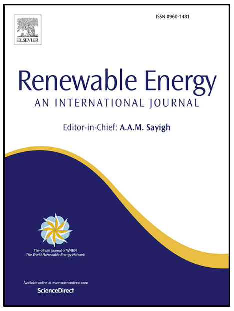
Accepted Manuscript



Optimal orientation angles for maximizing energy yield for solar PV in Saudi Arabia

Hassan Z. Al Garni, Anjali Awasthi, David Wright

PII: S0960-1481(18)31232-1
DOI: 10.1016/j.renene.2018.10.048
Reference: RENE 10698

To appear in: *Renewable Energy*

Received Date: 6 June 2018
Revised Date: 29 September 2018
Accepted Date: 9 October 2018

Please cite this article as: Al Garni HZ, Awasthi A, Wright D, Optimal orientation angles for maximizing energy yield for solar PV in Saudi Arabia, *Renewable Energy* (2018), doi: https://doi.org/10.1016/j.renene.2018.10.048.

Optimal orientation angles for maximizing energy yield for solar PV in Saudi Arabia

Hassan Z. Al Garni [a,b*], Anjali Awasthi [b], David Wright [c]

[a] *Department of Electrical and Electronic Engineering Technology, Jubail Industrial College, Jubail Industrial City, Saudi Arabia*

[b] *CIISE, Concordia University, 1455 De Maisonneuve Blvd. W., Montreal H3G 1M8, Quebec, Canada*

[c] *Telfer School of Management and Sunlab, University of Ottawa, Ottawa, ON, Canada, K1N 6N5*

Abstract:

This paper uses research-quality, ground measurements of irradiance and temperature that are accurate to ±2% to estimate the electric energy yield of fixed solar modules for utility-scale solar power plants at 18 sites in Saudi Arabia. The calculation is performed for a range of tilt and azimuth angles and the orientation that gives the optimum annual energy yield is determined. A detailed analysis is presented for Riyadh including the impact of non-optimal tilt and azimuth angles on annual energy yield. It is also found that energy yield in March and October are higher than in April and September, due to milder operating temperatures of the modules. A similar optimization of tilt and azimuth is performed each month separately. Adjusting the orientation each month increases energy yield by 4.01% compared to the annual optimum, but requires considerable labour cost. Further analysis shows that an increase in energy yield of 3.63% can be obtained by adjusting the orientation at five selected times during the year, thus significantly reducing the labour requirement. The optimal orientation and corresponding energy yield for all 18 sites is combined with a site suitability analysis taking into account climate, topography and proximity to roads, transmission lines and protected areas. Six sites are selected as having high suitability and high energy yield: Albaha, Arar, Hail, Riyadh, Tabuk and Taif. For these cities the optimal tilt is only slightly higher than the latitude, however the optimum azimuth is from 20° to 53° west of south due to an asymmetrical daily irradiance profile.

Keywords:

Solar irradiation; Solar PV; Optimal orientation; Tilt; Azimuth; Energy yield

---

*Corresponding Author: Tel: +1-514-581-0019

Email Address: h_algarn@encs.concordia.ca, garnihz@gmail.com (H. Al Garni), awasthi@ciise.concordia.ca (A. Awasthi), dwright@uottawa.ca (D. Wright)

1. Introduction

Solar photovoltaics (PV) has succeeded internationally, particularly for utility-scale projects in high irradiance locations (Yang et al., 2018) and a wealth of knowledge has been accumulated during these implementations, which is valuable to developers of new projects. Many operational parameters such as degradation rate, maintenance costs and PV efficiency have been recorded, of which Figure 1 provides an example. However, many factors impacting the economic viability of a project are site specific, for instance the "suitability" of the site including climate, topography and proximity to roads, transmission lines and protected areas. An early example of a suitability analysis is Carrion et al. (2008), which uses a multi-criteria approach to select PV sites taking these factors into account. Other factors can be selected by the developer, for instance whether to use a tracking device or fixed mounting for the solar modules, Single or dual axis tracking can increase energy yield at the expense of the tracking device. Fixed modules can have their azimuth and/or tilt angles manually adjusted at selected times during the year to increase energy yield at the cost of the associated labour. The present paper focuses on determining the optimal orientation of fixed modules and quantifies the extent to which energy yield can be improved by adjusting the orientation at selected times in the year. The analysis is performed for 18 sites in Saudi Arabia and the results are combined with a multicriteria site suitability analysis to select the best six sites for implementation of solar PV power plants.

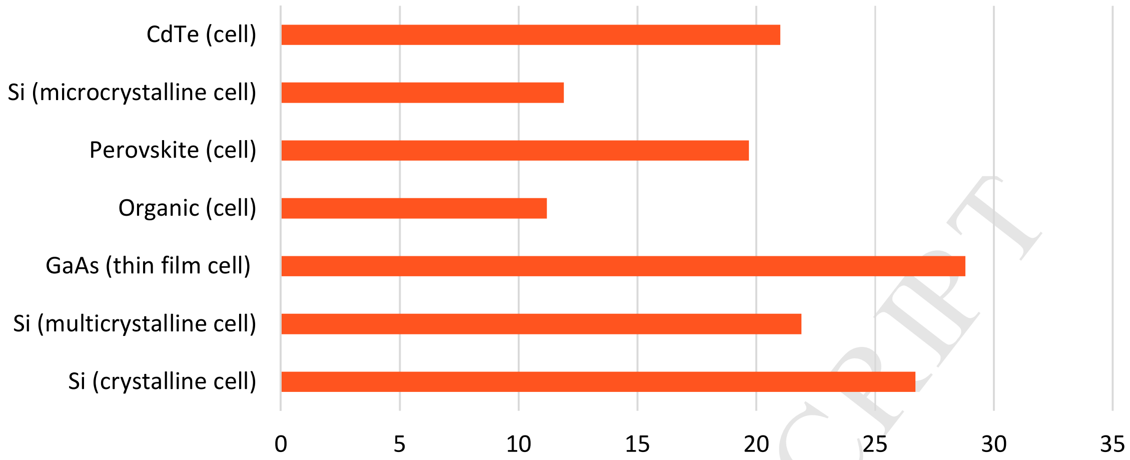


Figure 1. Efficiency comparison of PV technologies (Green et al., 2017)

When a tracking system is not preferred due to its capital and maintenance costs, several approaches have been proposed for optimizing the tilt angle of solar PV modules for different sites at various latitudes (Abdeen et al., 2017; Cheng et al., 2009; Dey et al., 2018; Elminir et al., 2006; Gharakhani Siraki and Pillay, 2012; Jacobson and Jadhav, 2018; Kaddoura et al., 2016; Lv et al., 2018; N.Nijegorodov et al., 1994; Rowlands et al., 2011). Sixteen different analytical formulae have been developed for calculating the optimum PV tilt angle for each month (N.Nijegorodov et al., 1994). Cheng et al., (2009) conducted a study for south orientated tilted PV panels at 20 different locations in 14 countries, ranging from 0° to 85° latitude, and concluded that more than 98% of the system performance can be achieved by using the latitude angle as the panel's yearly optimal tilt angle. Elminir et al., (2006) concluded that, for Helwan, Egypt, the optimum tilt is approximately latitude ± 15 degrees, where plus and minus signs are for winter and summer seasons, respectively. Monthly, seasonal, semi-annual and annual optimum tilt angles were determined for two cities in Iran (Moghadam et al., 2011), showing that two adjustments per year led to about 8% annual increase in the total received energy. Benghanem (2011) found that the average optimum tilt angle at Madinah, Saudi Arabia is 37° for the winter months and 12° for the summer months, whereas the annual optimum tilt angle is almost equal to the latitude of the site. Rowlands et al., (2011), MacDougall et al., (2018) and Tomosk et al., (2017) recommend that tilt angle be marginally less than latitude for different locations in Canada and in United States, given a particular pricing regime, while the desired azimuth is close to due south for each location. Kaddoura et al. (2016) investigated the optimum tilt angles for various cities in Saudi Arabia. For Jeddah city with the latitude of 21.5° N, the optimal tilt angle was found to be 19.28°. The authors concluded that adjusting tilt angles six times per year yields 99.5% of the energy yield compared to daily adjustment, thus achieving high yield at reasonable labour cost.

By optimizing solar panel tilt angles in a solar tree for San Francisco and Paris, Dey et al., (2018) demonstrated an energy yield increase of 2.04% and 7.38% respectively compared to latitude tilt. Lv et al., (2018) concluded that due to a low increase in total solar energy compared to the case without adjustment, it is not recommended to adjust the tilt angle monthly during the heating season in Lhasa, China.

Danandeh and Mousavi (2018) reviewed two main approaches of identifying optimum tilt angle, a search-based approach and a direct approach. They concluded that the accuracy of models varies with latitude and calculated the optimum tilt angle for the major cities of Iran. Babatunde et al., (2018) compared PV systems performance under different tilt and azimuth angles in Cyprus, concluding that the tilt angle for the PV panel should be equal to the local latitude. Guo et al. (2017) determined the optimum tilt angle and azimuth angle of PV panels using a meta-heuristic algorithm called harmony search (HS) in several cities in China. They concluded that HS is a reliable tool for estimating the optimum orientation, recommending that the tilt should be adjusted monthly whereas the best azimuth is generally due south in the designated cities. Hafez et al. (2017) reviewed the current methods to find the optimum tilt and concluded that PV systems showed a great improvement in performance when using optimum yearly tilt. In South Africa, Le Roux (2016) found that the optimal tilt of a fixed PV system is similar to the latitude and can collect 10% more annual solar insolation than a horizontally-oriented system. For determining the optimum tilt angle over mid-latitude zone, Soulayman and Hammoud (2016) proposed two approximate equations for predicting daily optimum tilt angle and recommended that adjusting the tilt angle twice a year is the best from a practical point of view. Almarshoud (2016) reviewed the characteristics of solar resources and solar PV performance in 32 sites across Saudi Arabia, including fixed tilt angle, 1-axis, and 2-axis tracking designs. In this study, the fixed tilt angle was equal to site latitude while the azimuth angle was due south. Despotovic and Nedic (2015) found the optimum tilt angles of roof-top solar PV in Belgrade, Serbia with yearly, biannual, seasonal, monthly, and daily adjustments and recommended changing the tilt angles at least twice a year. Khoo et al. (2014) used three Perez sky models to estimate the amount of solar irradiance received by a tilted PV module in Singapore and found that a panel tilted 10° and facing east gives the maximum annual irradiation. El-Sebaii et al. (2010) studied Jeddah, Saudi Arabia and concluded that the best performance of a PV system was achieved when oriented to face south with tilt equal to $(\text{latitude} + 15^{\circ})$ and $(\text{latitude} - 15^{\circ})$ during the winter and summer seasons, respectively.

A good tilt angle is essential to the performance of solar PV, and a rule-of-thumb that the tilt angle should be equal to the latitude of the location, with the azimuth angle towards the south, for a maximum annual energy has been considered in many studies (Al Garni et al., 2018; Duffie et al., 2003; Elminir et al., 2006). The rule-of-thumb approach may be appropriate for specific locations, however, it may result in increased costs due to oversizing of systems if considered without detailed analysis. The consequences are particularly notable for utility-scale solar power plants (Yadav and Chandel, 2013) due to their high capital costs. The present paper demonstrates that an optimized, data-driven determination of panel tilt and azimuth angles is crucial to maximizing the energy yield at a particular site, and that simply accepting panel tilt to be equal to location latitude is not the best approach for the locations studied.

2. Study objectives

The objective of this research is to calculate the optimal orientations for utility-scale solar PV systems to maximize energy yield in 18 cities in Saudi Arabia. We then combine the results with the suitability analysis provided by Al Garni and Awasthi, (2017) which included a broad range of economic and technical criteria for the whole country. In this research, the objectives are to:

- develop a model to analyze tilt angles between 0° and 90° and azimuth angles between -90° and 90° in one-degree steps to calculate the total energy yield produced monthly and annually thus identifying the orientation that leads to maximum energy yield.
- investigate the optimal tilt and azimuth angles for utility-scale projects in 18 cities in Saudi Arabia using high accuracy hourly ground-based irradiance measurements.
- include the air temperature effect on the PV performance, thus improving the accuracy of the energy yield.
- take into account the fact that some solar irradiation is lost when the angle of incidence (AOI) is greater than zero and to deal with such loss by using the incidence angle modifier (IAM).
- combine the results of this research with previous studies (Al Garni et al., 2016; Al Garni and Awasthi, 2017) on potential site suitability for utility-scale PV technology in Saudi Arabia.

For each combination of tilt and azimuth angles, a detailed energy yield model is developed to convert the hourly measured solar irradiation components, including global horizontal irradiation (GHI), diffuse horizontal irradiation (DHI) and direct normal irradiation (DNI) as well as ambient temperature (T_a) into hourly, monthly and yearly electric energy yield. These values are then used to find the optimal tilt and azimuth angles, which generate the maximum annual energy yield.

The optimal orientation of solar modules in Saudi Arabia was previously investigated by Kaddoura et al. (2016), using satellite-based data with uncertainties ranging from $\pm$6% to $\pm$12%. The data applied in the present paper is highly accurate solar irradiation data from ground stations with lower uncertainty (in the range of $\pm\mathbf{2}$%). Moreover, only tilt angle adjustment was considered by El-Sebaii et al. (2010) and Kaddoura et al. (2016), whereas the optimization approach in this study considers both the adjustment of tilt angle and the azimuth angle from the east ($+\mathbf{90}^{\circ}$) to the west ($-\mathbf{90}^{\circ}$). The approach in the present paper also uses a detailed model which accounts for air temperature and reflections from module cover material.

3. Methodology

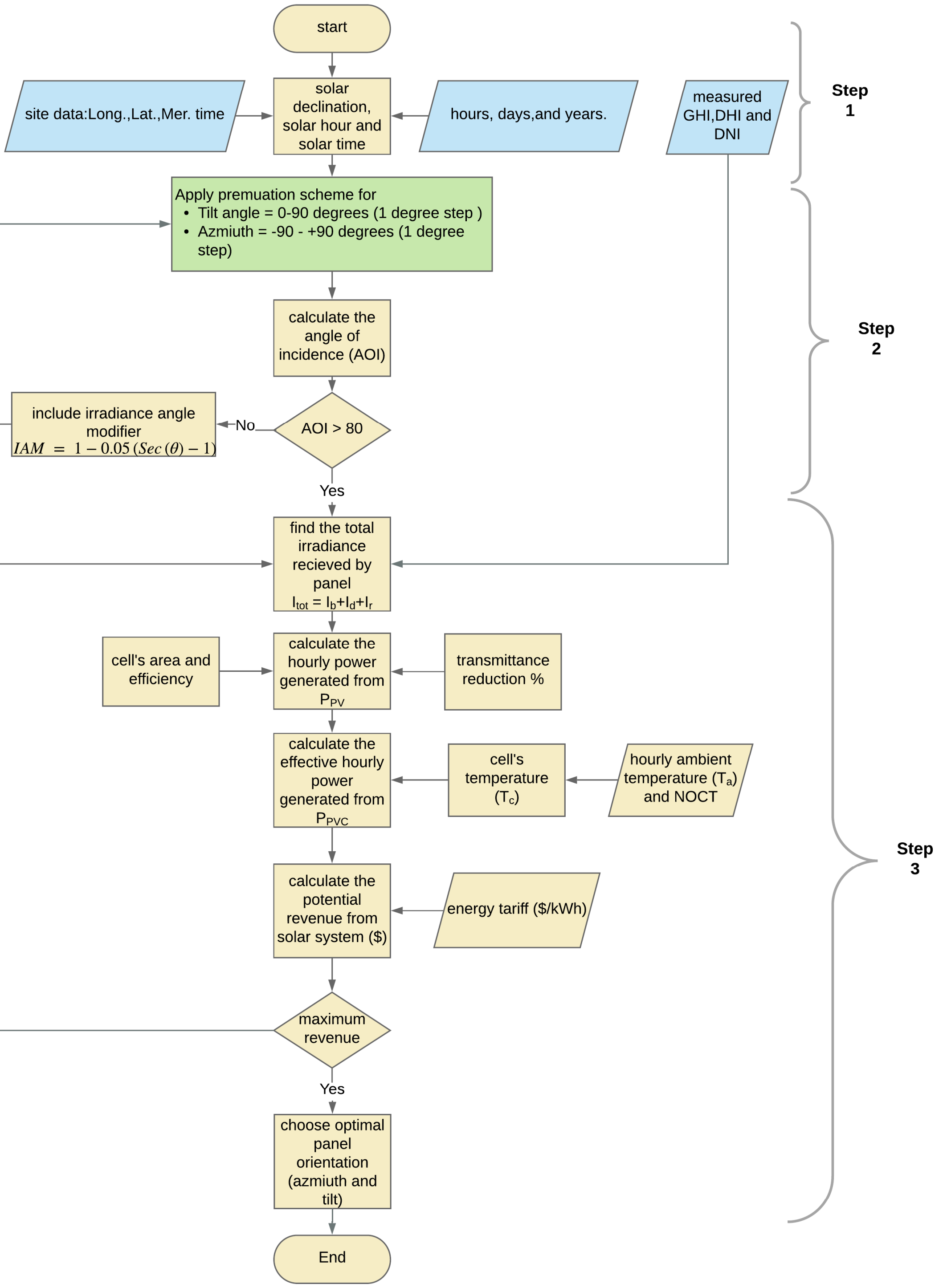
Figure 2 presents the proposed methodology, consisting of three steps:

1. collection of solar irradiance and weather data for the study region;
2. calculation of the solar irradiation incident on the PV module;
3. calculation of solar PV electric energy yield.

The methodology applied in this research examines every optimization loop to find the decision variables, including the tilt and azimuth angles that lead a tilted solar PV panel (also known as a

160 PV collector or a PV module) to capture the maximum solar irradiation with monthly, seasonal

161 and fixed orientation adjustments. These steps are explained in detail as follows:



162

Figure 2. Flowchart of the developed optimization methodology for maximum annual solar irradiation.

3.1 Input data

Symbols and abbreviations used in this paper are listed in Table 1.

Table 1. Symbols and abbreviations

Acronym	**definition**	**Acronym**	**Definition**
GHI	global horizontal irradiation (W/m^2)	φ_s	solar azimuth angle (°)
DHI	diffuse horizontal irradiation (W/m^2)	β	solar altitude angle (°)
DNI	direct normal irradiation (W/m^2)	L	latitude of the site (°)
STC	standard test condition	φ_c	collector azimuth angle (°)
$\boldsymbol{y}$	year	τ	tilt angle (°)
T_a	ambient temperature (°C)	θ_{AOI}	AOI angle (°)
AOI	angle of incidence (°)	I_{DNI}	total direct normal irradiation (W/m^2)
IAM	incidence angle modifier	I_{DHI}	total diffuse horizontal irradiation (W/m^2)
K.A.CARE	King Abdullah City for Atomic and Renewable Energy	I_b	total direct normal irradiation on collector (W/m^2)
$\boldsymbol{\rho}$	ground reflectance	I_d	total diffuse irradiation on collector (W/m^2)
$\boldsymbol{P_{dc}}$	DC power (W/m^2)	I_r	total reflected irradiation (W/m^2)
$\boldsymbol{T_C}$	cell temperature (°C)	$NOCT$	nominal operating cell temperature (°C)
$\boldsymbol{dp}$	PV temperature coefficient of power (%/°C)	n	day number

Hourly weather data including GHI, DNI, DHI and T_a for 18 cities in Saudi Arabia were obtained from the King Abdullah City for Atomic and Renewable Energy (K.A.CARE), which is the lead organization working to develop a renewable energy mix portfolio. From 2011, K.A.CARE started to build the renewable resource monitoring and mapping (RRMM) solar measurement network, which is deployed over Saudi Arabia with 50 metrological stations classified in three tiers (K.A.CARE, 2016). For this study, data from tier-1 RRMM weather stations is used, which is considered to be a research type station, providing the highest quality data, and is available for a complete year from January 2015 to December 2015. This class of station is maintained and cleaned on a daily basis and provides 1-minute interval data. The accuracy of these data is the main reason behind selecting such ground-measurement data rather than longer-term satellite estimates. Detailed analysis is presented for Riyadh city (latitude = 24.91° and longitude = 46.40°) in central Saudi Arabia and summaries are presented for the other 17 cities. Figure 3 shows the average monthly GHI and air temperature for Riyadh city.

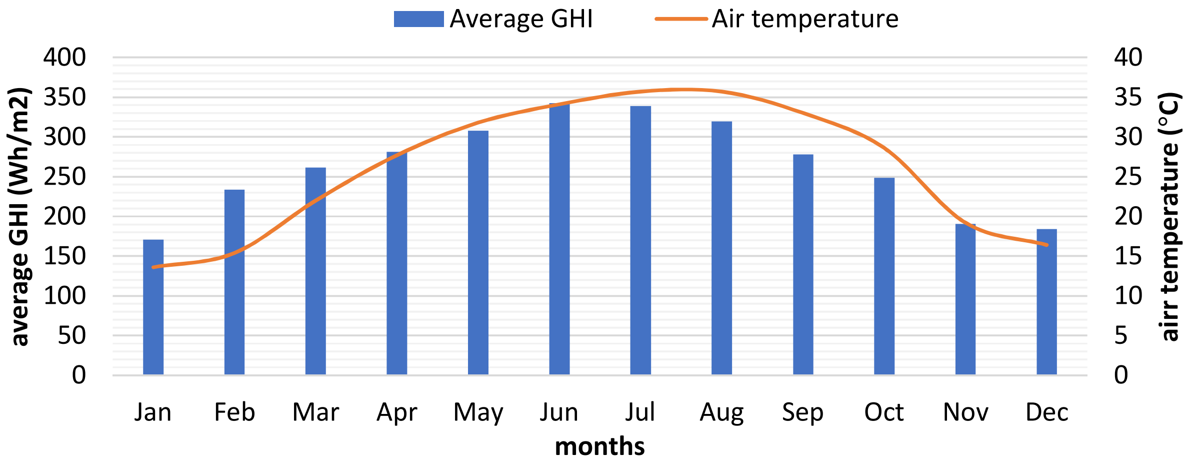


Figure 3. Monthly average of global horizontal irradiance (GHI) and air temperature for Riyadh city, Saudi Arabia.

3.2 Solar angles equations

The solar declination, defined as the angle between the equator and the center of the sun, varies between +23.45° and -23.45° (Lunde, 1980). At any time of day, the sun's location can be defined in terms of its altitude angle β and its azimuth angle φ_s as shown in Figure 4 (Masters, 2004).

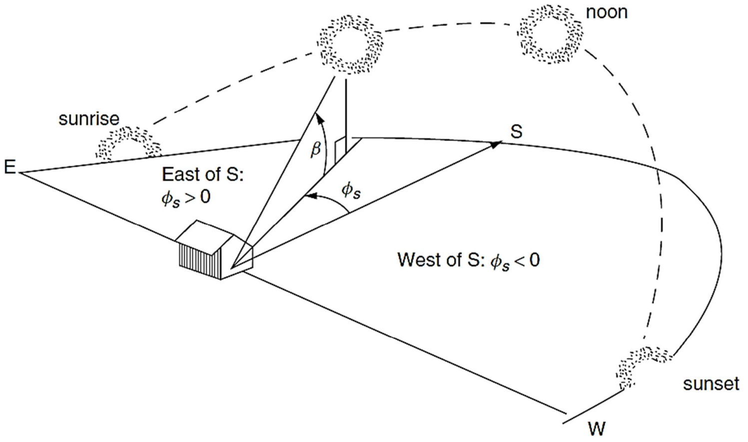


Figure 4. Sun's position for the different times of day with solar altitude, β, and azimuth, φ_S, angles (Masters, 2004)

The time of day, the day number, n, and the site latitude determine the solar azimuth, φ_S, and solar altitude angle, β (Anderson, 1983). The solar azimuth angle is considered positive before noon, when the sun is in the east, and negative in the afternoon when the sun in the west.

In the northern hemisphere, the solar path is high in altitude during summer and low (i.e. near the horizon) during winter, resulting in varying geometry of the sun's position at a particular place (Sengupta et al., 2015). The solar altitude angle β and solar azimuth φ_s can be calculated and graphed at any given latitude and Figure 5 illustrates the sun's path in altitude and azimuth angles for Riyadh (latitude 24.91°) for the 21st day of each month from 5:00 a.m. to 7:00 p.m. local time. At the center of the horizontal axis is the azimuth of zero at solar noon. In summer months, φ_S takes values beyond the $\pm 90°$ with low β. This understanding is essential for analyzing and modelling solar irradiation components as shown in next section.

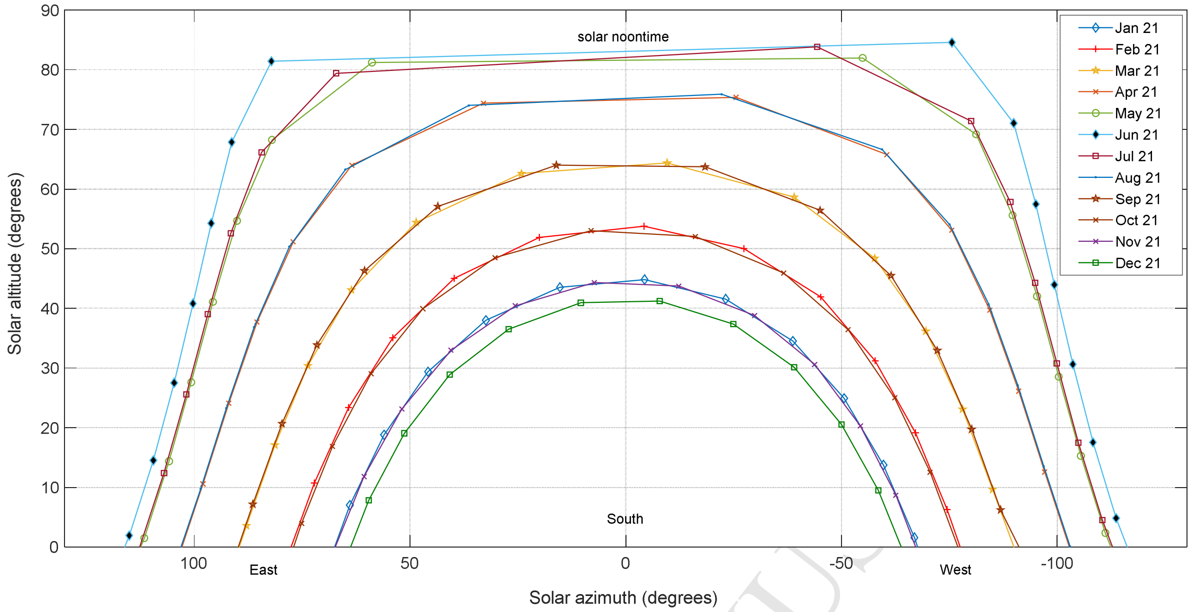


Figure 5. Sun path diagram giving solar altitude and azimuth angles in standard time for Riyadh, latitude, 24.91° N

3.3 Computing the impact of solar irradiation on solar PV

The irradiation received by the solar module is a combination of its components: direct beam irradiation, I_b, diffuse irradiation, I_d, and reflected irradiation, I_r, as shown in Figure 6. The following energy yield equations are based on Masters (2004). The translation of I_{DNI} into direct irradiance incident on the collector, I_b, is a function of AOI and an initial approximation is given by:

$$I_b = I_{DNI}\, Cos(\theta_{AOI}) \qquad \text{Eq. 1}$$

where θ_{AOI} is the angle of incidence between the direct beam and the normal to the panel, and can be calculated as follows:

$$\cos\theta_{AOI} = \cos\beta\cos(\varphi_S - \varphi_C)\ sin\,\tau\ + \sin\beta\cos\tau \qquad \text{Eq. 2}$$

where τ is the panel tilt angle and φ_C is the collector azimuth angle. PV modules have a protective coating on the front which can cause reflection of the direct irradiance depending on the angle of incidence, θ_{AOI}. Equation (1) is therefore modified to take into account this effect using the incidence angle modifier (IAM) from The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (Sandia lab., 2018):

$$IAM \;=\; 1 - b_0(Sec(\theta_{AOI}) - 1) \tag{Eq. 3}$$

ASHRAE recommends a b_0 value of 0.05 and using this equation only for $\theta_{AOI} < 80°$ (Solar First, 2016). The modified I_b component after considering IAM is as follows:

$$I_b = I_{DNI}\ Cos(\theta_{AOI})[1 - 0.05(Sec(\theta_{AOI}) - 1)] \tag{Eq. 4}$$

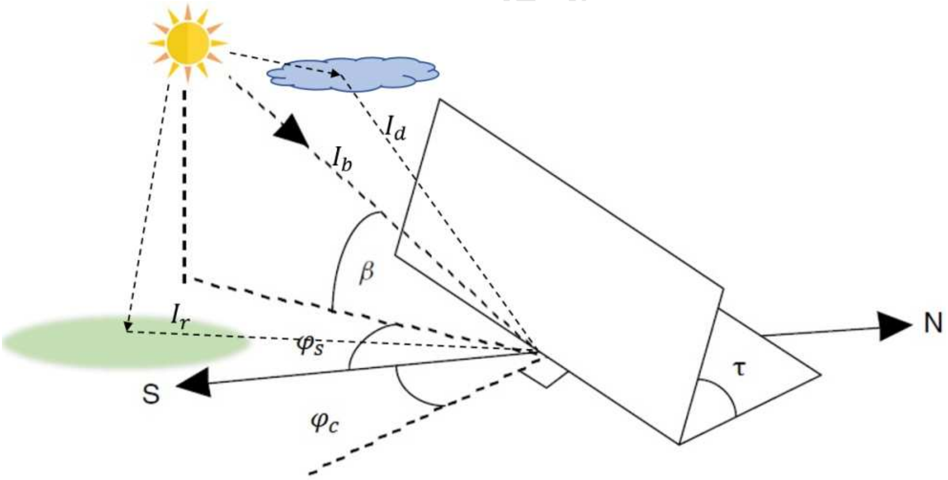


Figure 6. Irradiation components, I_b, direct, I_r, reflected, and I_d, diffuse, received from solar altitude, β, and azimuth, φ_s, by the module with azimuth, φ_c, (modified from Masters, 2004)

The estimation of diffuse solar irradiation, I_d, due to clouds, atmospheric particles or dust is given by:

$$I_d = I_{DHI}\left(\frac{1 + Cos(\tau)}{2}\right) \qquad \text{Eq. 5}$$

The irradiation reflected from soil, water or concrete in front of the panel, I_r, is given by:

$$I_r = \rho\,(I_{DNI}Sin(\beta) + I_{DHI})(1 - Cos(\tau))/2 \qquad \text{Eq. 6}$$

Where ρ is the ground reflectance, which could range from 0.1 for an urban environment to 0.8 for fresh snow. In this study, ρ is estimated as 0.2 (Gueymard, 2009). The total irradiance received by a PV panel is:

$$I_t = I_b + I_d + I_r \qquad \text{Eq. 7}$$

Like other semiconductor devices, a solar cell is sensitive to temperature and its performance decreases with increasing temperature according to a temperature coefficient. The cell temperature is dependent on the ambient temperature and the total irradiation on the cell using a relationship (9) based on the nominal operating cell temperature (NOCT). NOCT is often provided by the module manufacturer and gives the cell temperature when ambient temperature is 20°C, wind speed is 1 m/s, and solar irradiation is 800 W/m^2. In this study, the NOCT is assumed to be 45°C, and the temperature coefficient (dp) is -0.4%/°C (Sahin et al., 2017). Using a cell efficiency of 16% and an area of 1m^2, the DC electric power yield from irradiance I_t is:

$$P_{dc} = 0.16\, I_t(1 + dp(T_C - 25)) \qquad \text{Eq. 8}$$

$$where \quad T_C = T_a + [(NOCT - 20)/800] * I_t \qquad \text{Eq. 9}$$

4. Results

4.1 Annual optimal orientation and energy yield

The approach described in Figure 2 was coded in MATLAB to find the optimal orientation for Riyadh and 17 other cities in Saudi Arabia. The optimization code was run 16,472 times to investigate the hourly solar irradiation and electric energy yield (kWh/m^2) throughout the whole year for every combination of tilt and azimuth angles. The tilt angle ranges from 0° to 90° and the azimuth from -90° to 90° in 1° increments. Figure 7 presents a sample of such a simulation using collector azimuth, φ_c, ranging from -20° to +20° for each tilt angle between 0° and 90°. The energy yield swings between 181 to 330 kWh/m^2 per year. The energy yield increases as the tilt angle varies from 0° to approximately 30° and then starts to decrease. As the azimuth angles changes from -20° towards 0°, the peak energy yield remains almost constant, whereas it starts to decrease as the azimuth increases beyond zero.

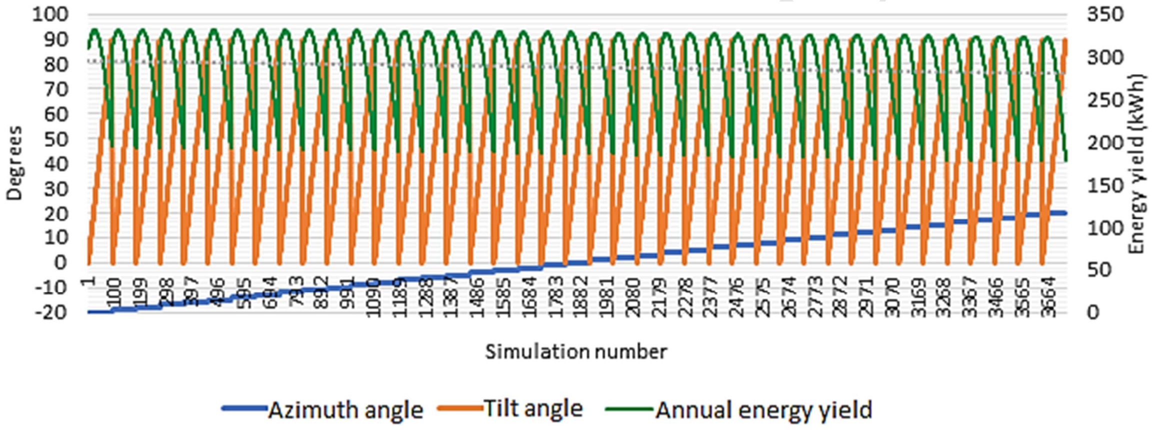


Figure 7. Sample of simulated annual energy yield (right axis) for different azimuth and tilt angles (left axis) for Riyadh

For a tilted collector, the annual energy yield has been calculated for different azimuth angles ranging from 90° (east) to -90° (west) in 1° increments, using the MATLAB code. Figure 8 shows the annual energy yield for different azimuth angles φ_c = -60°, -40°, -20°, 0°, 20°, 40° and 60°. The azimuth angles of -20°, -40° and 0° demonstrate similar potential with their maximum between the tilt of 20° and 30°. The energy yield decreases as the azimuth reaches or exceeds 20° east or 60° west of south-facing. For a panel close to vertical, the -60° or -40° azimuth is optimal, as vertical orientation misses the major solar irradiation during noontime, but it can capture more irradiation before sunset by directing the panel towards the west, especially during long summer days.

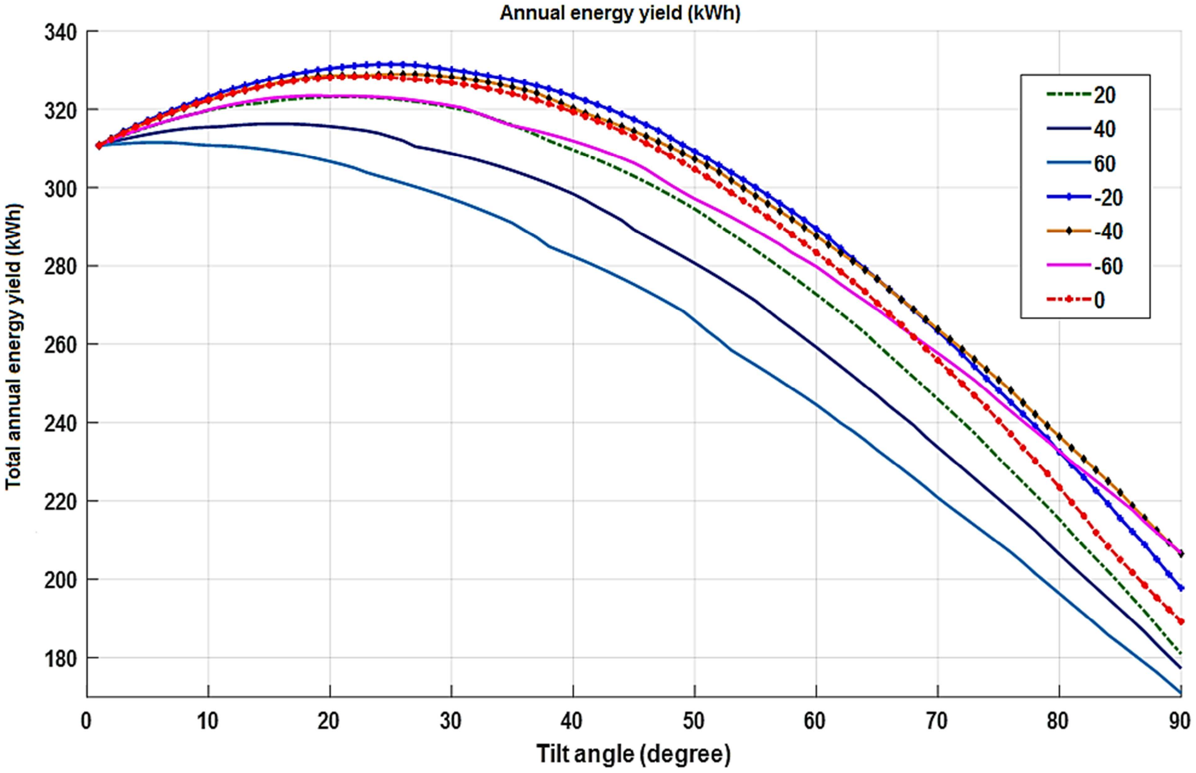


Figure 8. Annual energy yield versus tilt for different azimuths (°) in Riyadh

4.2 Monthly orientation adjustments

Figure 9 shows the energy yield plotted versus tilt angle for each month for a panel with a fixed azimuth angle (-20°). As observed from the graphs, the energy yield depends on the tilt angle. In winter months (January, February, November and December), it starts low (15-25 kWh/m^2) at the tilt angle of 0°, increases gradually as the tilt increases to approximately 50°, and then it starts to decrease. In summer months (May, June, July, and August), the energy yield reaches the highest values with low tilt angle near the horizontal, and it declines steeply beyond the tilt angle of 30° due to the high solar altitude during summer. It should be noted that tilt angles higher than 60° are not optimal for any month, and therefore this range need not be considered.

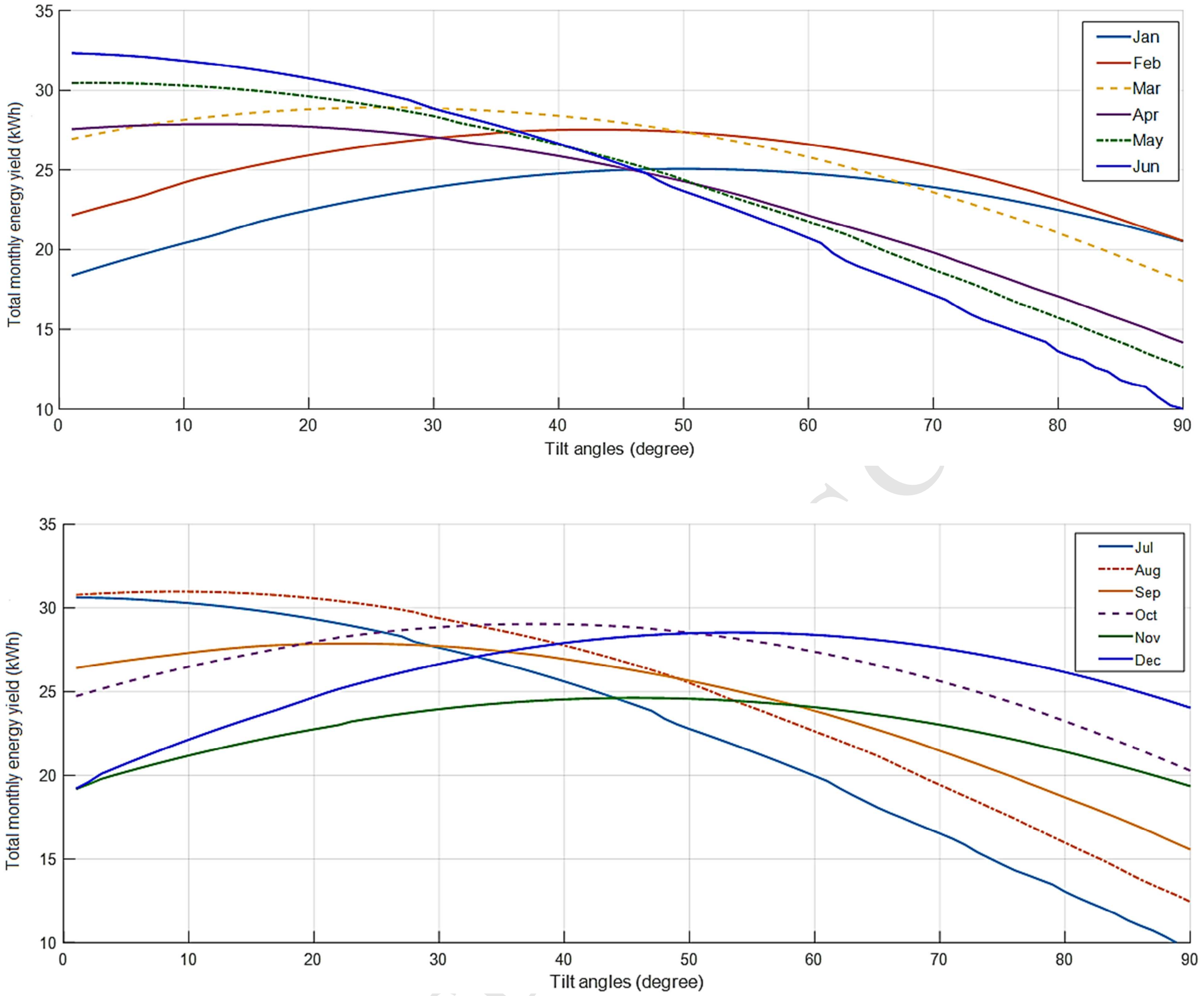


Figure 9. Total monthly energy yield, I_t, versus tilt angle for azimuth of -20° for Riyadh

Based on the maximum energy yield in each month, the optimum tilt angle was found for the azimuth angle of -20° as shown in Figure 10. Winter months including November, December, January and February show the highest tilt angles with a peak of 53° in December. The average of tilt angles in summer months, i.e., May, June, July, and August, is 9°. For the equinox months (March and September) when the sun is right over the equator, the tilt angles are 25° and 22°, respectively. Finally, the annual optimum tilt angle was 24° which is very close to the latitude of Riyadh (24.91° N).

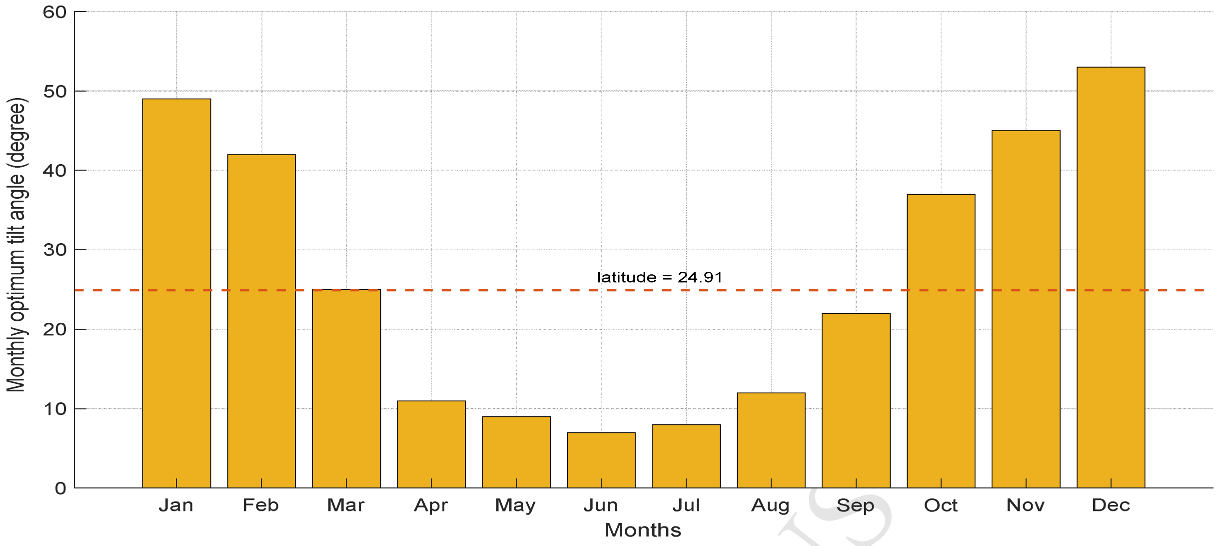


Figure 10. Monthly optimum tilt angles with azimuth of -20° for Riyadh

Figure 11 shows the total of monthly solar irradiance, I_t, at the annual optimum tilt angle (24.0° N). A maximum of 230 kWh/m^2 occurs in July with the azimuth of $-40°$. During summer months (June, July and August) the solar energy is at the maximum due to the high solar altitude and long days with an average of 225 kW/m^2/month. In these summer months, the sunrise is around 6:00 am and the sunset around 7:00 pm. The azimuth between $-20°$ and $-40°$ (towards the west) is suitable in these months, to capture more irradiation. In the equinox months, *i.e.*, March and September the azimuth angles between south-facing and $-20°$ are optimal, with around 200 kWh/m^2. Since the afternoon time shows higher solar availability compared to before noontime due to clearer sky in the afternoon, the optimal azimuth tends to be more to the west. In general, the azimuth of 0° (south-facing) and $-20°$ have similar performance except in summer months, when $-20°$ has a higher output. The monthly electric energy yield has the pattern similar to that of solar energy, as shown in Figure 12. However, due to the air temperature effect, the energy yield decreases sharply in April and September, while in the summer months the availability of solar irradiation compensates for the air temperature effects (see Figure 3).

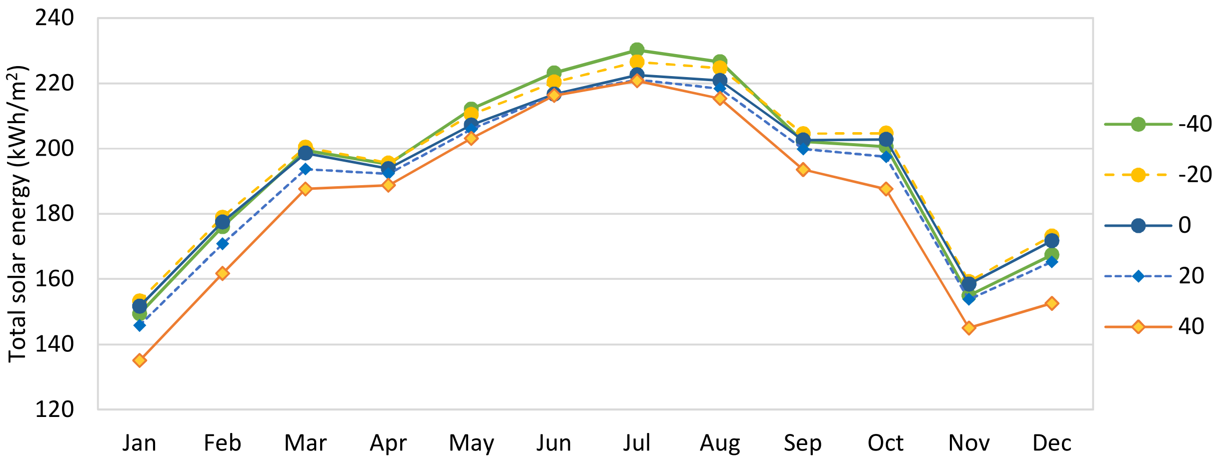


Figure 11. Total monthly solar irradiance (kWh/m^2) for different azimuths

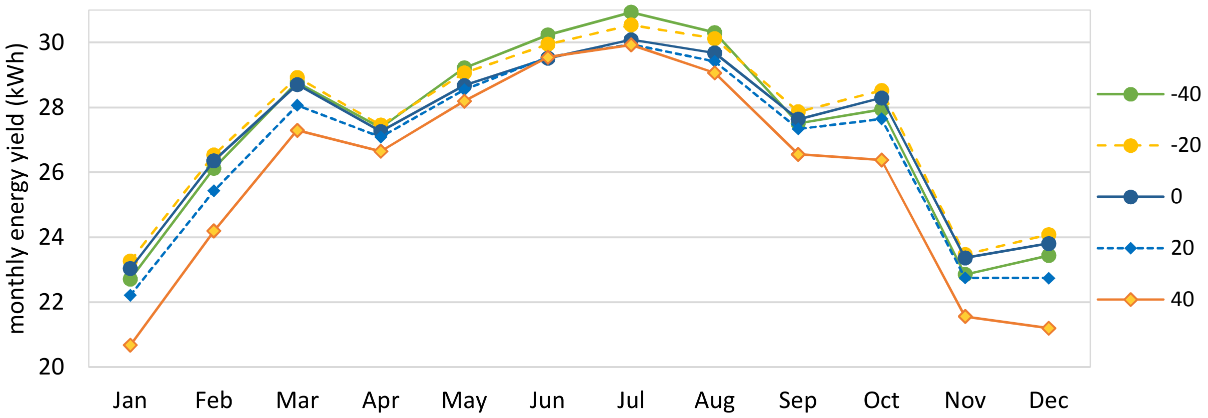


Figure 12. Total monthly electric energy yield (kWh/m^2) for different azimuths

4.3 Proposed orientation adjustment scheme

The fixed tilt angle of 24°, which is the same as the Riyadh's latitude, with -20° azimuth produces the maximum annual energy yield of 331.5 kWh/m^2. The azimuth of -20° indicates that the panel will generate more on the west, a result of high solar irradiation available in the afternoon due to clearer skies. Figure 13 presents the daily GHI on the 15th day of each month to highlight the times with high solar irradiation.

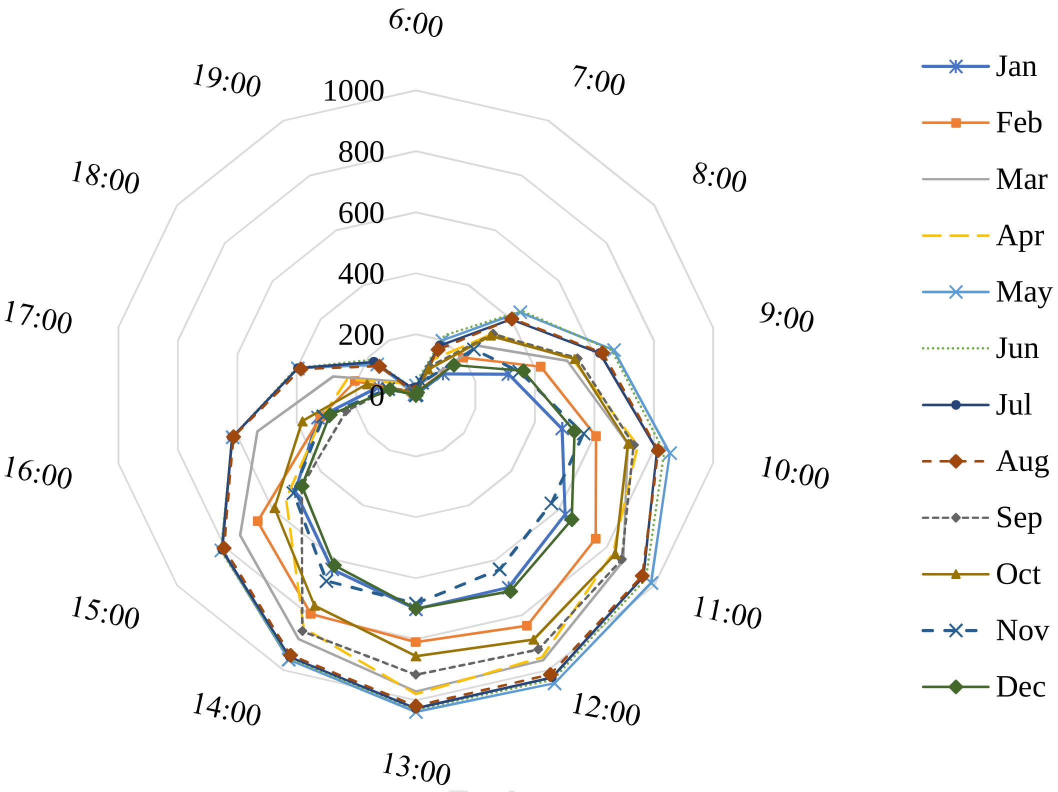


Figure 13. Daily GHI (W/m^2) on the 15th day of each month from 6:00am to 19:00pm

This is in accordance with the general “rule of thumb” that the tilt equal to latitude is optimal, and deviations in the azimuth angle of 10° to 20° from south have only a minor effect. The optimum monthly tilt and azimuth angles found in this study, with their energy yield are shown in Table 2, from which it can be seen that monthly adjustment increases the energy yield by 4.01% (13.3 kWh/m^2). The monthly adjustment might not be justified considering the cost of manpower for such a minor improvement in the system performance. From Figure 10 and Table 2, it can be noted that the summer tilt angles for May, June, July and August are very close to each other, with an average of 9.4°. Moreover, the energy yield differences between these months are less than 5 kWh. Therefore, there could be one tilt angle for the whole summer season. Similarly, for the winter months of November, December, January, and February there could be one tilt angle of 47.25°.

Table 2. The monthly optimum orientation (tilt, τ, and azimuth, φ_c) and the corresponding energy yield

Month	**Optimal (Base, Monthly)**		**Energy yield (kWh/m^2)**
	τ (°)	φ_c (°)	
Jan	49	-14	25.126
Feb	42	-15	27.5565
Mar	25	-18	28.9332
Apr	11	-24	27.8821
May	9	-90	30.5617
Jun	7	-90	32.4334
Jul	8	-90	30.8385
Aug	12	-64	31.074
Sep	22	-16	27.8855
Oct	37	-15	29.0833
Nov	45	-12	24.7242
Dec	53	-10	28.6875
Total annual			344.786
Fixed adjustment	24	-20	331.4937

For the summer season (May to August), the optimum tilt angles were found to be very close to horizontal, while the optimum collector azimuth is in the west direction, at $-90°$. Kaddoura et al., (2016) find a negative tilt, which means that the module is oriented towards the north. In mid and lower latitude of northern hemisphere locations, the sun rises from north-east and sets at north-west during the summer (Anderson, 1983). The optimal tilt angles of May to August are very low with an the azimuth of -90° (west-facing), which is due to the clearer sky in the afternoon and the sun path in summer months as shown in Figure 5.

Orienting at a high azimuth can result in a self-shading issue, which may reduce the system performance significantly. For a more practical azimuth range, modified azimuth angles are proposed. A 4th order polynomial (R^2 = 0.964) is fitted to the azimuths of January-April and September-December and used to estimate the azimuth for May-August as depicted in Figure 14. The results show that the new azimuths for summer season (May to August) have 98.5% efficiency compared to the obtained optimal azimuth as shown in Table 3.

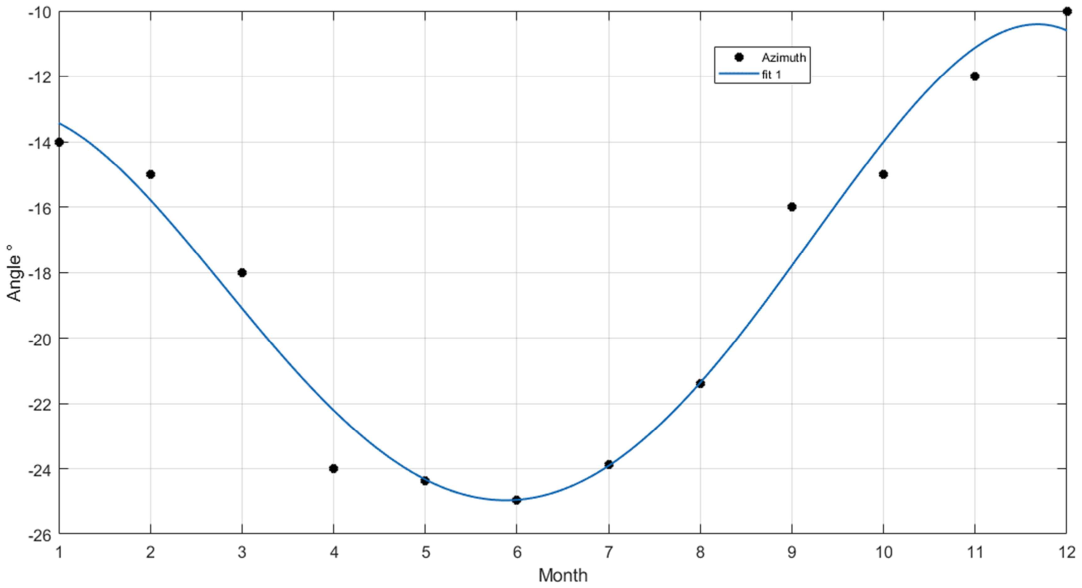


Figure 14. Proposed monthly azimuth angle for Riyadh

Table 3. Proposed solar PV orientation (tilt, τ, and azimuth, φ_c) for summer months

Month	**Optimal (Fitted model)**		**Energy yield (kWh/m^2)**	**Efficiency compared to optimal orientation (%)**
	τ (°)	φ_c (°)		
May	9	-24.5	30.3195	-0.792
Jun	7	-25	32.0213	-1.270
Jul	8	-24	30.3723	-1.51
Aug	12	-21.5	30.9340	-0.450
Total			123.6471	-1.01

The monthly adjustment of solar PV orientation might be quite challenging as it is labor intensive. Therefore, the proposed adjustment schedule for both tilt and azimuth angles is presented in Table 4. Adjusting the tilt angles according to the proposed scheme results in harvesting 3.63% more solar energy than with the fixed annual optimum orientation based on a comparison of the total vales in Tables 2 and 4. This scheme generates almost the same as the case of optimal monthly adjustments (with only 0.366% less) as shown in Table 4. The variation of tilt has a significant impact on the energy yield. By considering a monthly tilt equal to the latitude (24°) and adjusting the azimuth as shown in Table 4, the annual energy yield decreases by 4.1% (14 kWh). On the other hand, the impact of the azimuth angle has a minor effect on the energy yield. Using the optimum tilt with zero azimuth (south-facing), the system would generate less by only 0.77% in energy yield (3 kWh).

Table 4. Proposed scheme for periodic adjustments (tilt, τ, and azimuth, φ_c) and the corresponding energy yield

Period		**Optimal (Base, Fitted, Periodic)**		**Energy yield (kWh/m^2)**
		τ (°)	φ_c (°)	
1	Nov	47.25	-12.75	28.565
	Dec			24.712
	Jan			25.109
	Feb			27.468
2	Mar	25	-18	28.933
3	Apr	9.4	-23.8	27.8707
	May			30.3195
	Jun			31.8736
	Jul			30.3149
	Aug			30.9947
4	Sep	22	-16	27.886
5	Oct.	37	-15	29.083
Total annual				343.525

Figure 15 illustrates the impact of varying the panel orientation with respect to the energy yield. It can be noticed that both monthly tilt and azimuth angles are concave upward throughout the year. Compared to latitude tilt and due south orientation, the tilt has its peak of more than double (in December) whereas the azimuth has a minimum -20° (in June). In summer months, tilt angles start to decrease, while the azimuth tends to move to the west with a maximum of -5°. This will cause the panel to capture high solar irradiation and thus generate more energy (exceeding 30 kWh) as displayed in the sharp move in energy trend line in Figure 15. From November to February the tilt angle is at high (latitude +15°) whereas the azimuth angle is in the range of -10° to -15°. This drives the energy yield to be between 24-28 kWh per month.

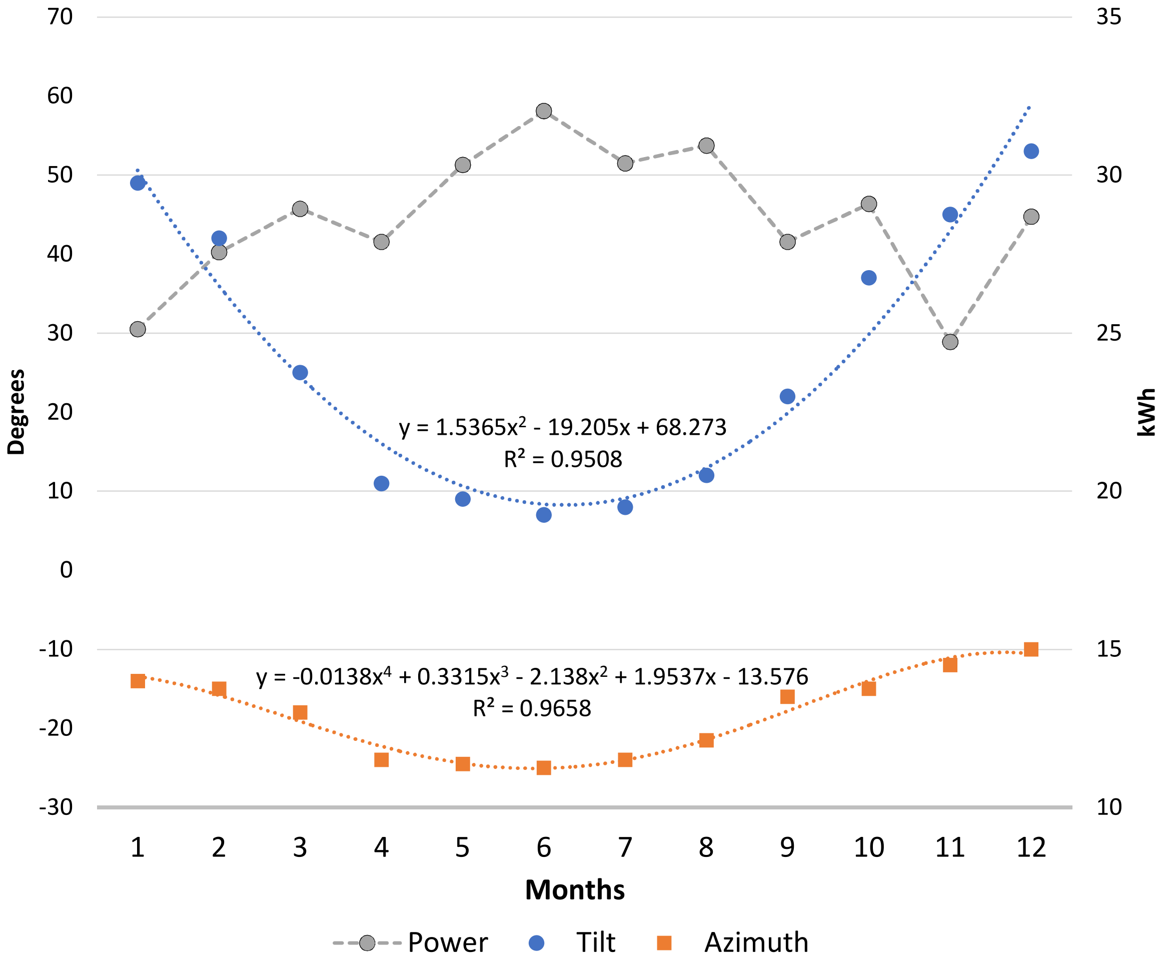


Figure 15. The orientation variation (*y* = angle; *x* = month) (left axis) and monthly energy yield (right axis)

4.4 Results validation and optimal annual orientation for 18 cities in Saudi Arabia

The same optimization procedure was applied for 18 cities in Saudi Arabia using the measurements of RRMM sensors from K.A.CARE from one year, with the results presented in Table 5. Since the data collection project is at its early stages, some stations had missing data. The 2015 data is utilized while, for the missing data, the values for the same hours of the previous or the following year are used. The annual optimum tilt angles for most of the cities are very close to their respective latitudes. The highest optimum tilt angles (40° and 39°) were found for Tabuk and Alwajh cities, which is consistent with their northern locations.

Table 5. Annual optimum orientation for 18 cities in Saudi Arabia with energy yield, revenues and suitability index

No.	**Location**	**latitude**	**Longitude**	**Annual optimal**		**Annual energy yield (kWh/m^2)**	**Suitability** (Al Garni and Awasthi, 2017)
				$\tau°$	$\varphi_c°$		
1	Abha	18.2227	42.546	22	-25	325.3645	Moderate
2	Albaha	20.1794	41.6357	24	-32	330.3742	High
3	Aljouf	26.2561	40.02318	33	-54	324.5771	Unsuitable
4	Riyadh	24.90689	46.39721	24	-20	331.4937	High
5	Alwajh	26.2561	36.443	39	-56	330.5207	Unsuitable
6	Arar	31.028	40.9056	33	-43	320.679	Most
7	Hail	27.39	41.42	28	-33	322.1703	High
8	Dammam	26.39497	50.18872	23	-8	309.1162	Moderate
9	Al Ahsa	25.34616	49.5956	23	-8	317.0333	Moderate
10	Qassim	26.34668	43.76645	25	-30	312.5703	High
11	Rania	21.21501	42.84853	24	-32	322.59	Unsuitable
12	Yanbu	23.9865	38.2046	34	-55	320.9651	Moderate
13	Al Khafji	28.48	48.48	24	-13	295.5449	Moderate
14	Tabuk	28.38284	36.48397	40	-53	343.9283	Most
15	Madinah	24.4846	39.5418	32	-50	307.7511	Moderate
16	Taif	21.43278	40.49173	26	-35	338.336	Most
17	Makkah	21.331	39.949	24	-43	296.139	High
18	Wadi Addawasir	20.4301	44.89433	23	-27	328.7003	Moderate

The results of this study were validated against Al Garni and Awasthi (2017), which offered a high-level overview of potential site suitability for utility-scale PV technology in Saudi Arabia, based on the integration of a geographical information system and multi-criteria decision-making tools. A land suitability index was computed to determine potential sites. The locations of the 18 cities are shown on the suitability map in Figure 16. The high suitability areas comprise 50% of the suitability areas considered and can be seen mainly spread around the central region.

Tabuk, with the highest suitability index (Figure 17), also demonstrates the highest annual energy yield of 343.93 kWh/m^2. This annual energy yield is 9% higher than the annual energy yield when the tilt equals the latitude and azimuth equals zero. Also, Taif which is located in the most suitable area presents the potential of 338.34 kWh/m^2. Riyadh is the third highest city regarding energy yield, due to the high solar irradiation and the mild air temperature year-round. From Al Garni and Awasthi (2017), Riyadh also has a high suitability index. There is therefore a strong indication that these three locations are the best sites to consider for solar PV.

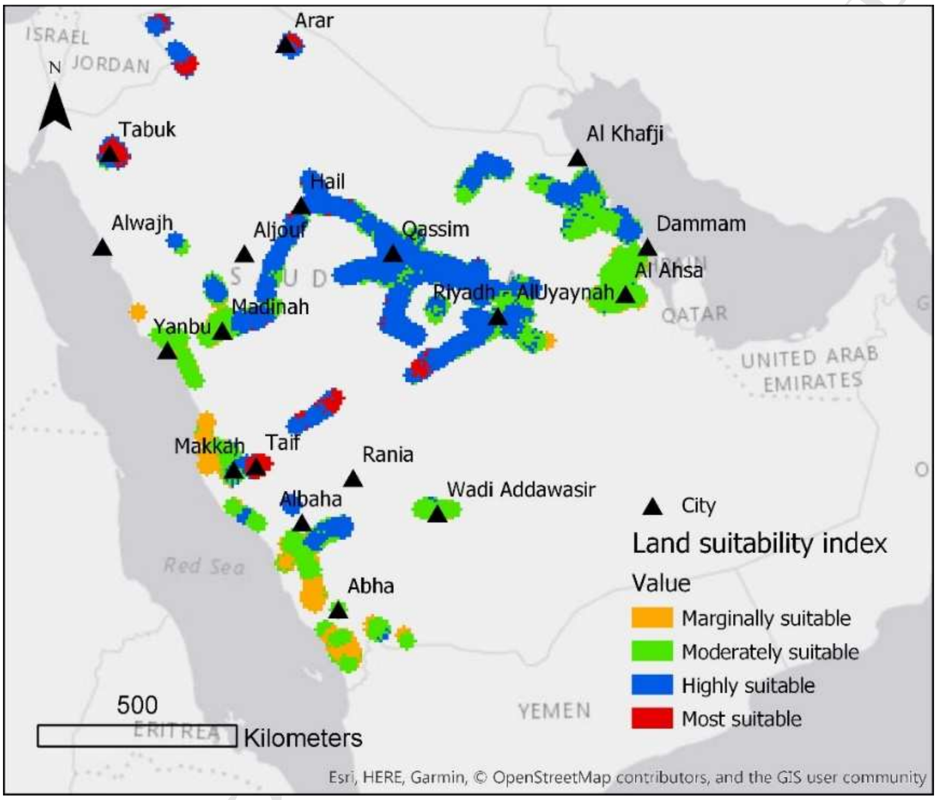


Figure 16. Suitability map and solar station sites (Al Garni and Awasthi, 2017)

Based on both results, the most suitable cities associated with a high annual energy yield more than 320 kWh/m^2 (the average of the annual potential for all the cities) are Tabuk, Taif and Arar as shown in Figure 17. Hail located in the North, together with Riyadh and Albaha would be the highly suitable sites to implement solar PV on a utility-scale. While these locations account for less than 33% of all the appropriate areas presented in Figure 17, they offer a potential for high-performance solar PV projects regarding energy yield and associated infrastructure costs.

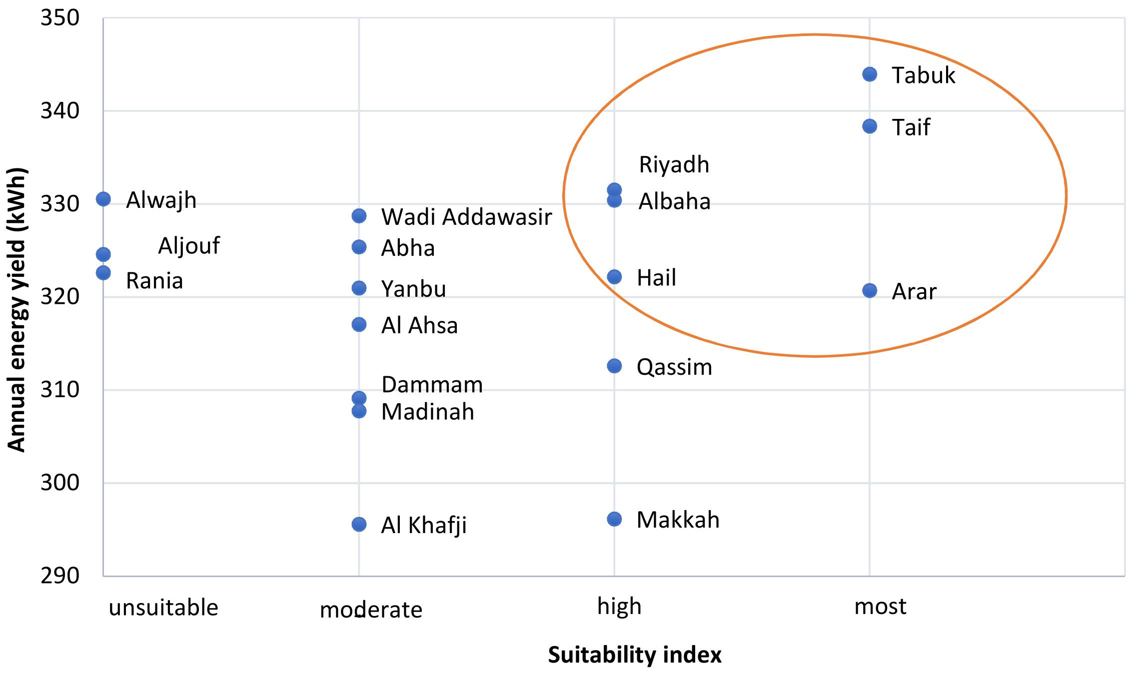


Figure 17. Cities suitability and annual energy yield

5. Conclusions

This paper has analysed the optimal orientation of fixed solar modules at 18 locations in Saudi Arabia so as to achieve maximum annual electric energy yield from utility-scale solar installations. The irradiance and temperature data are from ground measurements accurate to ±2%. The results indicate the importance of this work in that the optimal orientation differs considerably from the conventional orientation with tilt = latitude and azimuth due south. Over the 18 cities, the optimum tilt varies from 12.7° higher than the latitude to 4.5° lower. The optimum azimuth varies from 8° to 56° west of south, showing the asymmetrical irradiance pattern in these locations.

A detailed analysis is performed for the capital city, Riyadh for which the optimal orientation is a tilt 1° less than the latitude and an azimuth 20° west of south. If the orientation is adjusted each month, the electric energy yield can be increased by 4.01%. However this adjustment requires considerable labour cost and the optimal orientation during some consecutive months is similar. Analysis shows that, adjusting the orientation 5 times per year can achieve 3.63% increase in energy yield compared to the fixed annual orientation, for much less labour cost.

The optimal energy yield for the 18 cities is combined with a multicriteria site suitability analysis including climate, topography and proximity to roads, transmission lines and protected areas, in order to select sites that are both high in energy yield and also high in suitability. Six cities are selected: Albaha, Arar, Hail, Riyadh, Tabuk and Taif. Two cities, Qassim and Makkah have as high suitability but significantly less energy yield. Several cities have energy yield equivalent to the low end of the six selected cities but less suitability. For the six selected cities the optimal azimuth differs considerably from south, being 20° to 53° west of south, although the optimum tilt is only slightly higher than the latitude.

This study has focused on optimizing energy yield. Future work could take into account power purchase agreements with prices depending on time of day, to maximize revenue and return on investment. Also dust accumulation on solar modules could be taken into account from the point of view of its impact on optimum orientation and also on the cleaning cost.

6. Acknowledgments

The first author would like to thank The Royal Commission of Jubail and Yanbu – Jubail Industrial College for the financial support under their scholarship program. Also, the authors express sincere appreciation to King Abdullah City for Atomic and Renewable Energy (K.A.CARE) for providing the required data.

7. References:

Abdeen, E., Orabi, M., Hasaneen, E.S., 2017. Optimum tilt angle for photovoltaic system in desert environment. Solar Energy 155, 267–280. https://doi.org/10.1016/j.solener.2017.06.031

Al Garni, H.Z., Awasthi, A., 2017. Solar PV power plant site selection using a GIS-AHP based approach with application in Saudi Arabia. Applied Energy 206C, 1225–1240. https://doi.org/10.1016/j.apenergy.2017.10.024

Al Garni, H.Z., Awasthi, A., Ramli, M.A.M., 2018. Optimal design and analysis of grid-connected photovoltaic under different tracking systems using HOMER. Energy Conversion and Management 155C, 42–57.

Al Garni, H.Z., Kassem, A., Awasthi, A., Komljenovic, D., Al-Haddad, K., 2016. A multicriteria decision making approach for evaluating renewable power generation sources in Saudi Arabia. Sustainable Energy Technologies and Assessments 16, 137–150. https://doi.org/10.1016/j.seta.2016.05.006

Almarshoud, A.F., 2016. Performance of solar resources in Saudi Arabia. Renewable and Sustainable Energy Reviews 66, 694–701. https://doi.org/10.1016/j.rser.2016.08.040

Anderson, E., 1983. Fundamentals of Solar Energy Conversion. Addison-Wesley Publishing Company, Massachusetts.

Babatunde, A.A., Abbasoglu, S., Senol, M., 2018. Analysis of the impact of dust, tilt angle and orientation on performance of PV Plants. Renewable and Sustainable Energy Reviews 90, 1017–1026. https://doi.org/10.1016/j.rser.2018.03.102

Benghanem, M., 2011. Optimization of tilt angle for solar panel: Case study for Madinah, Saudi Arabia. Applied Energy 88, 1427–1433. https://doi.org/10.1016/j.apenergy.2010.10.001

Carrion JA, Estrella AE, Dols FA, Toro MZ, Rodrıguez M, Ridao AR, 2008, Environmental decision-support systems for evaluating the carrying capacity of land areas: Optimal site selection for grid-connected photovoltaic power plants, Renewable and Sustainable Energy Reviews, 12 (2008) 2358–2380. doi:10.1016/j.rser.2007.06.011

Cheng, C.L., Sanchez Jimenez, C.S., Lee, M.C., 2009. Research of BIPV optimal tilted angle, use of latitude concept for south orientated plans. Renewable Energy 34, 1644–1650. https://doi.org/10.1016/j.renene.2008.10.025

Danandeh, M.A., Mousavi G., S.M., 2018. Solar irradiance estimation models and optimum tilt angle approaches: A comparative study. Renewable and Sustainable Energy Reviews 92, 319–330. https://doi.org/10.1016/j.rser.2018.05.004

Despotovic, M., Nedic, V., 2015. Comparison of optimum tilt angles of solar collectors determined at yearly, seasonal and monthly levels. Energy Conversion and Management 97, 121–131. https://doi.org/10.1016/j.enconman.2015.03.054

Dey, S., Lakshmanan, M.K., Pesala, B., 2018. Optimal Solar Tree Design for Increased Flexibility in Seasonal Energy Extraction. Renewable Energy 125, 1038–1048. https://doi.org/10.1016/j.renene.2018.02.017

Duffie, J. a., Beckman, W. a., Worek, W.M., 2003. Solar Engineering of Thermal Processes, 4nd ed., 2nd ed, Journal of Solar Energy Engineering. New York, NY, USA. https://doi.org/10.1115/1.2930068

El-Sebaii, A.A., Al-Hazmi, F.S., Al-Ghamdi, A.A., Yaghmour, S.J., 2010. Global, direct and diffuse solar radiation on horizontal and tilted surfaces in Jeddah, Saudi Arabia. Applied Energy 87, 568–576. https://doi.org/10.1016/j.apenergy.2009.06.032

Elminir, H.K., Ghitas, A.E., El-Hussainy, F., Hamid, R., Beheary, M.M., Abdel-Moneim, K.M., 2006. Optimum solar flat-plate collector slope: Case study for Helwan, Egypt. Energy Conversion and Management 47, 624–637. https://doi.org/10.1016/j.enconman.2005.05.015

Gharakhani Siraki, A., Pillay, P., 2012. Study of optimum tilt angles for solar panels in different latitudes for urban applications. Solar Energy 86, 1920–1928. https://doi.org/10.1016/j.solener.2012.02.030

Green, M.A., Hishikawa, Y., Warta, W., Dunlop, E.D., Levi, D.H., Hohl-Ebinger, J., Ho-Baillie, A.W.H., 2017. Solar cell efficiency tables (version 50). Progress in Photovoltaics: Research and Applications 25, 668–676. https://doi.org/10.1002/pip.2909

Gueymard, C.A., 2009. Direct and indirect uncertainties in the prediction of tilted irradiance for solar engineering applications. Solar Energy 83, 432–444. https://doi.org/10.1016/j.solener.2008.11.004

Guo, M., Zang, H., Gao, S., Chen, T., Xiao, J., Cheng, L., Wei, Z., Sun, G., 2017. Optimal Tilt Angle and Orientation of Photovoltaic Modules Using HS Algorithm in Different Climates of China. Applied Sciences 7, 1028. https://doi.org/10.3390/app7101028

Hafez, A.Z., Soliman, A., El-Metwally, K.A., Ismail, I.M., 2017. Tilt and azimuth angles in solar energy applications – A review. Renewable and Sustainable Energy Reviews 77, 147–168. https://doi.org/10.1016/j.rser.2017.03.131

Jacobson, M.Z., Jadhav, V., 2018. World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. Solar Energy 169, 55–66. https://doi.org/10.1016/j.solener.2018.04.030

K.A.CARE, 2016. Solar monitoring network summary [WWW Document]. URL https://rratlas.kacare.gov.sa/RRMMDataPortal/en/Reports/Home/SolarMonitoringNetworkSummary (accessed 4.2.18).

Kaddoura, T.O., Ramli, M.A.M., Al-Turki, Y.A., 2016. On the estimation of the optimum tilt angle of PV panel in Saudi Arabia. Renewable and Sustainable Energy Reviews 65, 626–634. https://doi.org/10.1016/j.rser.2016.07.032

Khoo, Y.S., Nobre, A., Malhotra, R., Yang, D., Ruther, R., Reindl, T., Aberle, A.G., 2014. Optimal orientation and tilt angle for maximizing in-plane solar irradiation for PV applications in Singapore. IEEE Journal of Photovoltaics 4, 647–653. https://doi.org/10.1109/JPHOTOV.2013.2292743

Le Roux, W.G., 2016. Optimum tilt and azimuth angles for fixed solar collectors in South Africa using measured data. Renewable Energy 96, 603–612. https://doi.org/10.1016/j.renene.2016.05.003

Lunde, P.J., 1980. Solar thermal engineering: Space heating and hot water systems. New York, John Wiley and Sons, Inc.

Lv, Y., Si, P., Rong, X., Yan, J., Feng, Y., Zhu, X., 2018. Determination of optimum tilt angle and orientation for solar collectors based on effective solar heat collection. Applied Energy 219, 11–19. https://doi.org/10.1016/j.apenergy.2018.03.014

MacDougall, H., Tomosk, S., Wright, D., 2018. Geographic maps of the impact of government incentives on the economic viability of solar power. Renewable Energy 122, 497–506. https://doi.org/10.1016/j.renene.2017.12.108

Masters, G.M., 2004. Renewable and Efficient Electric Power Systems. A John Wiley & sons, inc., publication, New Jersey. https://doi.org/10.1002/0471668826

Moghadam, H., Tabrizi, F.F., Sharak, A.Z., 2011. Optimization of solar flat collector inclination. Desalination 265, 107–111. https://doi.org/10.1016/j.desal.2010.07.039

N.Nijegorodov, K.R.S.Devan, P.K.Jain, S.Carlsson, 1994. Atmospheric transmittance models and an of an absorber plate, variously oriented at any latitude. Renewable Energy 4, 529–543. https://doi.org/https://doi.org/10.1016/0960-1481(94)90215-1

Rowlands, I.H., Kemery, B.P., Beausoleil-Morrison, I., 2011. Optimal solar-PV tilt angle and azimuth: An Ontario (Canada) case-study. Energy Policy 39, 1397–1409. https://doi.org/10.1016/j.enpol.2010.12.012

Sahin, A.Z., Rehman, S., Al-Sulaiman, F., 2017. Global solar radiation and energy yield estimation from photovoltaic power plants for small loads. International Journal of Green Energy 14, 490–498. https://doi.org/10.1080/15435075.2016.1278374

Sandia lab., 2018. ASHRAE IAM Model [WWW Document]. URL https://pvpmc.sandia.gov/modeling-steps/1-weather-design-inputs/shading-soiling-and-reflection-losses/incident-angle-reflection-losses/ashre-model/ (accessed 5.10.18).

Sengupta, M., Habte, A., Kurtz, S., Dobos, A., Wilbert, S., Lorenz, E., Stoffel, T., Renné, D., Gueymard, C., Myers, D., Wilcox, S., Blanc, P., Perez, R., 2015. Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications.

Solar First, 2016. Module characterization angle of incidence response of first solar modules.

Soulayman, S., Hammoud, M., 2016. Optimum tilt angle of solar collectors for building applications in mid-latitude zone. Energy Conversion and Management 124, 20–28. https://doi.org/10.1016/J.ENCONMAN.2016.06.066

Tomosk, S., Haysom, J.E., Hinzer, K., Schriemer, H., Wright, D., 2017. Mapping the geographic distribution of the economic viability of photovoltaic load displacement projects in SW USA. Renewable Energy 107, 101–112. https://doi.org/10.1016/j.renene.2017.01.049

Yadav, A.K., Chandel, S.S., 2013. Tilt angle optimization to maximize incident solar radiation: A review. Renewable and Sustainable Energy Reviews 23, 503–513. https://doi.org/10.1016/j.rser.2013.02.027

Yang, D., Kleissl, J., Gueymard, C.A., Pedro, H.T.C., Coimbra, C.F.M., 2018. History and trends in solar irradiance and PV power forecasting: A preliminary assessment and review using text mining. Solar Energy. https://doi.org/10.1016/J.SOLENER.2017.11.023

Highlights:

- The impact of tilt and azimuth on PV energy yield is analyzed for Saudi Arabia
- The optimum orientation is derived for fixed PV modules in 18 cities
- Adjusting the orientation 5 times/year increases energy yield by 3.63% in Riyadh
- The results are combined with a site suitability analysis published previously
- 6 cities are recommended for PV based on high suitability and high energy yield