The impact of high latitudes on the optical design of solar systems

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Abstract

Irradiation distribution functions based on the yearly collectible energy have been derived for two locations; Sydney, Australia which represents a mid-latitude site and Stockholm, Sweden, which represents a high latitude site. The strong skewing of collectible energy toward summer solstice at high latitudes dictates optimal collector tilt angles considerably below the polar mount. The lack of winter radiation at high latitudes indicates that the optimal acceptance angle for a stationary EW-aligned concentrator decreases as latitude increases. Furthermore concentrator design should be highly asymmetric at high latitudes.

Introduction

Consider a stationary solar thermal collector or a photovoltaic panel. A conventional wisdom has evolved that is based upon low-to-mid-latitude sites: collectors should be aligned at zero azimuth and collector tilt equal to the local latitude. Yearly energy delivery is then maximized. Generation and analysis of the yearly distribution of collectible solar radiation, as a function of the angle projected in a north-south vertical plane, provide the key quantitative information for arriving at this conclusion. The north-south vertical plane is the same as the meridian plane of the concentrator trough for stationary low-concentration devices with the absorber axis east-west.

The yearly cumulative collection time as a function of projected incidence angle is derived on a purely geometric basis, i.e., based on solar motion. It is a symmetric distribution centered at the equinoxes and with two peaks at the solstices, as shown in Fig. 1 (Larson and Acquista, 1980). This kind of diagram is similar for all locations, the only difference being that the horizon will block direct irradiation for projection angles greater than ($\pi/2$ - latitude) on the side representing the solar position during winter. The projected incidence angle is of interest since it is the angle based upon which direct irradiation is accepted or rejected in stationary trough (2D) concentrators.

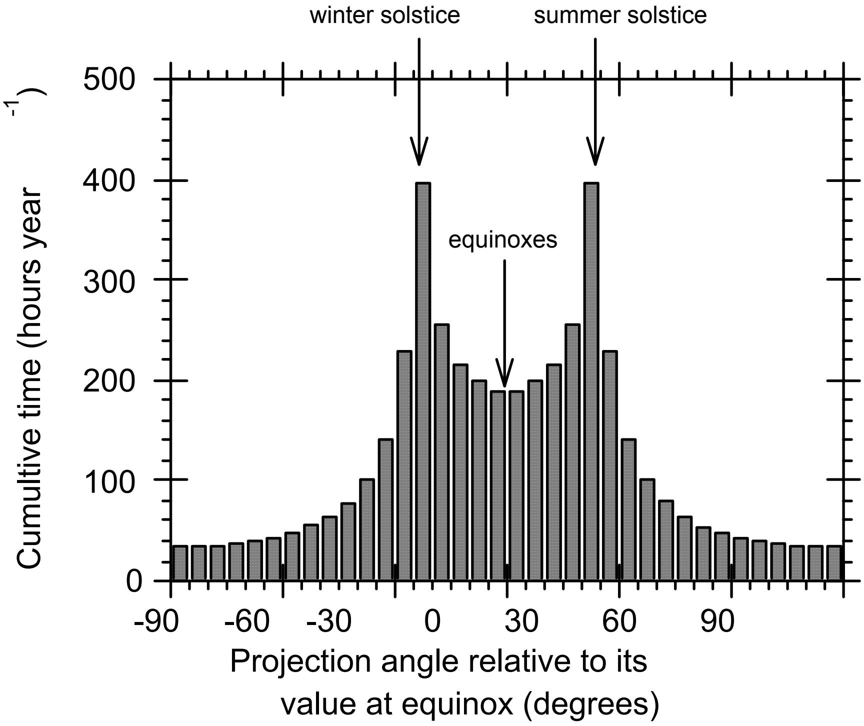


Figure 1. The annual cumulative time distribution function, as a function of projected incidence angle of the sun in the north-south vertical plane

Latitude dependent irradiation distribution functions

Previous analyses have related to the *time* rather than to the *irradiation* or *collectible energy* distribution function. Proper collector optimization must be based upon the latter. In order to derive irradiation distribution functions based on real climatic data for a specific site, we relate to the south projection angle $\theta_{p,NS}$ shown in Figure 2. For a specific location of the sun, the direct irradiation is projected

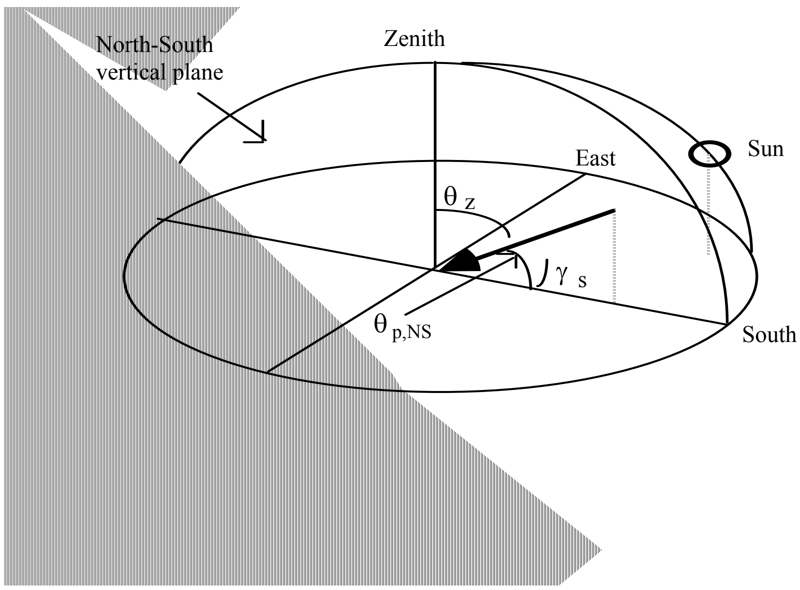


Figure 2. Definition of the south projection angle $\theta_{p,NS}$, which is the projection of the sun position vector onto a north-south vertical plane. θ_z = solar zenith angle; γ_s = solar azimuth angle.
into the north-south vertical plane, shown by the black arrow in Figure 2, and therefore $\theta_{p,NS}$ is the angle between the projection of the sun and the south horizon. The diffuse irradiation is assumed to be isotropic, for which all angular intervals of $\theta_{p,NS}$ will contribute with an equal part of diffuse radiation.

Figure 3 shows the sample results of typical-meteorological-year solar radiation data from Sydney, Australia (Morrison and Litvak, 1988), located at latitude 33.9 degrees south. The corresponding figure for Stockholm, Sweden, located at latitude 59.5 degrees north, is shown in Figure 4. In both figures, the yearly extraterrestrial irradiation (which of course is purely direct) is indicated for comparison. The graphs for extraterrestrial irradiation follow the trend of the annual cumulative time distribution function in Figure 1.

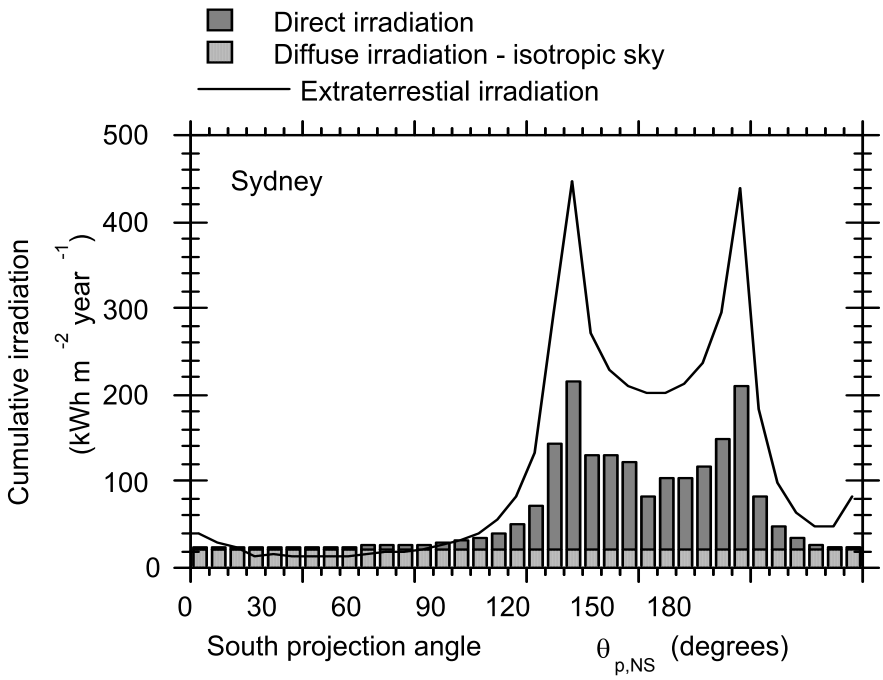


Figure 3. Cumulative irradiation distribution function for Sydney, Australia (latitude 33.9 degrees South), as a function of projected incidence angle in the north-south vertical plane.

The annual collectible energy H_T on any surface with azimuth 0° and a specified tilt β relative the north can thus be calculated by summing the incident irradiation H_i from each angular interval *i*

$$H_T = \sum_i H_i \cos(90° - \theta_{p,NS,i} - \beta)$$

Similar distribution functions for surfaces with other azimuths or tilted projection planes can easily be derived.

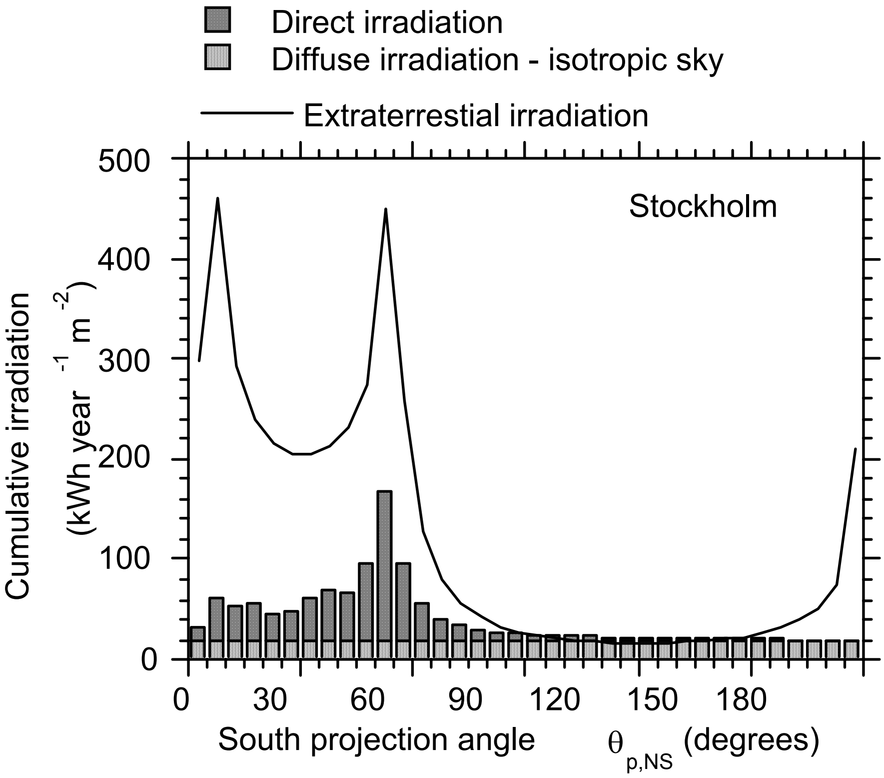


Figure 4. Cumulative irradiation distribution function for Stockholm, Sweden (latitude 59.5 degrees North), as a function of projected incidence angle in the north-south vertical plane.

While the irradiation distribution function for Sydney has two clear peaks for the solstices, the winter peak is barely evident in the irradiation distribution function for Stockholm. This is due to large solar zenith angles for direct radiation during the winter months in Sweden, which results in substantial absorption of the direct radiation in the atmosphere. While time distributions are purely a function of sun-earth geometry, the collectible energy distributions also fold in the effects of air mass and local climate.

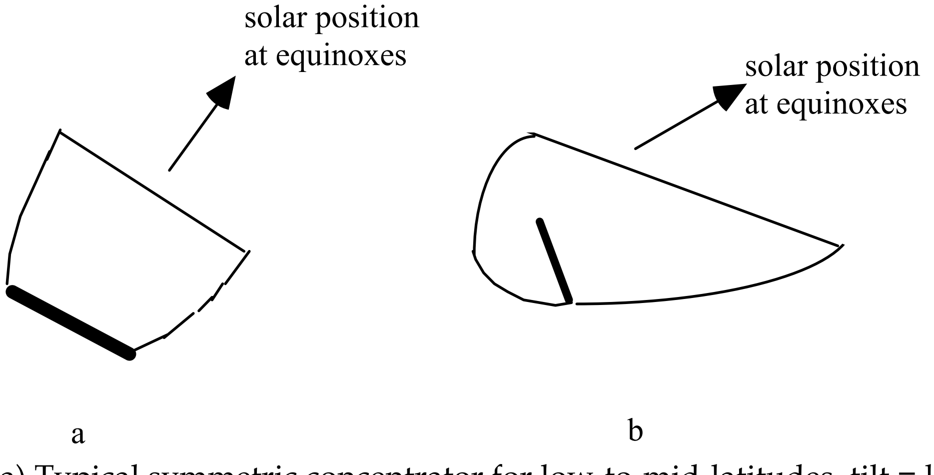
Discussion

From the irradiation distribution functions presented in Figure 3 and 4, some general conclusions can be drawn which point out differences in the preferred optical design of stationary solar energy systems between low-to-mid-latitude sites and high latitude sites:

a) The rule of thumb of the polar mount (tilt = latitude) maximizing yearly collectible energy is not valid for high latitudes since the irradiation distribution function is highly asymmetric. The optimum tilt is determined primarily by the position of the summer peak in Figure 4. The optimum tilt for mid Sweden (latitude = 60 degrees) is therefore $\beta \approx 45$ degrees.

b) The required acceptance angle θ_a for a stationary EW-aligned concentrator decreases - and hence achievable concentration increases - as latitude increases. If the collector operating threshold is taken into account, this point is even more pronounced since winter radiation has a low intensity and contributes only marginally to collector output when the latitude is greater than around 60 degrees.

c) The asymmetric irradiation distribution at high latitudes means that asymmetric EW-aligned Compound Parabolic Concentrators [Welford and Winston, 1989] are attractive. An EW-aligned concentrator for low-to-mid-latitudes is often symmetrical as shown in Figure 5a with its glazing normal to the solar position at equinox, this position being the mean position of the angular interval of interest for concentration. For high latitudes, the mean position of the angular interval of interest for concentration, and the direction of the concentrator for maximum annual collection, do not coincide. When the concentrator is truncated, it is often advantageous to truncate the reflector so as to reject radiation from angular intervals which have a low energy weighting, and to accept irradiation during the main peaks (Mills and Giutronich, 1978). The resulting asymmetric concentrator was described by Rabl (1976) and by Mills and Giutronich (1978). These stationary asymmetric concentrators have an effective concentration that changes with incidence angle. Usually, they are not designed for maximum *annual* energy delivery, but rather are tailored to fulfil the energy demand during specific limited periods of the year. A typical asymmetric concentrator for high latitudes therefore looks like Figure 5b. This concentrator is designed for the Stockholm climate and will accept all radiation in the range 20 degrees < $\theta_{p,NS}$ < 65 degrees. This concentrator is designed for reflector economy and high efficiency per ground area.



<u>Figure 5</u>. a) Typical symmetric concentrator for low-to-mid-latitudes, tilt = latitude. b) Proposed asymmetric concentrator for high latitudes (60 degrees North), tilt ≈ 20 degrees.

Summary

Irradiation distribution functions are a convenient and fast way to illustrate the availability of solar energy for stationary concentrators, and to identify optimal configurations quickly. Compared to time distribution functions, the distribution functions based on collectible energy can show a large asymmetry for high latitudes due to large atmospheric absorption of solar radiation. This implies significant latitude-dependent differences in the optical design of solar systems.

References

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