Paper presented at North Sun'99, Edmonton, Alberta, Canada, August 11-14, 1999

THE ORIGIN OF THE ASYMMETRY IN THE IRRADIATION DISTRIBUTION AT HIGH LATITUDES

Mats Rönnelid
Solar Energy Research Center, EKOS, Högskolan Dalarna, S-781 88 Borlänge, Sweden, phone +46 23 778712, fax +46 23 778701, email: mrd@du.se

Abstract

The possibility of using solar energy during winter depends on the available solar radiation and on the geometry of the receiving surface. For high latitudes, the annual distribution of the available radiation is characterized by high asymmetry with a large amount of solar radiation from high altitude angles during the summer and a small amount of direct radiation from small altitude angles during the winter. This article deals with the origin of the difference between available solar radiation during summer and winter at high latitudes. Factors like the tilt of the earth's axis, the eccentricity of the earth's orbit, absorption and scattering of radiation in the atmosphere and seasonal changes in the weather conditions are discussed. Numerical examples of how these factors contribute to the reduction of the winter radiation compared to the summer radiation on surfaces with different orientation in Stockholm, latitude 59.4°N, are given. It is shown that the influence of the atmosphere and seasonal changes in the climate, and not pure earth-sun geometry, are the main reasons why it is hard to utilize solar energy at high latitudes during the winter.

1. Introduction

This paper deals with the question of why we have so little output from solar energy devices, such as solar collectors or solar cells, during the winter compared with the summer at high latitudes. At low- to mid-latitude sites, purely geometrical aspects such as the earth-sun geometry are most important for understanding the performance of different solar energy technologies. However, the large solar zenith angles at high latitudes imply a considerable influence by the air mass on the performance (Rönnelid, 1999). Therefore, experiences from low latitudes on how the performance of solar energy systems changes during the season can not be transfered to high latitudes, and vice versa. It is, therefore, important to have knowledge of the origin of the change in irradiation over the seasons at high latitudes in order to understand the conditions for different solar energy technologies at different latitudes.

2. Irradiation distribution at high latitudes

Fig. 1 shows the irradiation distribution at four different European sites located at latitude 38 - 65°N. These graphs are produced by dividing the radiation component into two vectorial components; one aligned east-west and one in the north-south vertical plane. Since the east-west component never contributes to the irradiation on a south-facing surface (which is assumed in this study), only the component in the north-south vertical plane has to be summarized (Rönnelid and Karlsson, 1997). The direction of this component is defined by the south projection angle $\theta_{p,NS}$ which is the angle between the projected radiation and the south horizon.

The irradiation distribution diagram for low- to mid-latitude sites is more or less symmetrical with two clear peaks for the solstices. For sites at higher latitudes, the irradiation distribution diagram is changed in two ways. First it is moved towards lower south projection angles. Secondly the winter peak is reduced and the annual irradiation distribution becomes asymmetrical.

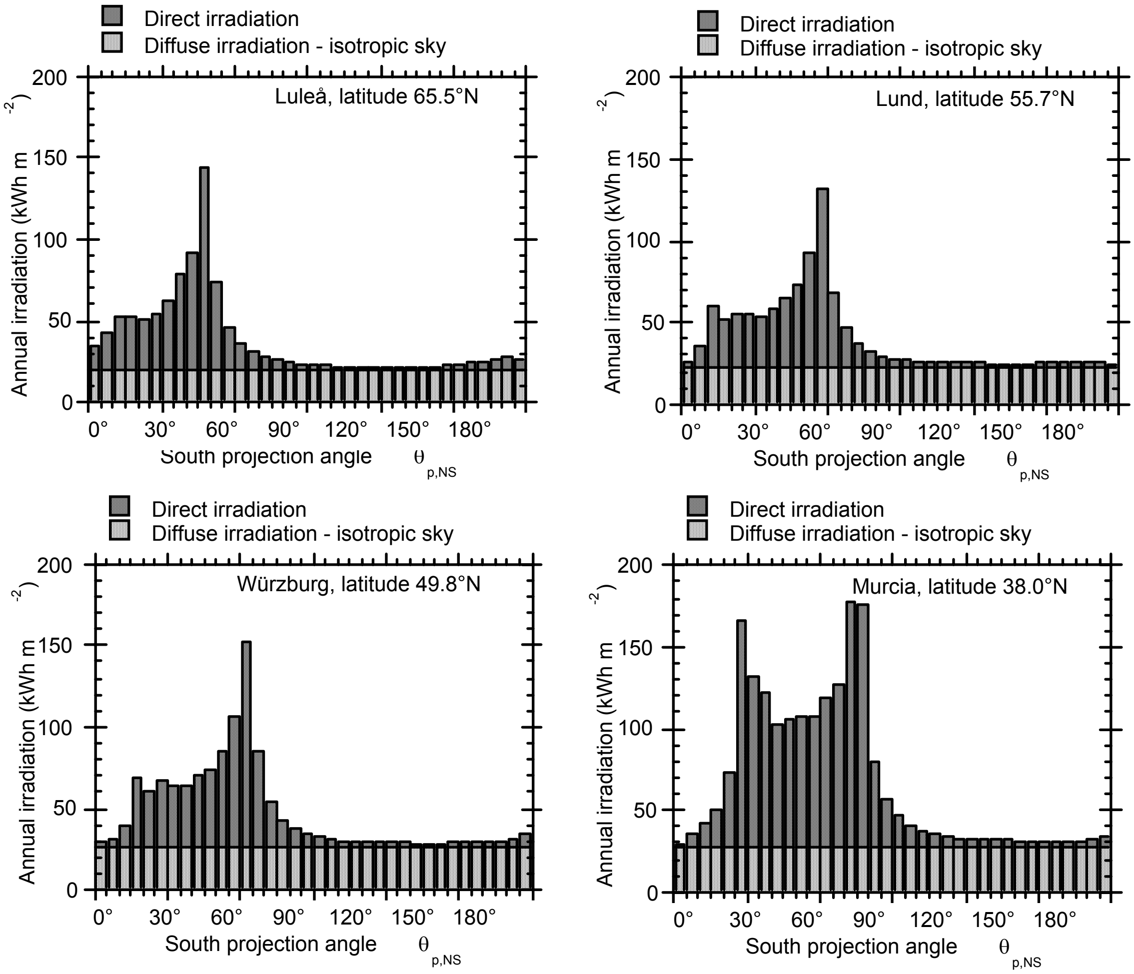


Fig. 1. Annual irradiation projection diagrams for four locations at different latitudes. The diagrams for Luleå and Lund (Sweden) are derived from hourly radiation data from 1983-91. The other diagrams are derived from daily radiation data: Würzburg (Germany) from 1990, 1991 and 1993, and Murcia (Spain) from 1988-90 and 1991-92.

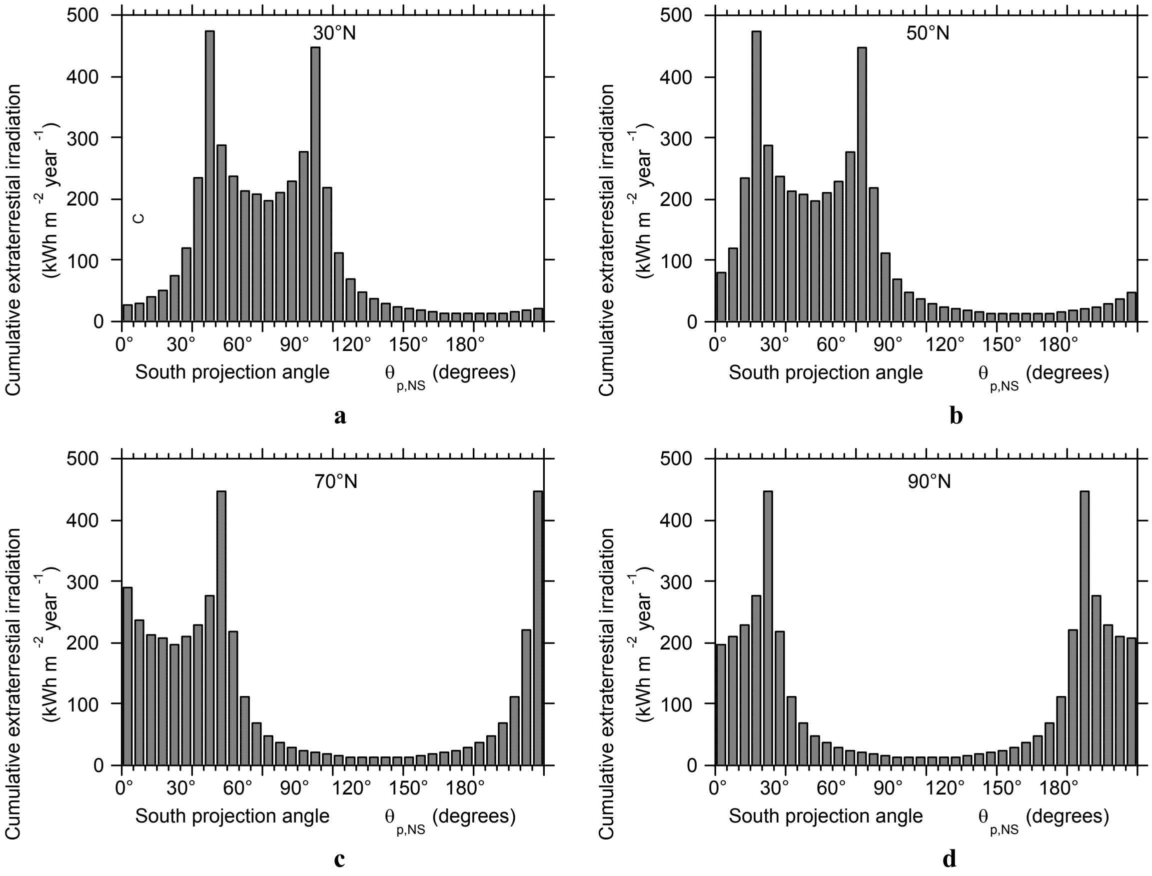
There are several reasons for the change in irradiation distribution when moving to higher latitudes and these are to some extent connected to one another. The most important factors that influence the shape of the irradiation distribution diagram are discussed one by one below.

2.1. The tilt of the polar axis.

The tilt of the polar axis relative to the normal of the earth's orbital plane, together with the earth's motion around the sun, are the basic reasons for the general shape of the annual irradiation distribution. If the polar axis were perpendicular to the orbital plane, day and night would always be of equal length and the irradiation distribution diagram would have only one narrow peak, since the projection of the radiation in a vertical plane from north to south would always be the same. Due to the 23.45° tilt of the polar axis, the sun will be at different solar declinations during different seasons. Since the declination only changes slowly near the summer and winter solstices, radiation from directions near noon at the solstices will be overrepresented, which explains the two peaks separated ± 23.45° in the irradiation distribution diagrams for low- to mid-latitude sites.

As long as we are at lower latitudes than the polar circle, there will be an (almost) equal contribution of extraterrestrial irradiation to the summer and winter peak. Therefore, the general shape of the irradiation distribution diagram for extraterrestrial irradiation will not change with latitude, but only move to lower (or higher) values of $\theta_{p,NS}$; that is to the left (or to the right) in the diagram.

To illustrate this, figure 2 shows the irradiation distribution of extraterrestrial irradiation for four different sites in the northern hemisphere, situated at latitude $\phi = 30°$, 50°N, 70°N and 90°N. It is seen that when the site is above the polar circle ($\phi > 66.5°$N) the ”winter peak” appears at extreme large values of $\theta_{p,NS}$. However, the radiation contributing to these peaks does not come from radiation during the winter half of the year, but from radiation around midnight during periods of the summer with midnight sun.



a **b**

c **d**

Fig. 2. The annual irradiation distribution of extraterrestrial irradiation for four different sites in the northern hemisphere.

2.2. Eccentricity of the earth’s orbit.

The variation of the earth-sun distance leads to variation in extraterrestrial irradiance G_{on} in the range ± 3%. According to (Duffie and Beckman, 1991)

$$G_{on} = G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right) \tag{1}$$

where n is the day number of the year. G_{sc} is the solar constant which is 1353 W/m^2. The earth is closest to the sun at the end of December / beginning of January. This influences the irradiation distribution for extraterrestrial irradiation at northern latitudesgiving a winter peak which is 5-6% larger than the summer peak, which can also be seen in Figures 2 a-b.

2.3. Absorption and scattering of radiation in the atmosphere.

Absorption and scattering of the direct radiation in the atmosphere are the most important factors which reduce the winter radiation at high latitudes. To calculate the direct normal irradiance G_{bn} during clear conditions, formulae presented by Meinel and Meinel (1977) and Liu and Jordan (1970) may be used.

Figure 3a shows the distribution of direct irradiation for Stockholm, based on measured radiation data from nine years. Calculated values of the direct irradiation distribution when clear weather has been assumed, are also included in Figure 3a. To allow comparison between the direct irradiation diagrams based on measured and calculated values for clear sky conditions, the two diagrams in figure 3a are presented graphically so the summer peaks for the two diagrams are at the same level. It is seen that the shape of the calculated irradiation distribution diagram for clear sky conditions agrees very well with the measured irradiation distribution diagram for $\theta_{p,NS} > 35°$.

For lower south projection angles, corresponding to the solar movement during the winter months, the winter peak is missing due to large solar zenith angles which reduce the atmospheric transmittance. However, there is a difference between the two irradiation distribution diagrams with values that are lower than expected for the diagram based on measured radiation data. Therefore the atmospheric transmittance alone cannot explain the reduction of annual irradiation for low south projection angles at high latitudes. Seasonal changes in the climate have also to be taken into account.

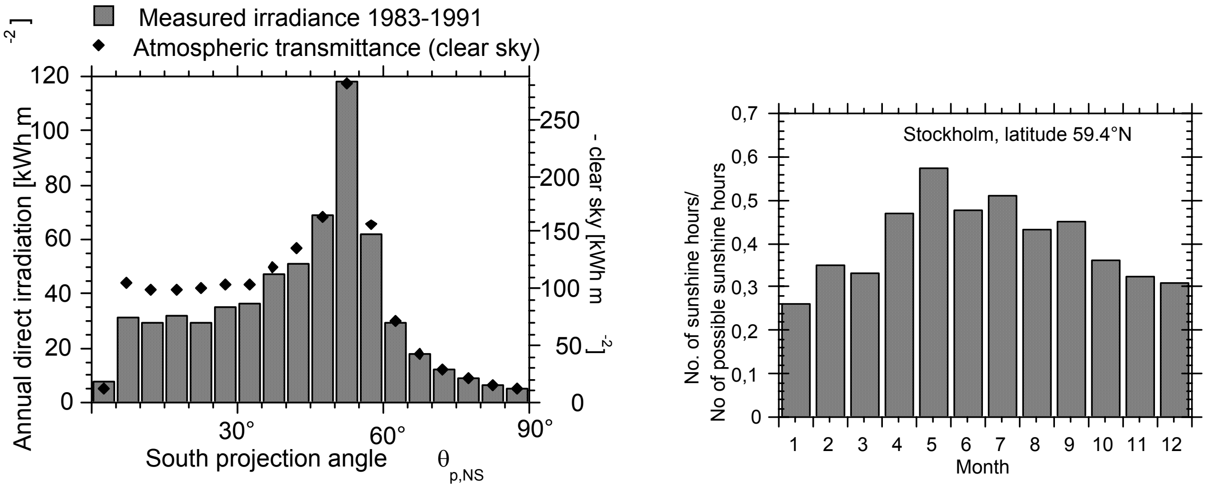


Fig. 3. a) Direct irradiation distribution for Stockholm (latitude 59.4°N) based on measured values (bars) and calculated values (dots) assuming clear sky conditions. b) Fraction of measured sunshine hours to the maximum possible sunshine hours assuming clear sky conditions. Radiation data from 1983-1991.

2.4. Seasonal changes in the weather.

During winter, the mean ambient temperature is decreased due to higher solar zenith angles and lower horizontal irradiation. These climatic changes in the environment influence the air humidity, cloudiness etc. Therefore, seasonal changes in the transmittance properties of the atmosphere can be expected. This is illustrated by fig. 3b. While there is about 50% probability of sunshine during the summer months, this probability is decreased to approximately 30% during the winter months. The lower fraction of sunshine hours during the winter means that the reduction of terrestrial irradiation due to absorption and scattering in clouds, fog and haze is larger during the winter than during the summer. Therefore, these seasonal changes in the climate explain the difference in shape between the two beam irradiation distribution diagrams presented in Figure 3a.

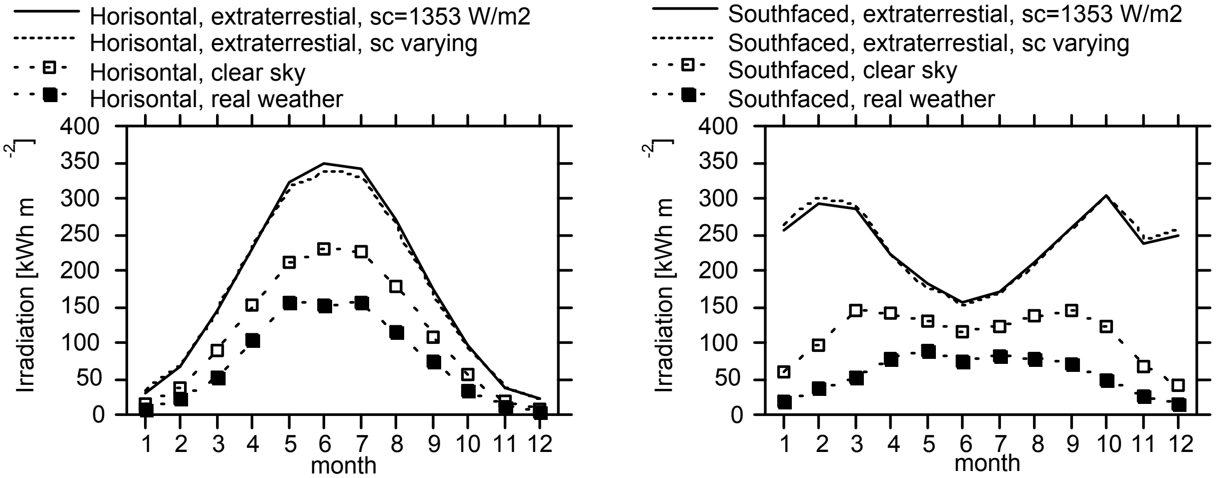
3. The origin of the reduced irradiation during winter at high latitudes - numerical example

All four factors discussed in section 2 will influence the solar irradiation and can be used to explain the difference in summer and winter irradiation at high latitudes. While the eccentricity of the earth's orbitis of minor significance for the explanation of the difference between summer and winter irradiation, the other three factors are more important. The factors discussed are not independent since the absorption and scattering of radiation in the atmosphere and the seasonal changes in the climate both have their origin in the earth-sun geometry. However, it can be illustrative to calculate their relative impact on the reduction of irradiation during the winter since this explains in more detail *why* the irradiation is reduced.

Figure 4a-b shows the calculated and measured monthly irradiation at Stockholm, latitude 59.4°N for two surfaces. Figure 4a shows the irradiation on a horizontal surface and is thus the mean energy that can contribute to heating up the earth's surface and contribute with energy input to the vegetation etc. Figure 4b shows the irradiation on a vertical south-facing surface and is therefore representative for the irradiation on a vertical south-facing solar panel or window. For each surface, four different calculations are presented:

A is the calculated extraterrestrial irradiation.
B is the calculated extraterrestrial irradiation taking into account the varying solar constant due to the eccentricity of the earth's orbit. This calculation shows the impact of the tilt of the earth's axis and the eccentricity of the earth's orbit on the irradiation.
C is the irradiation calculated by only assuming absorption and scattering of radiation in the atmosphere during clear sky conditions discussed under section 2C. These calculations show the impact of the tilt of the earth's axis, the eccentricity of the earth's orbit and the (dry) atmosphere on the irradiation.
D is the mean irradiation during nine years (1983-1991), derived from measured beam and diffuse horizontal radiation data.

Table 1 shows the calculated and measured irradiation at the two surfaces in figure 4. For each surface, the calculated and measured values are presented according to the procedures described by A - D above. The irradiation is calculated for two periods of three months each; May - July which is representative for summer and November - January which is representative for winter. The third column in table 1 shows the ratio between the irradiation during the three winter months to the irradiation during the three summer months. The difference between A and B for a certain surface shows the impact of the eccentricity of the earth's orbit on the irradiation. The difference between B and C shows the impact of the (dry) atmosphere on the irradiation, and the difference between C and D shows the impact of seasonal changes in the weather on the irradiation.



a b

Figure 4. Monthly irradiation on (a) a horizontal surface, (b) a surface with 60° tilt and (c) a vertical, south facing surface in Stockholm, latitude 59.4°N. Radiation data from 1983-1991.

Table 1 clearly tells us the origin of the difference between summer and winter irradiation at high latitudes. For a horizontal surface, the winter irradiation is about 6% of the summer irradiation. This striking reduction of horizontal irradiation is almost solely explained by the tilt of the earth's axis which alone explains the decrease of horizontal extraterrestrial irradiation during the winter to 9% of the summer amount. Absorption and scattering of solar radiation in the atmosphere is another factor that explains a further decrease in winter irradiation relative to the summer irradiation. For the irradiation on a vertical south-faced surface, the different factors discussed in section 3 play a different role than for the irradiation on a horizontal surface. If the tilt of the earth's axis, together with the eccentricity of the earth's orbit, was the only factor that contributed to the difference between summer and winter irradiation, we would expect the irradiation on a vertical south-facing surface to increase by approximately 50% during the winter months, compared to the summer months. However, during the winter months the measured irradiation on a latitude-tilted or vertical south-facing surface is less than 1/4 of the irradiation during the summer months. The attenuation of radiation in the atmosphere is the dominant effect for this reduction, but the influence of seasonal changes in the weather conditions also plays an important role.

It is a common misunderstanding, even among people in the solar energy business, that the many hours of day-light are the main reason for solar collectors working better in summer at high latitudes. This is wrong; instead it is the influence of atmosphere and seasonal changes in the climate, rather than pure earth-sun geometry, that is the main reason for the low output from solar energy devices during the winter months. One illustration of this is a study of the output from a typical south-faced solar collector during March-October at latitude 60°N (Brunström *et. al*, 1986). Although the sun is above the horizon on average for >14 hours a day during the period, 90% of the collector output is produced during the six hours when the sun is more or less to the south. During the three winter months, the mean day-length is longer than 6 hours. If pure geometrical factors were dominant for determining the output from a collector we would expect a high output also during the winter but in practice the output from a collector at latitude 60° is almost negligible during this period.

Table 1. Calculated and measured irradiation on two different surfaces during summer and winter at Stockholm.

		May-July (kWh m^{-2})	Nov.-Jan (kWh m^{-2})	Winter/Summer ratio
Horizontal surface	A	1011.5	93.9	0.093

	B	982.4	96.5	0.098
	C	670.3	43.2	0.064
	D	464.9	27.0	0.058
Vertical south-faced surface	A	512.4	742.4	1.449
	B	497.9	763.8	1.534
	C	367.4	168.1	0.457
	D	246.0	58.5	0.239

5. Summary

When looking at the potential for different solar energy technologies at different sites, it is important to understand how the available radiation changes with location. The decrease of irradiation on a given surface during the winter months at high latitudes depends on several factors. However, the importance of the different factors depends on which surface is considered. The reduction of irradiation on a horizontal surface, and thus the origin of the winter climate at high latitudes, is explained by the tilt of the earth's axis which implies large solar zenith angles and considerably reduced horizontal irradiation during winter months. On the other hand, the reduction of winter irradiation on a vertical south-facing surface depends on the asymmetrical irradiation distribution which has its origin in the attenuation of radiation in the atmosphere and seasonal changes in the weather conditions. Although the last two factors are secondary effects which have their origin in the tilt of the earth's axis, this shows that the influence of the atmosphere and the climate, and not pure earth-sun geometry, is the reason why it is hard to utilize solar energy at high latitudes during the winter.

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