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Investigating the Applicability of Horizontal to Tilted Sky-Diffuse Solar Irradiation Transposition Models for Key Libyan Cities

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***Abstract*—The global solar irradiation incident on a tilted surface with different tilt angles is one of the most important requirements for simulating solar energy systems. However, such data is often not available. For this reason scientists, database platforms and commercial software resort to employ transposition models to convert horizontal solar irradiation into tilted solar irradiation incident on any inclined surface at any degree. The present study considered a wide range of the most commonly used horizontal to tilted transposition models around the world. In the absence of measured information, the horizontal solar radiation was obtained from Solargis for six locations in Libya, which were carefully selected to represent all Libyan territories. Three cities were selected in the north (Tripoli, Sirte and Benghazi), a city in the middle (Al-Jufra) and two cities in the south (Sabha and Kufra). The proposed approach was applied to these cities for selected 22 transposition models and for various tilt angles (10°-90°) in order to determine the best model for use in each area at any given tilt angle. According to the obtained results, it is recommended to use Bugler; 1988 model as the most accurate model for the northern and central regions of the country, and Lui&Jordan model; 1963 as the most applicable model for the southern region.**

Keywords—Transposition model, solar irradiance, isotropic models, anisotropic models , Libya

Nomenclature

F_1	Circumsolar brightness coefficient
F_2	Horizon brightness coefficient
F_{ij}	Perez simplified model coefficient
I_h	Global solar irradiance on a horizontal plane, W/m^2
I_{bh}	Direct beam irradiance on a horizontal plane, W/m^2
I_{dh}	Sky-diffuse irradiance on a horizontal plane, W/m^2
I_{DN}	Direct normal solar irradiance, W/m^2
I_t	Global solar irradiance on an inclined plane, W/m^2
I_{bt}	Direct beam irradiance on an inclined plane, W/m^2
I_{dt}	Sky -diffuse irradiance on an inclined plane, W/m^2
I_{rt}	Ground-reflected irradiance on an inclined plane, W/m^2
I_{sc}	Solar constant (1367 W/m^2)
I_{ext}	Extraterrestrial solar irradiance, W/m^2
$I_{i,c}$	Calculated solar irradiance for time i, W/m^2
$I_{i,m}$	Measured solar irradiance for time i, W/m^2
K_t	Hourly clearness index
M	Optical air mass
N	Number of data
R_b	Direct beam transposition factor
R_d	Sky-diffuse transposition factor
R_r	Ground-reflected transposition factor
ρ_g	Ground reflectivity or albedo
Δ	Brightness index
ε	Sky clearness index
β	Surface inclination
ψ	Surface azimuth angle
Θ_z	Solar zenith angle
Θ_i	Solar incident angle
γ	Solar altitude angle

I. Introduction

Fossil energy sources cause environmental pollution that mainly leads to global warming and climate change. In Libya, the energy industry sector is considered one of the most contributing sectors to environmental deterioration [1-3]. Therefore, scientists and decision-makers should search for alternative sources of energy that are environment-friendly compared to fossil energy. Libya is located in the "solar belt" region and therefore has very large amounts of solar energy. This can be a promising source of electric power generation not only for Libya but also for Europe. For instance, the Desertec project plans to import around 17% of European total electricity energy from North Africa [4].

Due to the importance of renewable energy as an alternative source of energy supply in Libya, and given that Libya is a rich country with various renewable resources, especially solar energy, the ministry of planning of the Libyan government has launched the National Strategy for Renewable Energy and Energy Efficiency 2020-2030. This plan was prepared by a committee formed by a decision of the Minister Delegated Planning No. 48 in 2017. The strategic plan indicated that 10% of solar energy must be achieved within the energy mix in 2030 [5].

The accurate determination of solar irradiation incident components on a surface that tilted and oriented to any tilt and azimuth angles at any location on the planet is considered as one of the priorities of any economic feasibility study for solar energy projects. The great challenge faced by designers of solar systems is the lack of data measured in meteorological stations, and therefore resorting to transposition models. However, the process of selecting the optimal model is very important since it could be the source of uncertainty in the obtained results and this will lead to making incorrect decisions [6].

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The formulation of the transposition models began in the 1960s. Jui and Jordan developed the first isotropic sky model in 1963 [7], and this model is still used by many researchers, commercial software, and database banks. The isotropic sky model assume that the intensity of diffuse sky radiation is uniform over the sky hemisphere. Liu & Jordan, Korokanis, Jimenez & Castro, Tian and Badescu belong to this school. About 15 years later, Bugler in 1977 introduced a more advanced model based on the anisotropy of the diffuse sky radiation in the circumsolar region in addition to the isotropic diffuse component [8]. Many researchers belong to this group, such as: Bugle, Temps&Coulson, and Steven & Unsworth. As for the most recent schools in this field, it is believed that the anisotropy of the diffuse sky radiation includes the horizon component in additional to the existing components. Perez, Reindl, Ma-Iqbal and many others belong to this school, which is relatively more accurate than isotropic models [9]. Therefore, 17 models of this group are considered in this study.

The investigation of transposition models has attracted several researchers due to their significance. In particular, some research studies focused on validating these models for certain regions, and others have developed models to match the available data related to other regions [10]. The significance of transposition models lies behind calculating the optimum tilt and azimuth angles of solar collectors [11], in addition to estimating the intensity of solar radiation falling on an inclined surface [12, 13].

Despite the intensive studies conducted by Libyan researchers on solar energy [14, 15], the modeling of solar radiation has not received the same attention. To the best of our knowledge, no study has considered the determination of the best transfer model for any region in Libya except the study by Alsadi and Nassar in 2017 about Sabha region in the south of Libya. That study determined the parameters that affect the intensity of solar radiation in the PV solar fields and it concluded that Liu & Jordan model is the closest model to the solar radiation data recorded at the meteorological station in the city of Brak at the faculty of engineering science and technology – Sebha university [16]. Regarding Arabic region, in general, there are many studies that have been conducted to identify the model that matches the weather information recorded in the meteorological stations. Some of these studies are included in Table (1).

TABLE 1
RECOMMENDED TRANSPOSITION MODEL FOR VARIOUS COUNTRIES

Country	Site	Transposition model	Ref.
Egypt	Cairo	Hay (1979)	[17]
Iran	Karaj	Skartveit and Olseth (1986)	[18]
Palestine	Jursalem	HDKR (1990)	[19]
Iraq	Baghdad	Liu and Jordan (1963)	[20]
Libya	Sebha	Liu and Jordan (1963)	[21]
Oman	Muscat	Perez (1990)	[22]
Saudi Arabia	Riyadh	Liu and Jordan (1963)	[23]
	Jeddah	Liu and Jordan (1963)	
	Dhahran	Liu and Jordan (1963)	
UAE	Jebel Hafeet	Perez (1990)	[24]

In addition, commercial solar energy software packages are usually developed according to a specific transposition model. Moreover, databases employ transposition models to generate solar irradiance incident on different tilt angles and to obtain the optimum tilt angles. Therefore, determining the correspondent transposition model is essential in exploring the appropriate database and solar software. Table 2 lists an inventory of database platforms and the utilised transposition model though their data generation phase, while Table 3 tabulates number of famous solar energy software.

TABLE 2
DATABASE PLATFORMS OF CLIMATIC DATA AND THE CORRESPONDING TRANSPOSITION MODELS.

No	Software	Transposition model
1	NASA	Liu & Jordan
2	SolarGis	Muneer
3	Solcast	Reindl
4	Global solar atlas	Perez
5	SoDa	Muneer
6	Meteonorm	Hay, Skartveit & Olseth
7	Meteoblue AG	HDKR

TABLE 3
SOME OF COMMERCIAL SOFTWARE AND THE CORRESPONDING TRANSPOSITION MODELS

No	Software	Transposition model
1	EnergyPro	HDKR
2	HOMER	HDKR
10	PVGIS	Muneer
12	PVSyst	Hay and Perez
13	PVWatts	Perez
16	SAM	Liu & Jordan, Perez and HDKR
18	TRNSYS	HDKR

II. METHODOLOGY

Due to the lack of solar radiation data for most sites in Libya, the data has been provided by the solargis company [https://solargis.com] which is the global horizontal solar radiation (I_h) and the horizontal sky-diffuse solar irradiation (I_{dh}). The approach begins with collecting the horizontal solar irradiation components for six cities in Libya, namely: three cities in the north (Tripoli, Sirte and Benghazi), a city in the middle (Al-Jufra) and two cities in the south (Sabha and Kufra) and then the data will be processed by applying 22 most widely used transposition models (Skartveit & Olseth, and Perez) via MS Excel. According to the outcome of the analysed data, the most accurate model for each location can be easily determined.

A. Calculation of global tilted solar irradiance

The global horizontal solar irradiance (I_h) consists of direct beam (I_{bh}) and sky-diffuse (I_{dh}) components, and estimated directly from the following relations [25]:

$$I_h = I_{bh} + I_{dh} \text{ , So} \quad (1)$$

$$I_{bh} = I_h - I_{dh} \quad (2)$$

Estimation of solar irradiance on tilted planes (I_t) can be performed as [25]:

$$I_t = I_{bt} + I_{dt} + I_{rt} \quad (3)$$

Eq. (3) can be rewritten again in terms of the available data (I_{bh} and I_{dh}) as following [25]:

$$I_t = I_{bh}R_b + I_{dh}R_d + I_h\, R_r \quad (4)$$

The conversion of direct radiation is straight forward and it is common to use the transportation factor R_b which is a function of geometrical parameters of the inclined surface and the position of the sun, which equal to [25]:

$$R_b = max\left(0, \frac{cos\,\theta_i}{cos\,\theta_z}\right) \quad (5)$$

Where: θ_i, θ_z are the solar incidence and zenith angles, respectively. R_d and R_r are the sky and the ground transposition factors, respectively. Over the last years, many researchers have presented albedo transposition models and it is common to assume isotropic albedo radiation [25]:

$$R_r = \rho_g \frac{1 - \cos\beta}{2} \quad (6)$$

Where ρ_g refers to the ground reflectivity or albedo and it considered as 0.2 in most cases [26].

The diffuse irradiance is calculated by using several models [27]:

Isotropic models

1. Liu & Jordan model (L, 1963):

$$R_{dL} = \frac{(1 + \cos\beta)}{2} \quad (7)$$

2. Korokanis model (K, 1986):

$$R_d = \frac{1}{3}(2 + \cos\beta) \quad (8)$$

3. Jimenez & Castro model (J, 1986):

$$R_d = 0.2(1 + \cos\beta) \text{ and } R_b = 0.8\frac{cos\theta_i}{cos\theta_z} \quad (9)$$

4. Tian model (T, 2001):

$$R_d = 1 - \frac{\beta}{180}, \beta \text{ is given in degree} \quad (10)$$

5. Badescu model (B, 2002):

$$R_d = \frac{(3 + \cos 2\beta)}{4} \quad (11)$$

Anisotropic models

6. Bugler model (B, 1977):

$$R_d = R_{dL} + 0.05\frac{I_{bh}}{I_d}R_b \quad (12)$$

7. Temps-Coulson model (T, 1977):

$$R_d = R_{dL}(1 + \cos^2\theta_i \sin^3\theta_z)\left(1 + \sin^3\left(\frac{\beta}{2}\right)\right) \quad (13)$$

8. Steven & Unsworth model (S, 1979):

$$R_d = 0.143\left[sin\beta - \beta cos\beta - \pi\sin^2\frac{\beta}{2}\right] + R_{dL} \quad (14)$$

9. Hay model (H, 1979):

$$R_d = F_{Hay}R_b + \left(1 - F_{Hay}\right)R_{dL} \quad (15)$$

Where: $F_{Hay} = I_{bh}/I_{ext}$ is Hay's sky-clarity factor

10. Klucher model (K, 1979):

$$R_d = R_{dL}(1 + f_k\cos^2\theta_i \sin^3\theta_z)\left(1 + f_k\sin^3\left(\frac{\beta}{2}\right)\right),\ f_k = 1 - \left(\frac{I_{dh}}{I_h}\right)^2 \quad (16)$$

11. Modified Steven & Unsworth model (M, 1980):

$$R_d = 0.51R_b + \frac{1.74}{1.26\pi}R_{dL} - \left[sin\beta - \beta cos\beta - \pi\sin^2\frac{\beta}{2}\right] \quad (17)$$

12. Willmot model (W, 1982):

$$R_d = \frac{I_{bn}R_b}{I_0} + C_\beta\left(1 + \frac{I_{bn}}{I_{sc}}\right), I_{bn} = \frac{I_b}{cos\theta_z}, \quad (18)$$

$C_\beta = 1.0115 - 0.20293\beta - 0.080823\beta^2$, β is in radians, and $I_{sc} = 1367\,W/m^2$

13. Ma-Iqbal model (M, 1983):

$$R_d = k_t R_b + (1 - k_t)R_{dL} \quad (19)$$

Where k_t is the clearness index $k_t = \frac{I_h}{I_{ext}}$

14. Skartveit & Olseth model (S, 1986):

$$R_d = F_{Hay}R_b + Zcos\beta + \left(1 - F_{Hay} - Z\right)R_{dL} \quad (20)$$

Where $Z = max\left[\left(0.3 - 2F_{Hay}\right), 0\right]$

Equations (17) and (22) show that the Skartveit-Olseth model is developed from Hay model. Therefore, the performance of these models is expected to have a high degree of similarity.

15. Modified Bugler model (B, 1988):

$$R_d = \left(1 - 0.05\frac{I_{bh}}{I_d}\right)R_{dL} + 0.05\frac{I_{bh}}{I_d}R_b \quad (21)$$

16. Perez model (P, 1988):

$$R_d = F_1\frac{a}{b} + (1 - F_1)R_{dL} + F_2\sin\beta \quad (22)$$

Where a, b, F_1 and F_2 are given by:

$$a = max(0, cos\theta_i),\ b = max(cos85^o, sin\gamma),$$
$$F_1 = F_{11}(\varepsilon) + F_{12}(\varepsilon)\Delta + F_{13}(\varepsilon)\theta_z \quad (23)$$
$$F_2 = F_{21}(\varepsilon) + F_{22}(\varepsilon)\Delta + F_{23}(\varepsilon)\theta_z$$

Where $\varepsilon = \frac{\frac{I_h}{I_{dh}} + 1.041\theta_z^3}{1 + 1.041\theta_z^3}$ and $\Delta = M\frac{I_{dh}}{I_{ext}}$, θ_z is in radians and M is the optical air mass.

TABLE 4

PEREZ SKY IRRADIANCE MODEL COEFFICIENTS (1988)

ε	F_{11}	F_{12}	F_{13}	F_{21}	F_{22}	F_{23}
0-1.065	-0.196	1.084	-0.006	-0.114	0.180	-0.019
1.065-1.23	0.236	0.519	-0.180	-0.011	0.020	-0.038
1.230-1.50	0.454	0.321	-0.255	0.072	-0.098	-0.046
1.500-1.95	0.866	-0.381	-0.375	0.203	-0.403	-0.049
1.950-2.80	1.026	-0.711	-0.426	0.273	-0.602	-0.061
2.800-4.50	0.978	-0.986	-0.350	0.280	-0.915	-0.024
4.500-6.20	0.748	-0.913	-0.236	0.173	-1.045	0.065
>6.200	0.318	-0.757	0.103	0.062	-1.698	0.236

17. Perez model (P, 1990)**:**

The model is the same as Perez model (1988). However, the values of F_{ij} coefficients and hence F_{ij} coefficients differ from those of 1988 version. Table 5 gives the F_{ij} coefficients for Perez's models 1990.

TABLE 5
PEREZ SKY IRRADIANCE MODEL COEFFICIENTS (1990)

ε	F_{11}	F_{12}	F_{13}	F_{21}	F_{22}	F_{23}
1.000-1.065	-0.008	0.588	-0.062	-0.060	0.072	-0.022
1.065-1.230	0.130	0.683	-0.151	-0.019	0.066	-0.029
1.230-1.500	0.330	0.487	-0.221	0.055	-0.064	-0.026
1.500-1.950	0.568	0.187	-0.295	0.109	-0.152	-0.014
1.950-2.800	0.873	-0.392	-0.362	0.226	-0.462	0.001
2.800-4.500	1.132	-1.237	-0.4112	0.288	-0.823	0.056
4.500-6.200	1.060	-1.600	-0.359	0.264	-1.127	0.131
>6.200	0.678	-0.3327	-0.250	0.156	-1.377	0.251

18. Modified Ma-Iqbal model (M, 1990):

$$R_d = \acute{k}_t R_b + (1 - \acute{k}_t) R_{dL} \quad (24)$$

Where $\acute{k}_t$ and the optical air mass, M, are given respectively by:

$$\acute{k}_t = \frac{I_h / I_{ext}}{1.031 exp\left(\frac{-1.4}{0.9 + \frac{9.4}{M}}\right) + 0.1} \quad (25)$$

$$M = [\cos\theta_z + 0.15(93.885 - \theta_z)^{-1.253}]^{-1}$$

19. Muneer model (1990):

$$R_d = T_M(1 - F_M) + F_M R_b, \text{ and} \quad (26)$$

$$T_M = R_{dL} + \frac{2b}{\pi(3+2b)}\left(sin\beta - \beta cos\beta - \pi \sin^2\left(\frac{\beta}{2}\right)\right)$$

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 partially cloudy sky conditions $F_M = F_{Hay}$, and F_{Hay} could be determined by solving the following quadratic equation,

$$F_{Hay}^2 + 0.404 F_{Hay} + \left(\frac{0.987\, b}{\pi(3 + 2\, b)} - 0.0197\right) = 0 \quad (27)$$

20. Hay, Davies, Klucher and Reindl (HDKR) model (R, 1990):

$$R_d = F_{Hay} R_b + (1 - F_{Hay}) R_{dL}\left[1 + f \sin^3\left(\frac{\beta}{2}\right)\right], \quad (28)$$

$$f = \sqrt{(I_{bh}/I_h)}$$

21. Hay model (1993):

$$R_d = \acute{F}_{Hay} R_b + (1 - \acute{F}_{Hay}) \cos^2\left(\frac{\beta}{2}\right), \quad \acute{F}_{Hay} = I_{bh}/I_{sc} \quad (29)$$

22. Modified Muneer model (M, 2020):

Nassar et al. modified the original model of Ma-Iqbal, 1990 to fit the solar radiation data for several cities in Palestine, and it is expressed as [19]:

$$R_d = T_{Mp}(1 - F_p) + F_p R_b \quad (30)$$

$$T_{Mp} = \left\{16.7362 + \frac{17.5317}{\left[1 + exp\left(\frac{0.97 - \beta}{0.1689}\right)\right]^{0.008}}\right\} + \frac{2b}{\pi(3+2b)}\left(sin\beta - \beta cos\beta - \pi \sin^2\left(\frac{\beta}{2}\right)\right) \quad (31)$$

F_b, as mentioned earlier, is a composite clearness function. It is equal to F_{Hay} , which is obtained from (27). β is given in radians.

B. Calculation of deviation rate (DR)

The deviation rate of certain transposition model (DR_i) is a critical parameter in this research, and it expressed as:

$$DR_i\% = \frac{I_{t,i} - I_{t,j}}{I_{t,i}} \times 100 \quad (32)$$

$i = 1,2,\ldots,n, \quad j = 1,2,\ldots,n$ and $i \neq j$

Where $I_{t,i}$ is the annual global tilted solar irradiation calculated by using the transposition model (i). Therefore, for the considered six models, the numbers of deviation rates for each transposition model are five values and then the maximum value will be chosen.

III. RESULTS AND DISCUSSION

An MS Excel worksheet has been prepared to process the solar irradiation component in order to generate the global tilted solar irradiation by using the previous mentioned 23 transposition models. The results are obtained by applying Eqs (1-31), that represent the considered models, and listed in tables from 6 to 11.

TABLE 6
COLOUR SCALE PRESENTATION FOR TRIPOLI CITY

β	L, 1963	B, 1977	B, 1988	H, 1979	H, 1993	S, 1986
10	3.2	4.9	2.9	2.6	2.6	2.6
20	3.5	5.9	3.0	4.3	3.6	4.3
30	4.5	6.4	3.9	5.4	4.5	5.3
40	5.2	6.6	4.5	5.9	4.9	5.9
50	5.6	6.9	4.9	6.5	5.3	6.4
60	5.6	7.4	5.0	7.1	5.8	6.9
70	5.4	7.1	4.8	6.7	5.4	6.5
80	4.7	5.7	4.3	4.9	4.0	4.6
90	4.5	2.4	4.3	3.4	4.5	3.8

TABLE 7
COLOUR SCALE PRESENTATION FOR SIRT CITY

β	L, 1963	B, 1977	B, 1988	H, 1979	H, 1993	S, 1986
10	3.3	5.0	3.1	2.6	2.7	2.6
20	3.4	6.1	3.0	4.5	3.6	4.4
30	4.1	6.8	3.8	5.7	4.5	5.6
40	4.9	7.1	4.3	6.4	5.0	6.3
50	5.7	7.5	5.0	7.2	5.6	7.1
60	6.2	8.2	5.5	8.0	6.2	7.8
70	6.4	8.1	5.8	7.8	5.9	7.5
80	6.4	6.5	6.0	6.0	5.8	5.6
90	6.1	3.4	5.9	4.4	6.2	5.0

TABLE 8
COLOUR SCALE PRESENTATION FOR BENGHAZI CITY

β	K, 1986	W, 1982	B, 1977	B, 1988	H, 1979	H, 1993	S, 1986
10	3.3	2.7	4.8	3.1	2.5	2.8	2.5
20	3.1	3.2	5.7	2.9	3.8	3.1	3.7
30	3.2	3.9	6.1	3.2	4.7	3.8	4.7
40	3.8	4.4	6.1	3.9	5.2	4.2	5.1
50	4.8	5.0	6.4	4.4	5.7	4.5	5.6
60	6.0	5.5	6.7	4.9	6.1	4.9	6.0
70	6.9	5.4	6.4	5.1	5.8	4.6	5.6
80	7.2	4.1	5.1	5.3	4.3	4.9	4.1
90	7.9	5.0	3.9	6.1	5.0	6.1	5.5

TABLE 9

COLOUR SCALE PRESENTATION FOR AL-KUFRA CITY

β	L, 1963	K, 1986	H, 1979	H, 1993	S, 1986	M, 2020
10	2.8	2.7	2.1	2.0	2.1	3.3
20	3.0	2.8	3.6	2.9	3.5	2.7
30	3.9	3.5	4.5	3.7	4.5	3.1
40	4.7	4.0	5.1	4.0	5.1	3.6
50	5.2	4.1	5.6	4.5	5.6	4.2
60	3.9	5.5	0.0	0.0	0.0	0.0
70	5.5	5.2	6.0	4.7	5.9	4.4
80	5.6	5.5	4.9	4.0	4.9	5.2
90	6.3	5.9	4.0	5.2	4.0	7.0

TABLE 10

COLOUR SCALE PRESENTATION FOR AL-JUFRA CITY

β	L, 1963	K, 1986	B, 1988	H, 1979	H, 1993	R, 1990
10	3.2	3.1	3.0	2.6	2.6	2.6
20	3.2	3.1	3.2	4.4	3.8	4.4
30	4.0	4.2	4.0	5.5	4.8	5.8
40	4.6	5.1	4.3	6.1	5.2	6.7
50	5.0	6.5	4.9	6.8	5.7	7.8
60	5.2	8.4	5.7	7.4	6.3	9.1
70	5.2	9.9	5.6	7.0	5.9	9.4
80	6.3	10.5	5.9	5.2	6.1	8.2
90	8.7	10.5	8.7	8.8	9.5	5.3

TABLE 11

COLOUR SCALE PRESENTATION FOR SEBHA CITY

β	L 1963	W, 1982	B, 1988	H, 1979	S, 1986	P, 1990
10	3.2	2.7	3.0	2.6	2.6	3.0
20	3.2	3.6	3.2	4.3	4.3	5.2
30	3.6	4.5	4.0	5.5	5.4	6.7
40	4.0	5.0	4.3	6.0	5.9	7.5
50	4.2	5.6	4.9	6.6	6.5	8.3
60	5.0	6.4	5.7	7.2	7.0	9.1
70	5.0	6.1	5.5	6.7	6.4	8.7
80	3.9	4.2	4.0	4.4	4.1	6.5
90	3.8	4.2	3.7	4.3	4.7	2.9

From the results listed in Tables 6-11, it is possible to determine the best model (indicated by dark green color) for a specific location at a given angle of inclination. It is also feasible to employ these tables to create an inventory of transposition models (Table 12) that can be used in Libya with the minimum risk at various tilt angles of solar collectors.

TABLE 12

INVENTORY OF RECOMMENDED TRANSPOSITION MODELS CORRESPONDING TO LOCATIONS

β	Tripoli	Sirt	Benghazi	Al-Kufra	Al-ufra	Sebha
10	S, 1986	S, 1986	S, 1986	H, 1993	H, 1979	S, 1986
20	B, 1988	B, 1988	B, 1988	M, 2020	B, 1988	L, 1963
30	B, 1988	B, 1988	B, 1988	M, 2020	B, 1988	L, 1963
40	B, 1988	B, 1988	B, 1988	M, 2020	B, 1988	L, 1963
50	B, 1988	B, 1988	B, 1988	M, 2020	B, 1988	L, 1963
60	B, 1988	B, 1988	B, 1988	M, 2020	L, 1963	L, 1963
70	B, 1988	B, 1988	H, 1993	M, 2020	L, 1963	L, 1963
80	H, 1993	S, 1968	W, 1982	H, 1993	H, 1979	L, 1963
90	B, 1977	B, 1977	B, 1977	H, 1979	R, 1990	P, 1990

It is obvious from Table 12 that many of the transposition models are not valid for Libyan cities. For the northern and central regions of the country, Bugler; 1988 model was the most suitable model while the most suitable model for the southern region was Lui & Jordan model; 1963.

Considering that the optimum tilt angles β in Libya ranges between 20°-60° according to the type and period of application, as indicated in many scientific researches regarding this area [13, 28-32], so it is feasible to recommend one transposition model for each city as demonstrated in the Libyan map as shown in Fig.1, while Fig. 2 recommended the transposition models for vertical walls or façade of buildings.

As it is evident from the Tables 6-11, the maximum deviation value of the selected models for each city at any angle of inclination is 5.8%, which occurred at Sirt for the modified Bugler (1988) model when $\beta = 70°$, which is an equivalent to 80 kW/m^2/year.

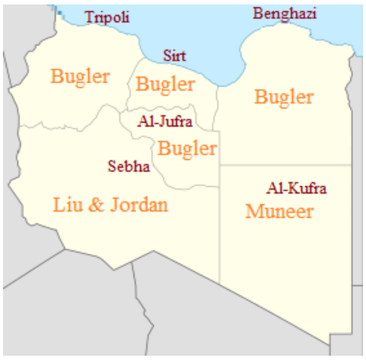

Fig.1: Recommended transposition models for tilted solar collectors within $20° \leq \beta \leq 60°$

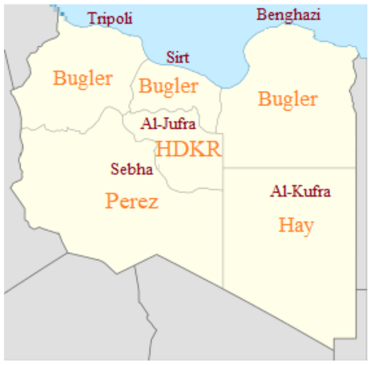

Fig.2: Recommended transposition models for vertical surface or building façade

V. CONCLUSIONS

This work utilised the transposition models, as an alternative to meteorological data in many sites in Libya, to demonstrate the solar energy potential as wel as economic and technical feasibility of solar energy in a certain location. In this context, this work may enhance the efforts made by the Libyan Government towards switching to renewable energies in order to eliminate environmental pollution. More specifically, this work validates 22 horizontal to tilted solar radiation transposition models by introducing a statistical procedure to figure out the most accurate transposition model in the main cities of Libyan territory without the need to measure data. This study showed that the correct transposition model depends on the tilt angle of solar collector in addition to the location. The proposed approach was able to figure out the most accurate transposition model for each location and also for each tilt angle. The study identified models with deviation rates within 5% for most cities, that is mean the annual deviation from the correct values of annual global tilted solar irradiance within $\pm 60\ kW/m^2/year$, which is an engineering reasonable percentage, and this encourages the authors to recommend this approach to determine more accurate transposition models for wider regions in Libya. Finally, it is recommended to take care when adopting a transposition model that has been validated at low tilt angles to be applied on building façades.

VI. Recommendations

It is advisable to conduct a comparison of the recommended models by this research and the existing one to show the validity of the presented approach. Unfortunately, there is only one study on the city of Sebha, whose results match with the research conducted by Al-Sadi and Nassar [21]. To the best of our knowledge, there are no other studies related to the rest of cities considered in this work to facilitate the comparison of the model's accuracy. Therefore, the authors recommend that a comparison must be made for all the cities included in this study.

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