## SOLAR INSTALLATIONS
## AND THEIR APPLICATION

# Optimum Tilt Angles of Solar Panels: A Case Study for Gansu Province, Northwest China

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**Abstract**—The article deals with optimizing tilt angles of photovoltaic panels for fixed and manually adjusted solar photovoltaic system with due south-facing orientation to maximize the output of solar electricity in Gansu province, northwest China. There are three models by Liu and Jordan, Hay and Kliein and Theilacker selected to calculate the seasonal and yearly optimum tilt angles of solar panels through Matlab programs on seven sites in Gansu province. Meanwhile, the outdoor experiment was conducted to measure the yearly sum of global solar irradiance at different tilt angles. The study found that (1) the calculated yearly optimum tilt angles by three models are close among each other especially between Liu and Jordan's and Klein and Theilacker's models; (2) the annual optimum tilt angles of solar panels for fixed installation could be set at model's angle for higher latitude sites with most-rich solar energy, and latitude angle for lower latitude sites with medium-rich and less-rich solar resources; (3) the seasonal optimum tilt angles should be set at average models' angle for manual adjustment of photovoltaic system across a year; (4) for all sites, the model's angle could be selected for a photovoltaic system when considering limitation of land-use area.

## 1. INTRODUCTION

Currently, renewable energy is considered as an appropriate way to satisfy energy consumption without environmental degradation [1]. Utilization of solar photovoltaic is growing increasingly in recent years. Solar photovoltaic accounted for 2.4% of globle electricity production and the world capacity of photovoltaic have achieved at 505 GW by the end of 2018 [2]. This is mainly because recently the capital cost per unit of photovoltaic has been decreasing while the efficiency has been improved gradually [3].

In order to maximize the amount of electricity generated from photovoltaic system, the maximized solar radiation need to be captured by solar panels. Generally, when solar rays arrive at solar panels vertically, solar radiation intercepted is maximized. The photovoltaic tracking system with a mechanical device can follow the sun direction on its daily sweep across the sky [4]. Nevertheless, the tracking photovoltaic system is more expensive than fixed ones and the use of tracking system also increase the operation and maintainess cost. In addition, mechanical failure might occur in future expecially in desert/Gobi because of dust and sand. Therefore, fixed installation and manually adjusted installation are used in practice.

In Northern hemisphere, the optimum orientation is considered to be true south, which can be followed in most cases [5, 6]. Guo et al. [7] proved that the optimal orientation in China is due South. The optimum tilt angle of solar panels is related to geographic latitude, local climate conditions and the period of using. Thus, different locations have different optimum tilt angles [8].

There are a few studies on optimum tilt angles of solar panels across the world. Benghanem [9] and Herrera-Romero et al. [10] investigated the optimum tilt angles of solar panels and solar collectors facing toward equator in Madinah, Saudi Arabia, Coatzacoalcos, Veracruz respectively. They found the annual optimum tilt angle equals to local latitude. Kuvshinov et al. [11] compared both theoretical and tested maximum power produced by photovoltaic panels at different tilt angles in Sevastopol, Russia and they found the optimum tilt angle is around its latitude. Meanwhile, Abdallah et al. [12] calculated the optimum tilt angles and solar radiation on tilt surfaces in Palestine. They concluded the monthly adjustment of tilt angle will increase 17% more energy than that of horizontal surface and the annual optimum tilt angle is about 29° which is lower than its latitude. Nfaoui and El-Hami [13] calculated the monthly, seasonal and yearly optimum tilt angles of solar panels in Khouribga

city, Morocco and their results showed that the yearly optimized tilt angles are all slightly lower than their latitudes. Ramadan and Elistratov [14] illustrated the optimum tilt angle in Umm Al-Zaytun, Syria is lower than its latitude using PVsyst software. Nevertheless, Garni et al. [15] investigated the optimum orientation angles in Saudi Arabia for maximizing energy from solar panels. They found the most suitable 6 cities for installing solar PV system considering topography, climate and proximity to roads and for these cities the optimum tilt angles are only slightly higher than their latitudes while the optimal azimuth angle if from 20° to 53 West of South.

Therefore, a majority of latest studies demonstrated the yearly optimum tilt angle of solar panels is equal to or only slightly lower than local latitude. And most of the studies are conducted using mathematical models. There is only a small part of them combining theory and experimental data to estimate the optimum tilt angle for fixed PV panels. Moreover, there is few study focused on optimum tilt angles of solar panels in Gansu province, northwest China since the area is still on the developing stage with sparse population and low-lever economy. However, accumulative installed capacity of solar PV in Gansu province arrived at 9.08 GW by the end of 2019 [16] (most of them are large-scale fixed installation systems) due to its abundance in solar energy. Thus, it is meaningful to optimize the solar panels' tilt angle in Gansu province to maximize the PV output. In addition, in Gansu, photovoltaic systems are generally installed in vast desert/Gobi, which ensures solar panels can be due south-facing. Therefore, this article will study on optimum tilt angle of fixed − installation and oriented due south solar panels via comparing Liu and Jordan [17], Hay [18, 19] and Kliein and Theilacker [20] models with one-year on-site measured data of solar irradiance at different tilt angles assuming due south-facing orientation in Gansu province.

## 2. STUDY LOCATION

Gansu province with an area of 450000 km$^2$ is located in China's Northwest part from 92°13′ E to 108°46' E and from 32°31′ N to 42°57′ N. Gansu is the one of the underdeveloped provinces in China. It is weak in ecological environment. However, among all productive needs, fossil fuel still ranks the first. This will put great pressure on sustainable development of ecological environment [21]. Therefore, it is worth to develop renewable energy in Gansu province to reduce fossil fuel reliance.

On the other hand, Gansu is the one of the provinces whose renewable energy is most abundant in China, especially in solar energy. The yearly sum of global horizontal irradiance (GHI) in Gansu is about 4800−6400 MJ/m$^2$ with 1700−3300 h sun shine hours per year. In Hexi corridor shown in Fig. 1, the yearly

sum of GHI arrives at 5800−6400 MJ/m$^2$ with 2800−3300 h sun shine hours which is higher than other eastern part of China at the same latitude. In fact, yearly sum of GHI in central, northern Gansu, and desert, can reach 5850−6680 MJ/m$^2$, 6680−8400 MJ/m$^2$ and over 6000 MJ/m$^2$ respectively. Furthermore, the atmosphere transparency is high and sunshine time is long. Additionally, there is vast desert/Gobi in northern and central Gansu suitable for installing large-scale solar photovoltaic power system.

To begin with, major cities including Dunhuang, Juanquan, Minqing, Lanzhou, Yuzhong, Xifeng and Tianshui were selected for modeling in Gansu province. The city of Longnan is not selected since it is the southernmost city with a hot and humid weather which is not suitable for solar photovoltaic utilization and actually very few photovoltaic systems are installed there.

Secondly, in order to determine the yearly optimum tilt angles, the yearly sum of global tilt isolation (GTI) is measured and recorded at the sites of Dunhuang, Lanzhou and Tianshui that represent most-rich, medium-rich and less-rich solar resources in Gansu province.

## 3. MATERIALS AND METHODS

### 3.1. The Data of Solar Radiation on Horizontal Surface

Normally, the horizontal irradiance data for a specific location can be collected from local meteorological stations, sometimes from National Aeronautics and Space Administration (NASA) and Meteonorm that is based on more than 20 years experiences of meteorological data supplier for solar application, system design and any other application with provision of the meteorological data at any location in the world since local meteorological stations for solar irradiance are relatively sparse compared to other meteorological parameters. In this study, the data of monthly-average GHI, direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) are obtained from China's National Meteorological Information Center (1971−2000) for the sites of Dunhuang, Minqing, Lanzhou, Yuzhong and Jiuquan (In Gansu province, only these sites have completed solar radiation data for decades), and Meteonorm 6.1 (1981−2000) for the site of Xifeng and Tianshui.

### 3.2. The Models of Solar Radiation on Tilt Surfaces

There are several existing mathematic models to calculate solar irradiance on tilted surface via available horizontal solar irradiance data. GTI includes beam, ground-reflected and diffuse components in which the beam and ground-reflected irradiance on inclined surface can be calculated through simple models. However, the diffuse irradiance on tilt surface is more complicated since it has no define or (singular) angle

of incidence on a horizontal surface. There are a great many of diffuse irradiation models that generally can be classified as sky isotropic model and sky anisotropic model. Sky isotropic model assumes that there is a uniform distribution of diffuse sky radiation over the sky dome while sky anisotropic model assumes that there is non-uniform intensity of diffuse sky radiation over the sky. It presumes the anisotropy of the diffuse sky radiation in the circumsolar region (sky near the solar disk) plus the isotropically distributed diffuse component for the rest of the sky dome. Sky isotropic model by Liu and Jordan, sky anisotropy models by Hay and Kliein and Theilacker were selected in this study since these three models are the most classical theoretical model and they have been applied in different locations in the world. They are also universal models which could be used in Gansu province, northwest China. The following part will show the details of three models respectively.

## NOMENCLATURE

$N$ —number of days from 1st Jan. in a year,

$\Phi$ —latitude,

$\Delta$ —solar declination which can be defined by Eq. (4),

$B$ —surface tilt from horizontal,

$H$ —monthly-average daily total radiation on a horizontal surface,

$H_T$ —monthly-average daily total radiation on an inclined surface,

$H_d$ —monthly-average daily diffuse radiation on a horizontal surface,

$H_b$ —monthly-average daily direct radiation on a horizontal surface,

$H_o$ —monthly-average daily extraterrestrial radiation (Eq. (8)),

$I_{sc}$ —solar constant (normally, $I_{sc}$ = 1367 W/m$^2$),

$\rho$ —ground reflectance (normally, $\rho$ = 0.2),

$\omega_s$ —sunset hour angle on a horizontal surface (Eq. (1)),

$\omega'_s$ —sunset hour angle on an inclined surface (Eq. (3)),

$R_b$ —ratio of monthly-average beam radiation on a tilted surface to that on a horizontal surface ($H_{bT}/H_b$),

$R$ —ration of monthly-average total radiation on a tilt surface to that on a horizontal surface ($H_T/H$),

where 
$$\omega_s = \arccos(-\tan\varphi\tan\delta), \tag{1}$$

$$\omega'_s = \arccos(-\tan(\varphi - \beta)\tan\delta)\,(\text{In southern hemisphere, replace } (\varphi - \beta) \text{ with } (\varphi + \beta)), \tag{2}$$

$$\omega'_s = \min(\omega_s, \omega''_s), \tag{3}$$

$$\delta = 23.45\sin\left(360(284 + N)/365\right). \tag{4}$$

Here, the representative day of each month in a year proposed by Klein [22] is applied for three models. It is shown in Table 1.

### 3.2.1. The sky isotropic model by Liu and Jordan

$$R_b = \frac{\cos(\varphi - \beta)\cos\delta\sin\omega'_s + (\pi/180°)\omega'_s\sin(\varphi - \beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_s + (\pi/180°)\omega_s\sin\varphi\sin\delta}, \tag{5}$$

$$H_T = H\left(1 - \frac{H_d}{H}\right)R_b + H_d\left(\frac{1 + \cos\beta}{2}\right) + H\left(\frac{1 - \cos\beta}{2}\right)\rho. \tag{6}$$

### 3.2.2. Sky anisotropy model by Hay

$$R_b = \frac{\cos(\varphi - \beta)\cos\delta\sin\omega'_s + (\pi/180°)\omega'_s\sin(\varphi - \beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_s + (\pi/180°)\omega_s\sin\varphi\sin\delta}, \tag{7}$$

$$H_o = \frac{24}{\pi}I_{sc}\left[1 + 0.033\cos\left(\frac{360N}{365}\right)\right] \times \left(\cos\varphi\cos\delta\sin\omega_s + \frac{\pi}{180°}\omega_s\sin\varphi\sin\delta\right), \tag{8}$$

$$H_T = H_bR_b + H_d\left[\frac{H - H_d}{H_o}R_b + \frac{1}{2}(1 + \cos\beta)\left(1 - \frac{H - H_d}{H_o}\right)\right] + \frac{\rho}{2}H(1 - \cos\beta). \tag{9}$$
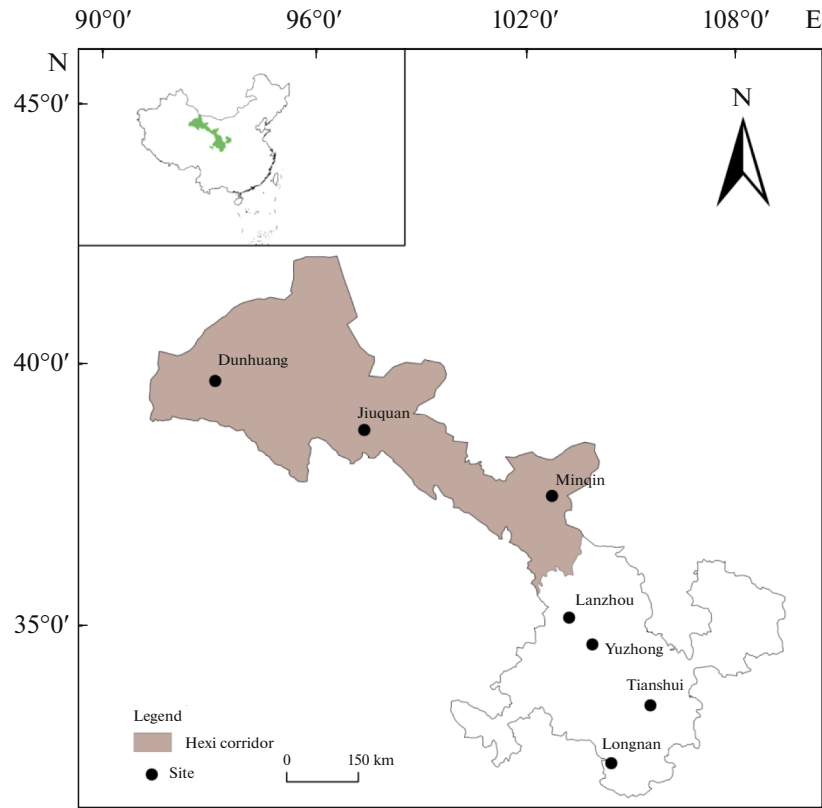
**Fig. 1.** The map of Gansu province and the selected sites.

### 3.2.3. The improved sky anisotropy model by Kliein and Theilacker

$$R = \frac{\cos(\varphi + \beta)}{d \cos\varphi} \left\{ \left( a - \frac{H_d}{H} \right) \left( \sin \omega_s' - \frac{\pi}{180} \omega_s' \cos\omega_s'' \right) \right.$$
$$\left. + \frac{b}{2} \left[ \omega_s' \frac{\pi}{180} + \sin\omega_s' \left( \cos\omega_s' - 2\cos\omega_s'' \right) \right] \right\} \quad (10)$$
$$+ \frac{H_d}{H} \left( \frac{1 + \cos\beta}{2} \right) + \rho \left( \frac{1 - \cos\beta}{2} \right),$$

$$a = 0.409 + 0.5016 \sin(\omega_s - 60), \quad (11)$$

$$b = 0.6609 - 0.4767 \sin(\omega_s - 60), \quad (12)$$

$$d = \sin\omega_s - \frac{\pi}{180} \omega_s \cos\omega_s, \quad (13)$$

$$H_T = HR. \quad (14)$$

### 3.3. Modeling the Optimum Tilt Angles under Three Models by Matlab Program

The Matlab program is applied to model the optimum tilt angles under these three models. Herein, the Matlab program using Liu and Jordan's model to calculate the optimum tilt angle and the yearly sum of solar radiation is as following for example:

% input monthly average daily global solar radiation $h(i)$, diffuse radiation $d(i)$, and direct solar radiation $b(i)$

%$c(i)$—the $i$th month's solar declination angle

%c = 23.45*sin[360/365*(284+n)]($n$—the number of days from 1st Jan in a year)

$a$ = input('input the latitude (°):')

$j = 0$;

for $t = 0 : 0.5 : 90$

$j = j + 1$,

**Table 1.** The representative day of each month in a year

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Date | 17 | 16 | 16 | 15 | 15 | 11 | 17 | 16 | 15 | 15 | 14 | 10 |
| N | 17 | 47 | 75 | 105 | 135 | 162 | 198 | 228 | 258 | 288 | 318 | 344 |

**Table 2.** Different tilt angles set on three sites for a whole year measurement

| Site | Model's angle −5, deg | Model's angle, deg | Latitude, deg | Latitude +5, deg |
|---|---|---|---|---|
| Dunhuang | 29 | 34 | 40 | 45 |
| Lanzhou | 19 | 24 | 36 | 41 |
| Tianshui | 20 | 25 | 34.6 | 40.6 |

for $i = 1 : 1 : 12$

$h = [6.9\ 8.94\ 10.77\ 14.49\ 16.66\ 17.37\ 17.34\ 16.64\ 11.56\ 9.18\ 7.22\ 6.27]$;

$d = [4.35\ 5.63\ 6.94\ 8.71\ 9.11\ 8.82\ 8.29\ 7.82\ 6.16\ 5.2\ 4.39\ 3.96]$;

$b = [2.55\ 3.31\ 3.83\ 5.78\ 7.55\ 8.55\ 9.05\ 8.82\ 5.4\ 3.98\ 2.83\ 2.31]$;

$n = [17\ 47\ 75\ 105\ 135\ 162\ 198\ 228\ 258\ 288\ 318\ 344]$;

$c(i) = 23.45 \sin d(360(284 + n(i))/365)$;

$s = a\cos d(-\tan d(a)\tan d(c(i)))$;

$sss = a\cos d(-\tan d(a-t)\tan d(c(i)))$;

$ss = \min(s, sss)$;

$r = (\cos d(a - t)\cos d(c(i))\sin d(ss) + pi/180\ ss$ $\sin d(a - t)\sin d(c(i)))/(\cos d(a)\cos d(c(i))\sin d(s) + pi/180\ s\sin d(a)\sin d(c(i)))$;

$A = 24 \times 1.367 \times 3.6/pi(1 + 0.033\cos d(360n(i))/365)(\cos d(a)\cos d(c(i))\sin d(s) + pi/180\ s\sin d(a)\sin d(c(i)))$;

$ht(i) = b(i)r + d(i)(b(i)/Ar + (1 + \cos d(t))/2(1 - b(i)/A)) + 0.1h(i)(1 - \cos d(t))$;

end

$hty(j) = ht(1)31 + ht(2)28 + ht(3)31 + ht(4)30 + ht(5)31 + ht(6)30 + ht(7)31 + ht(8)31 + ht(9)30 + ht(10)31 + ht(11)30 + ht(12)31$;

end

$[hy\ I] = \max(hty)$;

$tt = (I - 1)0.5$

$hy = \max(hty)$.

### 3.4. Measuring Solar Radiation on Different Tilt Surfaces

It is traditionally considered that when solar panels tilt at latitude angle, solar irradiance could be maximized and maximum electricity generated from photovoltaic could be gained. This conventional wisdom has been accepted and applied in engineering projects because of its simplicity and convenience. However, whether the tilt angle set to local latitude could maximize solar radiation on tilt surface or not should be analyzed through comparing measured solar radiation at different tilt angles. In order to identify the yearly optimum tilt angle for a geographical site, the solar irradiance on different tilt angles at the sites of Dunhuang, Lanzhou and Tianshui is measured for a whole year by pyranometer and acquisition and recording instrument made in Liaoning Jinzhou technology Co.

Ltd., China. The experimental tilt angles were set to be Models' angle-5 (deg), Model's angle (deg), Latitude (deg), Latitude + 5 (deg) for each site. As the yearly optimum tilt angles calculated by the three models through Matlab simulation are close among each other (see Table 3), thus, the one angle was selected as model's angle. Table 2 shows the different tilt angles set on three sites for a whole year measurement. The periods of the three sets of recorded data for Dunhuang, Lanzhou and Tianshui are 04/2016−03/2017, 05/2016−04/2017 and 05/2016−04/2017, respectively.

## 4. RESULTS

### 4.1. The Seasonal and Yearly Optimum Tilt Angles at Seven Sites through Matlab Programs

The seasonal and yearly optimum tilt angles and the yearly sum of GTI at seven sites are shown in Table 2. $\beta_{opt}$ (deg) is optimum tilt angle calculated by models and YR is the yearly sum of GTI at yearly optimum tilt angles (MJ/m$^2$).

For seasonal optimum tilt angles at seven sites, Table 3 shows, in summer, the optimum angle is lowest ($\leq 10°$) while winter's optimum angle is highest. In autumn, the optimum angle is lower than that of winter but higher than spring's which is higher than summer optimum tilt angle. For seasonal optimum tilt angles, there is no obvious rules to find, and the biggest differences of seasonal optimum tilt angles among three models is 5.5°. Thus, the average value of three models' can be as the optimum tilt angle for each season.

Refer to the yearly optimum tilt angles, the calculated yearly optimum tilt angle by three models are close among each other especially between Liu and Jordan's and Klein and Theilacker's models. The angle by Hay is only slightly higher than that of other models. The highest amount of yearly sum of GTI is estimated by Hay's model, which is accordance with the findings by Shukla et al. [23].

### 4.2. The Measured Data of Yearly Sum of GTI

The measured data of yearly sum of GTI on three sites are shown in Table 4.

Table 4 illustrates thatfor the relatively higher latitude site with most-rich solar resources (Dunhuang), the yearly optimum tilt angle should beset at model's angle (34 deg) with gaining maximized solar irradiance (6623.009 MJ/m$^2$) which is 63.875 MJ/m$^2$ more

**Table 3.** The seasonal and yearly optimum tilt angles for solar panels using three models

| Sites | Latitude | Models | Spring | Summer | Autumn | Winter | Yearly | |
|---|---|---|---|---|---|---|---|---|
| | | | $\beta_{opt}$ | $\beta_{opt}$ | $\beta_{opt}$ | $\beta_{opt}$ | $\beta_{opt}$ | YR, MJ/m$^2$ |
| Dunhuang | 40.15 | Liu and Jordan | 20 | 6.5 | 48.5 | 60.0 | 34.00 | 7224.8 |
| | | Klein and Theilacker | 21.5 | 10 | 47.5 | 58.5 | 33.50 | 7186.1 |
| | | Hay | 23.5 | 7.5 | 52.0 | 63.5 | 38.00 | 7620.6 |
| Jiuquan | 39.77 | Liu and Jordan | 22.5 | 6 | 50.0 | 62.5 | 36.00 | 7103.6 |
| | | Klein and Theilacker | 23.5 | 9.5 | 49.0 | 61.0 | 36.0 | 7065.1 |
| | | Hay | 25 | 6.5 | 52.5 | 64.5 | 39.0 | 7393.6 |
| Minqin | 38.63 | Liu and Jordan | 19 | 5 | 47.5 | 60.0 | 34.0 | 6772.6 |
| | | Klein and Theilacker | 20 | 8.5 | 46.5 | 58.5 | 33.5 | 6728.0 |
| | | Hay | 22 | 5.5 | 50.5 | 63.0 | 37.5 | 6901.4 |
| Lanzhou | 36.05 | Liu and Jordan | 15.5 | 3 | 39.5 | 49.5 | 23.5 | 5525.2 |
| | | Klein and Theilacker | 16 | 6.5 | 38.0 | 46.5 | 23.5 | 5498.5 |
| | | Hay | 17.5 | 3 | 43.0 | 54.0 | 27.0 | 5656.8 |
| Yuzhong | 35.87 | Liu and Jordan | 17.5 | 2.5 | 43.5 | 55.0 | 29.5 | 5983.0 |
| | | Klein and Theilacker | 18.5 | 6 | 42.5 | 53.0 | 29.0 | 5943.5 |
| | | Hay | 20 | 2.5 | 47.0 | 58.5 | 33.0 | 6173.2 |
| Xifeng | 35.73 | Liu and Jordan | 19.5 | 2 | 45.5 | 60.0 | 34.5 | 6200.9 |
| | | Klein and Theilacker | 20.5 | 5.5 | 44.5 | 58.5 | 34.0 | 6153.7 |
| | | Hay | 21.5 | 2 | 48.5 | 61.5 | 37.0 | 6408.8 |
| Tianshui | 34.58 | Liu and Jordan | 14 | 1.5 | 39.5 | 52.5 | 24.5 | 5338.0 |
| | | Klein and Theilacker | 16 | 5 | 38.5 | 50.5 | 24.5 | 5311.2 |
| | | Hay | 16 | 1.5 | 43.0 | 56.0 | 27.5 | 5452.4 |

**Table 4.** The measured data of yearly sum of GTI on different tilt angles (MJ/m$^2$)

| Site | Model's angle − 5° | Model's angle | latitude | Latitude + 5° |
|---|---|---|---|---|
| Dunhuang | 6380.072 | 6623.009 | 6559.134 | 6308.693 |
| Lanzhou | 5672.941 | 5762.884 | 6056.385 | 5927.35 |
| Tianshui | 4360.394 | 4494.823 | 4516.935 | 4446.952 |

than that of latitude angle. And it is shown that at the sites of Lanzhou and Tianshui (belong to medium-rich and less-rich solar resources areas), both yearly optimum tilt angles should tilt at local latitude with the maximum solar irradiance of 6056 and 4517 MJ/m$^2$, respectively. The differences of solar radiation between maximum and sub-maximum values become 129 and 22 MJ/m$^2$ for Lanzhou and Tianshui respectively. Consequently, for the true south-facing photovoltaic installations, relatively lower latitude sites (Lanzhou, Tianshui) in Gansu province, the yearly optimum tilt angle should be set to local latitude, which is in accordance with some previous findings [9−11]. Therefore, we may conclude that the locations to the north of Lanzhou with relatively higher latitude and richer solar resources, the model's angle could be selected and likewise the locations to the south of Lanzhou with relatively lower latitude and less-rich solar resource, the latitude angle could be chosen in Gansu province.

On the other hand, for all three sites, the differences of the yearly sum of GTI intercepted by solar panels that tilt at model's angle and latitude angle is very small(only 63.875, 129 and 22 MJ/m$^2$ for Dunhuang, Lanzhou and Tianshui respectively). According to Zhao et al. study [24], around latitude angle, the lower tilt angle of solar panels, the less land area occupied by photovoltaic system. Therefore, if there is a
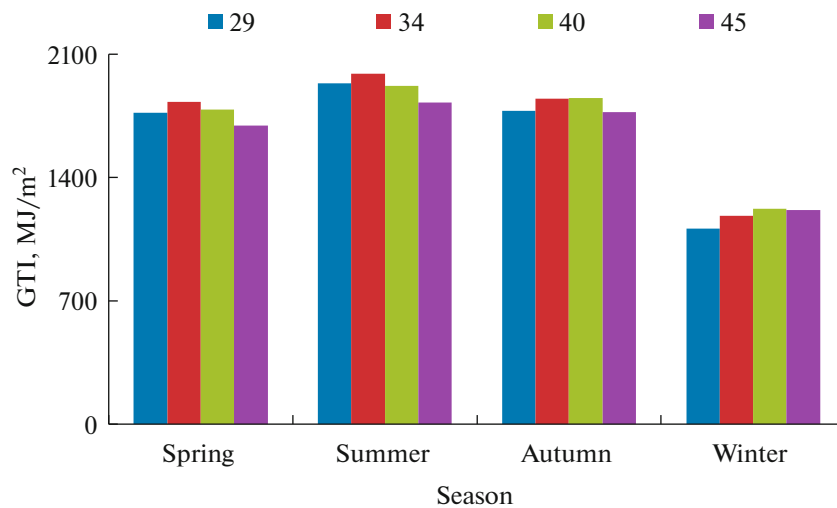
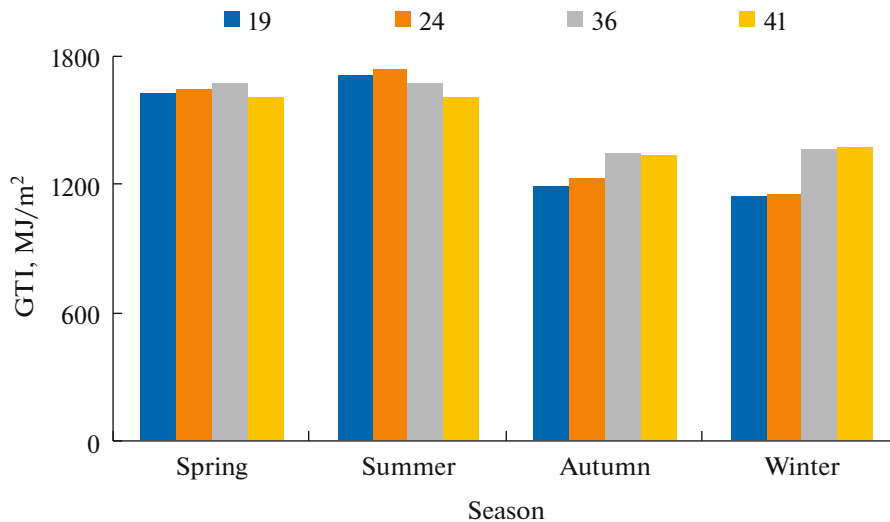**Fig. 2.** The seasonal sum of GTI at different tilt angles in Dunhuang.



**Fig. 3.** The seasonal sum of GTI at different tilt angles in Lanzhou.

limitation of land-use area, the model's angle could be selected for solar panels because model's angle that is lower than latitude will decrease land-use area. Additionally, the lower tilt angle of solar panels, the cost of bracket for solar photovoltaic system will be less.

Figures 2–4 show the measured data of seasonal sum of GTI on different tilt surfaces in Dunhuang, Lanzhou and Tianshui for a fixed installation with a yearly optimum tilt angle. It is demonstrated that, in summer, model's angle could maximize sum of GTI for these three sites and in winter model's angle+5° could be the optimum angle for Lanzhou and Tianshui while latitude angle will be selected for Dunhuang. On the other hand, at the yearly optimum angles (equal to model's angle for Dunhuang and latitude

angle for Lanzhou and Tianshui), it cannot obtain the maximum seasonal sum of GTI although the yearly sum of GTI is maximized.

Additionally, the average calculated yearly sum of GTI at optimum tilt angles (CYR) under three models and the measured maximum yearly sum of GTI (MYR) are compared. Table 5 shows the differences between each other are 720.791 MJ/m$^2$ (under-estimated), 496.185 MJ/m$^2$ (over-estimated) and 850.265 MJ/m$^2$ (under-estimated) in Dunhuang, Lanzhou and Tianshui respectively in which the difference is smallest in Lanzhou. This demonstrates that using mathematic models to estimate the yearly sum of solar radiation under optimum tilt angles may be more suitable for the site with medium solar resources.
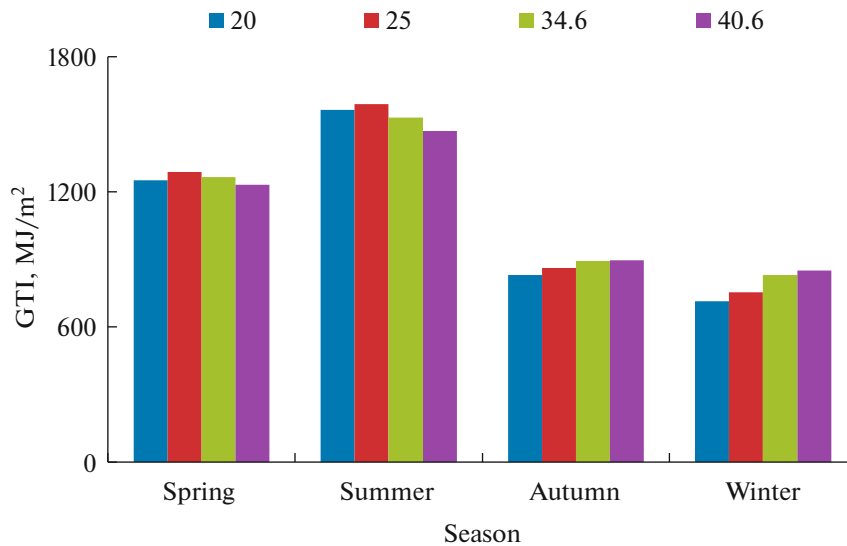
**Fig. 4.** The seasonal sum of GTI at different tilt angles in Tianshui.

## 5. DISCUSSION

For seasonal optimum tilt angles, we concluded: winter > autumn > spring > summer, which is consistent with the study by Nfaoui and El-Hami [13]. This might be because of the movement of the solar elevation angle across a year.

For annual optimum tilt angles in Gansu province, our results showed the optimum tilt angles in this area are equal or 6 degrees lower than its latitude. While in the research by Tang and Wu [25] which calculated optimum tilt angle of solar collector in China using mathematical models showed the optimum tilt angle should be set to latitude-3° in Gansu province, which is different from our study. This might be because we take both mathematical models and one-year on-site measurements into consideration.

According to Jacobson and Jadhav's research [26], they estimated the optimum tilt angles of solar panels across the world. They found the optimum tilt angle of Beijing (north China) is about 37° with latitude of 39.93° which is close to Dunhuang's latitude (40.15°) while Dunhuang's optimum tilt angle is 34°. The study also gives the optimum tilt angle for Lhasa (31°) (Qinghai Tibet Plateau) is slightly higher than its latitude (29.67). Hence, when it comes to the optimum tilt angle for different areas, specific conditions (different meteorological conditions resulted from geographical locations) should be considered and analyzed.

## 6. CONCLUSIONS

In summary, first of all, the calculated yearly optimum tilt angles by three models are close among each other especially between Liu and Jordan's and Klein and Theilacker's models. Furthermore, the annual optimization of tilt angles for solar panels with south-facing orientation for fixed installation could be set at model's angle and latitude angle for relatively higher latitude sites with most-rich solar energy (the sites to the North of Lanzhou) and relatively lower latitude sites with medium-rich and less-rich solar resource (the sites to the South of Lanzhou) respectively in Gansu province. Moreover, the seasonal optimum tilt angles should be set at average models' angle from the three models for manual adjustment of photovoltaic panels across a year. In addition, the model's angle could be selected for a photovoltaic system if there is a limitation of land-use area since low tilt angle may decrease land-use area and bracket cost of solar photovoltaic system.

Finally, three sites selected for experimental measurements seem to be a little sparse for Gansu province even in Hexi corridor. The future work will increase the number of outdoor experimental sites to refine the study. Furthermore, the one-year measurement may be short for this study. Therefore, long-time monitory on more sites in Gansu province will be recommended for future work.

**Table 5.** The differences between AYR and MYR (MJ/m$^2$)

| Site | AYR | MYR | Differences |
|------|-----|-----|-------------|
| Dunhuang | 6623.009 | 7343.8 | 720.791 |
| Lanzhou | 6056.385 | 5560.2 | 496.185 |
| Tianshui | 4516.935 | 5367.2 | 850.265 |

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