DIFFUSING REFLECTORS FOR BIFACIAL PHOTOVOLTAIC PANELS

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(Received June 27, 1984; accepted August 3, 1984)

Summary

We present here a model for the collection of energy on both sides of a bifacial photovoltaic panel surrounded by white-painted planes which produce diffuse reflections of the energy reaching them. The model is verified experimentally and is applied to an example related to the collection of energy by a large field of bifacial panels on white-painted ground. Under practical conditions the amount of energy collected in a year is 59% greater than that collected by monofacial cells.

1. Introduction

Efficient bifacial cells capable of converting into electricity the light incident on both sides of the cell have been developed in the last few years [1, 2]. In addition, the fact that these cells receive an increased amount of power compared with that received by monofacial cells when placed in a flat panel with transparent covers on both sides has been shown [3] experimentally; this additional power comes from energy reflected from the surroundings which are painted white. This type of bifacial panel is now manufactured industrially [4]. The purposes of this paper are to present a model for the collection of light by a bifacial panel in arbitrary surroundings, to verify the model experimentally and to carry out a theoretical analysis of a simple configuration in order to determine the additional energy that can be expected from a field of bifacial, as opposed to monofacial, panels. These calculations will be used in a demonstration project of 40 kW to be installed in the outskirts of Madrid, Spain, and connected to the public electricity network.
2. Theoretical model

2.1. The radiance on the collector

The bifacial panel is placed in such a manner that the front surface is illuminated in a way similar to that of a conventional panel. It is installed facing south (in the northern hemisphere) with an angle of inclination that depends on the application and that in general is not very different from the latitude. The back surface receives a substantial amount of diffuse light reflected from the floor and walls surrounding the panel.

Let us assume that the floor and walls, which are in general planes placed at arbitrary positions and with different shapes, are diffusing reflectors radiating as lambertian sources (i.e. according to the cosine law). This assumption will be checked experimentally in Section 3. Under this assumption the power flux received by an element \( dS_r \) of area of the receiver (the panel) coming from an element \( dS_e \) of area of the emitter (the floor) is given by (Fig. 1)

\[
dE_r \, dS_r = \frac{E_e}{\pi} \cos \theta_e \, dS_e \, d\Omega_r
\]

where

\[
d\Omega_r = \frac{dS_r}{r^2} \cos \theta_r
\]

In the preceding equations, \( E_e \) and \( E_r \) are the irradiances (the power flux per unit area) emitted by the reflecting plane and received by the panel. The factor \( 1/\pi \) accounts for the radiation on all the solid angles, so that \( E_e/\pi \) is a radiance (power flux per unit area normal to the emitting direction and per unit of solid angle); \( d\Omega_r \) is the solid angle under which the element \( dS_r \) of area of the panel is seen from the emitting plane.

Equation (1) can also be written as

\[
dE_r = \frac{E_e}{\pi} \cos \theta_r \, d\Omega_e
\]

where the element \( d\Omega_e \) of solid angle is given by

Fig. 1. Reception of albedo rays at the back surface of a bifacial panel.
\[ d\Omega_e = \frac{dS_e}{r^2} \cos \theta_e \]  

(4)

and is the solid angle under which the receiver sees the element \( dS_e \) of area of the emitter. As a consequence

\[
E_r = \frac{E_e}{\pi} \int \cos \theta_r \, d\Omega_e
\]

\[
= \frac{E_e}{\pi} \int \, d\Gamma
\]

(5)

We can observe that eqn. (5) represents the area of the projection onto the plane of the panel of the figure drawn on the sphere of radius unity by the bundle of rays which link the emitting plane to the point of the panel whose irradiance, received from the emitting plane, we are investigating (we call \( d\Gamma \) an element of this area). In Fig. 2 we present an emitting triangle ABC which is conically projected onto the sphere of radius unity as a spherical triangle A'B'C' and is then projected normally into the plane of the panel as an elliptical triangle A''B''C''. The area \( \Gamma(ABC) \) of this elliptical triangle multiplied by \( E_e/\pi \) is the radiance received at point O.

![Fig. 2. Schematic representation of the method used to calculate the light cast by a triangular plane on the back surface of a bifacial panel.](image)

The preceding \( d\Gamma \) is the element of the "view factor" used commonly in heat transfer text books [5]. The area \( \Gamma(ABC) \) of the elliptical triangle is the view factor of such a triangle from the panel point O.

Obviously, if the plane is infinite, parallel to the panel and placed somewhere behind it (above it in Fig. 2), the solid angle will be a whole hemisphere and its projection onto the plane of the panel will be a circle of radius unity and area \( \pi \), so that according to eqn. (5) \( E_r = E_e \).
The circle of unit radius is, in fact, a representation of the directions of
the space behind the panel projected onto a plane. If we consider a given
direction \( D \), the projection \( D'' \) in the plane of the panel has two coordinates
\((p, q)\) which are the direction cosines with respect to two orthogonal axes
\((x, y)\) of the plane of the panel. We call the albedo map the map of points
\((p, q)\) representing directions behind the panel. The points of the albedo map
are restricted to the above-mentioned circle of radius unity, as is obvious
from Fig. 2 (and also from the fact that \( p^2 + q^2 = 1 - r^2 \leq 1 \)). A second
circle of direction cosines \((p, q)\) similar to the albedo map corresponds to
directions above the panel (the values of \( p \) and \( q \) are the same but \( r \) has a dif-
ferent sign. We call this map the sky map. This representation is the same as
that used by Welford and Winston in their classical work on non-imaging
optics [6].

2.2. Calculation of view factors

The calculation of elliptical polygons is theoretically simple. We
recommend the following easy procedure for calculating their areas (view
factors).

As a first step we calculate the vectors \( \overrightarrow{OA}, \overrightarrow{OB} \) and \( \overrightarrow{OC} \), corresponding
to points A, B and C. It is convenient to write them in terms of the coordi-
nates \((x, y, z)\) of Fig. 2. Then we calculate the areas of the circular sectors
\( OA'B', OB'C' \) and \( OC'A' \), a simple task since these areas are such that

\[
S(OA'B') = \frac{1}{2} \cos^{-1}\left( \frac{\overrightarrow{OA} \cdot \overrightarrow{OB}}{|\overrightarrow{OA}| |\overrightarrow{OB}|} \right)
\]

(where the angles are in radians). We can see from Fig. 2 that the view factor
\( \Gamma(ABC) \) is the algebraic sum of the areas of the elliptical sectors \( OA''B'' \),
\( OB''C'' \) and \( OC''A'' \) (it is important to keep the order of circular permutation
of \( A''B'' \) and \( C'' \) to ensure that the signs are correct). These areas are simply
the projections of the areas of the circular sectors \( OA'B' \), \( OB'C' \) and
\( OC'A' \). We therefore have to find the angle of projection and multiply it by
the areas of the circular sectors. Then

\[
S(OA''B'') = \frac{1}{2} \cos^{-1}\left( \frac{\overrightarrow{OA} \cdot \overrightarrow{OB}}{|\overrightarrow{OA}| |\overrightarrow{OB}|} \right) \left| \frac{\overrightarrow{OA} \times \overrightarrow{OB} \cdot \mathbf{n}}{|\overrightarrow{OA}| |\overrightarrow{OB}|} \right| \sin\left\{ \cos^{-1}\left( \frac{\overrightarrow{OA} \cdot \overrightarrow{OB}}{|\overrightarrow{OA}| |\overrightarrow{OB}|} \right) \right\}
\]

(6)

where \( \mathbf{n} \) is the unit vector normal to the panel (i.e. \( n = k \) in the recom-
mended coordinates). The second factor enclosed by square brackets is the
cosine of the unit vectors normal to the plane \( OAB \) and to the panel. Now

\[
S(A''B''C'') = |S(OA''B'') + S(OB''C'') + S(OC''B'')| = \Gamma(ABC)
\]

(7)

If the order of permutation is kept, the algebraic sum where the sign of each
term is given by \( \overrightarrow{OA} \times \overrightarrow{OB} \cdot \mathbf{n} \) will give the correct result for \( \Gamma(ABC) \). The
same procedure can be followed for polygons of more sides, rectangles being
the most common.
Obviously, a similar area calculation can be done for the sky hemisphere. Usually, the diffuse reflections on the sky hemisphere are less important than those on the albedo hemisphere, although they are taken into account in classical books on solar energy [7].

2.3. Illumination by the sky sphere

The panel is tilted and so it sees from its back surface only portions of the sky, in particular those facing north (in the northern hemisphere). The front surface sees a lot of sky. The above procedure can be used in both cases to calculate the energy received by the panel:

\[
E_r = \int B_D \cos \theta_r \, d\Omega_{\text{sky}}
\]

\[
= \int B_D \, d\Gamma_{\text{sky}}
\]

(8)

where \( B_D \) is the radiance of each direction of the sky. If we assume that the sky has a homogeneous radiance (for the diffuse component), \( B_D \) is constant and with \( B_D = H_D / \pi \) (where \( H_D \) is the irradiance on a horizontal surface) we again obtain the form of eqn. (5). As a result, we can deal with the portions of the sky seen by the panel as if they were emitting planes and the calculation of the view factor \( \Gamma \) of the sky on the albedo map can be used to calculate the irradiance on the panel from this source. This view factor is the projection on the plane of the panel of the solid angle \( \omega \) at which the sky is seen.

2.4. The irradiance of the reflecting plane

The irradiance \( E_e \) of an emitting plane is proportional to the irradiance incident on the same plane, the constant of proportionality being the coefficient of reflection. This incident irradiance is composed of three basic components: the direct beam irradiance, the diffuse irradiance and the irradiance cast by other emitting planes. Usually the direct and diffuse irradiances are measured and recorded on a horizontal surface and their values are \( H_B \) and \( H_D \) respectively. To calculate the irradiance cast onto an emitting plane by the remaining planes, as well as that from diffuse radiation, we simply project onto the emitting plane under consideration the solid angle under which each source is seen by the plane, according to a natural extension of the theory presented in Sections 2.1 - 2.3. To calculate the direct Sun illumination we make an elementary projection. Thus we write

\[
E_e = \rho \left( H_B \frac{\cos \beta}{\cos \alpha} + H_D \Gamma_D + \sum_i E_i \Gamma_i \right)
\]

(9)

where the first term is the irradiance of the solar beam with an angle \( \alpha \) of incidence on a horizontal surface and an angle \( \beta \) of incidence on the plane
under study, the second term constitutes the irradiance from diffuse radiation and the $\Sigma_i$ term is the irradiance from the surroundings. We must check that $\Gamma_D + \Sigma \Gamma_i = \pi$ to complete the irradiance from a whole hemisphere.

If the irradiance from the surroundings is very important we can be led to undertake an iterative calculation since these surroundings are illuminated by our plane, which in turn is illuminated by them. However, in the example in Section 4 this iterative procedure is not required. (The surroundings are a simple plane, i.e. the ground.)

On sunny days $H_B$ is very high and the highest irradiance will occur for planes normal to the solar beam. On cloudy days under an isotropic sky the highest irradiance occurs on a horizontal plane.

3. The measurement of the coefficient $\rho$ of reflection

The experimental set-up for the measurement of the coefficient of reflection consists of a horizontally placed, 1 m$^2$ in area, wooden board painted white with the kind of paint we want to study. A 2.25 cm $\times$ 2.25 cm calibrated cell is placed 10 cm above the board, facing downwards (towards the painted board), supported by four very taut threads tied to metal rods placed at the corners of the board. With this set-up very little shadow is cast on the painted board. An additional calibrated cell is placed on a corner of the board, facing upwards, in order to measure the irradiance from the sky on a horizontal surface. A schematic diagram of the experimental set-up is presented in Fig. 3. The area $\Gamma_a$ subtended by the wooden board in the albedo plane for the dimensions given above is 0.97$\pi$. The irradiances received on the wooden board and on the cell facing upwards are the same and equal the global irradiance $H_G$ (= $H_B + H_D$) on the horizontal surface. The irradiance emitted by the wooden board is $\rho H_G$. The irradiance received by the cell facing downwards is 0.97$\rho H_G$, according to eqns. (5) and (9). Since this irradiance is measured with the calibrated cell facing downwards.

Fig. 3. Graphic representation of the experimental set-up for measuring the coefficient $\rho$ of reflection.
and $H_G$ is measured with the calibrated cell facing upwards, we can determine an approximate value for $\rho$ by dividing the short-circuit current of the two cells, corrected by their calibration constants.

Because of the dimensions of this wooden panel we can affirm that the albedo reflected by the areas outside it has very little effect on the measurement (less than 3%), so we do not have to take it into account. Also, some shadow is cast onto the wooden panel by the downward-facing cell. In general, this shadowed area is a square with the same dimensions as the cell placed in a determined position which depends on the hour of the day. The area in the albedo map corresponding to this shadow is at a maximum when the Sun is at the zenith. In this situation, for the size of the above-mentioned experimental set-up, this area is given by $\Gamma_s = 0.04\pi$, so that the calculation of $\rho$ with no correction for the shadow results in an underevaluation of less than 4%. Although a correction can be effected by considering that the shadowed area is illuminated only by diffuse light and that $\rho = 0$ outside the board, this is not commonly done and therefore the expected accuracy of $\rho$ is within 1% - 2%.

Obviously, the method presented here is not standard for measuring the integrated reflectivity of a material. Standard methods are generally based on the use of an integrating sphere and a monochromatic beam source. However, our method is simpler and more suitable for people working in photovoltaics. As regards the spectral aspects of our measurement, the radiances received and emitted are measured with a solar cell, so that we obtain information only in the region of spectral sensitivity of silicon cells. However, this is a highly relevant measurement in photovoltaic design. If the calibrated cells are similar to the bifacial cells used in the actual panels, the value of $\rho$ calculated here corresponds to the relevant part of the spectrum.

We used two bifacial cells in our measurements, calibrated with their back surfaces covered. Both cells were calibrated in our institute using a xenon simulator, and these were compared with a cell calibrated at the Lewis Research Center, National Aeronautics and Space Administration. We do not describe the calibration procedure in detail here, since it does not affect the value of $\rho$ (which is a quotient of irradiances and does not require an absolute measurement).

The angular distribution of the irradiance is very different in the upward-facing cell (where on clear days a large amount comes from the direction of the Sun) from that in the downward-facing cell (where we always have almost isotropic irradiance). The levelling rays with an angle of incidence greater than 65° are strongly reflected by a solar cell. For the remaining rays the cell behaves approximately as a lambertian collector (i.e. it follows the cosine law). This means that the value of the coefficient $\rho$ includes the effect of levelling rays. However, the value of $\rho$ that we are calculating is more relevant from an engineering point of view than the accurate value of $\rho$, since the levelling ray effects also occur in actual panels. Even so, it is advisable to avoid determining $\rho$ very early in the morning or very late in the afternoon. We plotted values of $\rho$ obtained at different times
of the day in Fig. 4, selecting a group of measurements which were made in a day that was generally clear, but with two periods of cloud to show that the clearness factor has little influence on the determination of \( \rho \). The slightly higher values of \( \rho \) observed early in the morning and late in the afternoon are attributed to the levelling rays of the Sun, which are strongly reflected by the upward-facing cell.

Fig. 4. Measurement of the coefficient of reflection for two white-painted boards (date, May 31, 1983): \( \Delta \), paint 1; \( \odot \), paint 2; \( \blacksquare \), irradiance.

The first point to be checked is the lambertian character of the diffuse reflectors. Two effects seem to indicate a certain departure from lambertian radiance: the mirror reflection of the Sun on the board and the difference in brightness that is apparent at certain times and which depends on whether the observer looks at the board facing the Sun or with the Sun behind it.

To analyse the effect of mirror reflection we placed a small mirror (3 cm \( \times \) 3 cm) on the board at the spot where the Sun was expected to produce mirror reflection. The determination of this spot is very easy both from visual observation and because the downward-facing cell gives maximum output when the mirror is placed there. Then the mirror was covered with a piece of black fabric to avoid any noticeable mirror reflection on the
panel. In all the cases analysed, even in those in which some mirror reflection is observed optically, the output of the cell decreased very little (2% - 5%) after it had been covered with the black fabric. In all cases this reduction was thought to be caused by the reduction in the lambertian emitter area (due to the black fabric), and no mirror reflection was detected in terms of energy.

To investigate the second effect, we placed our measuring board in position with one side normal to the Sun's azimuth. After this, we covered our 1 m × 1 m board with black fabric measuring 1 m × 0.5 m, covering the half of the board closer to the Sun, and we determined the current ratio of downward-facing cells to upward-facing cells. Then we repeated the operation, this time covering the half of the board farther from the Sun. In both cases the current ratio was basically the same, so that in all the cases we measured the lack of symmetry in the emission pattern was lower than 5%.

The preceding results are valid for smooth surfaces. To determine the effect of roughness on \( \rho \), we whitewashed a smooth board and a bed of pebbles (average diameter, 3 cm) and we then measured \( \rho \). A lack of symmetry of about 5% was again found.

Obviously, we do not mean that white polished surfaces do not have mirror reflection or that the degree of roughness does not affect \( \rho \). In fact, with dark surroundings (low \( \rho \) values) we have observed a clear influence of the direction of the Sun in the apparent reflectivity, but we can conclude that when most of the usual white coatings are used in normal building materials they behave like lambertian emitters when illuminated and we can regard them as such for design purposes.

4. Increase in radiance in a field of bifacial panels

We present here an application of the preceding model to a field of panels placed on a white floor. We apply the model to some simple cases containing all the relevant information concerning a large facility on specific days, and we compare the results with those of measurements on the same days. In this way we confirm the validity of our model. Then we forecast the behaviour of a large facility using the irradiation data corresponding to an average year.

We started by measuring the irradiance collected at the front and back surfaces of a standard bifacial panel. For this purpose we painted white a plot of ground 10 m × 10 m in area using one of the paints analysed previously, for which \( \rho = 0.80 \). On this ground we installed a bifacial panel with six calibrated cells, three cells facing upwards and three cells facing downwards. The cells were placed at the top left, the centre and the bottom right of the panel so that the homogeneity of the illumination on each face could be analysed and also to have some redundancy. The data were recorded every 15 min with a data logger. In general, we can say that the differences in illumination were lower than 5%.

The size of the panel was 106 cm × 44 cm and it was placed 100 cm above the ground. We carried out measurements at different angles of
inclination, including the horizontal position. In this position the effects of the uncontrolled surroundings and of a heterogeneous distribution of irradiance on the sky are minimized, so that we can reproduce the measuring techniques of small-size experiments described in Section 3.

In Fig. 5 we present the ratio of the irradiance at the back surface to that at the front surface at the centre of the panel. The open triangles represent the experimental points. The full line is the result of applying the model of Section 2, taking into account (a) the actual size (10 m × 10 m) of the white-painted floor with a coefficient $\rho$ of reflection of 0.75, (b) the effect of the shadow of the panel that causes the small curvature at about noon and (c) the reflection of the ground outside the white-painted floor with an estimated coefficient $\rho$ of reflection of 0.25.

In this way we estimate the apparent reflectivity $\rho$ for the large-size area to be 0.75, instead of 0.80 as was determined from small-size measurements. The difference could be due to (a) a thinner layer of white paint in the large area and (b) the effect of some shadows caused by large-size beams running in the north-south direction through the field to provide support for the panels (such beams should be avoided in the design of future facilities).

![Fig. 5. Ratio of back-surface irradiance to front-surface irradiance at the centre of a panel installed on a white-painted plot 10 m × 10 m in area (date, July 7, 1983; paint 1; large-range reflectivity): —, theoretical data; △, experimental data; ■, irradiance.](image-url)
To apply the model, either in the previous calculations or in those that follow, we integrated the global irradiance during the day (this integration was done in a system connected to a pyranometer that takes samples every minute). We then calculated the clearness factor and used the correlations of Liu and Jordan (corrected by Collares-Pereira and Rabl [8]) to obtain the hourly distribution of direct and diffuse radiation. This method permits the irradiance \( H_G \) of the ground to be calculated at any moment of the day and also the calculation of the irradiance at any surface using the procedure described in Section 2.

Let us analyse, as an example, the central panel of a group of 36 panels, placed in three rows with a north–south separation of 2.8 m. The east–west separation between the panels is 25 cm. The panels are tilted by 40° and the central point is located at 1.55 m from the ground.

The albedo map and the sky map seen from the centre of the central panel of the field are represented in Fig. 6(a) and Fig. 6(b) respectively. These maps look as if they are seen through a fisheye objective lens. We observe in the albedo map the white ground and sky projections with view factors \( \Gamma_{GA} \) and \( \Gamma_{SA} \). An elliptical shape appears near the edges of the circle, corresponding to the edges of the white-painted ground. The view factor of the normal soil is then \( \Gamma_{LA} \).

In the sky map the sky and the ground have interchanged their area values. With our nomenclature (see Fig. 6(b)) their view factors are \( \Gamma_{SS} \) and \( \Gamma_{LS} \) respectively. No significant white-painted ground is seen here by the panel.

A set of view factors \( \Gamma_0^{(l)} \) appears on the ellipse of the horizon, corresponding to the back-row panels in the albedo map or to the front-row panels in the sky map (the back row is the row facing north). The part of the view factor of these panels projected against the ground in the sky map is \( \Gamma_{OG}^{(l)} \) and the part projected on the sky is \( \Gamma_{OS}^{(l)} \). In the albedo map these values are reversed (i.e. \( \Gamma_{OS}^{(l)} \) is cast on the ground and \( \Gamma_{OG}^{(l)} \) on the sky).

The shadows cast by the panels at noon on August 24th, 1983, are also presented in the albedo map. Only the central and back rows project their shadows onto the albedo map, whereas the front row projects its shadow onto the sky map, and since its importance is small it has not been represented. The view factors of these shadows are \( \Gamma_{SH}^{(l)} \).

We wish now to remind the reader that the irradiance received on the panel from each part of the surroundings depends on its view factor, i.e. on the area of its projection onto the albedo map or the sky map.

The emitted irradiance of the white-painted ground is \( \rho(H_B + H_D) \) in the illuminated portion and \( \rho H_D \) in the shadowed portions (\( \rho = 0.75 \) in the white-painted zone and \( \rho = 0.25 \) in the zones outside the white-painted zone). The neighbouring panels are supposed to be good absorbers of light and therefore their emitted irradiance is zero. The irradiance emitted by the sky is \( H_T \). As a consequence, the irradiance received from the surroundings at the centre of the back face of the central panel is
\[ E_{BA} = \frac{0.75(H_B + H_D)}{\pi} \left( \Gamma_{GA} - \sum_j \Gamma_{SH}^{(ij)} \right) + \frac{0.25(H_B + H_D)}{\pi} \left( \Gamma_{LA} - \sum_i \Gamma_{0S}^{(i)} \right) + \frac{0.75H_D}{\pi} \sum_j \Gamma_{SH}^{(ij)} + \frac{H_D}{\pi} \left( \Gamma_{SA} - \sum_i \Gamma_{0G}^{(i)} \right) \] (10)

Fig. 6. (a) Albedo and (b) sky maps seen from the centre of the central panel of a group of 36 panels (north–west separation, 2.8 m; south–east separation, 0.25 m; panel size, 0.45 m x 1.10 m; panel height (control point), 1.55 m; panel inclination, 40°; date, August 14, 1983; time, noon).
where the four terms represent the radiance from the unshadowed white-painted ground, the normal soil, the shadowed white-painted ground and the sky respectively.

The main contribution to the total irradiance on the back of the panel is $E_{BA}$; however, in the summer near sunrise and sunset the Sun hits the back surface of the panel. Thus

$$E_B = E_{BA} + H_B \frac{\cos \beta_B}{\cos \alpha} \{1 - e_B(t)\}$$

(11)

where $\beta_B$ is the angle between the Sun's rays and the normal to the panel and $e_B(t)$ is a function which equals unity if the Sun hits the front surface of the panel and which is zero otherwise.

The irradiance on the front surface is

$$E_F = H_B \frac{\cos \beta}{\cos \alpha} e_B(t) + \frac{H_D}{\pi} \left(\Gamma_{SS} - \sum \Gamma_{0S}^{(i)}\right) + \frac{0.25(H_B + H_D)}{\pi} \left(\Gamma_{LS} - \sum \Gamma_{0G}^{(i)}\right)$$

(12)

The first term of this equation corresponds to the direct beam and the second term to the diffuse light from the sky (whose area $\Gamma_{SS}$ in the sky map is $\pi$ minus the area $\Gamma_{SA}$ of the sky in the albedo map). We have not taken into account the area of the white-painted ground seen by the front of the panel because it is very small (as a result of the specific location of our panel in our case it is nearly zero).

We call the ratio of the irradiance at the front and back surfaces to that at the front surface the albedo factor. This is a measure of the concentration ratio of the surroundings. These values were measured with the calibrated cells and calculated with the model outlined in this paper for three points of the central panel of our group of 36 panels. We observed reasonable agreement with our measurements.

In Fig. 7 we present the variation in the albedo factor as a function of the solar hour measured with three calibrated bifacial cells held at the centre of three panels of a group of 36, i.e. in the central panel and in the two panels at the northwest and southeast extremes. We observe that the albedo factor is symmetrical with respect to the Sun at noon only for the central panel. This is due to the fact that at other times the neighbouring panels cast shadows on this central panel, i.e. in the morning it is shadowed by the panels located to its right, and in the afternoon by those to its left. The panel at the northwest extreme is shadowed by the panels to its right in the morning, resulting in a smaller albedo factor in the morning than in the afternoon. In the southeast panel the opposite effect occurs. We also observe that the theoretical curves show better agreement with the experimental results obtained in the morning, as a result of the uncontrolled environmental effects during the day.

Of the group of 36 panels, most of them (for cost reasons) were simulated (to produce shadows and to hide the horizon) and only six were real. The measurements were taken with calibrated cells attached to a
simulated panel (made of a glass board with 36 aluminium discs of the same size as the cells and painted blue). On the specific day of our example the radiation (the integral of the horizontal irradiance) was 6.5 kWh day m\(^{-2}\), corresponding to a clearness factor of 0.65. The hourly distribution of irradiance is presented on the figure. We observed the applicability of the Liu and Jordan correlation for Madrid.

We can then conclude that the model used here is adequate for calculating the energy collected in a field of panels on white-painted ground. We have been able to verify the model in short-term measurement periods, and we can now, through calculations, forecast the behaviour of a field of panels over a long period of time. For this forecast we used the daily values of global irradiance on horizontal planes obtained from the Madrid station of the Spanish Meteorological Service, averaged over 10 years. We present the result of this calculation for different angles of inclination and different east–west separations between the panels in Fig. 8.

As a result of these calculations we conclude (a) that the best angle for monofacial panels in a total energy application is 50° but that the best angle
for bifacial panels is 30° and (b) that we can increase the collection of energy by 59% using a field of bifacial panels rather than monofacial panels (on the assumption of monofacial or bifacial panels in their best orientations) if the separation between the panels is 25 cm.

5. Conclusions

We have developed a model that has been experimentally checked to determine the amount of energy which enters a bifacial panel through its back surface. We applied this model to a large facility in the climate and latitude of Madrid, Spain, and we concluded that it collects 59% more energy than monofacial panels with a white-painted floor.

Once this calculation has been done, the proper way to obtain the rating of these bifacial panels in this specific application is to illuminate them using a Sun simulator with 1 air mass (AM) 1.5 suns on the front face and 0.59 × AM 1.5 suns on the back face. The details of this rating procedure are beyond the scope of this paper.
References