Multi-Factorial Comparison for 24 Distinct Transposition Models for Inclined Surface Solar Irradiance Computation in the State of Palestine: A Case Study

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Solar energy industries require an accurate estimation of global solar irradiation particularly on inclined planes. This improves the accuracy of the sizing procedures and optimizes the performance of the solar energy platforms as photovoltaic modules and flat-plate solar collectors. A variety of the transposition models have been developed and reportedly determine incidences of solar irradiance on an inclined surface. However, there is a gap in the literature regarding identifying the most promising transposition model, particularly for the Middle East and North Africa region (MENA). Therefore, this article serves two main objectives. Firstly, it compares comprehensively 24 different transposition models. Several statistical methods are used to quantify the performance of the tilted surface transposition models. Furthermore, the transposition models are compared with real, hourly measured time-series data for several Palestinian cities to identify the promising and most accurate model. The analysis was carried out on three bases: annually, monthly, and a clearness index. The transposition models prove their ability to represent the measured data during the annual and monthly analyses, but they all failed to achieve complacency in the clearness index ($K_t > 0.78$). Secondly, the article advises a reliable and accurate transposition model for the area of the MENA for clear sky conditions. The proposed model was tested for the sites under investigation, and it produces significantly better performance than the candidate transposition models.

Keywords: diffuse, Palestine, MENA, diffuse solar irradiance, transposition models, isotropic models, anisotropic models, clearness index

INTRODUCTION

Accurate meteorological data, particularly different components of solar radiation, are mandatory for the different stages of the solar energy project, such as design, sizing, performance evaluation, and implementation phases. However, there is a lack of accurate data for the global solar irradiance on titled surfaces for the MENA region, particularly Palestine state. The transposition models could compensate for the deficiency in the measured solar irradiance data. They estimate the global solar
radiation with acceptable accuracy (Ulgen and Hepbasli, 2004; Noorian et al., 2008; Chwieduk, 2009; Besharat et al., 2013; Escobedo et al., 2014; Pandey and Katiyar, 2014; Horváth and Csoknyai, 2015; Tuomiranta and Ghedira, 2015; Michael et al., 2016; Vasar et al., 2016; Moretón et al., 2017; Zhang et al., 2017; Pérez-Burgos et al., 2018). The transposition models in general depend on the measured values of horizontal irradiance (Idh) and the global horizontal irradiance (Ih) to compute the global solar irradiance on a tilted surface. Moreover, they could be used to optimize the tilt and azimuth of Photovoltaic (PV) arrays (Yadav and Chandel, 2013; Camelia and Dorin, 2014; Khatib et al., 2015; Hafez et al., 2017; Raptis et al., 2017), which boost the conversion efficiency of PVs and allows accurate tracking for maximum power point under different operating conditions.

Recently, many transposition models are developed and reported for estimating the hourly global solar radiation on inclined surfaces. These models, as the literature claimed, could predict solar irradiation with sufficient accuracy (Ulgen and Hepbasli, 2004; Noorian et al., 2008; Tuomiranta and Ghedira, 2015; Michael et al., 2016; Moretón et al., 2017; Zhang et al., 2017). However, it is difficult to identify a promising transposition model that could be considered as a reference. The literature shows a major difference between the transposition model output and the measured data. In general, the transposition model, as the literature claimed, is site dependent. This also is obvious in Table A1, where list of recommended models for various countries is shown. Moreover, a discrepancy is quite obvious in the literature. For example, the isotropic model is claimed in Reindl et al. (1990a) to be the least efficient for the hourly diffusion of radiation on tilted surfaces. However, Table A1 in the appendix shows the contrary; here, the isotropic model is adopted as a transposition model for diffuse solar irradiance on inclined plane for different countries.

Solar energy software shows the significance of transposition model accuracy. These simulation programs are developed by commercial and governmental bodies for facilitating the sizing, design, and economical/dynamic evaluation of solar energy projects. Their performance is solely transposition model dependent. Thus, uncertainty and/or inaccurate estimations of solar irradiance result in economic and technical inconveniences. Table A2 tabulates the widely used solar energy software, including the software name, the country, and the transposition model used for developing.

Recently, several databases, such as NASA-SSE1 SOLARGIS2, Meteoblue AG3, HELIOS4, European Solar Radiation Atlas (ESRA)5, Satel-Light6, and Meteonorm7, have begun to provide different components of solar irradiances, such as Ih, Idh, and It, freely to users in a simplified manner. However, these databases face the same limitation as solar energy evaluating software; they principally depend on a transposition model. They use different models to compute the sky-diffuse and ground-reflected components of the solar irradiance on inclined surfaces. For example, the HelioClim3 database uses a Muneer model for the sky-diffuse and isotropic model for ground-reflected components8. Therefore, it is necessary to identify the most reliable, applicable, and accurate transposition model, which has the objective of determining the most reliable database and solar energy software.

The literature lacks clear comparative studies between the different transportation models. Usually, the literature has a peer-to-peer comparison between a proposed and an existing model. This comparison usually focuses on the ability of the proposed model to fit the measured data for a particular site and specific time span (Yadav and Chandel, 2013; Camelia and Dorin, 2014; Khatib et al., 2015; Hafez et al., 2017; Raptis et al., 2017). Therefore, this article introduces a comprehensive and statistically authenticated comparison between 24 different transposition models to identify the most promising candidate for the MENA region and the Palestine state in particular. The article addresses different problems of the widely used transposition models, such as site dependency and the mechanism for forecasting global solar irradiance on inclined surface. The analysis was carried out on three bases: annually, monthly, and a clearness index. The transposition models are compared with real, hourly measured time-series data over the course of 15 months (June 2017 to August 2018) of the selected cities to identify the promising and most accurate model. The article also advises a simple and robust transportation model for estimating the solar irradiance of inclined surface for clear sky. The MENA region enjoys a clear sky scenario, Kt > 0.78, for a high percentage of daylight hours.

The article has several contributions:

1. Identifying the most accurate models for representing the sky-diffuse solar irradiance under different sky conditions, and Palestinian territories are used as a case study. Consequently, the appropriate solar energy software/database could be easily determined for the study case and the similar geographical sites.
2. Advising a model that achieves better performance in predicing climatic data for clear sky than the reported transposition models. A clear sky scenario, Kt > 0.78, represents a high percentage of daylight hours for the region of the MENA.

### DATA AND METHODOLOGY

The research methodology commenced by discussing the studied sites and the data control. This was to confirm the validity and applicability of the obtained results. Then, the transposition models concerned were highlighted. Finally, the methodology

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1. Satellite Solar Radiation Data. Available online at: http://www.eosweb.larc.nasa.gov/sse/
2. SOLAR GIS. Available online at: http://www.solargis.info/index.html
3. Meteoblue AG - Switzerland. Available online: http://www.meteoblue.com
4. HELIOS. Available online: http://www.helios.ies-def.upm.es/
5. ESRA. The European Solar Radiation Atlas. Available online: https://www.scribd.com/document/142793445/The-European-Solar-Radiation-Atlas-Esra-1.
6. Global radiation data based on satellite images. Available online: http://www.satellight.com.
7. http://www.meteonorm.com/
8. http://www.soda-pro.com/web-services/radiation/helioclim-3-archives-for-free/info
The three components, \(I_{bh}\), \(I_{dh}\), and \(I_{rt}\), of the global inclined solar irradiance were determined from the measured values of \(I_t\), \(I_h\), and \(I_{dh}\). Three pyranometers were used for values of \(I_t\), \(I_h\), and \(I_{dh}\). \(I_{dh}\) is usually obtained from an eye shaded pyranometer. This research used the data recorded from 7th June 2017 up to 12th September 2018 for Rafah, Gaza, Hebron, Jericho, Nablus, and Tulkarm. The data of global, sky-diffuse horizontal, and global for tilt angle 30\(^\circ\) south-facing pyranometers were recorded. A specimen of these measurements and calculations are presented graphically in Figure 2 for horizontal and 30\(^\circ\) south-facing planes for the four cities during the day of 21st November 2017.

Figure 2 shows that the city of Rafah receives more solar irradiance than other cities. Jericho has the highest peak. Each city has distinctive solar irradiance patterns despite the small geographical zone of them (Figure 1). The global inclined irradiance is more than the horizontal one, which is attributed to the reflected component. Figure 2 shows that Gaza and Hebron have high degree of similarity. The data in the article have passed a quality control by many solar energy research centers in Gaza Strip and West Bank Universities (such as An-Najah National University, Polytechnic University, University of Palestine, The Palestinian Energy & Environment Research Center, and many others). The data are also authorized to be used by the Palestinian Central Bureau of Statistics, and they are handled by local researchers.

### TABLE 1 | Geographical data for selected cities.

| City   | Latitude   | Longitude | Elevation; m | Inclination of the pyranometer | Optimum tilt angle* |
|--------|------------|-----------|--------------|---------------------------------|---------------------|
| Rafah  | 31.275     | 34.251    | 75           | 30                              | 23                  |
| Gaza   | 31.511     | 34.46     | 31           | 30                              | 29                  |
| Hebron | 31.528     | 35.094    | 957          | 30                              | 25                  |
| Jericho| 31.857     | 35.464    | -257         | 30                              | 18                  |
| Nablus | 32.21      | 35.256    | 748          | 30                              | 23                  |
| Tulkarm| 32.302     | 35.021    | 67           | 30                              | 23                  |

*Recommended by the local solar energy centers.

section introduces the statistical tools used for evaluating each transposition model individually.

### Data and Studied Sites

Six different cities in the Palestine state were used for assessing the feasibility of these models. The location and geographical data for these cities are illustrated in Figure 1 and Table 1. These cities are selected to represent different characteristics of the Palestine State. For example, Rafah and Gaza depict the terrains with relatively long coasts, Hebron and Nablus represent territories surrounded with mountains, and Jericho and Tulkarm represent the terrains with valleys and plains, respectively. The analysis carried out in this research is generic. It could therefore act as a valuable reference for similar territories.
The transposition factor $R_b$ could be given as a function of geometrical parameters of the inclined surface and the position of the sun by Nassar (2006), Duffie and Beckman (2013)

$$R_b = \max \left( 0, \frac{\cos \theta_i}{\cos \theta_z} \right)$$

where $\theta_i, \theta_z$ are the solar incidence and zenith angles, respectively. Similarly, $R_r$ is the transposition factor for ground-reflected solar irradiance. It is given by

$$R_r = \rho_g \frac{1 - \cos \beta}{2}$$

$\rho_g$ is the albedo radiation factor, which is alternatively themed for the ground reflectivity. It is generally assumed to equal 0.2 (Moretón et al., 2017). For a ground covered with a layer of water or with plants having glossy leaves, the reflection of such radiation is usually anisotropic. The ground transposition factor $R_r$ is given by Temps and Coulson (1977)

$$R_r = \rho_g |\cos \psi| \left( \frac{1 - \cos \beta}{2} \right) \left[ 1 + \sin^2 \left( \frac{\theta_z}{2} \right) \right]$$

where $\psi$ is the surface azimuth angle. The diffuse irradiance is due to scattering of the solar radiation by the different

FIGURE 2 | Fifteen-minute time-series measurements and estimated solar radiation components for Gaza, Hebron, Jericho, Tulkarm, Nablus, and Rafah on November 21st, 2017.
components of the atmosphere. Therefore, it has naturally a non-uniform distribution throughout the sky. However, some models consider diffuse irradiance to be uniform and isotropic. Other models try to depict the scattering processing by adding to the isotropic background, the diffuse irradiance coming from the circumsolar region and the horizon band. Therefore, the models for estimating $I_d$, and hence the transposition models, could be divided into two groups: isotropic and anisotropic. The anisotropic group is further divided depending on the region and/or the band used in considering $I_d$ (Gracia and Huld, 2013).

### Isotropic Models

The isotropic models assume that the intensity of diffuse sky radiation is uniform over the sky hemisphere. Hence, the diffuse radiation depends only on the transposition factor $R_d$. Equations (5)–(7) could be used for determining $R_b$ and $R_d$ for these groups (Liu and Jordan, 1963; Temps and Coulson, 1977; Jimenez and Castro, 1986; Koronakis, 1986; Tian et al., 2001; Badescu, 2002; Nassar, 2006; Psiloglou and Kambezidis, 2009; Duffie and Beckman, 2013; Gracia and Huld, 2013; Bilbao et al., 2014; Lave et al., 2015; Alsadi and Nassar, 2016). This group includes several models:

1. **Liu and Jordan model, 1963** (Liu and Jordan, 1963),
   \[ R_d = \left( \frac{1 + \cos \beta}{2} \right) \] (8)

2. **Koronakis model, 1986** (Koronakis, 1986),
   \[ R_d = \left( \frac{2 + \cos \beta}{3} \right) \] (9)

3. **Jimenez & Castro model, 1986** (Jimenez and Castro, 1986),
   \[ R_d = \left( \frac{1 + \cos \beta}{5} \right) \] (10)

The transposition factor $R_b$ of Jimenezvand Castro model is given by (Jimenez and Castro, 1986)

\[ R_b = 0.8 \frac{\cos \theta_i}{\cos \theta_z} \] (11)

4. **Tian model, 2001** (Tian et al., 2001),
   \[ R_d = 1 - \left( \frac{\beta}{180} \right) \] (12)

where $\beta$ is given in degree

5. **Badescu model, 2002** (Badescu, 2002),
   \[ R_d = \frac{(3 + \cos 2\beta)}{4} \] (13)

### Anisotropic Models

The anisotropic models assume the anisotropy of the diffuse sky radiation in the circumsolar region and the horizon in addition to the isotropic diffuse component. This group is relatively more accurate than isotropic models. Therefore, around 19 models of this group are considered in this comparative study. These include:

6. **Bugler model, 1977** (Bugler, 1977),
   \[ R_d = \left( \frac{1 + \cos \beta}{2} \right) + 0.05 \frac{I_{bh}}{I_d} \] (14)

7. **Temps-Coulson model, 1977** (Temps and Coulson, 1977),
   \[ R_d = \left( \frac{\cos^2 \frac{\beta}{2}}{2} \right) \left( 1 + \cos^2 \theta_i \sin^2 \theta_z \right) \left( 1 + \sin^2 \frac{\beta}{2} \right) \] (15)

8. **Steven and Unsworth model, 1979** (Steven and Unsworth, 1980),
   \[ R_d = 0.143 \left( \sin \beta - \beta \cos \beta - \pi \sin^2 \frac{\beta}{2} \right) + \cos^2 \frac{\beta}{2} \] (16)

9. **Hay model, 1979** (Hay, 1979),
   \[ R_d = F_{Hay} R_b \left( 1 - F_{Hay} \right) \left( \frac{1 + \cos \beta}{2} \right) \] (17)

where $F_{Hay} = \left( \frac{I_{bh}}{I_{sc}} \right)$ is Hay’s sky-clarity factor

10. **Klucher model, 1979** (Klucher, 1979),
   \[ R_d = \left( \frac{\cos^2 \frac{\beta}{2}}{2} \right) \left( 1 + f_k \cos^2 \theta_i \sin^2 \theta_z \right) \left( 1 + f_k \sin^3 \left( \frac{\beta}{2} \right) \right) \] (18)

where $f_k = 1 - \left( \frac{I_{bh}}{I_{sc}} \right)^2$

11. **Modified Steven and Unsworth model, 1980** (Steven and Unsworth, 1979),
   \[ R_d = 0.51 R_b + \frac{1 + \cos \beta}{2} - \frac{1.74}{1.26 \pi} \left[ \sin \beta - \beta \cos \beta - \pi \sin^2 \frac{\beta}{2} \right] \] (19)

12. **Willmot model, 1982** (Willmot, 1982),
   \[ R_d = \frac{I_{bh} R_b}{I_0} + C_{\beta} \left( 1 + \frac{I_{bh}}{I_{sc}} \right) \] (20)

where: $I_{bh} = \frac{h}{\cos \gamma_f}$, $C_{\beta} = 1.0115 \cdot 0.20293 \cdot 0.080823 \beta^2$, $\beta$ is in radians, and $I_{sc} = 1367 \text{ W/m}^2$

13. **Ma-Iqbal model, 1983** (Ma, 1983),
   \[ R_d = k_i R_b \left( 1 - k_i \right) \left( \frac{1 + \cos \beta}{2} \right) \] (21)

where $k_i$ is the clearness index $k_i = \frac{I_{bh}}{I_{sc}}$

14. **Skartveit-Olseth model, 1986** (Skartveit and Olseth, 1986),
   \[ R_d = F_{Hay} R_b + Z \cos \beta + \left( 1 - F_{Hay} - Z \right) \cos^2 \left( \frac{\beta}{2} \right) \] (22)

where $Z = \max \left\{ 0.3 - 2F_{Hay} - Z \right\}$.

Equations (17) and (22) show that the Skartveit-Olseth model is evolved from the Hay model. Therefore, the performances of these models are forecasted to have a high degree of similarity.
15. *Gueymard model, 1987 (Gueymard, 1986)*,

\[ R_d = (1-N_g) R_{d0} + N_g R_{d1} \]  \hspace{1cm} (23)

where \( N_g, R_{d0} \) and \( R_{d1} \) are given by

\[
N_g = \max \{ \min \{ Y, 1 \}, 0 \} \hspace{1cm} (24)
\]

\[
Y = \begin{cases} 
6.6667 \frac{L_a}{L_i} - 1.4167 & \text{if } \left( \frac{L_a}{L_i} \right) \leq 0.227 \\
1.2121 \frac{L_a}{L_i} - 0.1758 & \text{otherwise}
\end{cases} \hspace{1cm} (25)
\]

\[
R_{d0} = \exp \left( a_0 + a_1 \cos \theta + a_2 \cos \theta \cos \phi + a_3 \cos \phi \right) + F(\beta) G(\gamma) \hspace{1cm} (26)
\]

where coefficients \( a_i \) are a function of the solar elevation angle in \( \gamma \) degrees,

\[
a_0 = 0.897 3.364 \gamma^3 + 3.96 \gamma^2 + 1.990 \gamma \hspace{1cm} (27)
\]

\[
a_1 = 4.448 12.962 \gamma^3 + 34.600 \gamma^2 + 48.874 \gamma \hspace{1cm} (28)
\]

\[
a_2 = 2.77 + 9.164 \gamma^2 \hspace{1cm} (29)
\]

\[
a_3 = 0.312 0.217 \gamma^2 + 0.805 \gamma^2 + 0.318 \gamma^3 \hspace{1cm} (30)
\]

where \( \gamma = 0.01 \gamma \)

\[
F(\beta) = \frac{1.02249 \sin^2 \beta + 0.1231 \sin 2\beta + 0.0342 \sin 4\beta}{1.02249} \hspace{1cm} (31)
\]

\[
G(\gamma) = 0.408 0.323 \gamma^3 + 0.384 \gamma^2 - 0.17 \gamma \hspace{1cm} (32)
\]

\[
R_{d1} = \frac{\cos \beta}{2} - \frac{1}{\pi} \left( \beta \cos \beta - \sin \beta \right) + \left( \frac{1 - \cos \beta}{2} \right) \hspace{1cm} (33)
\]

where \( \beta = 1.5 \)

16. Modified Bugler model, 1988 (Hay and McKay, 1988),

\[
R_d = \left( 1 - 0.05 \frac{L_b}{L_i} \right) \frac{1 + \cos \beta}{2} \hspace{1cm} + 0.05 \frac{L_b}{L_i} R_b \hspace{1cm} (34)
\]

17. Perez model, 1988 (Perez and Scott, 1983; Perez and Stewart, 1983; Perez and Arbogast, 1985; Perez et al., 1986, 1987a,b, 1990a,b).

The Perez model is subjected to continuous revisions. This is to improve its performance capabilities and fit the measured data more accurately (Perez and Scott, 1983; Perez and Stewart, 1983; Perez and Arbogast, 1985; Perez et al., 1986, 1987a,b, 1990a,b).

In this research study, two versions of the Perez models are investigated: Perez model 1988 and 1990. Perez model 1988, is given by

\[
R_d = F_1 \frac{a}{b} + (1 - F_1) \left( \frac{1 + \cos \beta}{2} \right) + F_2 \sin \beta \hspace{1cm} (35)
\]

where \( a, b, F_1, \) and \( F_2 \) are given by

\[
a = \max \{ 0, \cos \theta \} \hspace{1cm} (36)
\]

\[
b = \max \{ \cos 85^\circ \sin \gamma \} \hspace{1cm} (37)
\]

\[
F_1 = F_{11}(\varepsilon) + F_{12}(\varepsilon \Delta) + F_{13}(\varepsilon) \theta \hspace{1cm} (38)
\]

\[
F_2 = F_{21}(\varepsilon) + F_{22}(\varepsilon \Delta) + F_{23}(\varepsilon \Delta) \theta \hspace{1cm} (39)
\]

where \( \varepsilon = \frac{\ln \lambda + 1.041 \theta}{1 + 1.041 \theta} \), and \( \Delta = M \lambda_{0 \cos \gamma} \), \( \theta \) is in radians, and \( M \) is the optical air mass.

Perez published many versions of the \( F_{ij} \) coefficients for different locations. Table A3 tabulates the \( F_{ij} \) coefficients for Perez model 1988.

18. Perez model, 1990 (Perez and Scott, 1983; Perez and Stewart, 1983; Perez and Arbogast, 1985; Perez et al., 1986, 1987a,b, 1990a,b).

Perez model 1990 reported in the literature (Perez et al., 1987a,b) has the same equations as Perez model 1988, Equation (35)–(39). However, the values of \( F_{ij} \) coefficients, and thus \( F_{ij} \) coefficients, differ from those in Table A3. Table A4 gives the \( F_{ij} \) coefficients for Perez model 1993.

19. Modified Ma-Iqbal model, 1990 (Kasten, 1966),

\[
R_d = k_t R_b + (1 - k_t') \left( \frac{1 + \cos \beta}{2} \right) \hspace{1cm} (40)
\]

Where \( k_t' \) and the optical air mass, \( M \) are given, respectively, by

\[
k_t' = \frac{k_t}{1.031 \exp \left[ \frac{-1.4}{0.9 + \frac{\beta}{\pi}} \right] + 0.1} \hspace{1cm} (41)
\]

\[
M = \left[ \cos \theta + 0.15 (93.885 - \theta) \right]^{-1.253} \hspace{1cm} (42)
\]

\( k_t \) is as given by Equation (21)

20. Muneer model, 1990 (Muneer, 1990, 1997; Muneer et al., 2004),

\[
R_d = TM (1 - F_M) + F_M R_b \hspace{1cm} (43)
\]

\[
TM = \left( \frac{1 + \cos \beta}{2} \right) + \frac{2b}{\pi (3 + 2b)} \left( \sin \beta - \beta \cos \beta - \pi \sin^2 \left( \frac{\beta}{2} \right) \right) \hspace{1cm} (44)
\]

\( F_M \) is a composite clearness function. For shaded surface or overcast sky conditions \( F_M = 0 \) and \( b = 2.5 \), while for clear sky and partly cloudy sky conditions \( F_M = F_{Hay} \) and \( F_{Hay} \) could be determined by solving the following quadratic equation

\[
F_{Hay}^2 + 0.404 F_{Hay} + \left( \frac{0.987b}{\pi (3 + 2b)} - 0.0197 \right) = 0 \hspace{1cm} (45)
\]

21. HDKR model, 1990 (Reindl et al., 1990a,b):
$$R_d = F_{Hay} R_b + (1 - F_{Hay}) \left( \frac{1 + \cos \beta}{2} \right) \left[ 1 + f \sin^2 \left( \frac{\beta}{2} \right) \right]$$

(46)

where \( f = \sqrt{\frac{I_b}{I_h}} \)

22. **Hay model, 1993 (Hay, 1993):**

$$R_d = F_{Hay}' R_b + \left( 1 - F_{Hay}' \right) \cos^2 \left( \frac{\beta}{2} \right)$$

(47)

Where \( F_{Hay}' = \frac{I_h}{I_h} \)

This late model of Hay 1993 is the modified version of Hay’s 1979. However, Hay’s factor \( F_{Hay} \) in Equation (47) is normalized to the maximum value of solar irradiance, \( I_{sc} \).

23. **Modified Olmo model, 1999 (Olmo et al., 1999),**

$$R_d = \exp \left( -k_t (\theta_i^2 - \theta_o^2) \right) I_c$$

(48)

where \( \theta_i \) and \( \theta_o \) (in radians) are the incidence and solar zenith angles, respectively, \( k_t \) is the hourly clearness index, and the \( \rho_b \) is the albedo of the underlying surface. The function \( f_c' \) is given by

$$f_c' = \begin{cases} 1 - \rho_k \cos^2 \frac{\theta_i^2 - \theta_o^2}{2} & \text{if } 0 \leq k_t \leq 0.35 \\ 1 - \rho_k \sin^2 \frac{\theta_i^2 - \theta_o^2}{2} & \text{if } 0.35 \leq k_t \leq 0.65 \\ 1 & \text{otherwise} \end{cases}$$

(49)

24. **CIBSE model, 2008 (CIBSE, 2008),**

This is a modification of Klucher model, where the diffuse horizontal radiation was corrected:

$$I_{dh} = I_{dh} x f_{\beta} (1 - k_b) + k_b R_b$$

(50)

where \( k_b \) and \( f_{\beta} \) are given by

$$k_b = \frac{I_{dh}}{\epsilon_j I_{ext}}$$

(51)

$$f_{\beta} = \left[ \cos^2 \frac{\beta}{2} + \left( \frac{2 \epsilon}{\pi (3 + 2 \epsilon)} \right) x \left( \sin \beta - \frac{\pi \beta}{180} \right) \cos \beta \right.$$ \right.

$$\left. - \frac{\pi \sin^2 \frac{\beta}{2}}{2} \right]$$

(52)

\( \epsilon_j \) is the correction to mean solar distance on day \( j \), and \( c \) is a constant. The values for constant \( c \) are as follows: Shadow surface: \( c = 5.73 \), Sunlit surface under overcast sky: \( c = 1.68 \), and Sunlit surface under non-overcast sky: \( c = -0.62 \).

**Transposition Models Assessment**

Four different statistical methods are used to assess the potential of the transposition models. This is to identify the most reliable and accurate model, particularly for the area under concern. RMSE, MBE, PAD, and t-stat are the tools of the comparison. Furthermore, the outputs of the different transposition models are compared with measured values to visualize the fitting ability of each model. RMSE, MBE, PAD, and t-stat are defined by Alsadi and Nassar (2016),

$$\text{RMSE} = \left[ \frac{1}{n} \sum_{i=1}^{n} \left( I_{sc} - I_{m} \right)^2 \right]^{1/2}$$

(53)

$$\text{MBE} = \frac{1}{n} \sum_{i=1}^{n} \left( I_{sc} - I_{m} \right)$$

(54)

$$\text{PAD} = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{I_{sc} - I_{m}}{I_{sc}} \right|$$

(55)

$$t - \text{stat} = \left[ \frac{(n - 1) \text{MBE}^2}{\text{RMSE}^2 + \text{MBE}^2} \right]^{1/2}$$

(56)

The statistical methods Equations (53)–(56) could provide a logical pattern for comparing the different models. The Equations (53)–(56) indicates that the smaller values of RMSE, PAD, and t-stat the more accurate the transposition models are. The Equations (53)–(56) show that the results of RMSE, PAD, and t-stat are positive, while MBE produce \( \pm \) values according to the deviation of the estimate from the measured values. The most promising transposition model should have the smallest values for RMSE, MBE, PAD, and t-stat simultaneously. However, they may not agree simultaneously on single transposition model (Khan and Ahmad, 2012). Therefore, the graphical comparison is introduced to show visually the correlation between the measured values and the output of each model.

**RESULTS AND DISCUSSION**

The analysis is carried according to three bases: annual, monthly, and a clearness index. This diversity in the analysis widens the comparison and thus increases the feasibility and reliability of the conducted results.

**All Sky Conditions (Annual) Base Analysis**

The evaluation was carried out on an hourly basis for almost 1 year’s worth of data records. The sky-diffuse solar irradiance on a 30° tilted south-facing surface was determined from measured horizontal data using the 24 models and compared with the semi-measured data for a tilted surface during the same period. Table 2 tabulates the statistical analysis results of the 24 considered transposition models for Hebron city.

Skartveit-Olseth and HDKR are the most promising candidates according to RMSE. For t-stat, Perez 1990 has the best performance; however, HDKR is a reliable candidate. According to MBE, Perez 1990 is the most accurate model for Herbon city. It is clear from Table 2 that there is a difficulty for a model to achieve the best performance according to the different comparison statistical tools simultaneously. It could be concluded that HDKR model produces the better overall performance than the others for Herbon city. The table mandates the application of an additional comparison tool in order to confirm the feasibility and applicability of a definite transposition model. This tool could be the graphical comparison between the
**TABLE 2** | Results of the transposition models, for Hebron city for a tilted angle of 30° south facing.

| No | Transposition model | RMSE, (W/m²) | MBE, (W/m²) | PAD% | t-stat |
|----|---------------------|--------------|-------------|-------|--------|
| 1  | Liu and Jordan      | 13.58        | −6.22       | 6.94  | 2.47   |
| 2  | Koroknis            | 12.36        | −4.96       | 6.24  | 2.10   |
| 3  | Badescu             | 17.41        | −9.49       | 9.75  | 3.12   |
| 4  | Tian                | 20.54        | −11.83      | 12.37 | 3.38   |
| 5  | Jimenez & Castro    | 59.84        | −37.74      | 88.47 | 3.90   |
| 6  | Willmot             | 47.88        | 31.87       | 3.66  | 4.28   |
| 7  | Gueymard            | 12.27        | 2.06        | 3.52  | 15.98  |
| 8  | Bugler              | 14.52        | 1.98        | 4.68  | 0.66   |
| 9  | M. Bugler           | 12.67        | −6.28       | 4.30  | 2.73   |
| 10 | Ma-Iqbal            | 11.18        | 6.70        | 3.23  | 3.59   |
| 11 | M. Ma-Iqbal         | 15.04        | 10.41       | 6.72  | 4.60   |
| 12 | Steven and Unsworth | 22.49        | −13.57      | 11.89 | 3.63   |
| 13 | M. Steven & Unsworth| 52.48        | 28.70       | 14.92 | 3.13   |
| 14 | Hay (1979)          | 8.89         | −3.30       | 1.42  | 1.92   |
| 15 | Hay (1993)          | 10.84        | −5.06       | 3.30  | 2.53   |
| 16 | HDKR                | 8.79         | −2.96       | 1.25  | 1.72   |
| 17 | Skartveit-Olseth    | 8.96         | −3.43       | 1.50  | 1.99   |
| 18 | Muneeer             | 37.15        | −20.50      | 35.68 | 3.17   |
| 19 | Temps-Coulson       | 59.04        | −37.79      | 75.54 | 4.00   |
| 20 | M. Olmo             | 14.32        | 0.93        | 4.03  | 0.18   |
| 21 | Klucher             | 10.91        | 0.66        | 2.81  | 0.29   |
| 22 | CIBSE               | 12.750       | 3.54        | 4.44  | 27.03  |
| 23 | Perez et al. (1988) | 16.86        | −5.81       | 7.77  | 1.76   |
| 24 | Perez et al. (1990a)| 12.71        | −0.19       | 5.24  | 0.07   |

Also, MBE fails to identify the appropriate transposition model for a specific city/zone. **Table 2 and Figure 3** validate this finding. Therefore, RMSE and PAD are only considered in the remaining research as the authenticated comparative tools. The results of RMSE and PAD of different transposition models for different cities under investigations are given in **Table 3**.

**Table 3** shows that there is coherent between RMSE and PAD. For a transposition model they converge simultaneously to optimal solutions. They could therefore also identify the quality of the transposition model at the same time. The bold numbers in **Table 3** show the best solution. HDKR is the most promising solution for 83% of territories under concern. Again, Hay 1979 and Skartveit-Olseth produced comparable performance to HDKR at the majority of the cities under concern. Skartveit-Olseth produced better results than HDKR at Nablus. The preferred transposition models for Gaza, Rafah, Jericho, Tulkram, and Nablus are shown in **Figure 4**, where a visual comparison between estimated and measured values of $I_d$ for these cities is shown.

**Figure 4** shows that HDKR is the most accurate for majority of cities under concern except Nablus where the Stratveit-Olseth model is the most accurate model.

**Monthly Based Analysis**

The monthly based approach was adopted to improve the accuracy of the obtained results. PAD was the tool used in the monthly based analysis to differentiate between the different transposition models. Again, the analysis was carried out from August 2017 until September 2018 for six different cities in the Palestine State. **Table 4** shows the most promising transposition model for the different cities during each month.

**Table 4** confirms the annually based analysis, as HDKR is the most promising candidate at different sites except Nablus, where Skartveit-Olseth model is preferred. However, there was some disparity in the behavior of the models over the months. The similarity between Rafah and Gaza is attributed to same climatological conditions for the two cities.

**Clearness Index ($k_d$) Based Analysis**

This analysis assesses the ability of the different transposition models in manipulating solar irradiance for different sky conditions. The sky conditions are classified into three scenarios (Burgess et al., 2011): overcast, intermediate, and clear conditions. The clearness index, $k_d$, usually differentiated between the different conditions the sky. For example, overcast condition clearness index is below 0.3, $k_d < 0.3$, while for intermediate conditions the clearness index is between 0.3 and 0.78, 0.3 < $k_d < 0.78$, and clearness index is more than 0.78, $k_d > 0.78$ for clear conditions. The RMSE and PAD were calculated for all cities under different values of $k_d$. The most accurate models having the lowest value of the RMSE and PAD are given in **Table 5**.

**Table 5** again shows that there is no single transposition model that could produce an accurate estimation for the global solar irradiance on a tilted plane and its component for different sky conditions, even for the same city. HDKR produced a satisfactory performance for intermediate sky condition for all cities except Nablus. However, for overcast and clear conditions, HDKR

In the graphical comparison, **Figure 3**, the red line represents the locus of the ideal transposition model. Therefore, the quality of a transposition model performance is evaluated via the shape of the distribution of blue dots around the red line. The average of the blue dots should be as close as possible to the red line for a reliable transposition model. **Figure 3** shows that the majority of transposition model could produce reasonable accuracy in predicting $I_d$ for Herbon city. However, HDKR, Skartveit-Olseth, and Hay 1979 are the most promising models. Meanwhile, Jimenez and Castro, Muneer, Temps-Coulson, and M. Steven deviated significantly from the measured values.

It could be concluded from **Table 2** and **Figure 3** that HDKR could be considered as the reference transposition model for Herbon city.

**Table 2** shows that t-stat is the least efficient comparison tool as it diverges from the remaining tools. Moreover, the graphical comparison, **Figure 3**, validates the deficiency of t-stat. The authors, when assessing the transposition models in the other cities concerned, found again that t-stat could not identify the promising model. Therefore, it could be concluded that t-stat is not recommended for identifying a transposition model for particular zone. This, however, differs from the conclusion in reference (Togrul, 1989), which recommends adopting t-stat as the standard tool for determining the best transposition model.
FIGURE 3 | Continued
FIGURE 3 | Continued
FIGURE 3 | Sky-diffused solar irradiance estimation vs. measures for south-facing 30° tilt angle inclined surface in Herbon city for 24 models during all sky conditions (8,700 points depicted in the graph) (blue dot), $y = x$ relation (red line).
The proposed model is basically a modification of the Muneer model. It is realized by increasing the share of the isotropic term in Equations (41) and (42). Different regression methods are used for developing the proposed model. Then, a refining is carried out to the model via trial and error technique. The proposed model is given by

\[
R_d = T_{Mp} (1-F_p) + F_p R_b
\]

\[
T_{Mp} = \left(16.7362 + \frac{17.5317}{\left[1 + \exp \left(\frac{0.97-\beta}{0.1689}\right)\right]^{0.008}} \right)
+ \frac{2b}{\pi (3+2b)} \left( \sin \beta - \beta \cos \beta - \pi \sin^2 \left(\frac{\beta}{2}\right)\right)
\]

\(F_b\) is as mentioned before a composite clearness function. It is equal to \(F_{Hay}\), which is obtained from Equation (42) and is given in radians.

Table 6 tabulates the performance of the proposed model is compared against the best models for the different cities under investigations for clear sky conditions, \(k_t > 0.78\). RMSE and PAD are used as the comparison tools.

Table 6 shows that the proposed model is better at predicting sky-diffused solar irradiance on a titled surface for a clear sky than reported transposition models. There is around 600% reduction in the values of RMSE and PAD. This indicates that the proposed model outputs are similar to the measured values. Table 6 corroborates the reliability and functionality of the proposed model. The feasibility of the proposed model is validated further via a graphical comparison with the measured data, as shown in Figure 7.

Figure 7 shows the applicability of the proposed model in predicting global diffused solar irradiance on a titled surface. It fits the measured data efficiently.
Comparing Figures 5–7 reveals the evaluated quality of the proposed model. It produces much higher quality than even the best models. This model could be considered as a reference for Palestine city under investigations for this 30° south-facing inclined surface. Moreover, the feasibility of the proposed model is examined in other cities for the same climatological conditions. It again produces the best performance for clear sky condition, $k_t > 0.78$.

CONCLUSION

The transposition model is a basic element in the solar energy conversion systems. It generates the data of the incidence of different solar irradiance components on inclined surfaces. These data are mandatory for the phases of design, sizing, and implementation of a solar energy project.
TABLE 4 | The monthly preferred model for each city from August 2017 until September 2018.

| Month    | Hebron  | Jericho | Tulkarm | Nablus     | Rafah | Gaza   |
|----------|---------|---------|---------|------------|-------|--------|
| January  | HDKR    | Ma-Iqbal| Hay (1979) | Skartveit-Olseth | HDKR  | HDKR   |
| February | HDKR    | HDKR    | HDKR    | Skartveit-Olseth | HDKR  | HDKR   |
| March    | HDKR    | HDKR    | HDKR    | Skartveit-Olseth | HDKR  | HDKR   |
| April    | Ma-Iqbal| HDKR    | HDKR    | Willmot     | M.Ma-Iqbal | Ma-Iqbal |
| May      | HDKR    | HDKR    | HDKR    | HDKR        | Hay (1993) | HDKR   |
| June     | HDKR    | HDKR    | HDKR    | HDKR        | M. Bugler | M.Bugler |
| July     | HDKR    | HDKR    | HDKR    | HDKR        | Hay (1993) | Hay (1993) |
| August   | HDKR    | HDKR    | HDKR    | Ma-Iqbal    | HDKR  | HDKR   |
| September| Ma-Iqbal| HDKR    | HDKR    | Skartveit-Olseth | HDKR  | HDKR   |
| October  | HDKR    | HDKR    | HDKR    | Skartveit-Olseth | HDKR  | HDKR   |
| November | HDKR    | HDKR    | HDKR    | Skartveit-Olseth | HDKR  | HDKR   |
| December | HDKR    | Ma-Iqbal| Skartveit-Olseth | Willmot | HDKR | HDKR   |

TABLE 5 | The best transposition models for different $K_t$.

| Clearness index | Hebron  | Jericho | Tulkarm | Nablus     | Rafah     | Gaza     |
|-----------------|---------|---------|---------|------------|-----------|----------|
| $K_t < 0.30$    | Hay (1979) | Hay (1979) | Skartveit-Olseth | Willmot | Hay (1979) | Hay (1979) |
| $0.30 \leq K_t \leq 0.78$ | HDKR | HDKR | HDKR | Skartveit-Olseth | HDKR | HDKR |
| $K_t > 0.78$    | Perez (1990) | Perez (1990) | Perez (1990) | Ma-Iqbal | Perez (1990) | Perez (1990) |

FIGURE 5 | Preferred transposition model for different sky conditions for Hebron city (8,700 points depicted in the graph) (blue dot), $y = x$ relation (red line).

Solar energy software is usually developed according to specific transposition model. Moreover, the databases employ transposition models to generate the different solar irradiance data. Therefore, evaluating the performance of the dominant transposition models is elementary in determining the appropriate database and solar software.
This article compared comprehensively 24 different transposition models. The comparison is multi-factorial; it includes statistical and graphical phases. In the statistical part, four different methods—RMSE, MBE, PAD, and t-stat—were used to identify the most promising transposition model. In the graphical, the outputs of the transposition models were compared with the measured data to visualize the accuracy of the different models. Moreover, the comparison was carried out on three bases: annual, monthly, and a clearing index. Climatological data over 15 months (June 2017 to August 2018) of six different cities in the Palestine State were used to identify the potential of these 24 models, thus identifying the most accurate model for this region.

The results reveal a number of conclusions:

1. The Transposition model is site dependent; it is therefore difficult to adopt one model for entire zone/region with diverse climatological conditions. This conclusion complies with the literature (Kasten, 1966; Bugler, 1977; Hay, 1979, 1993; Klucher, 1979; Steven and Unsworth, 1979, 1980; Willmot, 1982; Ma, 1983; Perez and Scott, 1983; Perez and Stewart, 1983; Perez and Arboagast, 1985; Gueymard, 1986; Perez et al., 1986, 1987a,b, 1988, 1990a,b; Skartveit and Olseth, 1986; Hay and McKay, 1988; Munee, 1990, 1997; Reindl et al., 1990b; Olmo et al., 1999; Tian et al., 2001; Badescu, 2002; Munee et al, 2004; CIBSE, 2008; Padovan and Del-Col, 2010; Khan and Ahmad, 2012). Moreover, the accuracy of the transposition model varies according to the sky clearness, as the model could produce the best performance for overcast sky, but it suffered
from deteriorated performance under clear sky conditions, Table 5.
2. The HDKR model showed a relatively better performance than the others for depicting the sky-diffuse inclined solar irradiance for a majority of Palestinian cities. For Nablus, however, the Skartveit-Olseth model produced a better overall performance than the other candidate models. It produced 3.4% higher than the HDKR model.
3. A majority of the investigated models suffered from inefficient performances for clear sky conditions, \( k_t > 0.78 \), which represents the majority of climatological conditions in the MENA; a robust, efficient, and reliable transposition model is therefore proposed in this article for \( k_t > 0.78 \). The proposed model, as shown in Table 6, Figures 5–7, produced a better performance than the best models for different the Palestine terrains under investigation.
4. It is difficult to identify a single software that could be used for the different cities in the entire region as these software are developed according to single transposition model, Table A2 in the appendix. A number of these are recommended for investigating the performance of solar energy projects in the Palestine
state, such as HOMER, Energypro, and PVdesignPro. Matlab Simulink is appropriate for clear sky conditions, $k_t > 0.78$.

It is worth mentioning that further investigations are required for assessing the feasibility of the studied transposition models and the proposed model for other tilt and azimuth surface angles.

**DATA AVAILABILITY STATEMENT**

All datasets generated for this study are included in the article/Supplementary Material.

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**AUTHOR CONTRIBUTIONS**

YN conceptualized the project and carried out the analysis. AH performed the editing. SA performed the data collection and graphical presentation.

**SUPPLEMENTARY MATERIAL**

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2019.00163/full#supplementary-material
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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| F1     | Circumsolar brightness coefficient |
| F2     | Horizon brightness coefficient |
| Fij    | Perez simplified model coefficient |
| Ih     | Global solar irradiance on a horizontal plane, W/m² |
| Ibh    | Direct beam irradiance on a horizontal plane, W/m² |
| Idh    | Sky-diffuse irradiance on a horizontal plane, W/m² |
| IDN    | Direct normal solar irradiance, W/m² |
| It     | Global solar irradiance on an inclined plane, W/m² |
| Ibt    | Direct beam irradiance on an inclined plane, W/m² |
| Idt    | Sky-diffuse irradiance on an inclined plane, W/m² |
| Irt    | Ground-reflected irradiance on an inclined plane, W/m² |
| Isc    | Solar constant (1367 W/m²) |
| Iext   | Extraterrestrial solar irradiance, W/m² |
| li,c   | Calculated solar irradiance for time i, W/m² |
| li,m   | Measured solar irradiance for time i, W/m² |
| Kt     | Hourly clearness index |
| M      | Optical air mass |
| N      | Number of data |
| Rb     | Direct beam transposition factor |
| Rd     | Sky-diffuse transposition factor |
| Rr     | Ground-reflected transposition factor |
| ρg     | Ground reflectivity or albedo |
| Δ      | Brightness index |
| ε      | Sky clearness index |
| β      | Surface inclination |
| ψ      | Surface azimuth angle |
| θz     | Solar zenith angle |
| θi     | Solar incident angle |
| γ      | Solar altitude angle |