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Measurements of the angular distribution of diffuse irradiance

Elsa Andersen[a], Kristian Pagh Nielsen[b], Janne Dragsted[a], Simon Furbo[a]

[a]Technical University of Denmark, Institute of Civil Engineering, Nordvej 119, 2800, Kgs. Lyngby, Denmark
[b]Danish Meterological Institute, Lyngbyvej 100, 2100 Copenhagen Ø, Denmark

Abstract

Advanced solar resource assessment and forecasting is necessary for optimal solar energy utilization. In order to investigate the short-term resource variability, for instance caused by clouds it is necessary to investigate how clouds affect the solar irradiance, including the angular distribution of the solar irradiance. The investigation is part of the Danish contribution to the task 46 within the International Energy Agency and financed by the Danish Energy Agency. The investigation focuses on the distribution of the diffuse solar irradiance and is based on horizontal measurements of the solar irradiance from 8 different parts of the sky as well as horizontal measurements of the total beam and total diffuse irradiance.

Peer-review by the scientific conference committee of SHC 2014 under responsibility of PSE AG

Keywords: Measurement of diffuse solar irradiance; Angular distribution of diffuse solar irradiance.

1. Introduction

The International Energy Agency (IEA) Solar Heating and Cooling programme (SHC) Task 46: "Solar Resource Assessment and Forcasting" has two major goals: 1) To understand short-term resource variability caused by clouds and 2) To assess the application of short term forecast for planning the operation of multiple solar energy systems.

In order to investigate the short-term resource variability caused by clouds it is necessary to investigate how fractional 3-dimensional cloud fields affect the solar irradiance, including the angular distribution of solar irradiance.

This investigation is done by applying high temporal resolution measurements of the solar irradiance from ground based stations operated by the Technical University of Denmark, Department of Civil Engineering (DTU) in Kgs. Lyngby and in Sisimiut, Greenland, and at a number of stations across Denmark operated by the Danish Meterological Institute (DMI) in Copenhagen.

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At the DTU climate station in Kgs. Lyngby detailed measurements of solar irradiance have been performed for 25 years, providing a long set of historical data, which are very valuable in this investigation. In particular, DTU have focused on measuring both the global irradiance and the diffuse irradiance on horizontal.

The objective of the investigation described in this paper is to better understand short-term resource variability caused by clouds. The short-term resource variability caused by clouds is investigated with a set of 8 high temporal resolution pyranometers that measure the total horizontal solar irradiance from 8 different sky directions and measurements of the beam normal and global irradiances. The detailed measurements are carried out at the DTU climate station.

2. The experimental set-up

2.1. The climate station

The climate station is located at the technical university of Denmark. The latitude is 55.6°N and the longitude is 12.5°E. See in Fig. 1, left. The total diffuse irradiance on horizontal is measured with a pyranometer mounted on a sun tracker that screens of the beam irradiance. The beam normal irradiance is measured with a pyrheliometer mounted on the sun tracker, see Fig 1, right.

Fig. 1. (Left) The climate station. (Right) The sun tracker.

The equipment is from Kipp and Zonen. The pyranometer is type CMP 11, the pyrheliometer is type CHP 1 and the sun tracker is type SOLYS 2. The sun tracker is equipped with shadow balls that screen of the beam irradiance from the pyranometer mounted on the horizontal top plate on the sun tracker and the pyranometer measures only the diffuse irradiance. The sun tracker is further equipped with a sun sensor that fine tunes the position of the sun tracker. The view angle from the pyrheliometer to the sky is 5°. The view angle from the pyranometer to the shadow ball is also 5°.

2.2. Fractional irradiance measurement set-up

The fractional solar irradiance is measured with 8 pyranometers also type CMP 11 from Kipp and Zonen. On top of each pyranometer, domes with openings corresponding to 1/8 part of the sky are mounted. The domes point in 8 different directions in such a way that solar irradiance is measured from the entire sky. The domes are half balls with diameters of 291 mm. The domes are held in position with metal plates with multiple holes which allows for good ventilation inside the domes. The inside of the domes and the metal plate is painted with black low reflection paint. The reflection from the black paint is < 5%. The domes are shiny white on the outside. Fig. 2 shows a top view of the climate station where it can be seen how the domes point in 8 different directions, covering the whole sky and pictures of the fractional measurement set-up. The sun tracker is located in the North West corner of the climate station.

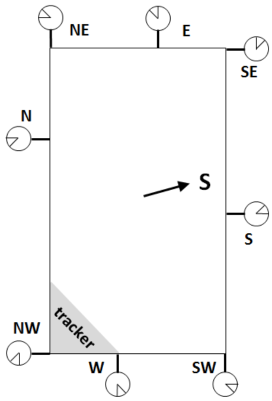

Fig. 2. (Left) Top view of the climate station. (Right) The experimental set-up with the dome mounted on top of the pyranometer.

3. Measurements

3.1. Side-by-side "calibration" measurements

Initially the pyranometers are tested side-by-side in order to investigate if the measured values from the different pyranomerers are identical when the pyranometers are exposed to the exact same weather conditions. Fig. 3 shows a picture of 16 pyranometers mounted on horizontal at the climate station. 8 of the pyranometers are used for the fractional horizontal measurements and 1 pyranometer is used for measuring the total horizontal diffuse irradiance with the sun tracker. Fig. 4 shows the measurements from all 16 pyranometers on a sunny day. It can be seen that the pyranometers measure exactly the same global solar irradiance, except in the morning and in the evening with low solar elevation where shading from the climate station influence the measurements.

Fig. 3. The 16 pyranometers mounted on horizontal for side-by-side "calibration" measurements.

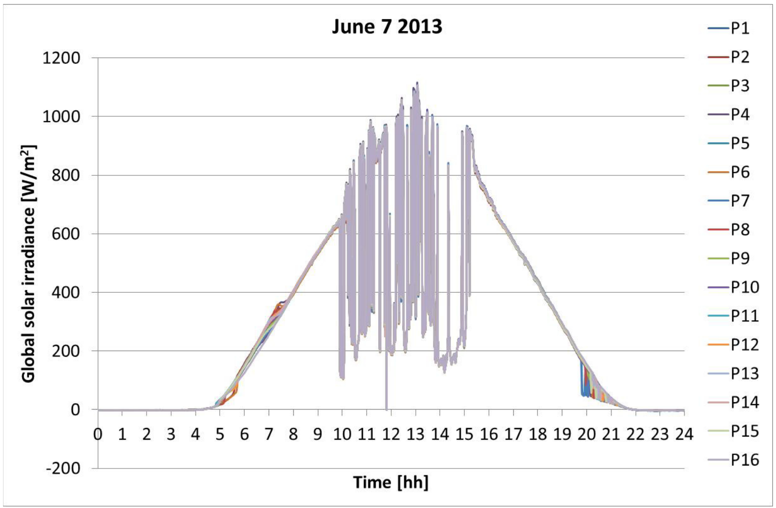

Fig. 4. Side-by-side measurements of the global irradiance with 16 different pyranometers on a sunny day. The pyranometers are named P1, P2,…, P16.

3.2. Measurement period

The measurement period is from June 19 2014 to October 6 2014. Unfortunately there are periods without measurements, see Table 1.

Table 1. Measurement period and missing data during the measurement period.

Measurement period in 2014	Number of missing days	The missing days
June 19 – June 30	1	30.
July 1 – July 31	11	1.-11.
August 1 – August 31	6	19.-20., 26.-29.
September 1 – September 30	0	
October 1 – October 6	0	

3.3. Fractional horizontal diffuse irradiance measurements

The fractional horizontal diffuse irradiance is calculated by subtracting the horizontal beam irradiance from the fractional measurement which is exposed to beam irradiance. The geometry of the domes result in shadows on the pyranometer close to the beginning and the end of the dome opening, see Fig 5. Measurements from the shaded areas are left out and the fractional horizontal diffuse irradiance is interpolated between the unshaded areas.

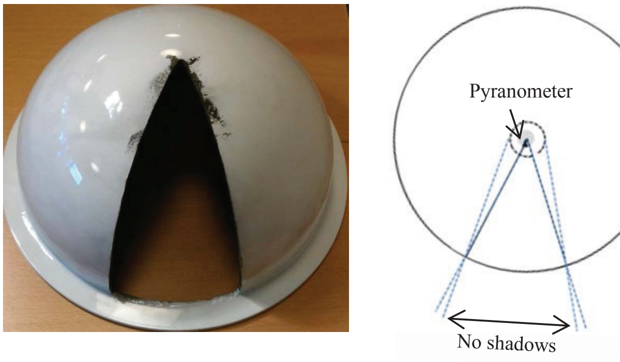

Fig. 5. (Left) Picture of dome with the opening. (Right) Schematic illustration of how the dome leads to shading on the pyranometer where the dome opening begins and ends.

3.4. Investigations on measured inaccuracies and correction of the measured inaccuracies

During cloudy days, the sum of the 8 fractional horizontal diffuse irradiance measurements is similar to the total horizontal diffuse irradiance. However, on sunny days, the sum of the 8 fractional horizontal diffuse irradiance measurements is larger than the total horizontal diffuse irradiance. Fig. 6 shows the fractional horizontal diffuse irradiance from the 8 pyranometers and the sum of the 8 fractional measurements and the horizontal diffuse measurement carried out with the sun tracker on a sunny day. In the figure, the areas shaded by the domes are left out. It is clear to see that the sum of the fractional horizontal diffuse irradiance measurements differ from the total horizontal diffuse irradiance when there is beam irradiance.

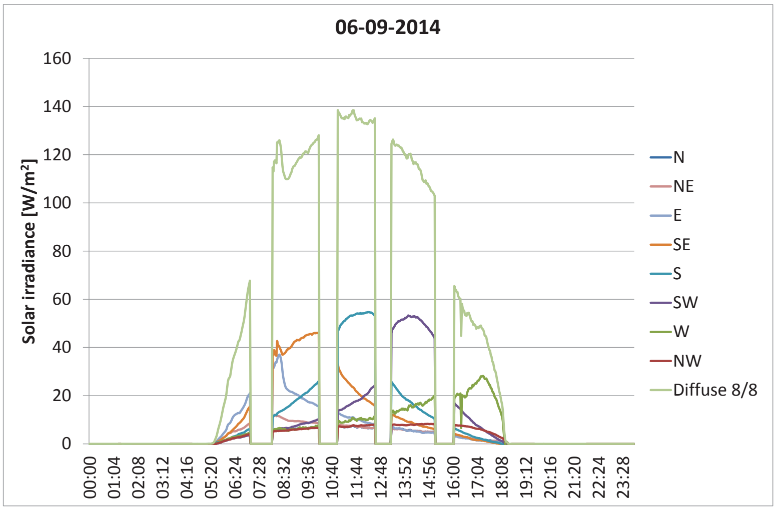

Fig. 6. Measured fractional horizontal diffuse irradiance, the sum of the fractional irradiances and the total horizontal diffuse irradiance measured with the sun tracker on a sunny day.

In order to investigate if a temperature difference between the inside of the dome where the glass dome of the pyranometer is located and outside the dome where the body of the pyranometer is located is causing the measured inaccuracies, measurement are compared between the experimental set-up with the dome and a similar set-up where the dome is removed and the glass dome of the pyranometer is covered leaving only 1/8 part open to the sky. The 1/8 openings in the two different experimental set-ups are pointing in the same direction. The measured irradiances are exactly the same when the sun is shining through the middle of the openings. Also smoke tests are carried out to see how fast the air is exchanged inside the dome. The smoke is ventilated away instantly. Based on these investigations it is concluded that the measured inaccuracies are due to interreflections inside the domes.

The visible opening areas of the domes are projected on a plane perpendicular to the beam solar irradiance and the corrections are distributed according to the visible opening areas of the domes. Also the area of the glass dome of the pyranometer is subtracted from the visible opening area of the dome with the sun, See Fig. 7. It is clear to see that even if only one pyranometer is exposed directly to beam irradiance, the sun shines through the openings of the neighboring domes as well. In Fig. 8 the measured fractional horizontal diffuse irradiances and the sum of the fractional horizontal diffuse irradiances corrected for interreflections and interpolated between the shaded areas caused by the domes and the total horizontal diffuse irradiance measured with the sun tracker on a sunny day are shown. The dotted lines show the uncorrected measurements and the full blown lines show the corrected and interpolated measurements. The figure shows that the corrections result in a good degree of similarity between the sum of the fractional horizontal diffuse irradiance measurements and the total horizontal diffuse irradiance measured with the sun tracker.

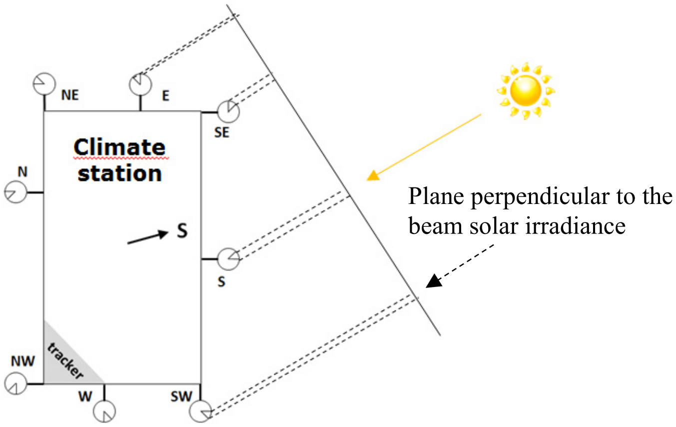

Fig. 7. Illustration of the applied method for correcting the measurements for interreflections inside the domes.

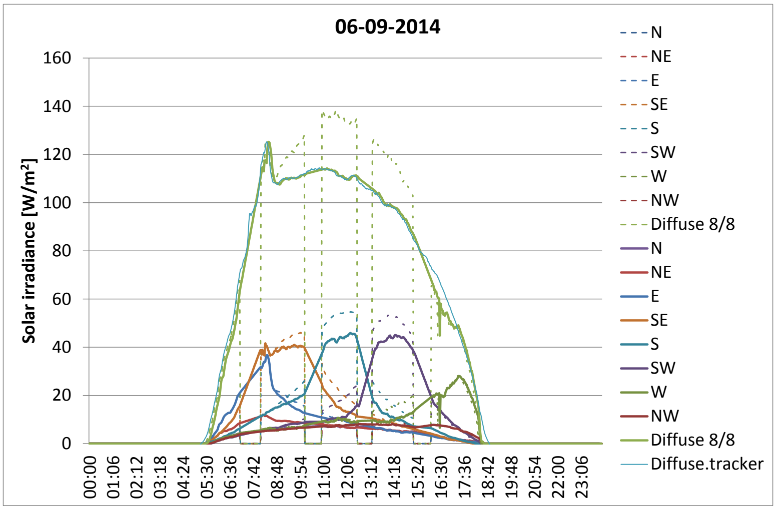

Fig. 8. Measured fractional horizontal diffuse irradiances and the sum of the fractional irradiances corrected for interreflections and interpolated between the shaded areas and the total horizontal diffuse irradiance measured with the sun tracker on a sunny day. The dotted lines show the uncorrected measurements and the full blown lines show the corrected measurements.

4. Results

The fractional horizontal diffuse solar radiation measurements from the whole measurement period are shown in Fig. 9. The figure shows as expected that most diffuse solar radiation comes from the pyranometers with the south facing dome openings.

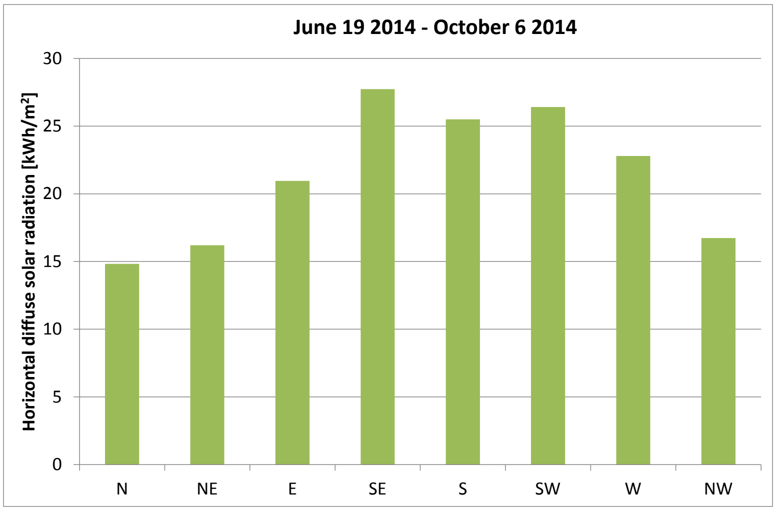

Fig. 9. Measured fractional horizontal diffuse solar radiation from the whole measurement period.

The solar diffuse fraction, SDF is defined as shown in eq. (1).

$$\mathrm{SDF} = \frac{\sum \text{Horizontal diffuse solar radiation from the dome opening with the sun}}{\text{Total horizontal diffuse solar radiation}} \tag{1}$$

Fig. 10 shows the daily solar diffuse factor as function of the daily beam solar radiation on horizontal. The figure shows that the daily horizontal diffuse solar radiation is highly influenced by the daily beam solar radiation on horizontal. From the figure it can be seen that during sunny days, most horizontal diffuse solar radiation comes from the area around the sun. On sunny days, the solar diffuse fraction can be up to 42 % and the figure also shows that there are large variations from day to day. Hence, the distribution of the horizontal diffuse irradiance on sunny days is unevenly distributed or non-isotropic distributed. The figure also shows that during days without any beam irradiance, the horizontal solar diffuse factor is around 12.5 % which exactly correspond to the opening area of a dome. Hence, it is seen that during days without any beam irradiance the horizontal diffuse irradiance is evenly distributed or isotropic distributed over the azimuth direction.

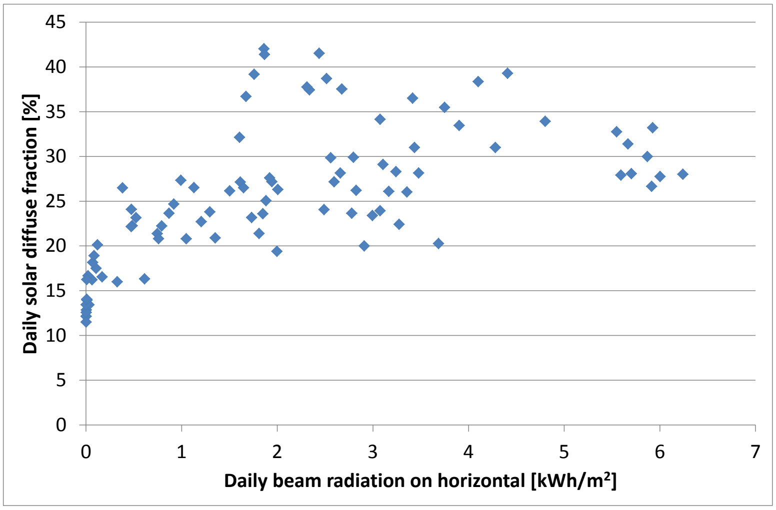

Fig. 10. Daily horizontal solar diffuse fraction from the whole measurement period as function of the measured daily beam radiation on horizontal.

5. Conclusions

The fractional diffuse solar irradiances on horizontal from 8 different parts of the sky were investigated by means of ground based measurements with high temporal resolution pyranometers. Also the total horizontal diffuse and beam irradiances were measured. The measurements were carried out at the climate station located at the Technical University of Denmark at latitude 55.6°N and longitude12.5°E. The measurement period is from June 19 2014 to October 6 2014. The fractional horizontal measurements are facilitated by experimental set-ups with domes with openings corresponding to 1/8 part of the sky mounted over the glass domes of the pyranometers. The domes are half balls with diameters of 291 mm painted black on the inside with low reflection paint. The experimental set-ups result in shading on the pyranometers at the beginning and end of the dome openings and some measured inaccuracies caused by unintended interreflections inside the domes during periods with beam irradiance. The measurements are corrected for the shades and the interreflections, resulting in a good degree of similarity between the sum of the fractional diffuse irradiance on horizontal and the total diffuse irradiance on horizontal.

The results show as expected that the distribution of horizontal diffuse irradiance is highly influenced by beam irradiance. On sunny days the horizontal diffuse irradiance is much higher around the sun than in the rest of the sky. The solar diffuse fraction around the sun, that is: the sum of the horizontal diffuse solar radiation from the dome opening with the sun divided with the total horizontal diffuse radiation can be up to 42% and the variations are large from day to day. On cloudy sky days without any beam irradiance, the horizontal diffuse irradiance is evenly distributed over all azimuth directions.

The measurements will be continued, analyzed further and used to improve solar radiation models for estimating beam and diffuse irradiance on horizontal and on tilted surfaces.