Renewable energy like heat in the upper lithosphere or wind is a mixture of two or more primary sources. In the case of heat in the upper lithosphere geothermal and solar energy are relevant, for wind the rotation of earth, planetary motion, and solar irradiance are important.

The largest flux of energy available on earth is solar irradiation. The total power emitted by the sun is approximately 380×10^{18} MW. This corresponds to 62.6 MW m^{-2} related to a surface calculated from the diameter of the sun. Even sources with high capacity too, the potential of geothermal and tidal energy are orders of magnitude smaller than that of solar irradiation.[1)]

The energy emitted by the sun results from different fusion processes (mainly the fusion of $4H^+$ to 1He). Owing to the distance between the sun and earth (approximately 1.5×10^8 km) the electromagnetic radiation arrives at the outer atmosphere highly diluted, with a power density of approximately 1367 W m^{-2}. This so-called *solar constant*, measured outside the atmosphere, has a fluctuation range of about

1) Solar energy approximately 5.6×10^6 EJ a^{-1}; geothermal energy approximately 9.7×10^2 EJ a^{-1}; tidal energy approximately 9.4×10^1 EJ a^{-1}.

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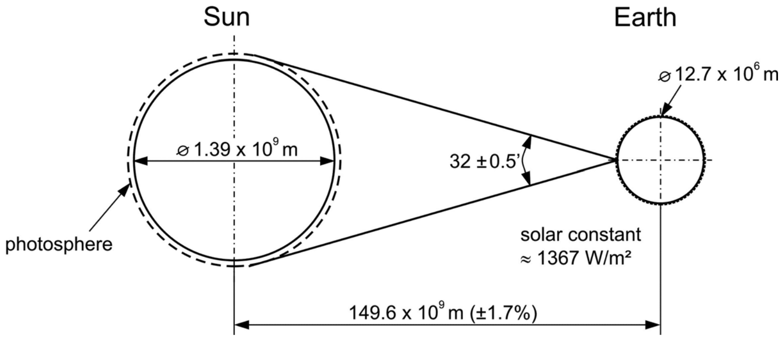

Figure 1.1 Geometrical proportions between the sun and the earth.

±3.5% that is mainly caused by the variation of the distance between the sun and the earth, sun activity, and sunspots (Figure 1.1).

The fraction of energy reaching the earth is only $0.045 \cdot 10^{-6}$% of the amount emitted by the sun. Related to this the actual worldwide primary energy consumption is less than 0.01%.

Outside the atmosphere electromagnetic radiation from the sun consists of wavelengths in a range 10^{-20} to 10^4 m. However, solar radiation is mainly emitted in wavelengths between 0.2 and 5 μm. Approximately 90% of the radiation is emitted with wavelengths between 0.3 and 1.5 μm, reaching from the near UV-B to UV-A, visible light, and near-infrared. The sun radiates similarly to a black body with a temperature of approximately 5800 K. For most of the radiation the atmosphere is practically opaque; however, an optical window that is transparent for wavelengths in the range 0.29–5 μm enables radiation with a total power of approximately 1000 W m^{-2} to pass. While even further diluted while passing through the atmosphere, the aforesaid optical window enables more than 90% of visible light within the solar spectrum to reach earth's surface. In the range 0.38–0.78 μm visible light represents almost 50% of the transmitted energy. This range is most important for the biosphere and also for technical use.

Figure 1.2 gives the spectral distribution of solar radiation outside the atmosphere. The range shown contains approximately 95% of the radiation power of the solar spectrum.

Extraterrestrial solar radiation (outside the atmosphere) is the sole direct radiation coming from the direction of the sun. Direct solar radiation is characterized by the capability to cause shadow and the possibility to be concentrated. On entering the atmosphere, part of this direct radiation is reflected (scattered) or absorbed by aerosols, dust, and diverse molecules (e.g., H_2O and O_3). The measure of extinction within the atmosphere depends on the amount and kinds of particles and the length of the path. In this respect and for calculating of the solar irradiation that is available on earth, the so-called *air mass* is an important figure. For solar radiation with perpendicular (normal) incidence an air mass of 1 is defined. An air mass of 1.5 corresponds to an incidence angle, θ_{Zenith} of 48.19° (Figure 1.3).

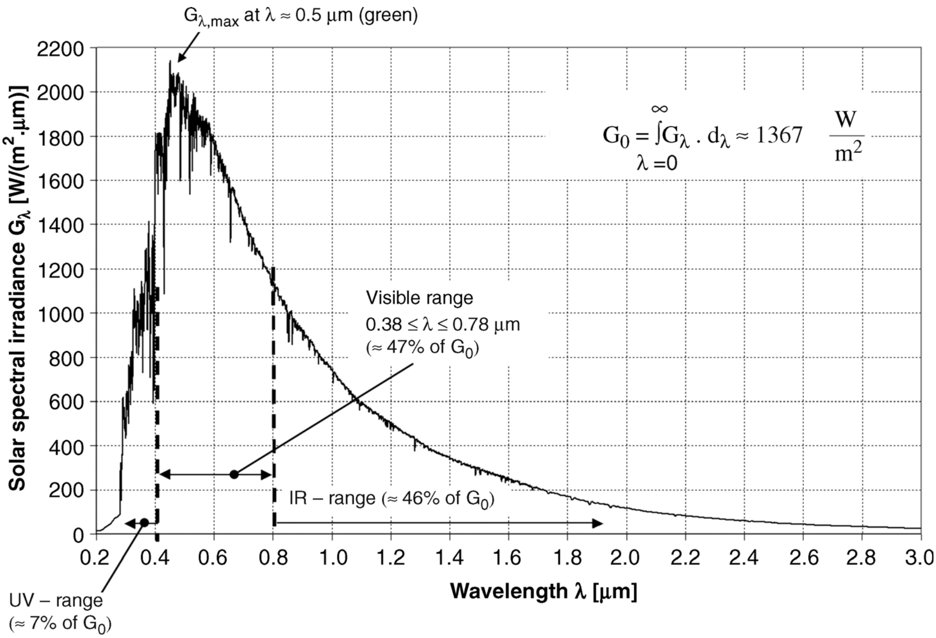

Figure 1.2 Spectral distribution of solar radiation outside the atmosphere.

The scattered part of the direct radiation becomes diffuse radiation. Different to direct radiation, diffuse radiation (idealised) has no defined direction and for this reason is not capable of causing shadow and cannot be concentrated.

The total irradiance that is available on earth is given by:

$$G = G_b + G_d \tag{1.1}$$

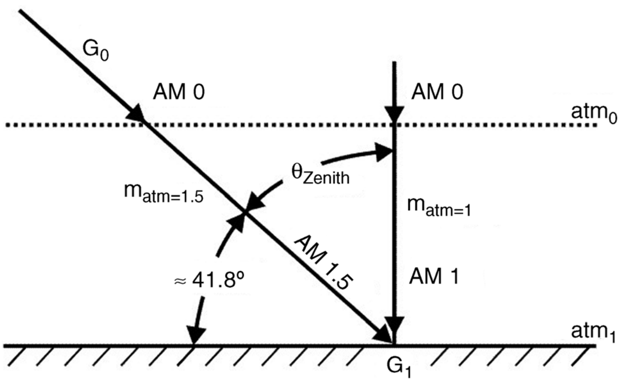

Figure 1.3 Path of solar radiation through the atmosphere.

where

G is the global solar irradiance,
G_b is the direct (beam) solar irradiance,
G_d diffuse solar irradiance.

The ratio between the radiation that is reflected to outer space by the atmosphere or after striking earth's surface and the radiation reaching the atmosphere is called *albedo*. The albedo ranges from less than 10% for forest areas to approximately 90% for fresh snow. Mainly depending on properties of the atmosphere and changes of earth's surface (e.g., ice/snow), the average albedo is around 30%. Besides the different amounts of solar energy reaching the diverse areas of the globe, particularly high values of the albedo in the Arctic and Antarctic regions are driving forces of the climate. Changes of the albedo, for example, due to melting of ice or snow, seem to cause significant climatic changes.

1.2 Solar Irradiance in Technical Applications

The energy emitted by the sun introduces different forms of appearance of solar energy on earth. Evaporation, rainfall, and melting of ice, ocean current and waves, movements and heating of the atmosphere and earth's surface, as well as the production of biomass are typical forms where solar energy appears, often indirectly. Photovoltaics and solar thermal systems represent almost direct ways of using solar irradiance by involving technical equipment. While photovoltaic is the direct conversion of sunlight into electricity, the thermal utilization of solar energy is versatile and characterized by numerous different applications. Solar thermal systems are applicable even where heat up to several hundreds degree centigrade is needed, for instance in industrial processes. Compared to photovoltaics, thermal applications often show advantages in efficiency and the comparatively simple feasibility of storage, even on large scales.

As described above, the fraction of extraterrestrial radiation hitting earth's surface, and hence technical equipment for using solar irradiance, depends on the air mass, that is, on the length of the optical path through the atmosphere in combination with the cloudiness and haze. After passing through the atmosphere the available irradiance consists of a direct and a diffuse part. In general, technical applications might use both direct and diffuse irradiance. In particular constructions, such as concentrating collectors or facilities with heliostats and central receivers, only direct irradiance can be utilized.

1.3 Quantifying Useful Solar Irradiation

For solar thermal applications and photovoltaic systems, but also with regard to passive use of sunlight in buildings, the amount of irradiation on surfaces with different orientations can be calculated. With respect to detailed performance predictions, particularly for solar thermal systems, the fractions of direct and diffuse irradiance on any surface have to be determined separately. As discussed, in the case of concentrating systems, knowledge of the direct irradiation is most important.

For direct irradiation, equations mainly referring to geometrical relations are available. For diffuse irradiation, geometric basics have been combined with correlations and models derived from empirical investigations and findings. In general the solar irradiance available on a horizontal surface ranges from around 100 W m^{-2} for a totally dull sky with only diffuse sunlight to more than 1000 W m^{-2} under clear sky conditions. Between these values the available amount of irradiance depends on the position of the sun in the sky, the cloudiness, and extinction processes within the atmosphere. In Central Europe, during a year roughly half of the irradiation is direct while the other half is diffuse irradiation. During winter the fraction of diffuse irradiance might reach 70%; however, approximately 75% of the irradiation reaches Central Europe between April and September. The amount of solar irradiation on one square meter horizontal surface per year is approximately 900 kWh in Northern Europe, around 1100 kWh in Central, and about 1400 kWh in Southern Europe. Within the sunbelt of the globe the yearly solar irradiation may exceed 2200 kWh m^{-2}. Notably, independent of the location or time within the year the irradiance perpendicular (normal) to a surface might exceed 1000 W m^{-2}. This is valid for all areas of the globe, whether having lavish sunshine like Africa or lower irradiation like regions at higher latitudes, for example, in Central or Northern Europe. Evidently, the differences in annual irradiation on a horizontal surface in various regions are caused mainly by the angle of incidence at the locations, the hours of sunshine, and the fraction of diffuse irradiance.

As the availability of solar irradiation on the globe is different between regions, the average ambient temperature differs as well. A rough classification reveals a correlation between regions with high solar irradiation and high ambient temperatures and regions with lower solar irradiation and lower ambient temperatures. Nevertheless, exceptions in both directions are common. For example, according to Meteonorm 5.1, with approximately 3.3 °C the average ambient temperature of Davos in Switzerland is quite low, while the irradiation on a horizontal surface reaches 1380 $\text{kWh m}^{-2}\,\text{h}^{-1}$ – a fairly high value – for Central Europe.[2)]

With respect to solar thermal collectors, as well as the irradiance the ambient temperature, inducing heat losses, is an important parameter.

1.4
Solar Thermal Applications

In combination with solar thermal systems the available amount of solar irradiation enables an economic use of solar energy and significant savings of conventional

2) Meteonorm is a global meteorological database for applied climatology, developed by Meteotest in Bern, Switzerland (http://meteonorm.com/).

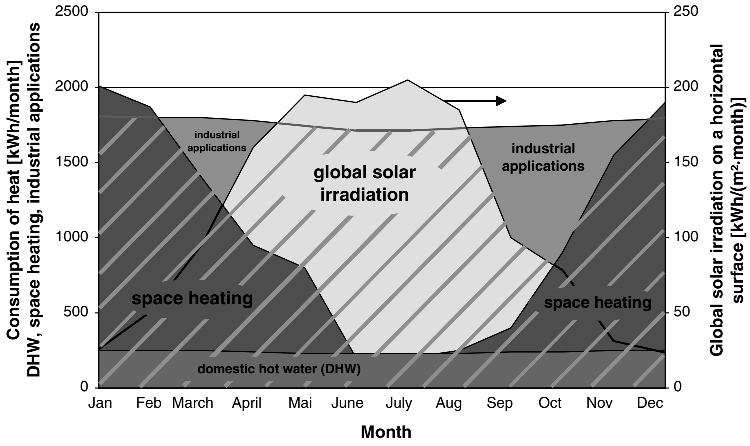

Figure 1.4 Global solar irradiation on a horizontal surface in Central Europe and different heat demands in households and industry in schematic manner.

energy sources. In particular in a temperature range below 130 °C, which is the main focus for solar collectors equipped with polymers, space heating, domestic hot water preparation, and approximately 50% of the heat that is demanded by industry can be supported.

However, solar thermal systems are used over a much wider temperature range. On the basis of different operating temperatures in IEA-SHC Task 33, Solar Heat for Industrial Processes (http://www.iea-shc.org/task33/), three different fields of thermal applications for solar energy have been defined (Figure 1.4):

Low temperature, below 20 up to 250 °C:

- pool heating,
- domestic hot water,
- space heating and cooling,
- solar drying, distillation, pasteurization, sterilization (e.g., of potable water),
- food, paper, textile, and chemical industry.

Medium temperature, 250–400 °C:

- solar cooling and air conditioning,
- process heat in various industry sectors,
- power stations for electricity generation,
- petroleum industry and heat treatment of metals.

High temperature, from 400 up to approximately 1700 °C:

- heat treatment of metals, metallurgy,
- process heat for cement, glass, and refractory industry,
- power stations for electricity generation, for example, tower concepts.

In all solar thermal applications solar irradiance is absorbed and converted into thermal energy. With respect to the particular ways of utilizing solar irradiance, passive and active use can be distinguished. A typical example for passive use is heating of buildings with solar irradiance entering the house through windows. This well-known kind of solar heating is particularly effective if the windows are equipped with glass. As glass is much more transparent to visible light and other high-energy wavelengths emitted by the sun, than for infrared radiation emitted by the floor, walls, and furniture in a house that have been heated by absorbing solar irradiance, solar energy is trapped. This so-called *greenhouse effect* is also present considering the globe, with the earth's surface as absorber and the atmosphere as transparent cover; technically it is applied and optimized in all kinds of solar thermal collectors featuring transparent covers.

From the absorber of a solar collector the heat is in most cases removed through a heat transfer medium, while in a few cases solar irradiance is directly absorbed by the heat transfer fluid. Commonly used fluids for heat transfer in solar heating systems for houses are water or mixtures of water and antifreeze/anticorrosion, in particular applications air or specific oils are employed. On leaving the collector, the heat is either transferred directly to the consumer and consuming devices, such as radiators or floor heating, or it is transferred to a heat store. Heat stores are introduced to decouple the supply of energy from the sun and other heat sources from the demands. Heat stores enable a level, high availability of energy at times without equal demand and vice versa; furthermore, they can supply energy with a power exceeding that of the original energy source. The capacity of heat stores range from several hours up to some days or a few weeks. In the case of pool heating, the pool water is a store with high capacity. A particular approach is the construction of seasonal stores designed to keep solar heat from summer for space heating and domestic hot water preparation during winter.

In some industrial applications and in the case of floor or wall heating an instantaneous supply of heat directly from a solar thermal system to the consumer might be possible.

In most applications the connection between the collector and the store or directly to the consumer is made by insulated pipes – in the case of air as heat transfer medium in the form of air ducts. Unless the motion of the heat transfer fluid is caused by gravity, introduced by differences in the density of the fluid between the collector and the store or consumer due to temperature differences, a circulation pump (or fan) has to be present in the collector loop.[3)] A controller determines the starting and stopping of this device as well as other temperature or time dependent operations. Thus, apart from the collector and the store the controller is another important component of many solar heating systems.

In cases where the amount of solar energy is not sufficient, auxiliary heating might be installed.

3) Circulation caused by gravity (thermosiphon effect) can only be achieved in cases where the store or the consumer is located above the collector. Today, for most technical applications in Central or Northern Europe the opposite is the case.

1.5
Calculating the Solar Contribution

The amount of heat delivered by a solar heating system can either be measured or calculated. Measurements are common for billing, system investigation and optimization, and, furthermore, for trouble-shooting in exiting set-ups. Calculation and numerical simulation of solar thermal systems are helpful to support general decisions during planning and design and in general cases of building and (re)construction.

Besides calculation "by hand", personal computers with simple spreadsheet programs and programs for numerical system simulation are available. Owing to interactions of the components in solar heating systems and the dependency of system performance on different transient parameters, for example, weather conditions and loads, the applicability of static calculations is limited. For several decades numerical simulation has been a well-established method that can take various system designs, load structures, and climatic conditions into account.

In cases where solar energy is not the only source supplying heat, the fraction of energy delivered by the sun and the amount of energy delivered by other sources are of interest. To define the fraction of energy delivered by the solar part of a heating system and thus, for example, the savings of conventional energy, depending on varying system designs, different methods are proposed. As a general and simple approach, universal for all kinds of solar heating systems, the fraction of energy delivered by the solar part, f_{sol} can be calculated as:

$$f_{sol} \frac{Q_{load} - Q_{aux}}{Q_{load}} 100\% \tag{1.2}$$

where

f_{sol} is the solar fraction of a given system,
Q_{load} is the total heat load to which f_{sol} is referred to,
Q_{aux} is energy supplied by heat sources different from solar.

In many cases Q_{aux} is the auxiliary heat delivered to the system if the solar contribution is not sufficient.

In this definition the kind of auxiliary heating and its individual performance are included and not taken into account separately. The solar fraction f_{sol} typically accounts for net energy and allows a rough and easy understandable calculation of the solar contribution. In the literature, other performance indicators are defined, such as the fractional energy savings f_{sav}. Particularly for solar heating systems for houses, detailed information is given in the results of IEA-SHC Task 26.

1.6
Conclusions

The energy content of solar irradiation that is available on earth is several orders of magnitude larger than world's energy consumption of today. Even in countries not situated in the sunbelt of the globe, the most of the needed energy can be provided by solar irradiance using available techniques.

With respect to Europe almost half of the final energy consumption is connected to the production of heat, the major part for heating of buildings. In the European Union currently approximately 75% of energy consumption in buildings is related to space heating and the preparation of domestic hot water. Besides the housing sector, considering industry within Europe, approximately $^2/_3$ of energy consumption is in the form of heat. About 30% of this heat is used at temperatures below 100 °C – which is easy to provide with solar thermal systems.