View Factors of Flat Solar Collectors Array in Flat, Inclined, and Step-Like Solar Fields

Nassar Yasser Fathi
Professor
Mechanical Engineering Department,
Engineering and Technology Faculty,
Sebha University,
Brack 721, Libya
e-mail: yasser_nassar68@ymail.com

Alsadi Samer
Associate Professor
Electrical Engineering Department,
Faculty of Engineering and Technology,
Palestine Technical University—Kadoorie,
Tulkarm 31, Palestine
e-mail: samer_sadi@yahoo.com

Solar radiation consists of direct beam, sky diffuse, and reflected radiations from the ground and adjacent surfaces. The amount of diffuse radiation falling on solar collector depends on the view factor of the collector to sky. The reflected radiation striking the collector's surface depends on the reflectivity of the surface, as well as on view factors and the amount of solar radiation reaching the reflecting surfaces. The amount of reflected radiation coming from the ground can be of an appreciable amount, and can be amplified using special reflector surfaces. This study develops general analytical expressions for the sky's view factors as well as factors related to the ground and those between collectors for the deployment of collectors in multiple rows, in three types of solar fields: flat, inclined, and steplike solar fields. All parameters presented in these expressions are measurable (edge-to-edge dimension). The effects of the design parameters such as the tilt of the angle of the collector, the distance between the collectors, the height of the collector, the position of the collector above the ground (as in the case of step-like field), and the inclination of the land of the field (as in the case of an inclined field) on the view factors are numerically demonstrated. The current study also specifies new terms such as the sunny zone and the shadow zone; these zones control the amount of solar radiation reflected onto the collector. As a result, the ground-view factor that depends on the altitude of the solar angle is considered to be a dynamic parameter. The results obtained may be used to estimate the solar radiation incident on all types of solar fields, with the possibility of increasing the incident radiation on a collector by using planar reflectors.
[DOI: 10.1115/1.4034549]

1 Introduction

The prediction of incoming solar radiation is acquiring more importance due to the growing increase in solar power generation. Solar radiation is an important parameter in solar energy application in all steps of design, analysis, and evaluation. In general, solar radiation incident on a surface normally consists of three components: beam, sky diffuses, and ground reflected. Beam radiation strongly depends on the position of the sun in the sky, whereas the ground-reflected and isotropic diffuse components depend on the view factors between the surface, the ground, and the sky, respectively.

Solar radiation and its components related to clear sky conditions at a horizontal surface can be obtained from meteorological centers, as well as from several world maps of solar radiations, databases, and mathematical models [1–4]. However, as illustrated in Fig. 1(*a*) large-scale solar energy systems often employ multiple rows of collectors on flat-solar fields. These rows are inclined in the east–west axis, with the collectors tilted toward the equator [5]. Figure 1(*b*) shows a slope on the land surface, and the inclined field suitable in such cases. Nevertheless, in some applications (such as the roof of a building), where the space for installation is limited, the step-like construction field, as illustrated in Fig. 1(*c*), may be considered a good-solution.

More recently, in the context of solar fields, several of the related studies [6–10] presented analytical expressions for the view factors to sky and for the deployment of collectors in multiple rows in flat solar fields. Therefore, the purpose of this study is to develop mathematical expressions and present numerical values for view factors of collectors deployed on grounds or on roofs of buildings in order to determine the incident solar radiation on the collectors. In general, the view factors may depend on five design parameters for flat solar fields and six design parameters for inclined and step-like fields: height of the rows (L_1, L_2), their inclination angles (S_1, S_2), the distance separating the rows (x), the inclination angle of the land (ε) (in case of inclined field), and the height of the step (y) (in case of step-like field). In this study, results are presented as a dimensionless ratio of the height of the collector and the distance that separates the rows (L_1/x). The other parameters are also examined to identify the most critical parameter affecting the view factors.

This study will be helpful in determining the solar radiation coming from the sky, ground, and from the rear-side of the previous row for the three types of solar fields.

2 Definition and Algebra of View Factor

The calculation of radiation exchange between two surfaces requires a quantity that describes the influence of their position and orientation. This is the view factor F_{i-j}, which is also known by the terms configuration factor and angle factor. This factor represents the fraction of radiation leaving a surface i that strikes surface j directly. The pair of view factors F_{i-j} and F_{j-i} are related to each other by the reciprocity rule, where A_i is the area of the surface i, and A_j is the area of the surface j. Therefore, $A_iF_{i-j} = A_jF_{j-i}$. The summation rule for an enclosure is expressed by $\sum_{j=1}^{N} F_{i-j} = 1$, where N is the number of surfaces of the enclosure. The summation rule states that the sum of the view factors from the surface i of an enclosure to all surfaces of the enclosure, including to itself, must be equal to unity. The superposition rule states that: as the view factor from a surface i to a surface j equals the sum of the view factors from surface i to parts of surface j, $F_{i-(j_1+j_2)} = F_{i-j_1} + F_{i-j_2}$ [11].

3 Methodology: General Expression

The crossed-strings method is applicable to geometries that are very long in one direction relative to the other directions. By

Contributed by the Solar Energy Division of ASME for publication in the Journal of Solar Energy Engineering: Including Wind Energy and Building Energy Conservation. Manuscript received April 23, 2016; final manuscript received August 26, 2016; published online September 15, 2016. Assoc. Editor: M. Keith Sharp.

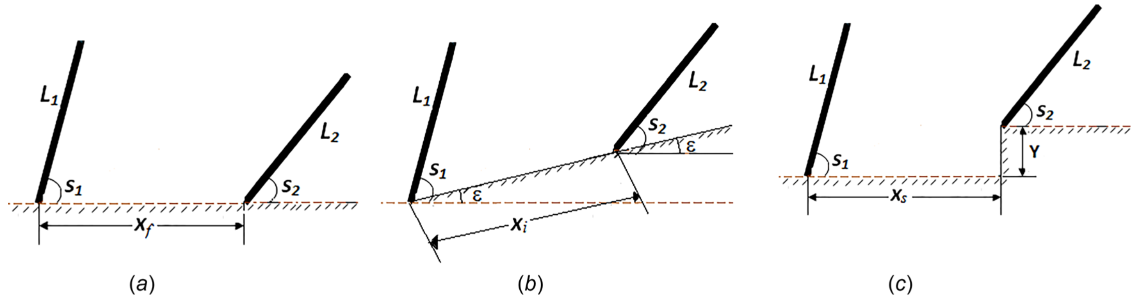

Fig. 1 Deployment of collectors on (*a*) a flat solar field, (*b*) an inclined solar field, and (*c*) a step-like solar field

attaching strings between corners, as illustrated in Fig. 2(*c*), the crossed-strings method is expressed as [11]

$$F_{i-j} = \frac{\sum \text{crossed strings} - \sum \text{uncrossed strings}}{2 \times \text{string on surface } i} \quad (1)$$

This technique is enhanced for the three types of solar fields; the view factor between the second row and any surface, which may be the sky, the ground, or the rear-side of the previous collector, is expressed in the form

$$F_{L_2-\text{any surface}} = \frac{\overline{ac} + \overline{bd} - \overline{ad} - \overline{bc}}{2\overline{ab}} \quad (2)$$

where the strings $\overline{ac}$, $\overline{bd}$, $\overline{ad}$, and $\overline{bc}$ are graphically illustrated and numerically determined locally; their magnitudes depend on the view factor type and the type of solar field. For simplicity, we used the following dummy variables for the three types of solar fields:

$$N_1 = L_1 \cos(S_1),\ N_2 = L_2 \cos(S_2),\ M_1 = L_1 \sin(S_1), \text{ and } M_2 = L_2 \sin(S_2) \quad (3)$$

3.1 Flat Solar Field. Figure 2 describes a case of a flat solar field, with two adjacent collectors of infinite length (length is much larger than height). The first collector is of height L_1 and is inclined with an angle S_1 with respect to the horizontal ground, and the second collector is of height L_2 and is inclined with an angle S_2 with respect to the horizontal ground. The distance between the collectors is x_f.

To satisfy the comprehensiveness of Eq. (2), we will use the same symbols to identify all the view factors for the three types of solar fields. Therefore, the collector in the second row is always assumed to be ***ab***. In order to determine the sky-view factor, we will consider the aperture through which the collector is seen from the sky as ***cd***, as illustrated in Fig. 2(*a*). The same applies to the ground-view factor, and we will consider the distance separating the two rows as ***dc***, as shown in Fig. 2(*c*). In this approach, one can use Eq. (2) for all types of solar fields.

Using the crossed-strings rule, the view factor to the sky of an inclined collector mounted on a horizontal plane can now be calculated from Fig. 2(*a*). The magnitudes of the strings $\overline{ac}$, $\overline{bd}$, $\overline{ad}$, and $\overline{bc}$ are given by

$$\overline{ac} = L_2, \overline{bd} = \sqrt{(L_1 \sin(S_1) - L_2 \sin(S_2))^2 + (x_f - L_1 \cos(S_1) + L_2 \cos(S_2))^2}$$
$$\overline{ad} = \sqrt{(L_1 \sin(S_1))^2 + (x_f - L_1 \cos(S_1))^2} \text{ and } \overline{bc} = 0 \quad (4)$$

Introducing all the strings in Eq. (2), the sky-view factor is given by

$$F_{L_2-\text{sky}} = \frac{L_2 + \sqrt{(M_1 - M_2)^2 + (x_f - N_1 + N_2)^2} - \sqrt{M_1{}^2 + (x_f - N_1)^2}}{2L_2} \quad (5)$$

Similarly, for the ground-view factor as illustrated in Fig. 2(*b*), The magnitudes of the strings $\overline{ac}$, $\overline{bd}$, $\overline{ad}$, and $\overline{bc}$ magnitudes are

$$\overline{ac} = x_f,\ \overline{bd} = L_2,\ \overline{ad} = 0 \text{ , and}$$
$$\overline{bc} = \sqrt{(L_2 \sin(S_2))^2 + (x_f + L_2 \cos(S_2))^2} \quad (6)$$

Consequently

$$F_{L_2-\text{ground}} = \frac{x_f + L_2 - \sqrt{M_2{}^2 + (x_f + N_2)^2}}{2L_2} \quad (7)$$

In the same manner, the rear-side of the previous collector's view factor is (Fig. 2(*c*))

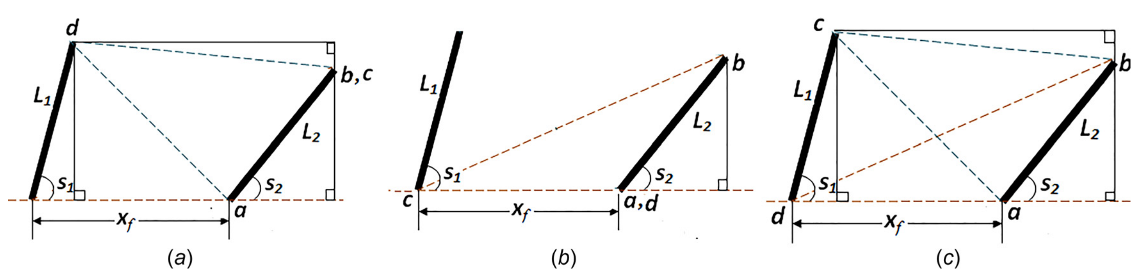

Fig. 2 Calculation of view factor by means of crossed-strings method for two surfaces of infinite length on a flat solar field; (*a*) sky-view factor $F_{L_2-\text{sky}}$, (*b*) ground-view factor $F_{L_2-\text{ground}}$, and (*c*) rear-side view factor F_{L_2-l1}

$$\overline{ac} = \sqrt{(L_1 \sin(S_1))^2 + (x_f - L_1 \cos(S_1))^2},\ \overline{bd} = \sqrt{(L_2 \sin(S_2))^2 + (x_f + L_2 \cos(S_2))^2}$$
$$\overline{ad} = x_f \text{ and } \overline{bc} = \sqrt{(L_1 \sin(S_1) - L_2 \sin(S_2))^2 + (x_f - L_1 \cos(S_1) + L_2 \cos(S_2))^2} \tag{8}$$

$$F_{L_2-L_1} = \frac{\sqrt{M_1^2 + (x_f - N_1)^2} + \sqrt{M_2^2 + (x_f + N_2)^2} - x_f - \sqrt{(M_1 - M_2)^2 + (x_f - N_1 + N_2)^2}}{2L_2} \tag{9}$$

3.2 Inclined Solar Field. When the terrain is slightly tilted by an angle ε from the horizontal plane, the land can be exploited to build a solar field without any additional efforts to level the land, and this is known as the inclined solar field. Figure 3 illustrates a case of an inclined solar field, with two adjacent collectors of infinite length (length is much larger than height). The first collector is of height L_1 and is inclined with an angle S_1 with respect to a horizontal plane, and the second collector is of height L_2 and is inclined with an angle S_2 with respect to a horizontal plane. The inclination of the ground is ε with respect to the horizontal plane. The distance between the collectors is x_i.

The geometric analysis of the strings for the inclined solar field is illustrated in Fig. 3(*b*).

For the sky-view factor as illustrated in Fig. 3(*a*), The magnitudes of the strings $\overline{ac}$, $\overline{bd}$, $\overline{ad}$, and $\overline{bc}$ are found from

$$\overline{ac} = L_2,\quad \overline{bd} = \sqrt{(x_i \sin(\varepsilon) + L_2 \sin(S_2) - L_1 \sin(S_1))^2 + (x_i \cos(\varepsilon) + L_2 \cos(S_2) - L_1 \cos(S_1))^2}$$
$$\overline{ad} = \sqrt{(L_1 \sin(S_1) - x_i \sin(\varepsilon))^2 + (x_i \cos(\varepsilon) - L_1 \cos(S_1))^2} \text{ and } \overline{bc} = 0 \tag{10}$$

Substituting all the strings in Eq. (2), the sky-view factor becomes

$$F_{L_2-\text{sky}} = \frac{L_2 + \sqrt{(x_i \sin(\varepsilon) + M_2 - M_1)^2 + (x_i \cos(\varepsilon) - N_1 + N_2)^2} - \sqrt{(M_1 - x_i \sin(\varepsilon))^2 + (x_i \cos(\varepsilon) - N_1)^2}}{2L_2} \tag{11}$$

For the ground-view factor as illustrated in Fig. 3(*b*), the magnitudes of the strings $\overline{ac}$, $\overline{bd}$, $\overline{ad}$, and $\overline{bc}$ are as follow:

$$\overline{ac} = x_i,\ \overline{bd} = L_2,\ \overline{ad} = 0 \text{ and } \overline{bc} = \sqrt{(x_i \sin(\varepsilon) + L_2 \sin(S_2))^2 + (x_i \cos(\varepsilon) + L_2 \cos(S_2))^2} \tag{12}$$

Consequently

$$F_{L_2-\text{ground}} = \frac{x_i + L_2 - \sqrt{(x_i \sin(\varepsilon) + M_2)^2 + (x_i \cos(\varepsilon) + N_2)^2}}{2L_2} \tag{13}$$

In the same manner, the rear-side of the previous collector's view factor is (Fig. 3(*c*))

$$\overline{ac} = \sqrt{(L_1 \sin(S_1) - x_i \sin(\varepsilon))^2 + (x_i \cos(\varepsilon) - L_1 \cos(S_1))^2},\ \overline{bd} = \sqrt{(x_i \sin(\varepsilon) + L_2 \sin(S_2))^2 + (x_i \cos(\varepsilon) + L_2 \cos(S_2))^2},\ \overline{ad} = x_i \text{ and}$$
$$\overline{bc} = \sqrt{(x_i \sin(\varepsilon) + L_2 \sin(S_2) - L_1 \sin(S_1))^2 + (x_i \cos(\varepsilon) + L_2 \cos(S_2) - L_1 \cos(S_1))^2} \tag{14}$$

$$F_{L_2-L_1} = \frac{\left[\begin{array}{c}\sqrt{(M_1 - x_i \sin(\varepsilon))^2 + (x_i \cos(\varepsilon) - N_1)^2} + \sqrt{(x_i \sin(\varepsilon) + M_2)^2 + (x_i \cos(\varepsilon) + N_2)^2} \\ -x_i - \sqrt{(x_i \sin(\varepsilon) + M_2 - M_1)^2 + (x_i \cos(\varepsilon) + N_2 - N_1)^2}\end{array}\right]}{2L_2} \tag{15}$$

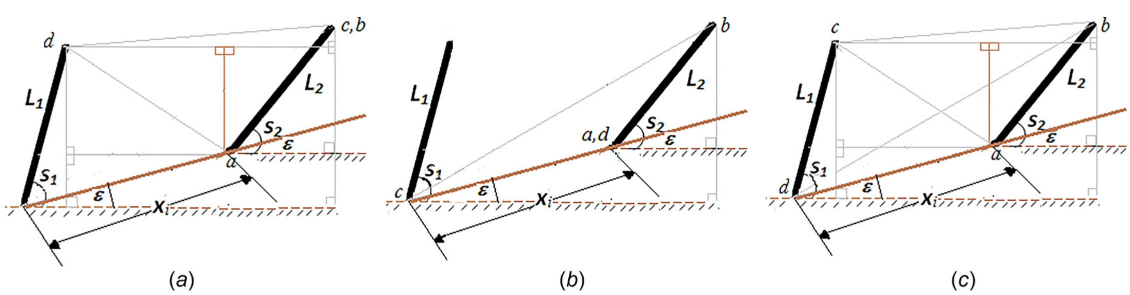

Fig. 3 Calculation of view factors by means of crossed-strings method for two surfaces of infinite length mounted on an inclined field; (*a*) sky-view factor $F_{L_2-\text{sky}}$, (*b*) ground-view factor $F_{L_2-\text{ground}}$, and (*c*) rear-side view factor F_{L_2-l1}

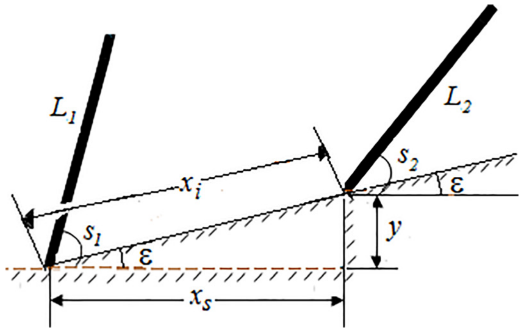

Fig. 4 Representation of the step-like solar field in terms of the inclined solar field

One can check up by substituting zero for plane declination ε, in which case the situation will return to the flat field.

3.3 Step-Like Solar Field. The construction of the step-like solar field is analogous to that of the inclined solar field, as illustrated in Fig. 4. Thus, the shape factors of the step-like solar field are the same as those of the inclined solar field, with the adoption of simple changes, as follows:

$$x_i = \left(\sqrt{x_s^2 + y^2}\right) \quad (16)$$

$$\varepsilon = \tan^{-1}\left(\frac{y}{x_s}\right) \quad (17)$$

4 Results and Discussion: Particular Case

Based on the abovementioned methodology, an excel comprehensive worksheet was created to calculate the view factors in accordance with the inputs given by the user. All the view factors for a flat, an inclined, and a step-like solar field are evaluated and presented graphically in Figs. 5–7, respectively. For a flat solar field and for $L_1 = L_2$, and $S_1 = S_2 = 30$ deg, the critical value of the collector's dimensionless height is $(L_1/x_f) = 0.65$, and the minimum values of the view factors are as follows: for sky-view factor $F_{L_2-\mathrm{sky}} = 0.850$, for ground-view factor $F_{L_2-\mathrm{ground}} = 0.041$, while the collector's rear-side view factor, $F_{L_2-\mathrm{back}} = 0.109$. Of course, the increase in the value of (L_1/x_f) (by decreasing the space separating the rows or by increasing the height of the collectors) is more than the critical value that is undesirable because the

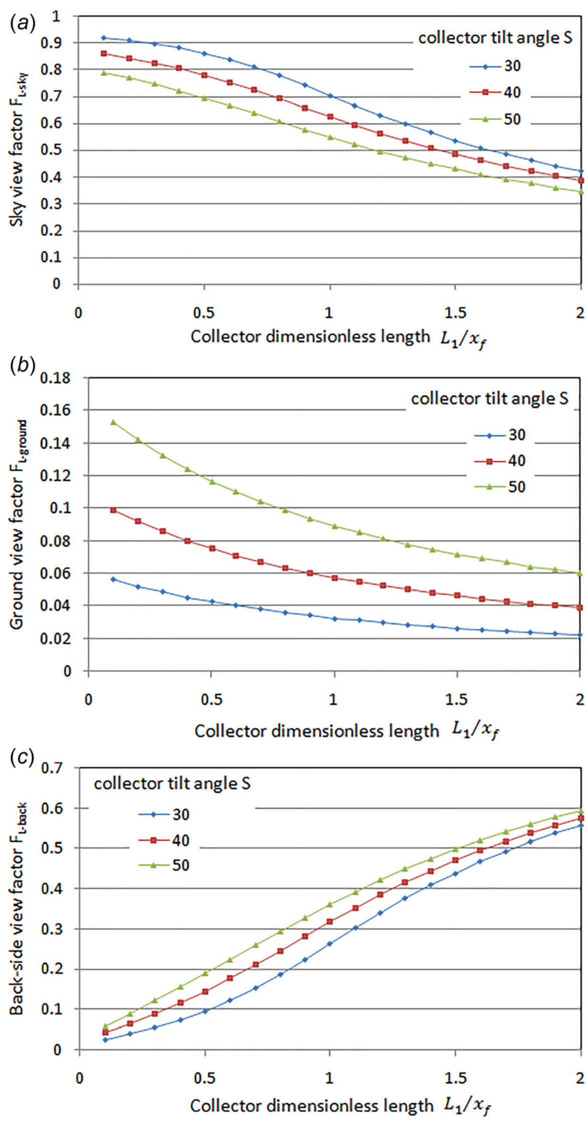

Fig. 5 View factors for a flat-solar field; (*a*) sky-view factor, (*b*) ground-view factor, and (*c*) collector's rear-side view factor

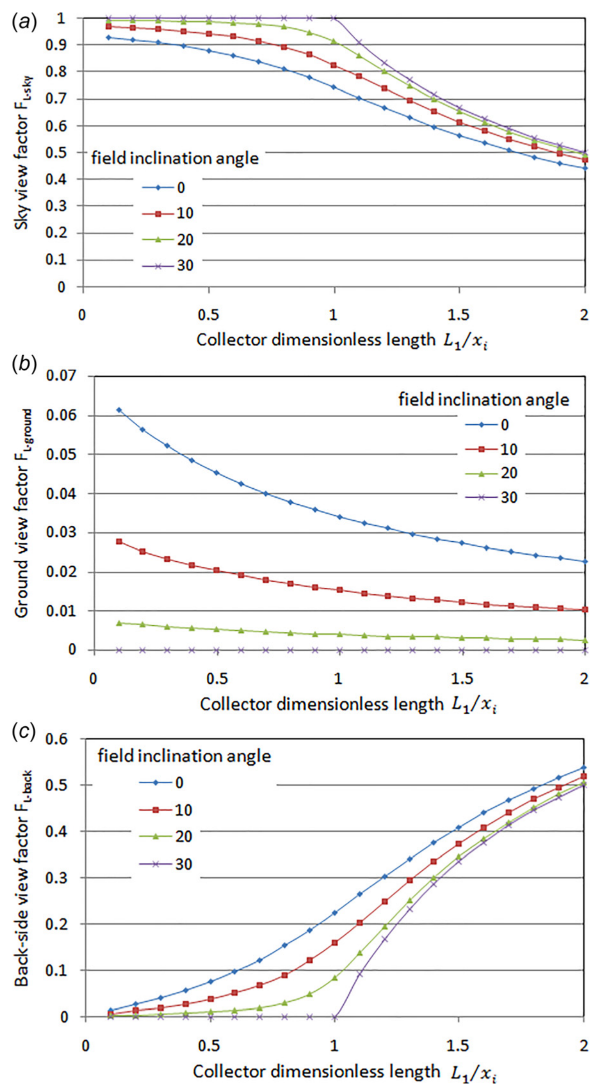

Fig. 6 View factors for an inclined solar field; (*a*) sky-view factor, (*b*) ground-view factor, and (*c*) collector's rear-side view factor

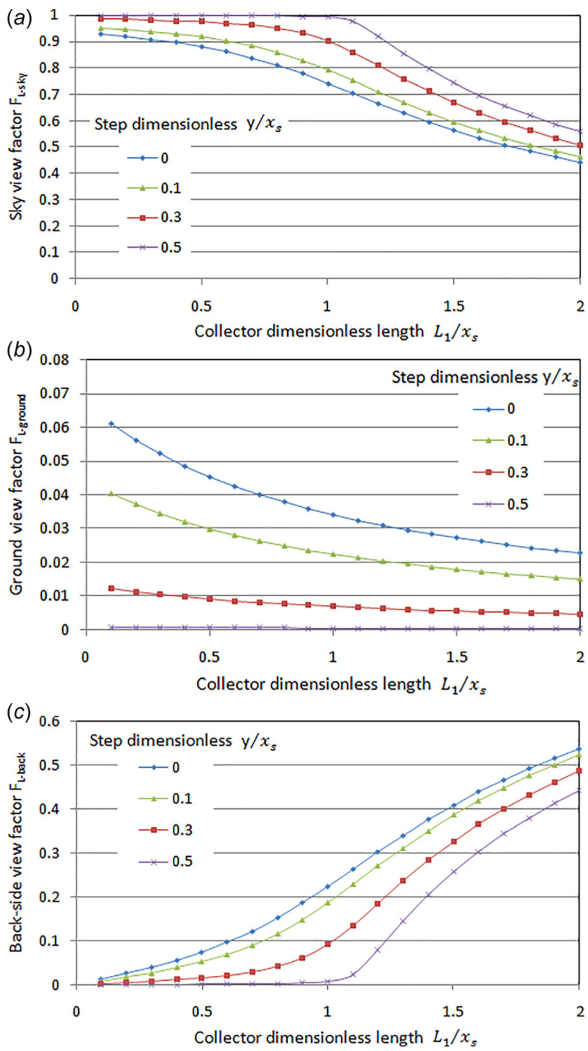

Fig. 7 View factors for a step-like solar field $S_1 = S_2 = 30$ deg; (*a*) sky-view factor, (*b*) ground-view factor, and (*c*) collector's rear-side view factor

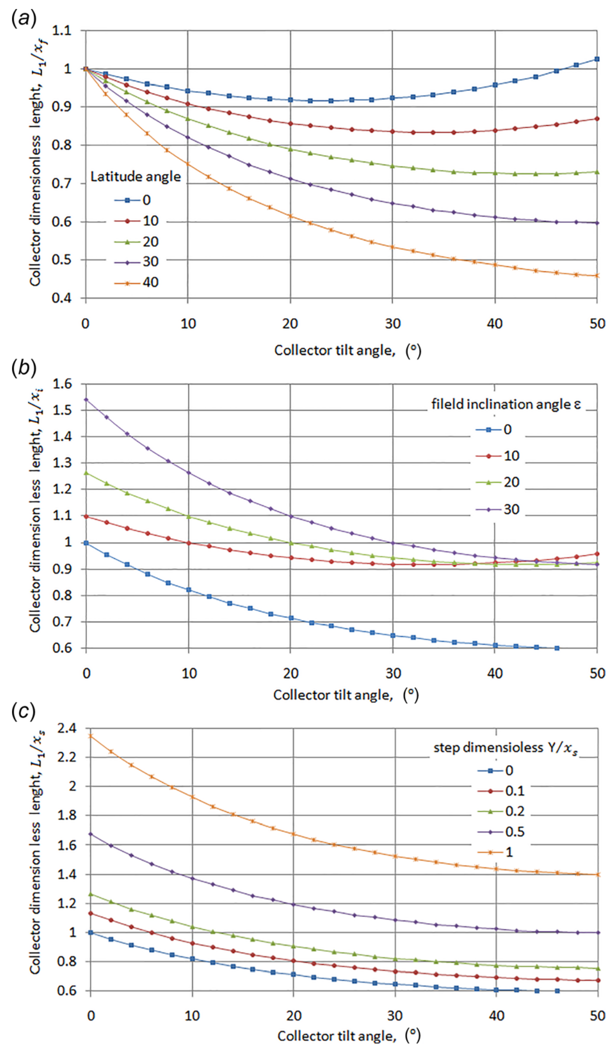

Fig. 9 Maximum collector's dimensionless height for deployment of collectors on (*a*) flat solar field with various latitudes, (*b*) inclined solar field for latitude 30 °N with various inclination field ε, and (*c*) step-like solar field for latitude 30 °N with various step dimensionless y/x_s

rows are partially shaded, which implies dramatically reducing the productivity of the solar field. One can obtain other view factors for different values of critical collector dimensionless height from Fig. 5, but for the inclined solar field there is a constraint, that is, the collector's tilt angles must not be less than the land inclination angle (S_1 and S_2 greater than or equal to ε). The results for the inclined solar field with various land inclination angles are illustrated in Fig. 6. When $S_1 = S_2 = \varepsilon = 30$ deg and $(L_1/x_f) = 1$, it implies that the collector lies on the land with zero angle between the collector and the land, and thus, the collector is fully facing the sky, while the ground- and rear-side view factors are zero. In the same manner, and for the step-like solar field, especially, the step height is presented as an inclination angle by means of replacing $\varepsilon = \tan^{-1}(y/x_s)$. The obtained results for the step-like solar field are presented in Fig. 7.

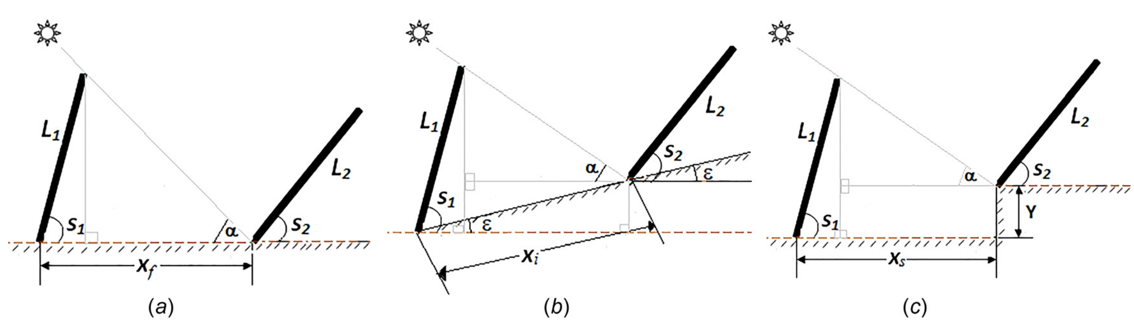

Fig. 8 Demonstration of calculation of *x* at the solar noon in (*a*) a flat solar field, (*b*) an inclined solar field, and (*c*) a step-like solar field

5 Determination of the Critical Collector's Dimensionless Height

To investigate the view factors in a practical manner we have to determine the critical collector's dimensionless height (*L*/*x*) that is required to avoid the shadow fall of a collector on the next collector [12]. The procedure is graphically demonstrated in Figs. 8(*a*)–8(*c*) for a flat, an inclined, and a step-like solar field, respectively.

The general equations are presented in Ref. [13]. For December 21 at solar noon, the three solar fields were found as:
For a flat solar field:

$$\frac{L_1}{x_f} = \frac{\tan(\alpha)}{\cos(S_1)\tan(\alpha) + \sin(S_1)} \quad (18)$$

For an inclined solar field:

$$\frac{L_1}{x_i} = \frac{\cos(\varepsilon)\tan(\alpha) + \sin(\varepsilon)}{\cos(S_1)\tan(\alpha) + \sin(S_1)} \quad (19)$$

For a step-like solar field:

$$\frac{L_1}{x_s} = \frac{\tan(\alpha) + \frac{y}{x_s}}{\cos(S_1)\tan(\alpha) + \sin(S_1)} \quad (20)$$

Figure 9 shows the maximum possible collector's dimensionless height for the three types of solar fields. As indicated in Fig. 9, for latitude 30 °N with the tilt angle equal to 30 °south facing, the maximum ratios were found as $(L_1/x_f) = 0.65$ for a flat solar field, $0.65 \le (L_1/x_i) \le 1.00$ for an inclined solar field with $0 \le \varepsilon \le 30$ deg, and $0.65 \le (L_1/x_s) \le 1.525$ for a step-like solar field with $0 \le (y/x_s) \le 1$. These results are important in order to focus the efforts within these domains of (L_1/x).

6 Specification of Ground-Reflected Solar Radiation

For a single solar collector, the ground-reflected solar radiation is $I\rho_g(1 - \cos(S_2))/2$, where I is the total radiation (both beam and diffuse) on a horizontal surface, ρ_g is the ground reflectivity, and the term $(1 - \cos(S_2))/2$ represents the ground-view factor [12]. The situation is different in the case of solar fields due to the change in position of the sun in the sky; two zones may appear on the space that separates the rows of the solar field: the adjacent zone to the front of the collector is the sunny zone, and the rear one is the shadow zone. These zones reflect the incident solar radiation with different values. The sunny zone reflects both beam and sky diffuse radiations with the ground-view factor and the shadow zone reflects only the sky diffuse radiation with another value of the ground-view factor. This fact must be considered for evaluation of solar radiation, as illustrated in Fig. 10, for the three types of solar fields.

According to Fig. 10, the dimensionless sunny zone length is given by:
For a flat solar field, see Fig. 10(*a*):

$$\frac{Z_2}{x_f} = 1 - \frac{L_1}{x_f}\left[\cos(S_1) + \frac{\sin(S_1)}{\tan(\alpha)}\right] \quad (21)$$

For an inclined solar field, see Fig. 10(*b*):

$$\frac{Z_2}{x_i} = 1 - \frac{L_1}{x_i}\left[\cos(S_1 - \varepsilon) + \frac{\sin(S_1 - \varepsilon)}{\tan(\alpha)}\right] \quad (22)$$

For a step-like solar field, see Fig. 10(*c*):

$$\frac{Z_2}{x_s} = 1 + \frac{y}{x_s \tan(\alpha)} - \frac{L_1}{x_s}\left[\cos(S_1) + \frac{\sin(S_1)}{\tan(\alpha)}\right] \quad (23)$$

However, in order to benefit the collector of the sunny region, it must fall on

$$\frac{Z_3}{x_s} = 1 - \frac{y}{x_s \tan(S_1)} - \frac{L_1}{x_s}\left[\cos(S_1) + \frac{\sin(S_1)}{\tan(\alpha)}\right] \quad (24)$$

The results obtained are illustrated as sunflowers in Figs. (11)–(13) for a flat, an inclined, and a step-like solar fields. The negative signs shown in the figures indicate no sunny zone at that time. The critical dimensionless sunny zone length clearly appears in all figures, which can be determined at the zero circle of the radial level. The situation is slightly complicated in the case of the step-like solar field due to the fact of yielding the benefit of the sunny zone by the collector. The sunny zone must be located in the field of its vision. Equations (23) and (24) deal with this problem; Eq. (23) calculates the whole sunny zone and is useful in the case of using reflectors on the rear-side of the previous collector as this zone in its vision.

The above described figures illustrate the effective use of the step-like structure in the case of limited area such as on the roofs of buildings. Using a step with 1 m height in a field with 1 m distance separating the rows, the height of the collector may be 1.5 m compared with 0.6 m height of the collector of a flat field. There is no difference between the inclined field and the step-like field from a geometrical analysis point of view; it is easy to recognize that $\varepsilon = \tan^{-1}(y/x_s)$.

Using view factor algebra yields:

$$F_{L_2-x_{\text{shaded}}} = F_{L_2-x} - F_{L_2-x_{\text{sunny}}} \quad (25)$$

where F_{L_2-x} is the same as $F_{L_2-\text{ground}}$ maintained above for all types of solar fields, $F_{L_2-x_{\text{sunny}}}$ is the ground-view factor for the

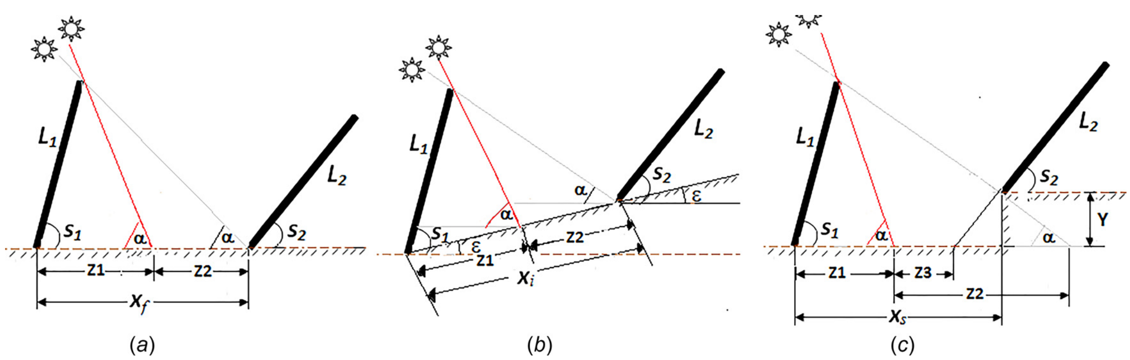

Fig. 10 State of problem for ground-reflect radiation, presenting the shadow zone and sunny zone, where Z_1 is the shadow zone, Z_2 is the effective sunny zone, and Z_3 is the actual sunny zone in the step-like field

sunny zone and is the same as $F_{L_2-\text{ground}}$, but x_{sunny} is placed instead of x, and $F_{L_2-x_{\text{shaded}}}$ is the ground-view factor for the shadow zone. It is easy to estimate the view factors when x_{sunny} and x_{shaded} are known.

The view factor of the rear-side of the previous collector by the reciprocity rule are

$$\begin{aligned} A_1F_{L_1-\text{sky}} &= A_2F_{L_2-\text{ground}} \\ A_1F_{L_1-\text{ground}} &= A_2F_{L_2-\text{sky}} \\ A_1F_{L_1-L_2} &= A_2F_{L_2-L_1} \end{aligned} \tag{26}$$

The view factors of the second collector are already discussed in this article.

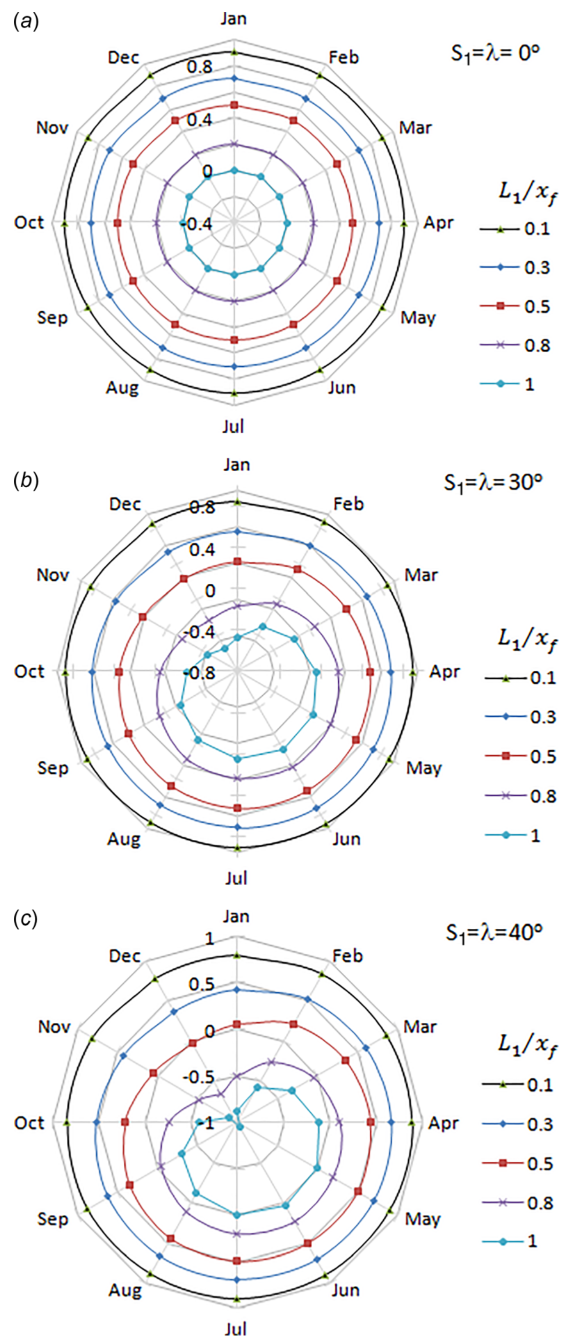

Fig. 11 The dimensionless sunny zone length for the 21st of every month for various collector's dimensionless height (L_1/x_f) at latitudes (λ) of (*a*) 0 °N, (*b*) 30 °N, and (*c*) 40 °N and the collector tilt angle $S_1 = \lambda$

7 Further Investigation

To our knowledge, this research is the first step to study the augmentation of solar radiation by using reflectors on the ground, especially on the sunny zone and in addition to the rear-side of the previous collector. Figures 5–7 reveal that the total view factors of the ground and rear-side are about 20%. The contribution of the reflected radiation surfaces may be substantial. The initial data obtained from the field measurements appear promising and encouraging to carry out more related investigations.

8 Conclusion

Knowledge of the view factors is important in estimating the solar radiation incident on the surface of a collector. General expressions for the view factors between a collector that is located

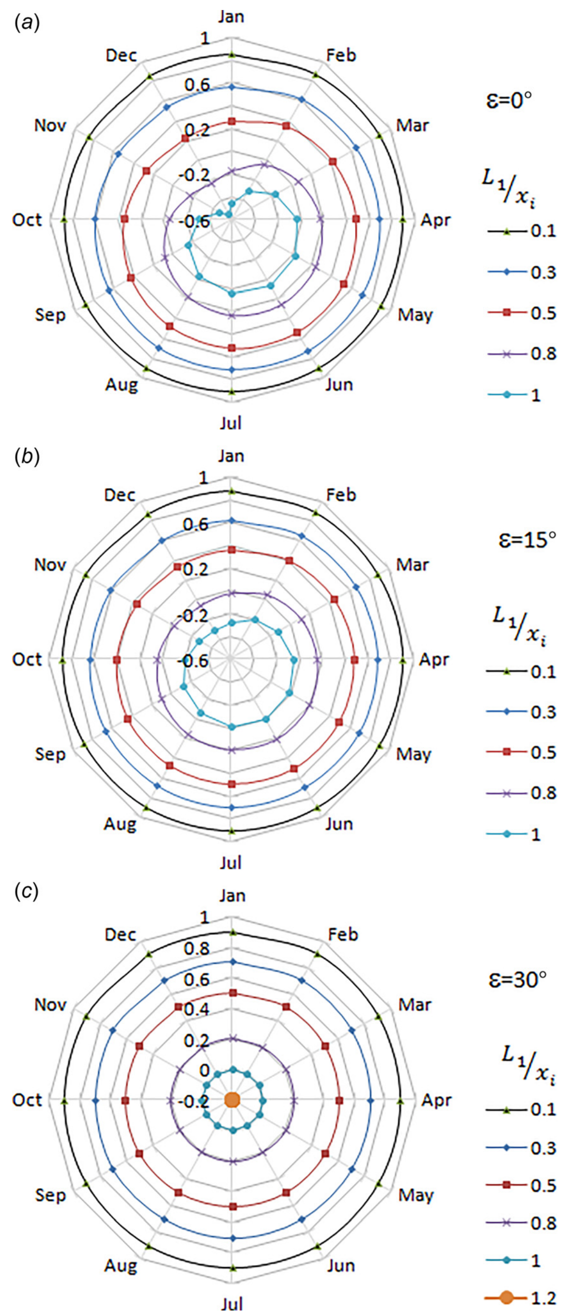

Fig. 12 The dimensionless sunny zone length for the 21st of every month for various collector's dimensionless height (L_1/x_i) and land inclination angles ε for latitude $S_1 = \lambda = 30$ deg

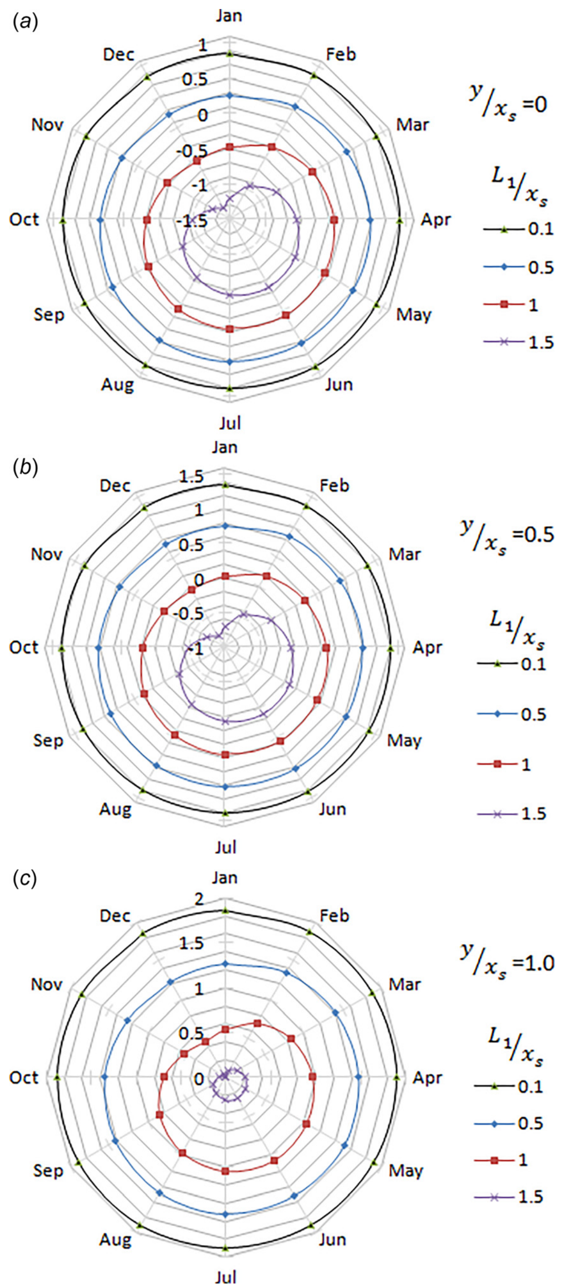

Fig. 13 The dimensionless sunny zone length for the 21st of every month for various collector's dimensionless height (L_1/x_s) and step dimensionless height y/x_s for latitude $S_1 = \lambda = 30$ deg

in the interior rows of a solar field and the sky, ground, and rear-side of the previous collector were developed for all types of solar fields: flat, step-like structure, and inclined. These expressions may be used to calculate the diffuse radiation on collectors for isotropic sky and may also be used to estimate the ground-reflected solar radiation. The results obtained may be used for the development of reflectors on both ground and on the rear-side of the previous collector. The view factors are of an appreciable value depending on the collector tilt angle, the distance separating the rows and the height of the collector in addition to the height of the step in the step-like field, and the inclination angle of the land in the inclined solar field. The dimensionless height of the critical collector is also determined. The view factors are presented as dimensionless parameters for all types of fields and are demonstrated graphically by using Microsoft Excel.

Nomenclature

L_1 = first-row height, m
L_2 = second-row height, m
S_1 = first-row tilt angle from the horizontal plane
S_2 = second-row tilt angle from the horizontal plane
x_f = distance separating the rows in case of flat solar field, m
x_i = distance separating the rows in case of inclined solar field, m
x_s = distance separating the rows in case of step-like solar field, m
y = height of the step in the step-like solar field, m
α = altitude solar angle
ε = land tilt angle from the horizontal plane in the inclined solar field
λ = latitude angle

References

[1] Duffie, J. A., and Beckman, W. A., 2013, *Solar Engineering of Thermal Processes*, 4th ed., Wiley, New York.
[2] Nassar, Y. F., 2006, *Solar Energy Engineering-Active Applications*, Sebha University, Libya.
[3] Badescu, V., Gueymard, C. A., Cheval, S., Opera, C., Baciu, M., Dumitrescu, A., Iacobescu, F., Milos, I., and Rada, C., 2012, "Computing Global and Diffuse Solar Hourly Irradiation on Clear Sky. Review and Testing of 54 Models," Renewable Sustainable Energy Rev., **16**(3), pp. 1636–1656.
[4] McIntyre, J. H., 2012, "Community-Scale Assessment of Rooftop-Mounted Solar Energy Potential With Meteorological, Atlas, and GIS Data: A Case Study of Guelph, Ontario (Canada)," Energy, Sustainability Soc., **2**(23), pp. 1–19.
[5] Elhab, B. R., Sopian, K., Sohif, M., Lim, Ch., Sulaiman, M. Y., Ruslan, M. H., and Saadatian, O., 2012, "Optimizing Tilt Angles and Orientations of Solar Panels for Kuala Lumpur, Malaysia," Sci. Res. Essays, **7**(42), pp. 3758–3765.
[6] Maor, J., and Appelbaum, J., 2012, "View Factors of Photovoltaic Collector Systems," Sol. Energy, **86**(6), pp. 1701–1708.
[7] Appelbaum, J., 2016, "Current Mismatch in PV Panels Resulting From Different Locations of Cells in the Panel," Sol. Energy, **126**, pp. 246–275.
[8] Appelbaum, J., and Aronescu, A., 2016, "View Factors of Photovoltaic Collectors on Roof Tops," J. Renewable Sustainable Energy, **8**(2), p. 025302.
[9] Appelbaum, J., 2016, "Bifacial Photovoltaic Panels Field," Renewable Energy, **85**, pp. 338–343.
[10] Rehman, N., and Siddiqui, M. A., 2015, "A Novel Method for Determining Sky View Factor for Isotropic Diffuse Radiations for a Collector in Obstacles-Free or Urban Sites," J. Renewable Sustainable Energy, **7**(3), p. 033110.
[11] Baehr, H. D., and Karl, S., 2011, *Heat and Mass Transfer*, 3rd ed., Springer, Berlin, Heidelberg, p. 588.
[12] Copper, J. K., Sproul, A. B., and, Bruce, A. G., 2016, "A Method to Calculate Array Spacing and Potential System Size of Photovoltaic Arrays in the Urban Environment Using Vector Analysis," Appl. Energy, **161**, pp. 11–23.
[13] Nassar, Y. F., Hadi, H. H., and Salem, A. A., 2008, "Time Tracking of the Shadow in the Solar Fields," J. Sebha Univ., **7**(2), pp. 59–73.