THE LATITUDE DEPENDENT IRRADIATION DISTRIBUTION IN EUROPE AND ITS IMPLICATION FOR THE DESIGN OF STATIONARY SOLAR CONCENTRATORS

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ABSTRACT. When a stationary solar concentrator is designed, the spatial distribution of the available irradiation is of vital interest. An irradiation distribution based only on solar geometry will look similar at different sites. The only difference is that the distribution of the incident irradiation is shifted to lower solar altitudes when latitude is increased. However, real irradiation distribution will show strong asymmetry at high latitude sites, since the winter irradiation is reduced by absorption and scattering in the atmosphere, and by seasonal changes in the climate. The reduced winter irradiation at high latitudes implies that the available annual radiation is concentrated to a narrower angular interval. This means that the degree of concentration that is possible increases with latitude.

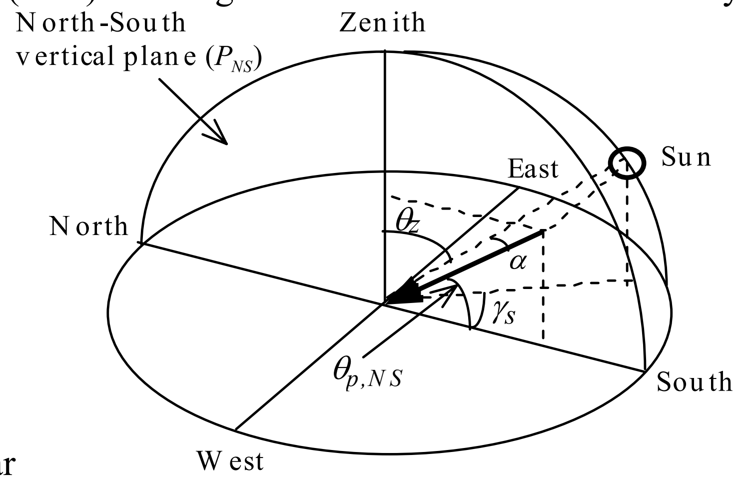
In the paper examples of irradiation distribution from different sites in Europe from latitude 38°N to 65°N are shown. The origin of the reduced winter irradiation with increased latitude is discussed, and numerical examples on the performance of different types of stationary concentrators for different latitudes are given.

1. THE IRRADIATION DISTRIBUTION FUNCTION

While studying the direct irradiance on a surface, the irradiance can be treated as a vector where the vectorial components are treated separately. Assume a surface facing south. With the division of the sun position vector into two vectorial components, one parallel with the east-west axis and one component in the vertical plane P_{NS} extending from north to south, we only have to consider the component in $P_{NS.}$ In this study, the direction of the component in P_{NS} is defined by the south projection angle $\theta_{p,NS}$, which is the angle between the projected component of the sun position vector and the south, see figure 1.

2. ANNUAL IRRADIATION DISTRIBUTION FOR EUROPEAN CONDITIONS

By adding all of radiation in $P_{N,S}$ for one year, it is possible to produce an irradiation distribution diagram (IDD) showing the cumulative radiation for the year (Rönnelid



year

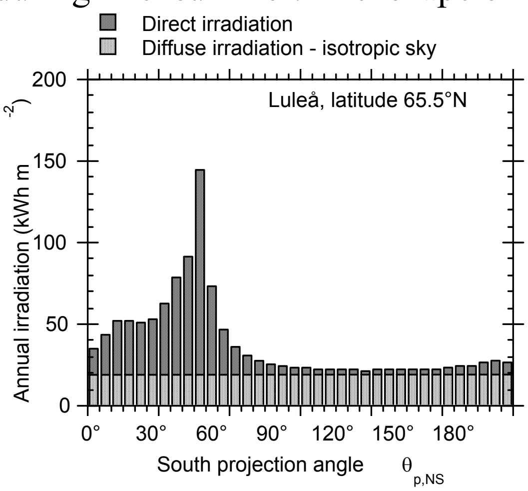
Figure 1. Definition of the south projection angle $\theta_{p,NS}$, which is the angle between the projection of the sun position vector on to a north-south vertical plane and the south horizon. θ_z = solar zenith angle; γ_s = solar azimuth angle.

and Karlsson, 1997). The IDD for low to mid latitude sites is almost symmetrical with two clear peaks for the solstices. For sites at higher northern latitudes, the IDD is changed in two ways. Firstly it is moved towards lower $\theta_{P,NS}$, secondly the winter peak is reduced and the IDD becomes asymmetric. This is illustrated in figure 2 which shows the IDD for six different European sites, located between latitude 38°N and 65.5°N.

Figure 2 is derived from radiation data from a limited number of years. Therefore these IDDs are not necessarily the same as the statistical mean function derived from data from a much longer period. However, the decrease of the winter peak with increasing latitude is clearly demonstrated.

The reason for the decreased winter peak in the IDD at high latitudes is illustrated in figures 3a-b. The bars in figure 3a show the IDD for Stockholm. Calculated values of the IDD when clear weather has been assumed are also included as dots in the figure. These calculations, which are based on observations made by Laue (1970) in the Mojave Desert of California, are assumed to be valid for clear weather with dry and clear air. Therefore the calculated values in figure 3a show the shape of the IDD when the only factors that reduce the intensity of solar radiation on the earth are absorption and scattering of the direct radiation in the atmosphere.

The shape of the calculated IDD for clear sky conditions agrees very well with the measured IDD for large south projection angles ($\theta_{p,NS} > 35°$), representative for the summer irradiation. However, there is a difference between the two cases with lower values for the monitored data for $\theta_{p,NS} < 35°$. This is explained by fewer days with sunshine during the winter months than during the summer months. This is seen in figure 3b which shows the fraction of measured hours of sunshine, defined as hours with a direct irradiance exceeding 200 [W m^{-2}], divided by the number of possible hours of sunshine if clear sky conditions are assumed. The lower relative number 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. The shape of the IDD is therefore



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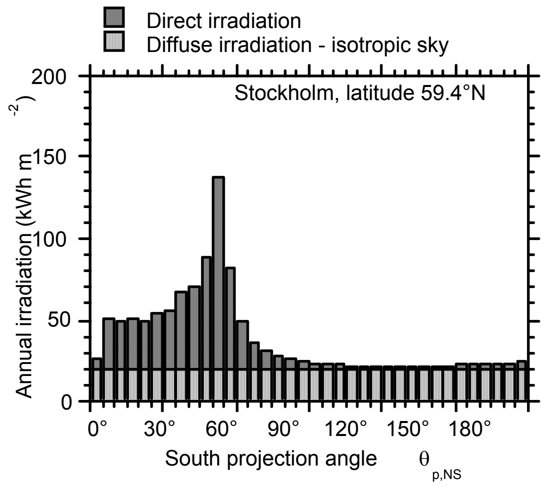

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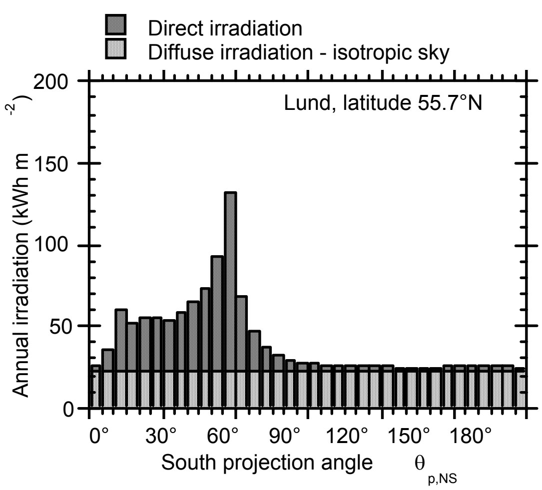

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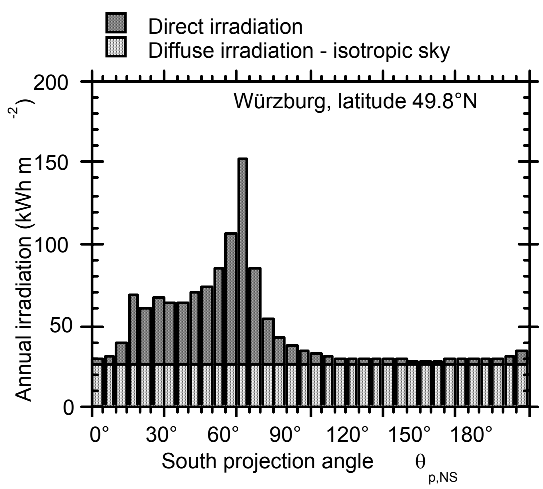

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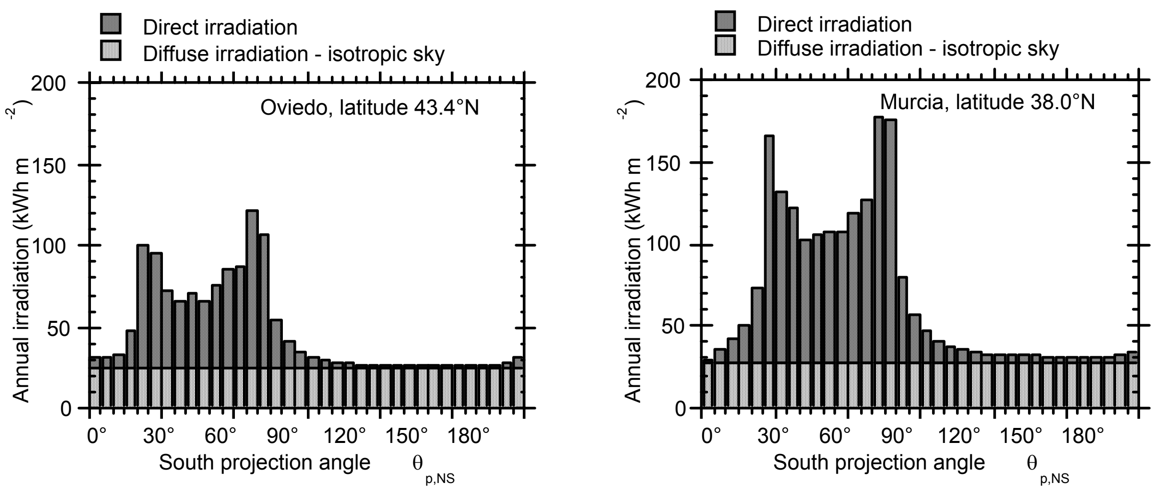

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Figure 2. IDDs for six locations. The diagrams for Luleå, Stockholm and Lund (Sweden) are derived from hourly radiation data from 1983-91. The other diagrams are derived from daily radiation data from WRDC (1998): Würzburg (Germany) from 1990, 1991 and 1993, Oviedo (Spain) from 1991-93 and Murcia (Spain) from 1988-90 and 1991-92.

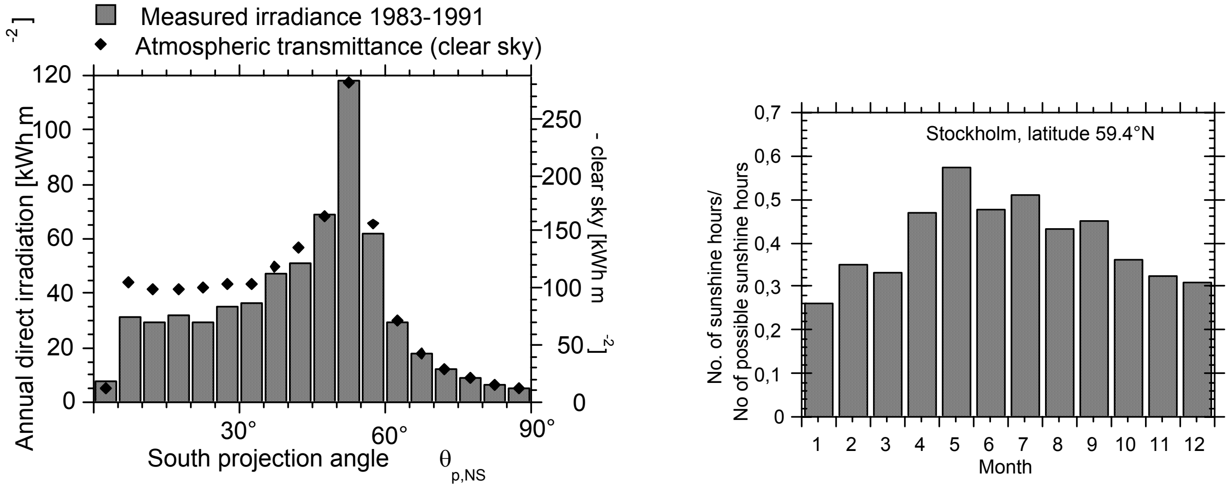

Figure 3. a) Direct IDD for Stockholm (latitude 59.4°N) based on measured values (bars) and calculated values (dots) assuming clear sky conditions. b) Fraction of measured sunshine hours to the maximum possible sunshine hours assuming clear sky conditions. Radiation data from 1983-1991.

influenced both by the attenuation of radiation in the atmosphere and by seasonal changes in the weather conditions. The former is most important for the reduction of the winter peak in the IDD at high latitudes.

3. LATITUDE DEPENDENT DESIGN OF STATIONARY CONCENTRATORS

Solar collectors are often designed to collect as much irradiation as possible. Use of a stationary concentrator implies that the view factor between the absorber and the sky is reduced. Since the maximum possible concentration from an isotropic radiation source is given by

$$C = \frac{1}{\sin(\theta_a)}, \tag{1}$$

where θ_a is the acceptance half-angle, this means that as the concentration of a solar concentrator increases, the area of the sky from which radiation can be collected decreases (Welford and Winston, 1989).

For a stationary concentrating collector such as a CPC collector, it is customary to relate the collected irradiation to a unit aperture area. Figure 4a shows the fraction of maximum annual irradiation that can be collected by east-west aligned concentrators with different acceptance half-angles in Stockholm (latitude 59.4°N) and Oviedo (latitude 43.4°N). This fraction is calculated as the ratio between the maximum collectable irradiation per unit aperture area for an ideal concentrator with a certain acceptance half-angle according to equation 1, and the maximum collectable irradiation per unit aperture area for a flat plate collector, both tilted to achieve as much annual irradiation as possible. The irradiation has been included in the total only when the total irradiance exceeds 200 [W m^{-2}] on a south-facing, 45° tilted surface in Stockholm and on a south-facing, 43° tilted surface in Oviedo. Thus the calculations are suitable for use for solar collectors with an assumed collector threshold of 200 [W m^{-2}]. For Stockholm and Oviedo, the maximum collectable irradiation on a flat plate collector was found to be 919 and 1213 [kWh m^{-2} $year^{-1}$] respectively.

For $\theta_a < 60°$, the fraction of collectable irradiation is less in Oviedo than in Stockholm if the collectors are EW-aligned. The difference between the two sites is pronounced for $\theta_a < 25°$. This is due to the lack of the winter peak in the IDD for Stockholm which makes the irradiation more concentrated to the summer position of the sun than in Oviedo.

While figure 4a is useful when the collectable irradiation per aperture area is of interest, it is sometimes also important to know the collectable irradiation per absorber area. This is, for example, the case when stationary concentrators for solar cells are to be designed. Figure 4b, therefore, shows the ratio between the maximum collectable irradiation incident on a unit area of absorber in an ideal concentrator with a certain acceptance half-angle according to equation 1, and the maximum irradiation on a unit area of a flat surface, both tilted to achieve as much annual irradiation as possible. The maximum incident irradiation on an unit area was found to be 1271 [kWh m^{-2} $year^{-1}$] in Oviedo and 1084 [kWh m^{-2} $year^{-1}$] in Stockholm.

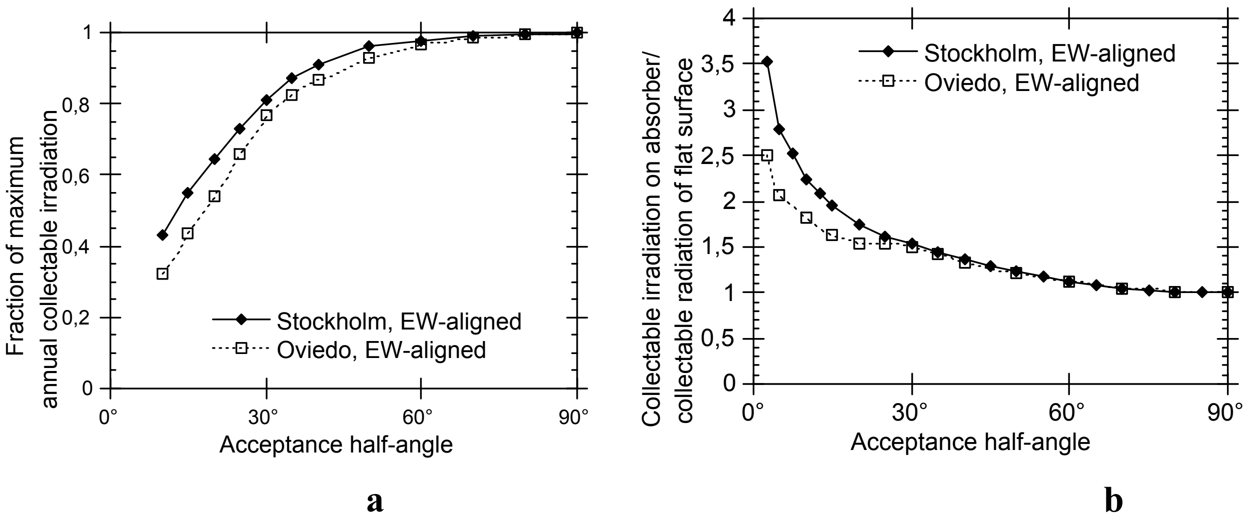

Figure 4. *a) The fraction of annual irradiation that is available for an EW-aligned CPC collector with acceptance half angle θ_a in Oviedo (Spain) and Stockholm (Sweden) compared to a flat plate collector tilted to receive maximal annual collectable energy. A collector threshold of 200 [W m^{-2}] is assumed. b) Ratio of the maximum collectable annual irradiation incident on a unit area of absorber in an ideal stationary concentrator to the maxi-mum irradiation on a unit area of a flat surface, both tilted to achieve as much annual irradiation as possible. Radiation data, see figure 2.*

The increasing annual irradiation on the absorber with decreased acceptance angle is a consequence of the non-isotropic distribution of the annual solar radiation. If the spatial distribution of the annual radiation were isotropic, no concentration would be possible. However, since the available radiation is concentrated to a certain angular interval (for example $5° \leq \theta_{P,NS} \leq 70°$ for Stockholm, see figure 2b) and since the radiation is non-isotropic in this interval, the effective concentration of radiation on the absorber will increase with maximum possible concentration according to equation 1. The difference in annual irradiation on the absorber for EW-aligned concentrators in Oviedo and Stockholm seen for $\theta_a < 25°$ is again a result of the missing winter peak in the irradiation distribution for Stockholm, which means that the essential part of the annual irradiation is concentrated to a narrow angular interval around the summer peak at high latitudes.

4. CONCLUSIONS

The Irradiation distribution diagram for low to mid latitude sites is almost symmetric with two clear peaks for the solstices. For sites at higher latitudes the winter peak is reduced and the IDD is asymmetric since the winter irradiation is reduced by absorption and scattering in the atmosphere and by seasonal changes in the climate. This means that the IDD shows large differences between sites in northern or southern Europe and that the benefits of and possibilities for different types of stationary solar concentrators depend on where they are to be used. In general, concentrators with larger concentration can be used at higher latitudes since the available annual irradiation is concentrated to a narrower angular interval, compared to lower latitudes. Furthermore, asymmetrical concentrators are of interest at high latitudes. One practical application is the Mareco-collector, presented elsewhere in the conference proceedings (Karlsson and Wilson, 1998).

ACKNOWLEDGEMENTS

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