Determination of the Most Accurate Horizontal to Tilted Sky-Diffuse Solar Irradiation Transposition Model for the Capital Cities in MENA Region

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2022 3rd International Conference on Smart Grid and Renewable Energy (SGRE) | 978-1-6654-7908-0/22/$31.00 ©2022 IEEE | DOI: 10.1109/SGRE53517.2022.9774146

Abstract **- Accurate solar radiation data is essential in designing, evaluating and optimizing solar energy systems. The meteorological recorded data is the mainly source of the solar irradiance data. Since solar irradiance incident on a specific tilted surface is not frequently recorded, the horizontal to tilted solar irradiation transposition models (HTTM) use to convert the measurable components of solar irradiation (global horizontal, sky-diffuse and ground reflected) to global tilted solar irradiation with high accuracy. The importance of the solar transposition model is in determining the optimum tilt angle of solar energy harvesters which is one of the important design parameters for maximizing solar radiation incident on the solar collectors. This paper introduces a statistical procedure to figure out the transposition model that is closest to the real model in the MENA region without needs for measured data. Also it provided a summary of optimum tilt angles and transposition models that recommended by local researchers for specific locations in MENA region. This study showed that the transposition models depend on the angle of inclination of the solar collector in addition to the location. The study identified models with deviation rates about 3% for most cities, which is an engineering reasonable percentage, and this encourages the authors to recommend this approach to determine more accurate transposition models for wider regions of the world. On the other hand, it showed that all models failed to achieve an acceptable deviation rate for high tilt angles especially vertical surfaces, which have great engineering applications. The authors advise researchers to take care when adopting a transposition model that has been validated at low tilt angles to apply it to high tilt angles and building façades. The study is also reveal that, the reduction in total annual global solar irradiation is not exceed than 1% due to the offset of tilt angle from the optimum angle for all considered transposition models and for all sites.**

Index Terms - Optimum tilt angle, transposition model, solar energy, MENA, solar irradiance

I. Introduction

The intensity of solar irradiance incident on the earth surface fluctuates as a result of continually changing of the sun position in the sky dome. This angular movement is prescribed in all textbooks of solar energy, as a function of (n,h) where n is the Julian day and h is the time [1, 2]. To maintain the highest level of solar radiation, the surface must be tilted at a certain angle, such that it can capture maximum solar energy. This approach can be instantaneous, as is the case of solar tracking systems [3], daily, monthly, seasonal, or fixed on one angle throughout the year [4]. Many studies have been conducted to obtain the annual optimal tilt angle (β_{opt}) for different locations as a function of latitude [4-6], weather data [7], and character of the energy demand [8-10]. The accurate determination of β_{opt} for any location is essential for maximum energy production by the system [11]. Hafez et al. reviewed the recommended optimum tilt angles with respect to solar altitude and latitude angles for several solar energy applications [12]. Many researchers have calculated the optimum tilt angles for many locations in MENA region, for example but not limited to: Assuit-Egypt [13], , Najaf-Iraq [14] , Kano-Nigeria [15], Settat-Morocco [16], Tabass-Iran [17], Gaza-Palestine [18]. Other researches attempt to derive a general expression for large zone, such as: Saudi [19], Algeria [20], Palestine [21], Turkey [22], Egypt [23], Iran [24], Arabic countries [4], Mediterranean Region [6], desert regions [25], high latitudes [26], northern hemisphere [27], all the world [28].

The theoretical approach for obtaining the optimum tilt angle of a solar collector at any location is passed through three steps: First, obtaining the horizontal solar irradiation components, which are: the beam normal (I_{bn}) and the sky diffuse irradiance (I_{dh}). Second, identifying the appropriate HTTM in order to convert the horizontal solar irradiance to tilted solar irradiance. Finally, getting the maximum solar irradiance during an interval of time and the corresponding tilt angle value by simulating the tilted solar irradiance over large range of tilt angles ($0° \leq \beta \leq 90°$). The certainty of the results is highly relying upon the accuracy of the solar irradiance components and the precision of the HTTM. These two requirements are very particularity for each specific location, and must be identified in advance before starting the optimization process. However, knowledge of the appropriate HTTM needs for measurements of the solar irradiation components at different tilt and azimuth angles for each location. Which in most cases is not available, and if it does exist, then the information is insufficient to figure out the correct HTTM. Although many studies opposed the use of isotropic models, nevertheless Tables 1 and 2 strongly demonstrate the avalbility of Liu & Jordan model to represent solar radiation data and still used to determine the optimum tilt angle in many scientific works [29-33].

This study comes to clarify the role of HTTM on the accuracy of the calculations in terms of the intensity of solar radiation and the optimum tilt angle.

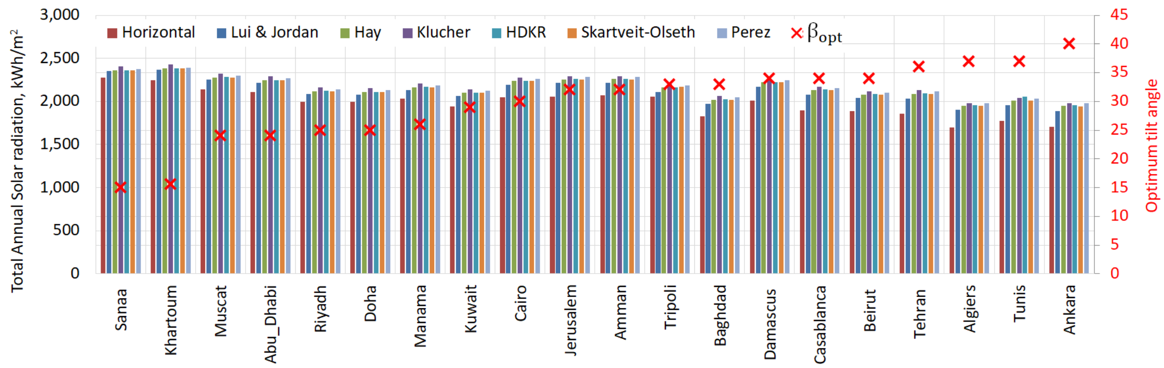

Fig.1: The optimum tilt angle and the corresponding total annual global tilted solar radiation [kWh/m^2] by several HTTM for Capital cities of countries in MENA region

II. Methodology

The approach begins with collecting the horizontal solar irradiation components for a certain location, and then the data will be processed by applying the most widely used HTTM (Liu&Jordan, HDKR, Klucher, Hey, Skartveit&Olseth, and Perez) via the MS Excel. As a result of the analysis, it can be locate the most accurate model for each location.

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 [1]:

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

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

Table 1: Commercial software of solar systems and the corresponding transposition models that used

No	Software	Transposition model
1	NASA	Liu & Jordan
2	SOLARGIS	Muneer
3	Solcast	Reindl
4	Global solar atlas	Perez
5	SoDa	Muneer
	Meteonorm	Hay, Skartveit & Olseth
6	Meteoblue AG	HDKR
7	EnergyPro	HDKR
8	HOMER	HDKR
9	INSEL	Liu & Jordan, Temps & Coulson, Bugler, Klucher, Hay, Willmott, Skartveit & Olseth, Gueymard, Perez and HDKR
10	PVToolbox	Liu & Jordan
11	Polysun	Hay & Davies
12	PV F-chart	Liu & Jordan
13	PV*Sol	Skartveit & Olseth, HDKR and Perez
14	PVDesign	HDKR and Perez
15	PVForm	Perez
16	PVGIS	Muneer
17	PVplanner	Perez
18	PVSyst	Hay and Perez
19	PVWatts	Perez
20	RAPSIM	Unknown
21	RETscreen	Liu & Jordan
22	SAM	Liu & Jordan, Hay & Davies, Perez and HDKR
23	SimulationX	Liu & Jordan
24	Solar Pro	Unknown
25	SolarSizer	Unknown
26	TRNSYS	HDKR

Estimation of solar irradiance on tilted planes (I_t) can be performed as [1]:

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

Where I_{bt}, I_{dt} and I_{rt} are the tilted plane beam, diffuse and ground reflected solar irradiations.

Eq. (3) can be rewritten again in terms of the available data (I_{bh} and I_{dh}) as following [1]:

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

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 [1]:

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

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 years, many authors have presented albedo transposition models. While it is common to assume isotropic albedo radiation [1]:

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

Where β is the surface tilt angle, ρ_g refers to the ground reflectivity or albedo and it considered as 0.2 in most cases [34].

The diffuse irradiance is calculated by using several models [35]:

1. **Liu & Jordan model; 1963 (L)**:

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

2. **Klucher model; 1979 (K)**:

$$R_d = \left(\cos^2\frac{\beta}{2}\right)\left(1 + f_k \cos^2\theta_i \sin^3\theta_z\right)\left(1 + f_k \sin^3\left(\frac{\beta}{2}\right)\right), \ f_k = 1 - \left(\frac{I_{dh}}{I_h}\right)^2 \quad (8)$$

3. **Skartveit-Olseth model; 1986 (S)**:

$$R_d = F_{Hay} R_b + Z cos\beta + \left(1 - F_{Hay} - Z\right)\cos^2\left(\frac{\beta}{2}\right), Z = max\left[\left(0.3 - 2F_{Hay}\right), 0\right] \quad (9)$$

Perez model; 1990 **(P):**

$$R_d = F_1 \frac{a}{b} + (1 - F_1)\left(\frac{1 + cos\beta}{2}\right) + F_2 \sin\beta \quad (10)$$

$$a = max(0, cos\theta_i)$$

$$b = max(cos85^o, sin\gamma)$$

$$F_1 = F_{11}(\varepsilon) + F_{12}(\varepsilon)\Delta + F_{13}(\varepsilon)\theta_z$$
$$F_2 = F_{21}(\varepsilon) + F_{22}(\varepsilon)\Delta + F_{23}(\varepsilon)\theta_z$$
$$\varepsilon = \frac{\frac{I_h}{I_{dh}} + 1.041\theta_z^3}{1+1.041\theta_z^3} \text{ and } \Delta = M\frac{I_{dh}}{I_{ext}}$$

Where θ_z is in radians and M is the optical air mass, Perez has published many versions of the $\boldsymbol{F_{ij}}$ coefficients for many locations. Table 3 tabulate the $\boldsymbol{F_{ij}}$ coefficients for 1990 Perez's model.

Table 3: 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

4. **Hay, Davies, Klucher and Reindl model; 1990 (R)**:

$$R_d = F_{Hay}R_b + \left(1 - F_{Hay}\right)\left(\frac{1+cos\beta}{2}\right)\left[1 + f\sin^3\left(\frac{\beta}{2}\right)\right],\ f = \sqrt{(I_{bh}/I_h)} \qquad (11)$$

5. **Hay model; 1993 (H)**:

$$R_d = \acute{F}_{Hay}R_b + \left(1 - \acute{F}_{Hay}\right)\cos^2\left(\frac{\beta}{2}\right), \qquad (12)$$
$$\acute{F}_{Hay} = I_{bh}/I_{sc}$$

B. Calculation of deviation rate (DR)

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

$$DR_i\% = \frac{I_{t,i} - I_{t,j}}{I_{t,i}} \times 100 \qquad (13)$$
$$i = 1,2, \dots, n\,, \qquad j = 1,2,..,n \text{ and } i \neq j$$

Where $I_{t,i}$ is the tilted solar irradiation calculated by using the transposition model (i). So, for the considerd six models the numbers of deviation rates for each transposition model are 5 values and then the largest value will be chosen.

III. Results and Discussion

Due to the lack of solar radiation data for most locations of the study, these data were obtained free from the SoDa database [http://www.soda-pro.com/web-services/radiation/helioclim-3-archives-for-free], which are the global horizontal solar radiation (I_h) and the component of the sky-diffuse solar irradiation (I_{dh}). A MS Excel worksheet had been prepared to process the solar irradiation component in order to calculate the global tilted solar irradiation by using six HTTM, these are: Liu & Jordan, Hay, Klucher, Reindl, Skartvet&Olseth and Perez models corresponding to the optimum tilt angle of the solar collectors that recommended by local researches as it maintained in the introduction. The obtained results are graphically presented in Fig. 1 for all capital cities of the countries locate in MENA region.

Fig. 1 demonstrates the worth of determining the optimum tilt angle of solar collectors through the increase in irradiation from the horizontal surface, this augmentation in incident solar radiation is high as 16% for high latitude locations and reaches to 6% in low latitudes. Also, the total annual global solar radiation incident on an inclined surface at different tilt angles ($10° \leq \beta \leq 90°$) was calculated for all the considered HTTMs. Then the percentage of deviation of each model from the rest of the models was calculated, and the largest value of deviation was chosen to represent the accuracy of that model. The aim of this step is to figure out the model with the least deviation, which represents the least risky model when used in case of absence of sufficient data to determine the correct model. Table 4 presents a colour scale of maximum deviation of each model from the rest of the models. Through the data included in the Table 4, it is possible to determine the least risky model (dark green color) for a specific location and at a specific angle of inclination. The results of the analysis indicate that both Liu&Jordan and Klucher models are the least accurate among the six selected models. The results also indicate a low accuracy rate for all the models considered when the angle of inclination is high ($\beta > 60°$) where the maximum deviation reaches to 11% at vertical surfaces. While models have been identified, the deviation rate is about 2% for most cities, which is a reasonable proportion geometrically, and this encourages the writers to use this method to determine more accurate relationships between wider regions of the world and test more models. Accordingly, it was able to recommend the most accuracy PHTM for each location and for each tilt angle as it tabulated in Table 5.

Table 2: The optimum tilt angles recommended by several sources and the HTTM for the capital cities in MENA region

Country	City	Lat.	Long.	Global solar atlas	PVGIS	NASA	PVWatts	SODA	Recommended HTTM
Yemen	Sanaa	15°21'N	44°12'E	20	18	16	15	19	N/A
Sudan	Khartoum	15°47'N	32°43'E	20	18	16	15	19	N/A
Oman	Muscat	23°35′N	58°24′E	24	25	22	25	23	Liu&Jordan [36]
UAE	Abu Dhabi	24°28′N	54°22′E	24	25	22	25	23	N/A
Saudi	Riyadh	24°39′N	46°46′E	26	25	23	24	23	HDKR [29]
Qatar	Doha	25°18′N	51°31′E	25	25	23	25	22	N/A
Bahrain	Manama	26°13′N	50°35′E	24	26	24	26	23	N/A
Kuwait	Kuwait	29°22′N	47°58′E	27	29	28	26	26	N/A
Egypt	Cairo	30°2′N	31°13′E	26	28	28	25	27	Klucher [37]
Palestine	Jerusalem	31°47′N	35°13′E	28	28	29	26	27	HDKR [35]
Jordan	Amman	31°57′N	35°56′E	29	28	29	26	28	N/A
Libya	Tripoli	32°52′N	13°11′E	29	31	31	28	30	N/A
Iraq	Baghdad	33°20′N	44°23′E	30	31	31	n/a	30	Liu&Jordan [38]
Syria	Damascus	33°30′N	36°18′E	29	29	31	29	29	N/A

Morocco	Casablanca	33°32′N	7°35′W	29	32	31	28	31	Liu&Jordan [39]
Lebanon	Beirut	33°54′N	35°32′E	28	29	30	n/a	29	N/A
Iran	Tehran	35°41′N	51°25′E	32	32	33	32	32	Skartveit&Olseth [40]
Algeria	Algiers	36°42′N	3°13′E	32	32	33	30	31	Perez [41]
Tunisia	Tunis	36°49′N	10°11′E	31	33	34	29	33	N/A
Turkey	Ankara	40°03′N	32°52′E	33	32	36	29	34	N/A

Table 4: Colour scale presentation of theDeviation rate of the HTTMs for all locations and under various tilt angles

	L	H	K	R	S	P	L	H	K	R	S	P
	$\beta = 10°$						$\beta = 20°$					
Sanaa	4	3	2	3	3	3	4	3	3	3	3	2
Khartoum	4	3	3	3	3	3	4	3	3	3	3	2
Muscat	4	3	3	3	3	3	4	3	3	2	3	2
Abu-Dhabi	4	3	3	3	3	3	4	3	3	3	3	2
Riyadh	3	3	3	3	3	2	3	2	3	2	2	2
Doha	4	3	3	3	3	2	4	2	3	2	2	2
Manama	4	3	3	3	3	2	4	2	3	2	2	2
Kuwait	4	3	3	3	3	2	4	2	3	2	2	2
Cairo	4	3	3	3	3	2	4	2	3	2	2	2
Jerusalem	4	3	3	3	3	2	4	2	3	2	2	2
Amman	4	3	3	3	3	2	4	2	3	2	2	2
Tripoli	4	3	3	3	2	2	4	2	4	2	2	3
Baghdad	4	3	3	3	3	2	4	2	4	2	2	3
Damascus	4	3	3	3	3	2	4	2	3	2	2	2
Casablanca	4	3	3	3	3	2	4	2	4	2	2	2
Beirut	4	3	3	3	3	2	4	2	3	2	2	2
Tehran	4	2	3	2	2	2	4	2	4	2	2	3
Algiers	4	2	3	2	2	2	4	2	4	2	2	3
Tunis	4	2	3	2	2	2	4	2	4	2	2	3
Ankara	4	2	3	2	2	2	4	2	4	2	2	3
	$\beta = 30°$						$\beta = 40°$					
Sanaa	4	3	3	3	3	2	4	3	3	2	3	2
Khartoum	4	3	3	3	3	2	4	3	3	2	3	2
Muscat	4	2	3	2	2	3	4	2	4	2	2	3
Abu-Dhabi	4	2	3	2	2	2	4	2	4	2	2	3
Riyadh	4	2	4	2	2	3	4	3	4	2	3	3
Doha	4	2	4	2	2	3	4	3	4	2	3	3
Manama	4	2	4	2	2	3	4	2	4	2	2	3
Kuwait	4	2	4	2	2	3	4	2	4	2	2	3
Cairo	4	2	4	2	2	3	4	2	4	3	2	4
Jerusalem	4	2	3	2	2	3	4	2	4	2	2	4
Amman	4	2	4	2	2	3	4	2	4	3	2	4
Tripoli	4	2	4	2	3	3	5	3	4	3	3	4
Baghdad	4	2	4	2	2	3	5	3	5	3	2	4
Damascus	4	2	4	2	2	3	4	2	4	3	2	4
Casablanca	4	2	4	2	2	3	4	3	4	3	3	4
Beirut	4	2	4	2	2	3	4	2	4	3	2	4
Tehran	4	2	4	3	2	4	5	3	5	3	3	4
Algiers	4	2	4	3	2	3	5	3	4	3	3	4
Tunis	4	2	4	4	2	3	6	3	4	5	3	4
Ankara	4	2	4	3	2	4	5	3	4	3	3	5
	$\beta = 50°$						$\beta = 60°$					
Sanaa	4	3	4	2	3	2	4	4	5	3	5	3
Khartoum	4	3	4	2	3	2	5	5	5	3	5	3
Muscat	4	3	4	2	3	3	5	4	5	3	4	3
Abu-Dhabi	4	3	4	2	3	3	5	4	5	3	4	3
Riyadh	5	3	5	2	3	3	6	4	5	3	5	4
Doha	5	3	5	2	3	4	6	4	5	3	5	4
Manama	5	3	4	2	3	3	5	4	5	3	4	4
Kuwait	5	3	5	3	3	4	5	3	5	3	4	4
Cairo	5	2	5	3	2	4	5	3	5	3	3	5
Jerusalem	5	2	4	3	2	4	5	3	5	3	3	5
Amman	5	2	4	3	2	4	5	3	5	3	3	5
Tripoli	5	3	5	3	3	5	6	3	5	4	3	5
Baghdad	6	3	5	4	3	5	6	3	6	4	4	5
Damascus	5	3	4	3	2	4	5	3	5	3	3	5
Casablanca	5	3	5	4	3	4	6	3	5	4	3	5
Beirut	5	2	4	3	2	4	5	3	5	3	3	4
Tehran	5	3	5	4	3	5	6	3	6	4	3	5
Algiers	5	3	5	4	3	5	6	3	5	4	3	5
Tunis	8	4	5	7	5	5	10	6	6	9	6	5
Ankara	6	3	5	4	3	5	6	3	6	4	3	6
	$\beta = 70°$						$\beta = 90°$					
Sanaa	6	7	7	4	7	5	9	15	17	10	17	11
Khartoum	6	7	7	5	7	5	10	16	17	11	16	11
Muscat	6	5	6	3	6	3	9	12	12	8	13	7
Abu-Dhabi	6	5	6	3	6	3	9	12	12	8	13	7
Riyadh	7	6	6	3	6	3	10	12	12	7	13	8
Doha	7	6	6	4	7	3	10	13	12	8	14	8
Manama	6	5	6	3	6	4	9	12	11	7	13	7
Kuwait	6	5	6	3	5	4	9	10	10	6	11	5
Cairo	6	4	6	4	4	5	9	9	9	5	9	5
Jerusalem	6	4	6	3	4	5	8	8	8	5	9	5
Amman	6	4	6	4	4	5	8	8	8	5	9	5
Tripoli	7	4	6	4	4	5	9	8	8	4	8	5
Baghdad	7	4	7	5	5	5	10	9	9	5	9	5
Damascus	6	4	6	4	4	5	8	7	8	4	8	5
Casablanca	6	3	6	4	4	5	8	7	8	5	8	5
Beirut	6	4	6	4	4	5	8	7	8	4	8	5
Tehran	7	4	6	5	4	6	9	7	8	5	8	5
Algiers	6	3	6	5	3	5	8	6	7	5	7	5
Tunis	11	8	6	10	8	5	12	9	8	10	10	6
Ankara	7	3	6	5	4	6	8	6	8	6	7	7

Table 5: The best HBTM for each site corresponding to the tilt angle

City	Tilt angle β								
	10	20	30	40	50	60	70	80	90
Sanaa	K	P	P	P	P	R	R	R	L
Khartoum	P	P	R	R	P	R	R	R	L
Muscat	P	P	R	R	R	R	R	R	P
Abu-Dhabi	P	P	R	R	R	R	R	R	P
Riyadh	P	P	R	R	R	R	R	R	R
Doha	P	P	R	R	R	R	R	R	R
Manama	P	P	R	R	R	R	R	R	R
Kuwait	P	R	R	H	H	R	R	R	R
Cairo	P	R	H	H	H	H	R	R	R
Jerusalem	P	R	H	H	H	H	R	R	R
Amman	P	R	H	H	H	H	R	R	R
Tripoli	P	R	H	H	H	H	H	R	R
Baghdad	P	R	H	H	H	H	H	R	R
Damascus	P	R	H	H	H	H	H	R	R
Casablanca	P	R	H	H	H	H	H	R	R
Beirut	P	P	H	H	H	H	H	R	R
Tehran	P	S	H	H	H	H	H	R	R
Algiers	P	S	H	H	H	S	H	H	P
Tunis	P	S	H	H	H	P	P	P	P
Ankara	P	S	H	H	H	S	H	H	R

It is implicity shown that the most available HTTMs for MENA region are Hay (32%), HDKR (42%) and Perez (21%), and Skartveit&Olseth (3%) models (Fig.2).

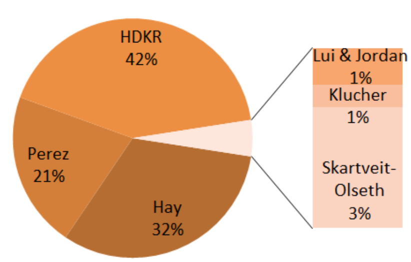

Fig.2: Breakdown of the used HTTMs in MENA region

The β_{opt} for south facing solar collector is also calculating according to the six HTTM for all considered sites and tabulated in Table 6 combined with the recommended tilt angles from local studies.

Table 6: Optimum tilt angles corresponding to the HTTM

City	L	H	K	R	S	P	β_{opt}	Ref.
Sanaa	17	18	17	18	18	19	18	[42]
Khartoum	17	18	17	18	18	19	19	[43]
Muscat	21	22	22	23	22	24	24	[44]
Abu Dhabi	21	22	22	23	22	24	22	[45]
Riyadh	20	22	22	23	22	24	24	[46]
Doha	20	21	21	22	21	23	25	[47]
Manama	21	22	22	23	22	24	26	[48]
Kuwait	24	25	25	26	25	26	20	[49]
Cairo	24	26	26	27	26	27	29	[50]
Jerusalem	25	27	27	27	27	28	29	[51]
Amman	25	27	27	28	27	29	32	[52]
Tripoli	27	29	28	29	29	30	31	[53]
Baghdad	26	28	28	29	28	30	30	[54]
Damascus	27	28	28	29	28	29	29	[55]
Casablanca	28	30	30	31	30	31	28	[56]
Beirut	26	28	28	28	28	29	28	[57]
Tehran	29	31	30	31	30	32	30	[58]
Algiers	31	33	33	34	33	34	32	[59]
Tunis	29	32	31	37	31	32	35	[60]
Ankara	30	33	32	33	32	34	33	[61]

It is notic from Table 6 that the Liu&Jordan model is under estimated the recommended optimum tilt angle, while the best model that fits the recommended optimum tilt angles for all sites is the Perez model.

The percentage of reduction in the total annual global solar radiation due to missing the tilt angle is calculated and precented graphically in Fig.3 for the Jursalem city corresponding to all HTTMs.

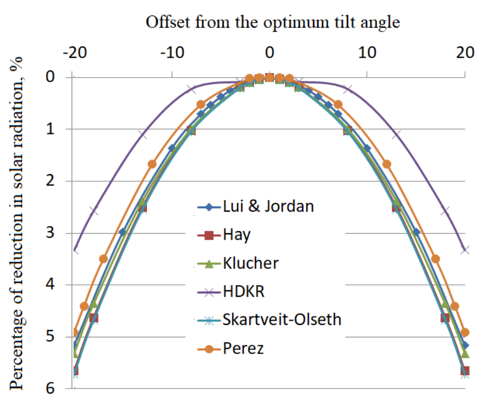

Fig. 3: The effect of offset from the optimum tilt angle on the total annual global tilted solar irradiation

As it tabulated in Table 5, the maximum offset of the optimum tilt angle from all HTTMs is 7° and according to the Fig.3 this will lead to annual reduction in solar energy no more than 1.0% which ranges from 23 (in case of Perez model at $\beta = 30°$) to 21 (in case of Lui&Jordan model at $\beta = 47°$) kWh/m^2/year

V. Conclusions

It has been found that due to the lack of access to meteorological data in many locations around the world, it is convenient for designers or users of solar collectors or photovoltaic (PV) systems to have access to a mathematical model for determining their optimal orientation. This paper introduces a statistical procedure to figure out the most accuracy transposition model in MENA region without needs to measured data. Also it provided a summary of optimum tilt angles and transposition models that recommended by local researchers for specific locations in MENA region. This study showed that the the most available transposition model for MENA region are Hay (32%), HDKR (42%) and Perez (21%), and it depends strongly on the angle of inclination of the solar collector in addition to the location. The study identified models with deviation rates about 3% for most cities, which is an engineering reasonable percentage, and this encourages to recommend this approach to determine more accurate transposition models for wider regions of the world.. The authors recommend researchers to take care when adopting a transposition model that has been validated at low tilt angles to apply it to high tilt angles and building façades. The reduction in total annual global solar irradiation is not exceeded 1% due to the offset of tilt angle from the optimum angle for all considered transposition models and for all sites.

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