Renewable and Sustainable Energy Reviews 81 (2018) 161–171

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The role of view factors in solar photovoltaic fields

J. Appelbaum

School of Electrical Engineering, Tel Aviv University, Israel

A R T I C L E I N F O

Keywords:
PV fields
View factors to sky, ground and between collectors
Shaded and unshaded grounds

A B S T R A C T

The solar radiation on photovoltaic collectors in a solar field, deployed in multiple rows, consists of the direct beam, diffuse and reflected radiation. The amount of the diffuse and reflected radiation on the collector depends on view factor of the collector to sky, to ground and to surrounding objects. As shading takes place in the PV field, part of the ground between the collector rows may be shaded and another part may not be shaded, at any instant of time. To calculate the incident radiation of a PV field it is important to calculate the various types of view factors. In this paper, analytical expressions and numerical values of view factors were developed between collectors to sky F_{sky}, between opposite collectors $F_{A\to H}$, and between collectors to *shaded* $F_{grd.s}$ and *not shaded* $F_{grd.us}$ grounds, for the front and rear sides of the collectors deployed on horizontal and inclined planes.

1. Introduction

The solar radiation on a photovoltaic (PV) panel (collector) in a solar field consists of the direct beam, diffuse and reflected radiation. The amount of the diffuse radiation on the collector depends on the view factor of the collector to sky. The reflected radiation on the collector depends on the reflection from the ground and from opposite collectors, in a multiple row deployment of PV fields. These two components of the reflected radiation depend on two types of view factors: the view factor of the collector to ground and the view of the collector to an opposite collector. As shading between collector rows may take place in solar fields, a distinction is made between view factors to *shaded* and *unshaded* grounds. In some cases the reflected radiation is small and may be neglected in comparison to the direct beam and diffuse radiation, however is other instances, the reflected radiation may constitute an appreciable amount. Fig. 1 shows a deployment a PV collector in multiple rows, where shadows are cast on the ground and on the adjacent collectors, at a given time. Fig. 2 is the same field at another time instance where shadows are cast on part of the ground. In Fig. 1, the view factor is calculated between the second collector to the shaded ground, and in Fig. 2 the view factor is calculated between the second collector and the *shaded* and *unshaded* grounds. Bifacial PV panels can absorb solar radiation by both the front and the rear side, therefore view factors to ground of the rear side are necessary to calculate.

View factors have wide applications in radiative heat transfer. Numerical methods have been developed to calculate the view factors by Monte Carlo method [1,2], Ray tracing method [3] and others [4,5]. Catalogues of view factors are published in [6–9]. All the above references deal with thermal radiation between surfaces. In photovoltaic (PV) systems view factors are related to electric power generation and may entail view factors to sky, to ground and between adjacent collectors. The calculation of the view factors to the sky for collectors deployed in multiple rows on horizontal and inclined planes are dealt in [10,11]. An application of view factor for building integrated PV system is reported in [12]. A general mathematical expression for the view factor to sky is developed in [13] for collector mounted on sloped planes where the azimuths of the planes and the collectors do not coincide. View factors to sky of photovoltaic collectors on roof tops are reported in [14] and view factors to ground are reported in [15]. A recent article on view factors of solar collectors deployed on horizontal, inclined and step-like planes is reported in [16]. The present article is a review on the various view factors and their developed mathematical expressions, and also includes additional view factors of collectors in PV fields, not dealt with in articles [10,11,13–16]. The expressions of the various view factors as shown in Fig. 3 include: view factors to sky, F_{sky}; view factor between opposite collectors, $F_{A\to H}$; and view factors between collectors to *shaded* $F_{grd.s}$ and *not shaded* $F_{grd.us}$ grounds, for both the front and rear sides of the collector. The view factors also include collectors mounted on horizontal and on inclined planes. Expressions of view factors to sky of the front-side of collectors deployed in multiple rows are developed in articles [10,11,13,14]. View factors to ground of the front and rear sides of collectors are given in [15]. Article [16] deals with view factors to sky, to ground and between collectors deployed in multiple rows. The expressions for the additional view factors in the present article, pertains to view factors of the rear-side of the collector to sky in multiple row deployment. In addition, view factors to ground of the rear side of a single collector row

E-mail address: appel@eng.tau.ac.il.

http://dx.doi.org/10.1016/j.rser.2017.07.026
Received 9 August 2016; Received in revised form 15 January 2017; Accepted 6 July 2017
1364-0321/

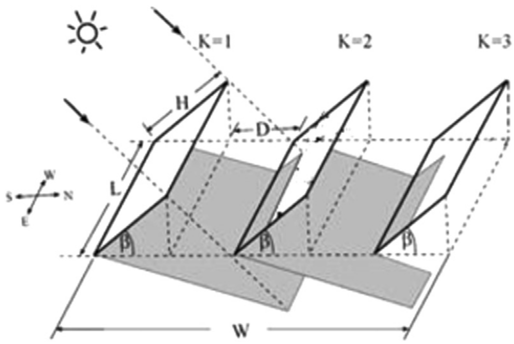

Fig. 1. Shading by collectors facing south in a solar field-ground totally shaded.

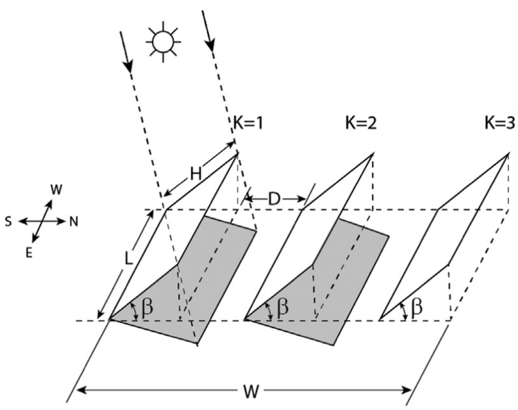

Fig. 2. Shading by collectors facing south in a solar field- ground partially shaded.

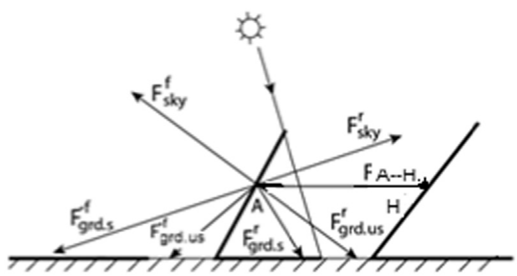

Fig. 3. View factor to sky and ground-front and rear sides.

are developed. View factors of vertical collectors on horizontal and inclined plane are also treated. These additional view factors are needed to determine the solar radiation on the rear-side of the collector, for example, on bifacial solar panels [17], and to determine the operating temperature of PV arrays [18], as the rear-side of the collector radiates heat to sky, shaded and not shaded ground under the PV arrays.

2. Solar radiation calculation

The irradiance G_β on an inclined surface β with respect to a horizontal plane is given by [19]:

$$G_\beta = G_b \cdot \cos\theta + F_{A\to sky} \cdot G_{dh} + al \cdot F_{A\to grd.} \cdot G_h + ref^f \cdot F^r_{A\to H} \cdot G^f_g \tag{1}$$

$$G_\beta = G_b \cdot \cos\theta + F_{A\to sky} \cdot G_{dh} + al \cdot F_{A\to grd.us} \cdot G_h + ref^f \cdot F^r_{A\to H} \cdot G^f_g \tag{2}$$

$$G_\beta = G_b \cdot \cos\theta + F_{A\to sky} \cdot G_{dh} + al \cdot F_{A\to grd.s} \cdot G_{dh} + ref^f \cdot F^r_{A\to H} \cdot G^f_g \tag{3}$$

where

G_b is the beam irradiance on the surface, in (W/m^2)
G_{dh} is the diffuse irradiance on a horizontal surface, in (W/m^2)
G_h is the global irradiance on a horizontal surface, in (W/m^2)
G^f_g is the global irradiance on the front side of the collector, in (W/m^2)
$F_{A\to sky}$ is the view factor of surface A to sky
$F_{A\to grd.}$ is the view factor of the surface A to ground
$F_{A\to grd.us}$ is the view factor of surface A to *not shaded* ground
$F_{A\to grd.s}$ is the view factor of surface A to *shaded* ground
$F^r_{A\to H}$ is the view factor between collectors A and H- rear side A to front side H
al is the ground albedo
ref^f is the reflectance of the front side of the collector
θ is the angle between the beam irradiance on a surface and the normal to that
surface

Eq. (1) pertains to not shaded ground at the given time of solar calculation (e.g., on a single collector row), therefore the global irradiance G_h on a horizontal surface is used. Eq. (2) is used for the same case as Eq. (1) but for not shaded ground between collectors in multiple rows. In this case the view factor is different. Eq. (3) pertains to shaded grounds, therefore only the diffuse irradiation G_{dh} on horizontal surface is used.

3. View factor

Photovoltaic collectors are deployed in rows in a solar field. The length of the row is much larger than its width, i.e., the collector may be considered of infinite length. The calculation of view factors may be based on [11]. In the present article the "cross-string rule" by Hottel [20] is used to develop the different kinds of view factors. The view factor between surface A_1 and surface A_2 may be determined with the help of Fig. 4, where A_1 and A_2 are two surfaces of infinite length.

The view factor is given by:

$$F_{A_1\to A_2} = \frac{CF + DE - CE - DF}{2 \cdot CD} \tag{4}$$

where CD and EF are the widths of surfaces A_1 and A_2, respectively, ED and CF are the diagonals, and CE and DF are the distances between the surface edges. According to Hottel, the view factor of collector H to sky (see Fig. 5) indicated by the view angle (VA) is given by:

$$F_{H\to sky} = \frac{L_1 + L_2 - L_3}{2L_1} \tag{5}$$

and the view factor of collector H to ground (see Fig. 6) is given by:

$$F_{H\to grd.} = \frac{L_1 + L_2 - L_3}{2L_1} \tag{6}$$

It should be noted that the sum of the view factors of the front side of the collector is 1, and the same applies to the rear side, i.e.,

$$\sum F^f = 1, \sum F^r = 1 \tag{7}$$

3.1. Single collector row-horizontal plane

The view factors to sky and ground of a single collector row H with *no ground shaded (grd.us)* in front and in rear sides of the collector are shown in Fig. 7.

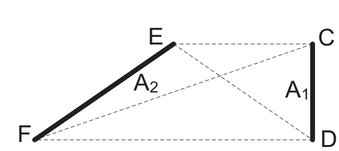

Fig. 4. Calculation of view factor- two surfaces of infinite length.

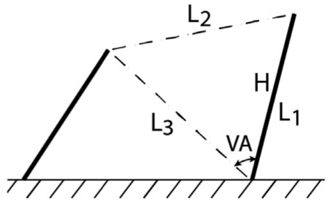

Fig. 5. View factor to sky.

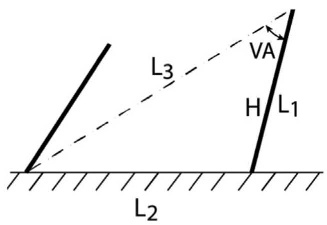

Fig. 6. View factor to ground.

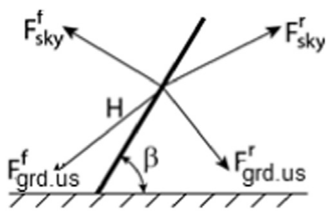

Fig. 7. View factors to sky and ground, front and rear sides - *no ground shaded.*

3.1.1. View factors of front side of collector-no front ground shaded

The view factor to *sky* of the front side is calculated based on Eq. (5), see Fig. 8,

$L_1 = CD = H$
$L_2 = BC$
$L_3 = BD$

As $L_3 \to \infty$, $L_2 - L_3 \cong L_1 \cos\beta$, obtaining

$$F^f_{H\to sky} = (1 + cos\beta)/2 \tag{8}$$

The view factor to *sky* of the front side of the collector for $\beta = 30^0$ is: $F^f_{H\to sky} = (1 + cos30^0)/2 = 0.933$, i.e., a rather large value implying that the diffuse radiation from the sky on the PV collector may be appreciable.

The view factor to *ground* of the front side is calculated based on Eq. (6), see Fig. 8,

$L_1 = CD = H$
$L_2 = BD$
$L_3 = BC$

As $L_2 \to \infty$, $L_2 - L_3 \approx -L_1 \cos\beta$, obtaining:

$$F^f_{H\to grd.} = (1 - \cos\beta)/2 \tag{9}$$

The view factor to *ground* of the front side of the collector for $\beta = 30^0$ is: $F^f_{H\to grd.} = (1 - \cos\beta)/2 = (1 - \cos 30)/2 = 0.067$, i.e., a rather small value implying that the reflected radiation from the ground on the PV collector may be negligible.

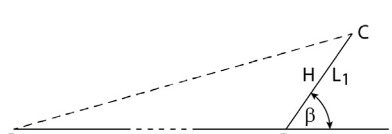

Fig. 8. View factor to sky and ground, single collector-*no front ground shaded.*

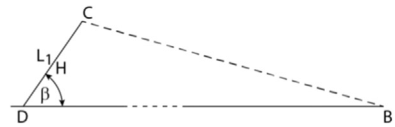

Fig. 9. View factor to sky and ground, single collector-no rear ground shading.

3.1.2. View factor of rear side-no rear ground shaded

The view factor to *sky* of the rear side is calculated based on Eq. (5), see Fig. 9,

$L_1 = CD = H$
$L_2 = BC$
$L_3 = BD$

As $L_3 \to \infty$, $L_2 - L_3 \cong -L_1 \cos\beta$, obtaining:

$$F^r_{H\to sky} = (1 - cos\beta)/2 \tag{10}$$

i.e., $F^r_{H\to sky} = F^f_{H\to grd.}$ and for $\beta = 30^0$ is rather small.

The view factor to *ground* of the rear side is calculated based on Eq. (6), see Fig. 9,

$L_1 = CD = H$
$L_2 = BD$
$L_3 = BC$

As $L_2 \to \infty$, $L_2 - L_3 \cong L_1 \cos\beta$, obtaining:

$$F^r_{H\to grd.} = (1 + cos\beta)/2 \tag{11}$$

The view factor to *ground* of the rear side of the collector for $\beta = 30^0$ is: $F^r_{H\to grd.} = (1 + cos\beta)/2 = (1 + \cos 30)/2 = 0.933$, i.e., a rather large value implying that the reflected radiation from the ground on the PV collector may be appreciable. Eqs. (8) and (11) indicate that $F^f_{H\to sky} = F^r_{H\to grd.}$.

3.2. View factor of rear side- rear ground shaded and not shaded

The view factors of a single collector row H with *rear* side shaded (*grd.s*) and not shaded (*grd.us*) grounds are shown in Fig. 10.

The view factor to *sky* of the rear side $F^r_{H\to sky}$ is given by Eq. (10).

According to Eq. (5), the view factor to *shaded* ground of the rear side of the collector, Fig. 11, is calculated as:

$L_1 = H$
$L_2 = S$
$L_3 = [H^2 + S^2 - 2H{\cdot}S \cos\beta]^{1/2}$

and is:

$$F^r_{H\to grd.S} = \frac{H + S - [H^2 + S^2 - 2HS\cos\beta]^{1/2}}{2H} \tag{12}$$

Note that the shaded ground S varies with time along the day with the position of the sun.

The view factor to *not shaded ground* of the rear side is calculated with the help of Eq. (4), see Fig. 11.

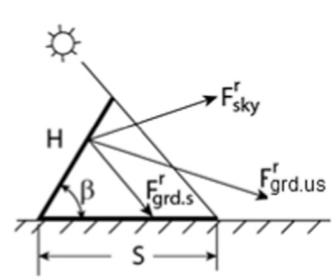

Fig. 10. View factors to sky and ground, rear side of collector- shaded and not shaded grounds.

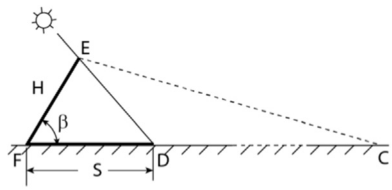

Fig. 11. View factor to *shaded* ground- *rear ground shaded.*

$CF - CE \cong H\cos\beta$
$DE = [H^2 + S^2 - 2H{\cdot}S\cos\beta]^{1/2}$
$DF = S$

obtaining:

$$F^r_{H\to grd.us} = \frac{H\cos\beta + [H^2 + S^2 - 2HS\cos\beta]^{1/2} - S}{2H} \tag{13}$$

To verify the results, substitute Eqs. (10), (12) and (13) into Eq. (7), obtaining

$$F^r_{H\to sky} + F^r_{H\to grd.s} + F^r_{H\to grd.us} = 1$$

3.3. Single collector row- inclined plane

A collector may be installed on inclined planes and the different view factors are now calculated.

3.3.1. View factor of front side of the collector-no front ground shaded

The view factor to *sky* of the front side is calculated based on Eq. (5), see Fig. 12,

$L_1 = CD = H$
$L_2 = BC$
$L_3 = BD$

As $L_3 \to \infty$, $L_2 - L_3 \cong L_1\cos(\beta - \varepsilon)$, obtaining:

$$F^f_{H\to sky} = [1 + \cos(\beta - \varepsilon)]/2 \tag{14}$$

The view factor to *sky* of the front side of the collector for $\beta = 30^0$, $\varepsilon = 15^0$ is: $F^f_{H\to grd.} = [1 + \cos(30 - 15)]/2 = 0.983$, i.e., a rather large value implying that the sky's
diffuse radiation on the PV collector may be appreciable.

The view factor to *ground* is calculated based on Eq. (6), see Fig. 12,

$L_1 = CD = H$
$L_2 = BD$
$L_3 = BC$

As $L_2 \to \infty$, $L_2 - L_3 \cong -L_1\cos(\beta - \varepsilon)$, obtaining:

$$F^f_{H\to grd.} = [1 - \cos(\beta - \varepsilon)]/2 \tag{15}$$

The view factor to *ground* of the front side of the collector for $\beta = 30^0$, $\varepsilon = 15^0$ is: $F^f_{H\to grd.} = [1 - \cos(30 - 15)]/2 = 0.017$, i.e., a rather small value implying that the reflected radiation from the ground on the PV collector may be negligible.

3.3.2. View factor of rear side-no rear ground shaded

The view factor to *sky* of the rear side is calculated based on Eq. (5), see Fig. 13,

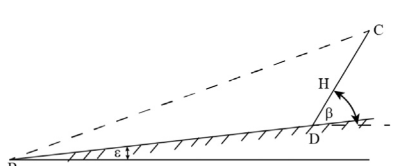

Fig. 12. View factor to sky and ground, incline plane-no front shading.

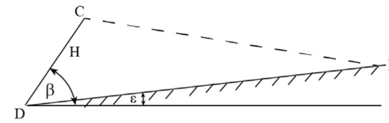

Fig. 13. View factor to sky and ground, inclined plane-no rear shading.

$L_1 = CD = H$
$L_2 = BC$
$L_3 = BD$

As $L_3 \to \infty$, $L_2 - L_3 \cong -L_1\cos(\beta - \varepsilon)$, obtaining:

$$F^r_{H\to sky} = [1 - \cos(\beta - \varepsilon)]/2 \tag{16}$$

i.e., $F^r_{H\to sky} = F^f_{H\to grd.}$ and for $\beta = 30^0$ the view factor is rather small.

The view factor to *ground* of the rear side is calculated based on Eq. (6), see Fig. 13,

$L_1 = CD = H$
$L_2 = BD$
$L_3 = BD$

As $L_2 \to \infty$, $L_2 - L_3 \cong L_1\cos(\beta - \varepsilon)$, obtaining:

$$F^r_{H\to grd.} = [1 + \cos(\beta - \varepsilon)]/2 \tag{17}$$

The view factor to *ground* of the rear side of the collector for $\beta = 30^0$ is $F^r_{H\to grd.} = (1 + \cos\beta)/2 = (1 + \cos 30)/2 = 0.933$, i.e., a rather large value implying that the reflected radiation from the ground on the PV collector may be appreciable. From Eqs. (14) and (17) we obtain $F^f_{H\to sky} = F^r_{H\to grd.}$

3.3.3. View factor of rear side- rear ground shaded

The view factor to *sky* of the rear side is given by Eq. (16) (see Fig. 14) and is:

$$F^r_{H\to sky} = [1 - \cos(\beta - \varepsilon)]/2 \tag{18}$$

According to Eq. (6) the view factor of the rear side to *shaded ground S*, Fig. 14, is calculated as:

$L_1 = H$
$L_2 = S$
$L_3 = [H^2 + S^2 - 2H{\cdot}S\cos(\beta - \varepsilon)]^{1/2}$

and is:

$$F^r_{H\to grd.s} = \frac{H + S - [H^2 + S^2 - 2H{\cdot}S\cos(\beta - \varepsilon)]^{1/2}}{2H} \tag{19}$$

The view factor of the rear side to *not shaded ground* is calculated with the help of Eq. (4), see Fig. 14.

$CF - CE \cong H\cos(\beta - \varepsilon)$
$DE = [H^2 + S^2 - 2H{\cdot}S\cos(\beta - \varepsilon)]^{1/2}$
$DF = S$

$$F^r_{H\to grd.us} = \frac{H\cos(\beta - \varepsilon) + [H^2 + S^2 - 2HS\cos(\beta - \varepsilon)]^{1/2} - S}{2H} \tag{20}$$

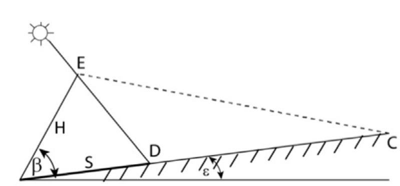

Fig. 14. View factors to sky; shaded and not shaded ground; inclined plane-rear ground shaded.

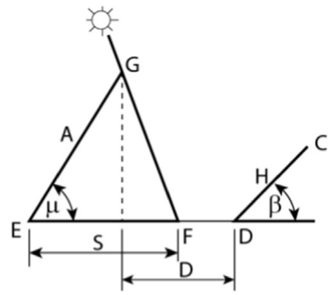

Fig. 15. Multiple collector rows A and H-shaded and not shaded grounds.

4. Multiple collector rows- *horizontal* plane

In a multiple collector rows, see Fig. 2, the different view factors are calculated between two adjacent rows. Fig. 15 describes a general case of two adjacent collectors A and H of infinite length. Collector A is of width A and is inclined with an angle μ with respect to horizontal, and collector H is of width H and inclined with angle β with respect to horizontal. The distance $EF = S$ is *shaded* and the distance FD is *not shaded*. The shaded and not shaded areas between the collectors vary with time along the day. The shaded area may be calculated based on [11].

4.1. View factors of front side of collector

The view factor of the front side to *sky* of collector H is calculated based on Eq. (5), see Fig. 16,

$$L_1 = CD = H$$

$$L_2 = CG = [(A\sin\mu - H\sin\beta)^2 + (D + H\cos\beta)^2]^{1/2}$$

$$L_3 = DG = [(A\sin\mu)^2 + D^2]^{1/2}$$

obtaining:

$$F^f_{H\to sky} = \frac{H + [(A\sin\mu - H\sin\beta)^2 + (D + H\cos\beta)^2]^{1/2} - [(A\sin\mu)^2 + D^2]^{1/2}}{2H} \tag{21}$$

For the case $A = H$, $\mu = \beta$ the view factor to *sky* is:

$$F^f_{H\to sky} = \frac{H + D + H\cos\beta - [(H\sin\beta)^2 + D^2]^{1/2}}{2H} \tag{22}$$

The view factor of the front side of the collector H to *not shaded ground* is calculated with the help of Eq. (6), see Fig. 16.

$$F^f_{H\to grd.us} = \frac{CD + FD - CF}{2CD}$$

$$L_1 = CD = H$$

$$L_2 = FD = A\cos\mu + D - S$$

$$L_3 = CF = [(A\cos\mu + D - S + H\cos\beta)^2 + (H\sin\beta)^2]^{1/2}$$

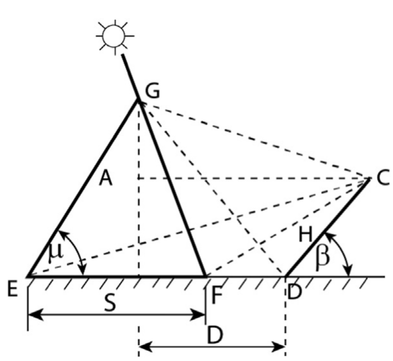

Fig. 16. View factors in multiple collector rows - *horizontal* plane.

obtaining:

$$F^f_{H\to grd.us} = \frac{H + A\cos\mu + D - S - [(A\cos\mu + D - S + H\cos\beta)^2 + (H\sin\beta)^2]^{1/2}}{2H} \tag{23}$$

According to Eq. (4) the view factor of the front side to *shaded ground*, Fig. 16, is calculated as:

$$F^f_{H\to grd.S} = \frac{CF + DE - CE - DF}{2CD}$$

$$DF = A\cos\mu + D - S$$

$$DE = A\cos\mu + D$$

$$CF = [(H\cos\beta + A\cos\mu + D - S)^2 + (H\sin\beta)^2]^{1/2} \tag{24}$$

$$CE = [(A\cos\mu + D + H\cos\beta)^2 + (H\sin\beta)^2]^{1/2}$$

obtaining:

$$F^f_{A\to grd.s} = \frac{[(H\cos\beta + A\cos\mu + D - S)^2 + (H\sin\beta)^2]^{1/2}}{2H} \\ \frac{-[(A\cos\mu + D + H\cos\beta)^2 + (H\sin\beta)^2]^{1/2} + S}{2H} \tag{25}$$

For vertical collectors $A = H$, $\mu = \beta = 90^0$ the view factor is:

$$F^f_{H\to grd.s} = \frac{[(D - S)^2 + H^2]^{1/2} - [D^2 + H^2]^{1/2} + S}{2H} \tag{26}$$

and for vertical collectors and $S = D$ the view factor is:

$$F^f_{H\to grd.s} = \frac{H + D - [D^2 + H^2]^{1/2}}{2H} \tag{27}$$

4.2. View factors of rear side of collector

The view factor to *sky* of the rear side is calculated based on Eq. (5), see Fig. 16.

$$L_1 = EG = A$$

$$L_2 = CG = [(D + H\cos\beta)^2 + (A\sin\mu - H\sin\beta)^2]^{1/2}$$

$$L_3 = CE = [(A\cos\mu + D + H\cos\beta)^2 + (H\sin\beta)^2]^{1/2}$$

obtaining:

$$F^r_{A\to sky} = \frac{A + [(D + H\cos\beta)^2 + (A\sin\mu - H\sin\beta)^2]^{1/2} - [(A\cos\mu + D + H\cos\beta)^2 + (H\sin\beta)^2]^{1/2}}{2A} \tag{28}$$

For $A = H$, $\mu = \beta$,

$$F^r_{A\to sky} = \frac{H + D + H\cos\beta - [(D + 2H\cos\beta)^2 + (H\sin\beta)^2]^{1/2}}{2H} \tag{29}$$

According to Eq. (6) the view factor of the rear side to *shaded ground*, Fig. 16, is calculated as:

$$L_1 = EG = A$$
$$L_2 = EF = S$$
$$L_3 = FG = [(S - A\cos\mu)^2 + (A\sin\mu)^2]^{1/2}$$

obtaining:

$$F^r_{A\to grd.s} = \frac{A + S - [(S - A\cos\mu)^2 + (A\sin\mu)^2]^{1/2}}{2A} \tag{30}$$

The view factor of the rear side to *not shaded ground* is calculated with the help of Eqs. (4) and (24), see Fig. 16.

$$F^r_{A\to grd.us} = \frac{GF + ED - GD - EF}{2EG}$$

obtaining:

$$F^{r}_{A\to grd.us}=\frac{[(S-A\cos\mu)^2+(A\sin\mu)^2]^{1/2}+A\cos\mu+D-[D^2+(A\sin\mu)^2]^{1/2}-S}{2A} \tag{31}$$

4.3. *View factor between collectors*

The view factor *between collector H to collector A* is determined by Eq. (4) and Fig. 16,

$$F_{H\to A}=\frac{CE+DG-CG-DE}{CD} \tag{32}$$

where

$$CE=[(A\cos\mu+D+H\cos\beta)^2+(H\sin\beta)^2]^{1/2}$$
$$DG=[(A\sin\mu)^2+D^2]^{1/2}$$
$$CG=[(D+H\cos\beta)^2+(A\sin\mu-H\sin\beta)^2]^{1/2}$$
$$DE=A\cos\mu+D$$

obtaining:

$$F^{f}_{H\to A}=\frac{[(H\sin\beta)^2+(A\cos\mu+D+H\cos\beta)^2]^{1/2}+[D^2+(A\sin\mu)^2]^{1/2}}{2H}\frac{-[(D+H\cos\beta)^2+(A\sin\mu-H\sin\beta)^2]^{1/2}-(A\cos\mu+D)}{2H} \tag{33}$$

For $A=H,\quad \mu=\beta$

$$F^{f}_{H\to A}=\frac{[(H\sin\beta)^2+(2H\cos\beta+D)^2]^{1/2}+[D^2+(H\sin\beta)^2]^{1/2}-2(D+H\cos\beta)}{2H} \tag{34}$$

The view factor between *collector A to collector H* is determined by Eqs. (4) and (32) and Fig. 16,

$$F^{r}_{A\to H}=\frac{CE+DG-CG-DE}{2EG}$$

obtaining:

$$F^{r}_{A\to H}=\frac{[(A\cos\mu+D+H\cos\beta)^2+(H\sin\beta)^2]^{1/2}+[(A\sin\mu)^2+D^2]^{1/2}}{2A}\frac{-[(D+H\cos\beta)^2+(A\sin\mu-H\sin\beta)^2]^{1/2}-(A\cos\mu+D)}{2A} \tag{35}$$

For $A=H$, $\mu=\beta$

$$F^{r}_{H\to A}=\frac{[(H\sin\beta)^2+(2H\cos\beta+D)^2]^{1/2}+[D^2+(H\sin\beta)^2]^{1/2}-2(D+H\cos\beta)}{2H} \tag{36}$$

5. Multiple collector rows- *inclined plane*

In a multiple collector rows, the different view factors are now calculated between two adjacent rows. Fig. 17 describes a general case of two adjacent collectors A and H of infinite length. Collector A is of width A and is inclined with an angle μ with respect to horizontal and collector H is of width H and inclined with angle β with respect to horizontal. The collectors are deployed on an inclined plane with an angle ε with respect to ground. The distance *EF* is *shaded* and the distance *FD* is *not shaded.*

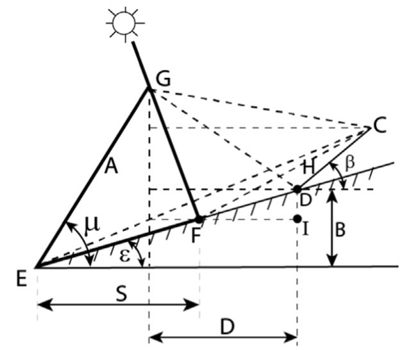

Fig. 17. View factors in multiple collector rows - *inclined* plane.

5.1. *View factors of front side of collector*

The view factor to *sky* of the front side is calculated based on Eq. (5), see Fig. 17.

$$L_1=CD=H,$$
$$L_2=CG=[(D+H\cos\beta)^2+(A\sin\mu-H\sin\beta-B)^2]^{1/2}$$
$$L_3=DG=[D^2+(A\sin\mu-B)^2]^{1/2}$$

obtaining:

$$F^{f}_{H\to sky}=\frac{H+[(D+H\cos\beta)^2+(A\sin\mu-H\sin\beta-B)^2]^{1/2}-[D^2+(A\sin\mu-B)^2]^{1/2}}{2H} \tag{37}$$

The view factor to *not shaded ground* of the front side is calculated with the help of Eq. (6), see Fig. 17.

$$F^{f}_{H\to grd.us}=\frac{CD+FD-CF}{2CD}$$

$$L_1=CD=H$$

$$L_2=DF=[(A\cos\mu+D-S)^2+[[(A\cos\mu+D-S)\tan\varepsilon]^2]^{1/2}$$

$$L_3=CF=[(A\cos\mu+D-S+H\cos\beta)^2+[(A\cos\mu+D-S)\tan\varepsilon+H\sin\beta]^2]^{1/2}$$

obtaining:

$$F^{f}_{H\to grd.us}=\frac{H+[(A\cos\mu+D-S)^2+[[(A\cos\mu+D-S)\tan\varepsilon]^2]^{1/2}}{2H}\frac{-[(A\cos\mu+D-S+H\cos\beta)^2+[(A\cos\mu+D-S)\tan\varepsilon+H\sin\beta]^2]^{1/2}}{2H} \tag{38}$$

According to Eq. (4) the view factor of the front side to *shaded ground*, Fig. 17, is calculated as:

$$F^{f}_{H\to grd.s}=\frac{CF+DE-CE-DF}{2CD}$$

$$CF=[(A\cos\mu+D-S+H\cos\beta)^2+[(A\cos\mu+D-S)\tan\varepsilon+H\sin\beta]^2]^{1/2}$$

$$DE=[(A\cos\mu+D)^2+B^2]^{1/2}$$

$$CE=[(A\cos\mu+D+H\cos\beta)^2+(H\sin\beta+B)^2]^{1/2}$$

$$DF=[(A\cos\mu+D-S)^2+[[(A\cos\mu+D-S)\tan\varepsilon]^2]^{1/2}$$

obtaining:

$$F^{f}_{H\to grd.s} = \frac{[(A\cos\mu + D - S + H\cos\beta)^2 + [(A\cos\mu + D - S)\tan\varepsilon + H\sin\beta]^2]^{1/2}}{2H} + \frac{[(A\cos\mu + D)^2 + B^2]^{1/2}}{2H} - \frac{[(A\cos\mu + D + H\cos\beta)^2 + (H\sin\beta + B)^2]^{1/2}}{2H} - \frac{[(A\cos\mu + D - S)^2 + [[(A\cos\mu + D - S)\tan\varepsilon]^2]^{1/2}}{2H} \tag{39}$$

5.2. View factors of rear side of collector

The view factor to *sky* of the rear side is calculated based on Eq. (5), see Fig. 17.

$L_1 = EG = A$

$L_2 = CG = [(D + H\cos\beta)^2 + (A\sin\mu - H\sin\beta - B)^2]^{1/2}$

$L_3 = CE = [(A\cos\mu + D + H\cos\beta)^2 + (H\sin\beta + B)^2]^{1/2}$

obtaining:

$$F^{r}_{A\to sky} = \frac{A + [(D + H\cos\beta)^2 + (A\sin\mu - H\sin\beta - B)^2]^{1/2}}{2A} - \frac{[(A\cos\mu + D + H\cos\beta)^2 + (H\sin\beta + B)^2]^{1/2}}{2A} \tag{40}$$

According to Eq. (6) the view factor to *shaded ground* of the rear side, Fig. 17, is calculated as:

$L_1 = EG = A$

$L_2 = EF = [(S^2 + [B - (A\cos\mu + D - S)\tan\varepsilon]^2]^{1/2}$,

$L_3 = GF = [[B - (A\cos\mu + D - S)\tan\varepsilon]^2 + (S - A\cos\mu)^2]^{1/2}$

obtaining:

$$F^{r}_{A\to grd.s} = \frac{A + [(S^2 + [B - (A\cos\mu + D - S)\tan\varepsilon]^2]^{1/2}}{2A} - \frac{[[B - (A\cos\mu + D - S)\tan\varepsilon +]^2 + (S - A\cos\mu)^2]^{1/2}}{2A} \tag{41}$$

The view factor of the rear side to *not shaded ground* is calculated with the help of Eq. (4), see Fig. 17.

$$F^{r}_{A\to grd.us} = \frac{GF + ED - GD - EF}{2EG}$$

$FG = [(S - A\cos\mu)^2 + [B - (A\cos\mu + D - S)\tan\varepsilon]^2]^{1/2}$

$ED = [(A\cos\mu + D)^2 + B^2]^{1/2}$

$DG = [D^2 + (A\sin\mu - B)^2]^{1/2}$

$EF = [S^2 + [B - [(A\cos\mu + D - S)\tan\varepsilon]^2]^{1/2}$

obtaining:

$$F^{r}_{A\to grd.us} = \frac{[(S - A\cos\mu)^2 + [B - (A\cos\mu + D - S)\tan\varepsilon]^2]^{1/2} + [(A\cos\mu + D)^2 + B^2]^{1/2}}{2A} - \frac{[D^2 + (A\sin\mu - B)^2]^{1/2} - [S^2 + [B - [(A\cos\mu + D - S)\tan\varepsilon]^2]^{1/2}}{2A} \tag{42}$$

5.3. View factor between collectors

The view factor *between collector H to collector A* is determined by Eq. (4) and Fig. 17,

$$F_{H\to A} = \frac{CE + DG - CG - DE}{2CH}$$

$CE = [(A\cos\mu + D + H\cos\beta)^2 + (H\sin\beta + B)^2]^{1/2}$

$DG = [D^2 + (A\sin\mu - B)^2]^{1/2}$

$CG = [(D + H\cos\beta)^2 + (A\sin\mu - H\sin\beta - B)^2]^{1/2}$

$DE = [(A\cos\mu + D)^2 + B^2]^{1/2}$

obtaining:

$$F_{H\to A} = \frac{[(A\cos\mu + D + H\cos\beta)^2 + (H\sin\beta + B)^2]^{1/2} + [D^2 + (A\sin\mu - B)^2]^{1/2}}{2H} - \frac{[(D + H\cos\beta)^2 + (A\sin\mu - H\sin\beta - B)^2]^{1/2} - [(A\cos\mu + D)^2 + (B^2]^{1/2}}{2H} \tag{43}$$

The view factor *between collector A to collector H* is determined by Eq. (4) and Fig. 17,

$$F_{A\to H} = \frac{CE + DG - CG - DE}{2CH}$$

$CE = [(A\cos\mu + D + H\cos\beta)^2 + (H\sin\beta + B)^2]^{1/2}$

$DG = [(A\sin\mu - B)^2 + D^2]^{1/2}$

$CG = [(D + H\cos\beta)^2 + (A\sin\mu - H\sin\beta - B)^2]^{1/2}$

$DE = [(A\cos\mu + D)^2 + B^2]^{1/2}$

obtaining:

$$F_{A\to H} = \frac{[(A\cos\mu + D + H\cos\beta)^2 + (H\sin\beta + B)^2]^{1/2} + [(A\sin\mu - B)^2 + D^2]^{1/2}}{2A} - \frac{[(D + H\cos\beta)^2 + (A\sin\mu - H\sin\beta - B)^2]^{1/2} - [(A\cos\mu + D)^2 + B^2]^{1/2}}{2A} \tag{44}$$

6. View factors for common PV plant configurations

The common configurations of collectors in a PV field are usually deployed on horizontal or on inclined planes with the same inclination angle β, collector width H and a distance between the collectors D.

6.1. Horizontal plane

Collectors deployed on a horizontal plane are shown in Fig. 18. The view factor to *sky* of the front side of the collector is given by Eq. (22) and is:

$$F^{f}_{H\to sky} = \frac{H + D + H\cos\beta - [(H\sin\beta)^2 + D^2]^{1/2}}{2H} \tag{45}$$

The effect of increasing the distance between the collectors on the view factor to

sky is shown in Fig. 19 for inclination angles $\beta = 30^0$ and $\beta = 50^0$ ($H = 2.0m$). The view factor value is rather large implying that the diffuse radiation from the sky on the PV collector may be appreciable.

The view factor to *ground* of the front side of the collector is obtained based on Eq. (6) and is:

$$F^{f}_{H\to grd.} = \frac{H + D + H\cos\beta - [(D + 2H\cos\beta)^2 + (H\sin\beta)^2]^{1/2}}{2H} \tag{46}$$

The variation of the view factors to ground of the front side of the collector with inclination angle β is shown in Fig. 20 for $H = 2.0m$, $D = 1.0m$. The view factor is rather small for small inclination angles.

The view factor to sky of the rear side of the collector is given by Eq. (29) and is:

$$F^{r}_{H\to sky} = \frac{H + D + H\cos\beta - [(D + 2H\cos\beta)^2 + (H\sin\beta)^2]^{1/2}}{2H} \tag{47}$$

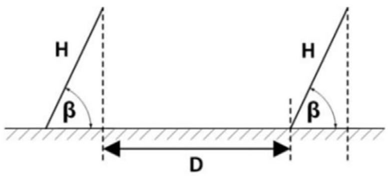

Fig. 18. Collectors H with inclination β on a horizontal plane.

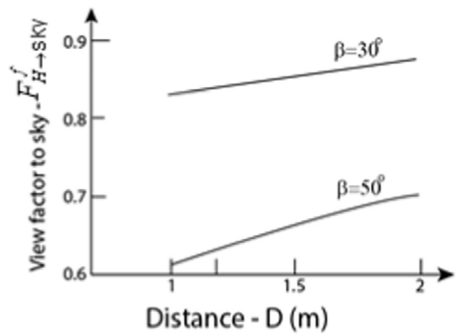

Fig. 19. Variation of view factor to *sky* of the front side with distance between the collectors on horizontal plane, $H = 2.0m$.

The view factor to *ground* of the rear side of the collector is obtained based on Eq. (6) and is:

$$F^r_{H\to grd.} = \frac{H + D + H\cos\beta - [(D^2 + (H\sin\beta)^2]^{1/2}}{2H} \tag{48}$$

The variation of the view factors to ground of the rear side of the collector with the inclination angle β is shown in Fig. 21. The view factor values are rather large for small inclination angles.

The view factor between collectors H is determined by Eq. (4) and Fig. 18 and is:

$$F_{H\to H} = \frac{[D^2 + (H\sin\beta)^2]^{1/2} + [(D + 2H\cos\beta)^2 + (H\sin\beta)^2]^{1/2} - 2(D + H\cos\beta)}{2H} \tag{49}$$

6.2. Inclined plane

Collectors deployed on an inclined plane are shown in Fig. 22.

The view factor to *sky* of the front side of the collector is given by Eq. (37), and for $A = H$, $\mu = \beta$ the view factor is:

$$F^f_{H\to sky} = \frac{H + [(D + H\cos\beta)^2 + B^2]^{1/2} - [D^2 + (H\sin\beta - B)^2]^{1/2}}{2H} \tag{50}$$

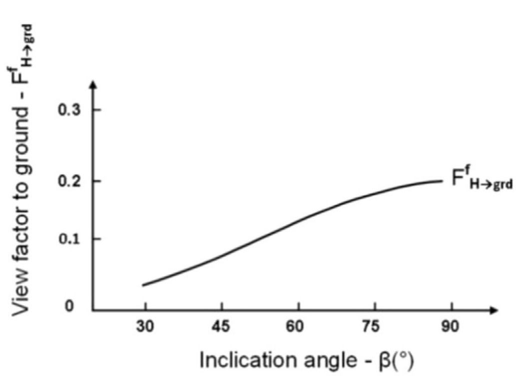

Fig. 20. Variation of view factors to ground with inclination angle β-front side, $H = 2.0m$, $D = 1.0m$.

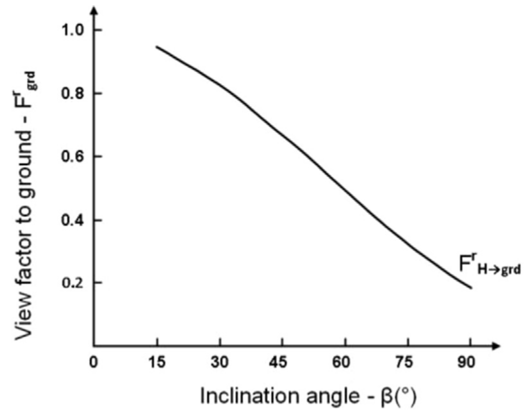

Fig. 21. Variation of view factors to ground with inclination angle β-rear side, $H = 2.0m$, $D = 1.0m$.

Fig. 23 shows the effect of raising the collector on the view factor to sky of the front side for inclination angles $\beta = 30^0$ and $\beta = 50^0$ ($H = 2.0m$, $D = 1.0m$). The corresponding inclination angles ε of the planes to raising values B of the collectors above ground by B = 0.2, 0.4, 0.6 and 0.8 m are ε= 11°, 22°, 31° and 39°, respectively.

The view factor to *ground* of the front side of the collector is obtained based on Eq. (6) and is:

$$F^f_{H\to grd.} = \frac{H + [(D + H\cos\beta)^2 + B^2]^{1/2} - [(D + 2H\cos\beta)^2 + (H\sin\beta + B)^2]^{1/2}}{2H} \tag{51}$$

Fig. 24 shows the effect of raising the collector on the view factor to ground of the front side for inclination angles $\beta = 30^0$ and $\beta = 50^0$ ($H = 2.0m$, $D = 1.0m$). For $B = 0.2, 0.4, 0.6m$ and $\beta = 30^0$, the corresponding plane inclination angles are: $\varepsilon = 4.2^0, 8.3^0, 12.4^0$, respectively and for $\beta = 50^0$ the plane inclination angles are: $\varepsilon = 5.0^0, 9.9^0, 14.7^0$. The view factor of the front side of the collector to ground is rather small.

The view factor to *sky* of the rear side of the collector is given by Eq. (40), and for $A = H$, $\mu = \beta$ the view factor is:

$$F^r_{A\to sky} = \frac{H + [(D + H\cos\beta) + B^2]^{1/2} - [(D + 2H\cos\beta)^2 + (H\sin\beta + B)^2]^{1/2}}{2H} \tag{52}$$

The view factor to *ground* of the rear side of the collector is obtained based on Eq. (6) and is:

$$F^r_{A\to grd.} = \frac{H + [(H\cos\beta + D)^2 + B^2]^{1/2} - [(Hsin\beta - B)^2 + D^2]^{1/2}}{2H} \tag{53}$$

The view factor between collectors H is determined by Eq. (4) and Fig. 22 and is:

$$F_{H\to H} = \frac{[(D + 2H\cos\beta)^2 + (H\sin\beta + B)^2]^{1/2} + [(H\sin\beta - B)^2 + D^2]^{1/2} - 2[(D + H\cos\beta)^2 + B^2]^{1/2}}{2H} \tag{54}$$

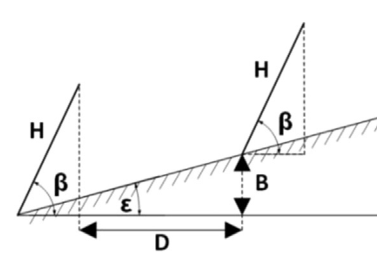

Fig. 22. Collectors H with inclination angle β on an inclined plane.

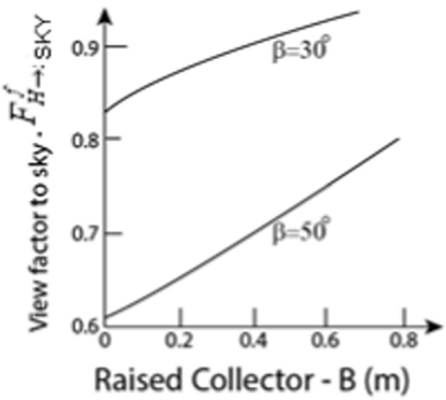

Fig. 23. Variation of view factor to sky of front side with raising the collector, $H = 2.0m$, $D = 1.0m$.

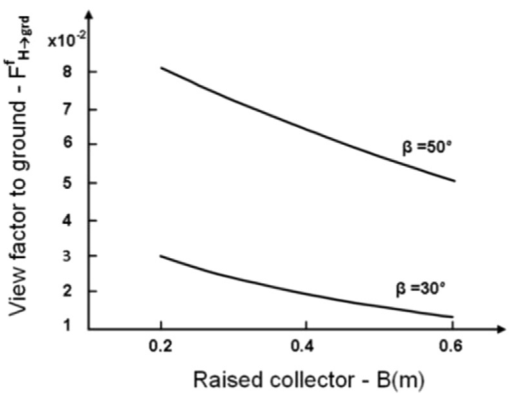

Fig. 24. Variation of view factor to ground with raising the collector-front side, $H = 2.0m$, $D = 1.0m$.

6.3. Vertical collectors

This type of collector installations may pertain to bifacial PV panels in solar PV fields [17].

6.3.1. Vertical collectors-horizontal plane

Fig. 25 shows vertical collectors deployed on a horizontal plane. The view factors to sky and to ground of front and rear sides of the collector are obtained based on Eq. (6) and are:

$$F^f_{H\to sky} = F^r_{H\to sky} = F^f_{H\to grd.} = F^r_{H\to grd.} = \frac{H + D - [D^2 + H^2]^{1/2}}{2H} \tag{55}$$

The variation of the view factors with the distance D is shown in Fig. 26 for $H = 2.0m$.

The view factor between vertical collectors is obtained based on Eq. (4) and is:

$$F_{H\to H} = \frac{[D^2 + H^2]^{1/2} - D}{H} \tag{56}$$

The variation of the view factor between vertical collectors with the distance D is shown in Fig. 27 for $H = 2.0m$. The view factor values are considerable amounts.

6.3.2. Vertical collectors-Inclined plane

Fig. 28 shows vertical collectors deployed on an inclined plane.

The view factors to *sky* and *ground*, front and rear sides of the collector are obtained based on Eq. (6) (see also Eqs. (49 and (50)) and are:

$$F^f_{H\to sky} = F^r_{H\to grd.} = \frac{H + (D^2 + B^2)^{1/2} - [(D^2 + (H - B)^2]^{1/2}}{2H} \tag{57}$$

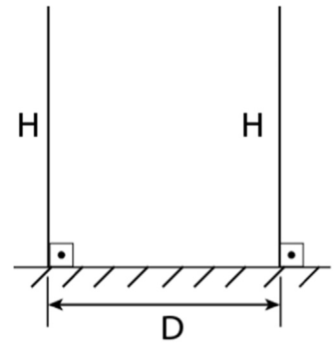

Fig. 25. Vertical collectors H, on a horizontal plane.

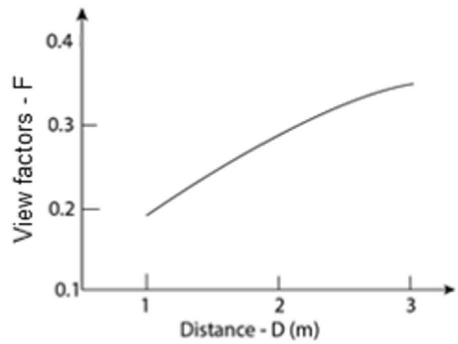

Fig. 26. Variation of the view factors with the distance between the collectors for vertical collectors-horizontal plane, $H = 2.0m$.

$$F^r_{H\to sky} = F^f_{H\to grd.} = \frac{H + (D^2 + B^2)^{1/2} - [D^2 + (H + B)^2]^{1/2}}{2H} \tag{58}$$

The effect of raising the collectors on the view factor to sky of the front side $F^f_{H\to sky}$ is shown in Fig. 29. Raising the collectors by $B = 0.2,\ 0.4,\ 0.6,\ 0.8\,m$ corresponds to $\varepsilon = 11.3^0,\ 21.8^0,\ 30.9^0,\ 38.7^0$, respectively.

The effect of raising the collectors on the view factor to ground is shown in Fig. 30 for $H = 2.0m$, $D = 1.0m$. Raising the collector above ground decreases the view factor to ground of the front side and increases the view factor of the rear side, and is a considerable amount.

Fig. 31 shows the effect of increasing the distance between the vertical collectors on the view factor to ground for $H = 2.0m$, $B = 0.25m$. Larger distances between collectors increase the view factors to ground.

The view factor between vertical collectors on an inclined plane is obtained based on Eq. (4) and is:

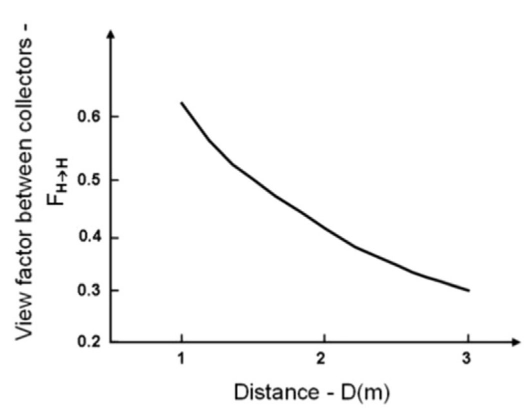

Fig. 27. The variation of the view factor between vertical collectors with the distance D, $H = 2.0m$- horizontal plane.

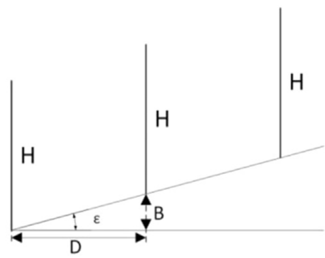

Fig. 28. Vertical collectors installed on inclined plane.

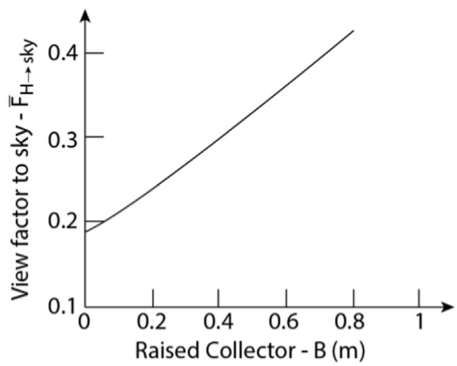

Fig. 29. Variation of view factor to sky of front side with the raise of the vertical collectors- inclined plane, $H = 2.0m$, $D = 1.0m$.

$$F_{H\rightarrow H} = \frac{[D^2 + (H + B)^2]^{1/2} + [D^2 + (H - B)^2]^{1/2} - 2[D^2 + B^2]^{1/2}}{2H} \tag{59}$$

7. Discussion

The expressions for the various view factors of a PV collector include: view factor to sky, F_{sky}; view factor between opposite collectors in multiple collector rows, $F_{A\rightarrow H}$; and view factors between collectors to *shaded* $F_{grd.s}$ and *not shaded* $F_{grd.us}$ grounds. PV collectors bay be deployed on horizontal and inclined planes with tilt angles and vertically. PV collector may also generate energy by its rear side. The various view factors (VF) are summarized in Tables 1–3. Table 1 includes view factors of a single collector row mounted in a horizontal and inclined planes. The ground may be shaded and not shaded (see Eqs. (1)–(3)). The table lists the equation number of the view factor expression in the text and the appropriate figure.

Table 2 lists general cases of various view factors for collectors deployed in multiple rows. The appropriate equation number and figure in the text are mentioned.

Table 3 lists view factors of PV collectors deployed in multiple rows for common collector configurations in solar fields. The collectors are of the same width H and inclined with the same tilt angle β. The table includes also vertical collectors installed on horizontal and inclined planes.

The two main components of solar radiation incident on PV collectors are the sky direct beam and the diffuse radiation. The reflected radiation from ground and from opposite collector are usually small, however is some instances, the reflected radiation from the ground may constitute an appreciable amount. Bifacial PV panels are designed to absorb solar radiation by both the front and the rear sides. The amount of radiation (direct and diffuse) reaching the rear-side of the collector depends on the orientation of the collector and its tilt. For a collector facing south and tilted with low angels (for example $\beta = 20^0$) the incident radiation on the rear-side is negligible. The percentage of incident radiation on the rear-side of the collector facing the east-west direction and tiled by $\beta = 30^0$ as compared to the front-side is 5.3%(Israel-latitude 32^0) and 18.8% for $\beta = 50^0$.

The reflected radiation from the ground on the front-side of the collector is usually small because of low albedo (less than 0.5 of regular grounds) and low view factor to ground (0.067 for $\beta = 30^0$). However, the reflected radiation from the ground on the rear-side of the collector may be appreciable as the view factor is high (0.8 and above), i.e. the reflected radiation is $0.5 \times 0.8 \times G_h$.

PV panels installed in rows and facing each other may reflect irradiation onto the opposite panel. The amount of reflected irradiation depends on the reflectivity of the PV panel, on the view factor of the reflecting panel to the opposite panel, and on the incident irradiation on the reflecting panel. PV panels are designed with anti-reflecting (AR) coating which reduces the sun's reflection from the PV panels. The AR coating brings down the reflectivity of the front-side of the PV panel to only a few percent therefore one may neglect the part of reflective irradiation on the rear-side of the opposite collector.

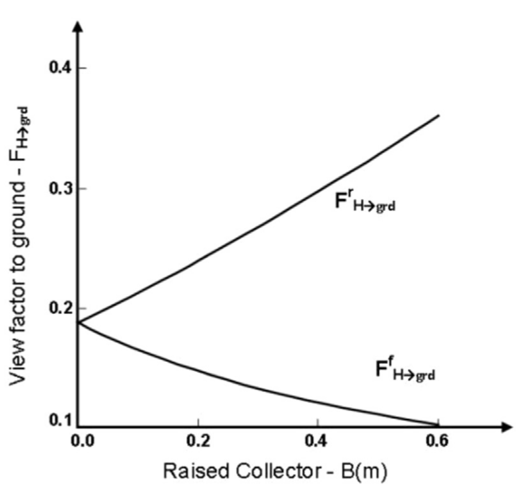

Fig. 30. Variation of view factor to ground with the raise of the vertical collectors- inclined plane, $H = 2.0m$, $D = 1.0m$-front and rear sides.

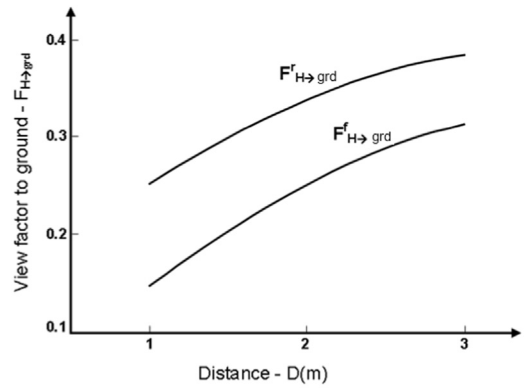

Fig. 31. Variation of view factor to ground with distance between vertical collectors- inclined plane, $H = 2.0m$, $B = 0.25m$.

Table 1
Single collector row.

SINGLE COLLECTOR ROW	
Horizontal plane	*Inclined plane*
Not shaded ground VF: Front-side (sky, ground), Eqs. (8) and (9), Fig. 8 VF: Rear-side (sky, ground), Eqs. (10) and (11), Fig. 9 Shaded and not shaded ground VF: Rear-side (sky, ground), Eqs. (10,12,13), Fig. 11	Not shaded ground VF: Front-side (sky, ground), Eqs. (14) and (15), Fig. 12 VF: Rear-side (sky, ground), Eqs. (16) and (17), Fig. 13 Shaded and not shaded ground VF: Rear-side (sky, ground), Eqs. (18)–(20), Fig. 14

Table 2
Multiple collector rows.

MULTIPLE COLLECTOR ROWS	
Horizontal plane	*Inclined plane*
Shaded and not shaded ground VF: Front-side (sky, ground), Eqs. (21,23,25),Fig. 16 VF: Rear-side (sky, ground), Eqs. (29)–(31), Fig. 16 VF: Between collectors, Eqs. (33) and (35), Fig. 16	Shaded and not shaded ground VF: Front-side (sky, ground), Eqs. (37)–(39), Fig. 17 VF: Rear-side (sky, ground), Eqs. (40)–(42), Fig. 17 VF: Between collectors, Eqs. (43) and (44), Fig. 17

Table 3
Common configuration of collectors in multiple rows.

COMMON CONFIGURATIONS (multiple rows)	
Horizontal plane	*Inclined plane*
VF: front-side to sky, Eq. (45), Fig. 18	VF: front-side to sky, Eq. (50), Fig. 22
VF: rear-side to sky, Eq. 47, Fig. 18	VF: rear-side to sky, Eq. (52), Fig. 22
VF: front-side to ground, Eq. (46), Fig. 18	VF: front-side to ground, Eq. (51), Fig. 22
VF: rear-side to ground, Eq. (48), Fig. 18	VF: rear-side to ground, Eq. (53), Fig. 22
VF: Between collectors, Eq. (49), Fig. 18	VF: Between collectors, Eq. (54), Fig. 22
Vertical collectors VF: front and rear (sky, ground), Eq. (53), Fig. 25 VF: between collectors, Eq. (54), Fig. 25	Vertical collectors VF: front and rear (sky, ground),Eqs. (57) and (58), Fig. 28 VF: between collectors, Eq. (59), Fig. 28

8. Conclusions

The solar radiation on a photovoltaic (PV) panel (collector) in solar field consists of the direct beam, diffuse and reflected radiation. The amount of the diffuse radiation on a collector depends on the view factor of the collector to sky. The reflected radiation on a collector depends on the reflection from the ground and the reflection from an opposite collector in a multiple row deployment of PV fields. To calculate the incident radiation on a PV field it is important to determine the various types of view factors. In this paper, analytical expressions for view factors were developed between collectors to *sky* F_{sky}, between opposite collectors $F_{A\rightarrow H}$, and between collectors to *shaded* $F_{grd.s}$ and *not shaded* $F_{grd.us}$ *grounds*, for the front and rear sides of collectors.

For deployment of PV collectors in multiple rows with common inclination angles, the view factor to sky of the front-side of the collector is rather large implying that the diffuse radiation from the sky on the PV collector is appreciable. The view factor to ground of the front-side of the collector is rather small and hence, the reflected radiation from the ground on the collector may be neglected compared to the direct beam and the diffuse components. However, in some cases the reflected radiation from the ground may constitute an appreciable amount as in snowy areas. Bifacial PV collector can absorb solar radiation by both the front and the rear sides of the collector and are usually deployed vertically in multiple rows. In this case, the view factors to ground of both the front and rear sides of the collector are considerable values and hence, the reflected radiation from the ground may be appreciable depending on the ground albedo.

Findings of the study show that:

1. Larger distances between collectors increase the view factor to sky of the front-side of the collector.
2. Larger distances between collectors increase the view factors of all types for vertical collectors.
3. Increasing the collector inclination angle increases the view factor to ground of the front-side, but decreases the view factor to ground of the rear-side.
4. Raising the collectors above ground affects all types of the view factors.

These results were derived from the sensitivity analysis of the view factor parameters.

The present article is a review article on various view factors of collectors in solar photovoltaic fields. The developed mathematical expressions for the view factors, in the present article, are based on "cross-string rule" by Hottel [20]. Previous studies have not consider view factors of the rear-side of the collector to sky and ground for collector deployed on horizontal and inclined planes. The present article supplies the additional expressions for view factors of the rear-side of collectors. These view factors have applications, for example, in bifacial PV panels and in determination of the operating temperature of PV collectors.

References

[1] Mirhosseini M, Saboonchi A. Monte Carlo method for calculating local factor for the practical case in material processing. Int Commun Heat Mass Transf 2011;38:1142–7.

[2] Vujicic MR, Lavery NP, Brown SGR. View factor calculation using the Monte Carlo method and numerical sensitivity. Commun Numer Methods Eng 2006;22:197–203.

[3] Walker T, Xue SC, Barton GW. Numerical determination of radiative view factors using ray tracing. J Heat Transf 2010;132:072702-1–.

[4] Bopche SB, Sridharan A. Determination of view factors by contour integral technique. Ann Nucl Energy 2009;36:1681–8.

[5] Yoo SH. Einstrahlzahlen fuer die Strahlungsaustausch-Berechnung in schiefwinkligen Raeumem. Gesundh Ing 1994;115:252–6.

[6] Howell JR. A catalogue of radiation configuration factors. New York: McGraw Hill; 1982.

[7] Walton GN. Calculation of obstructed view factors by adaptive integration. NISTIR 2002;6925.

[8] Martinez Isidor. Radiative view factors; 1995-2015.

[9] ⟨http://www1.accsnet.ne.jp/~aml00731/c/thermal/View%20factor%20definition.pdf⟩.

[10] Jones RE, Jr., Burkhart JF. Shading effect of collector row tilt toward the equator. Sol Energy 1981;26:563–5.

[11] Bany J, Appelbaum J. The effect of shading on the design of a field of solar collectors. Sol Cells 1987;20:201–28.

[12] Yoo SH. Simulation for an optimal application of BIPV through parameter variation. Sol Energy 2011;85:1291–301.

[13] Maor T, Appelbaum J. View factors of photovoltaic collector systems. J Sol Energy 2012;86:1701–8.

[14] Appelbaum J, Aronescu A. View factors of photovoltaic collectors on roof tops. J Renew Sustain Energy 2016;8:025302.

[15] Appelbaum J, View factors to ground of photovoltaic collectors. J Sol Energy Eng. 2916. 138. 064501-1-6, http://dx.doi.org/10.1115/1.4034316.

[16] Fathi NY, Samer A. View factors of flat solar collectors arrays in flat, inclined, and step-like solar fields. J Sol Energy Eng 2016;138, [061005-1-8].

[17] Appelbaum J. Bifacial photovoltaic panels field. Renew Energy 2016;85:338–43. http://dx.doi.org/10.1016/j.renene.2015.06.050, [2015].

[18] Matz E, Appelbaum J, Taitel Y, Flood DJ. Solar cell temperature on Mars. J Propuls Power 1998;14(1):119–25, American Institute of Aeronautics and Astronautics (AIAA).

[19] Duffie JA, Beckman WA. Solar engineering of thermal processes. John Wiley & Sons, Inc; 1991.

[20] Hottel HC, Sarofin AF. Radiative transfer. New York: McGraw Hill; 1967. p. 31–9.