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Estimating the Impact of Azimuth Angle Variations on Photovoltaic Annual Energy Production

Abstract:

The performance of a photovoltaic (PV) installation is affected by its tilt and azimuth angles, because these parameters change the amount of solar energy absorbed by the surface of the PV modules. Therefore, this paper demonstrates the impact of the azimuth angle on the energy production of PV installations. Two different PV sites were studied, where the first comprises PV systems installed at -13°, -4°, +12°, and +21° azimuth angles in different geographical locations, whereas the second PV site included adjacent PV systems installed at -87°, -32°, +2°, and +17° azimuth angles. All the investigated PV sites were located in Huddersfield Town, United Kingdom. In summary, the results indicate that PV systems installed between -4° and +2° presented the maximum energy production over the last four years, while the worst energy generation were observed for the PV system installed at an azimuth angle of -87°. Finally, the probability projections for all observed azimuth angles datasets have been assessed. Since PV systems are affected by various environmental conditions such as fluctuations in the wind, humidity, solar irradiance, and ambient temperature. Ultimately, these factors would affect the annual energy generation of the PV installations. For that reason, we have analysed the disparities and the probability of the annual energy production for multiple PV systems installed at different azimuth angle ranging from -90° to +90° degrees, and affected by different environmental conditions. The analysis are based on the cumulative density function (CDF) modelling technique as well as the normal distribution function.

Keywords: Photovoltaics; Azimuth angle; Energy production; CDF Modelling.

1. Introduction

Photovoltaic (PV) systems output energy yield strongly depends on weather conditions such as wind speed [1], humidity variations [2], temperature fluctuation, and solar irradiance, and some other factors such as dust/dirt [3], hot spots [4-5], snow [6], and micro cracks [7-8]. Still, the tilt and azimuth angles of PV installations play major role to increase the annual energy production.

Empirical equations were employed in early studies to estimate the optimum tilt angles at different sites, which are only related to local altitude described by Salim et al. [9]. Later, Mani et al. [10] explained that PV modules should be installed with the tilt angle of 2.8° greater than the latitude.

In 2017, Xu et al. [11] proposed an analysis of the optimum tilt angle for soiled PV panels. It was found that the optimum tilt angle for PV modules was 25.89° to 26.06° in dusty weather conditions. Authors in [12-13] estimated the optimum tilt angle for PV panels in the Saudi Arabia. It was found that PV panels tilt angle must be changed during the season of the year to increase the total energy production of PV systems by at least 6.38%.

In other studies, several recommendations for a fixed tilt and azimuth angles were suggested based on various locations in the following countries: South Africa [14], Northern Ireland [15], India [16], Iran [17], United States [18], Turkey [19], and United Arab Emirates [20].

Various studies on the optimization of tilt angles have considered the effect of cloudiness [21], wind speed cooling [1], maximizing radiation on flat plate collectors [22], clearness index optimization method [23], radiation transfer method [24], and maximizing different solar radiation in different geographical locations [25-26]. These methods are used to draw a relevant map for PV installations tilt and azimuth angles, and, thus, enhance the generation of the annual energy of PV systems.

Most recently, in 2018, Antonanzas et al. [27] proposed two predictive models to develop a single-axis tracking system which could determine the optimum position of PV panels. The study has been validated on some European Baseline Surface Radiation Network (BSRN) stations for the year 2015.

But still there is a lack of empirical observations based on various PV systems installed in different locations within a specific regional area. In addition, there are few studies about the impact of the azimuth angle of PV installations based on an annual energy production for several years, which would allow one to draw a relevant conclusion for the ideal angle documentation. Therefore, this article attempts to fill-in this gap of knowledge found in the literature.

The tilt angle is the angle of the PV modules from the horizontal plane, for a fixed (non-tracking) mounting [28], whereas the azimuth angle is the angle of the PV modules relative to the direction due south. -90° is east, 0° is south, and +90° is west [29-30].

Usually, PV operators/installers use an online application to determine the azimuth angle on the site at its optimum level. However, in residential sites, this cannot be the case since the rooftop is fixed and not flexible. This issue was investigated in 2013 by Kodysh et al. [31]. In this work, a new methodology for estimating solar potential on multiple building rooftops for PV panels is developed. The methodology considers input parameters, such as surface orientation, shadowing effects, elevation, and atmospheric conditions that influenced solar intensity on the earth surface. The methodology was implemented for some 212,000 buildings in Knox County, Tennessee, USA.

Later in 2017, Hong et al. [32] developed a new method for estimating the rooftop PV potential energy based on the tilt and azimuth angle at Gangnam city located in Korea. The physical, geographic, and technical potentials were estimated for 27,774 buildings. In summary, the total annual physical potential of the rooftop solar PV system in the Gangnam district was determined to be 9,287,982 MWh whereas the total annual technical potential was found to be 1,130,371 MWh, indicating that only 12.17% of the physical potential can be generated as electricity with the current spatial availability and technology levels. Meanwhile, the average geographic potential in the Gangnam district was found to be 4,964,118 m^2, which accounts for 66.03% of the total rooftop area in the district.

On the other hand, the variations of the azimuth angle can lead to significant loss in the output power, and also, will affect the PV system by various types of faults. PV faults can be mitigated using various techniques, such as the random forest (RF) based intelligent fault diagnosis system that is capable of detecting multi faults in PV array, is developed by Chen et al. [33]. The proposed algorithm ensemble learning algorithm is explored for the detection and diagnosis of PV arrays early faults (including line-line faults, degradation, open circuit, and partial shading), which combines multiple learning algorithms to achieve a superior diagnostic performance. However, another approach presented in [34-35] shows that PV faults can be detected using the analysis of the mathematical thresholds such as voltage, current, and output power, whereas the fault identification is based on intelligent mathematical modelling techniques.

In addition, the accuracy of the detection for PV faults is enhanced using machine learning techniques, such as artificial neural networks (ANN) [36-37], fuzzy logic classification systems [38-39], as well as the wavelet based classification methods [40].

In this article, firstly, a database of various PV installations in the region of Huddersfield Town, shown in Fig. 1 is analysed. From the observed data, it was possible to consider various PV installations with various azimuth angles (ranging from -87° to 21°). Therefore, the impact of various azimuth angles on the energy production for PV installations is deliberated.

Since PV systems are affected by various environmental conditions such as wind, humidity, solar irradiance, and ambient temperature, therefore these conditions would affect the annual energy generation for the PV installations. For that reason, we have analysed the disparities and the probability of the annual energy production for multiple PV systems installed at different azimuth angle ranging from -90° to +90° degrees.

By contrast with the main motivation of this work, the results could be used in various PV energy sectors, such as PV fault detection algorithms, PV forecasting and prediction, PV monitoring and performance analysis, as well as reliability analysis of power systems.

Fig. 1 Huddersfield town location in the United Kingdom

2. Methodology

The azimuth is the PV array's east-west orientation in degrees. In most of the solar PV energy calculator tools, an azimuth value of zero is facing the equator in both northern and southern hemispheres. Positive 90° degrees is facing due west, negative 90° degrees is facing due east. The compass angle shows 180° for south, 90° for east and 270° for west.

In the northern hemisphere, between the latitudes of 23° and 90°, the sun is always in the south. Therefore, the modules on an array are directed to the south in order to get the most out of the sun's energy. In the southern hemisphere, it is the opposite.

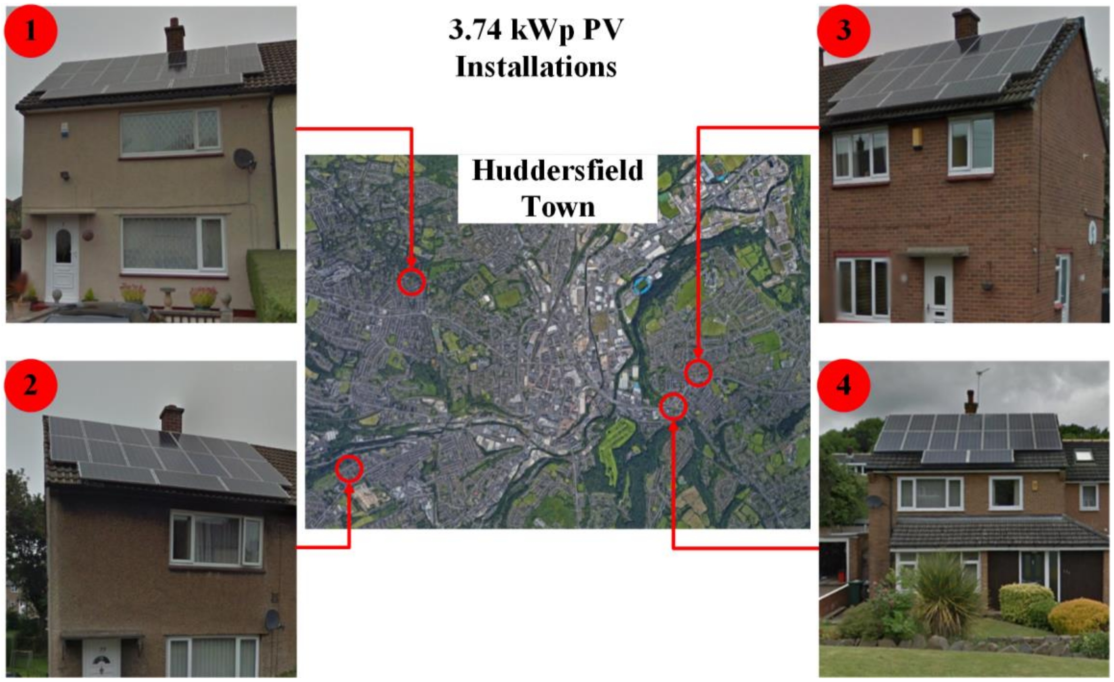
The meteorological conditions of the location are an important factor to consider. For example, an insolation analysis in Hawaii shows that an array facing to the east could generate more power compared to that of an array facing south or west [41]. The reason could be the frequent afternoon rains in that location.

For that reason, this paper examines various PV installations with several azimuth angles. However, in order to achieve that, the following conditions were taken into account in order to pick the right PV installations for the study:

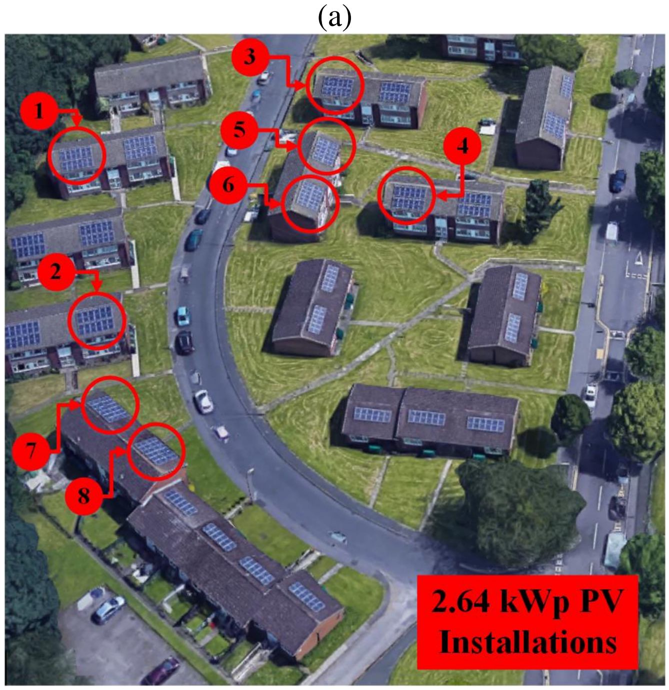
- The maximum PV installations are no older than 2 years, since old PV systems tend to have greater degradation rate, thus generating less energy over the years
- PV modules technology is crystalline-silicon (c-Si). This condition was selected to ensure that the operating mechanisms of the PV modules are identical
- In this research, the examination of the PV installations is based on the difference in the azimuth angle. Therefore, all examined PV installations have the same tilt angle between 40° to 41° degrees

The examined PV systems are shown in Fig. 2. Two PV sites with various azimuth angles have been considered in this study. Fig. 2(a) shows the first PV installation (referred as PV site A). PV systems 1, 2, 3, and 4 have -13°, -4°, +12°, and +21° azimuth angles respectively. As can be shown in Fig. 2(a), the PV site A is not adjacent. For that reason, we have studied another PV installations (referred as PV site B) which comprises adjacent PV systems as shown in Fig. 2(b).

Fig. 2(b) shows eight adjacent PV installations which are installed at the same tilt angle of 41°, but with different azimuth angles. The azimuth angles for the PV systems are as follows: +2° for 1 and 2; +17° for 3 and 4; -32° for 5 and 6; -87° for 7 and 8. It is worthy noticing that the capacity for all studied PV site A is equal to 3.74 kWp, whereas the capacity of PV site B is equal to 2.64 kWp.



(a)



(b)

Fig. 2 Examined PV installations. (a) PV site A comprising non adjacent PV systems, (b) PV site B comprising adjacent PV systems

Table 1 summarizes main electrical characteristics at standard test conditions (STC) of the PV modules installed in the studied locations.

Table 1 PV modules electrical characteristics

Electrical Characteristic	Value
PV peak power	220 W
One PV cell peak power	3.6 W
Voltage at maximum power point (V_{mpp})	28.7 V
Current at maximum power point (I_{mpp})	7.67 A
Open Circuit Voltage (V_{oc})	36.74 V
Short Circuit Current (I_{sc})	8.24 A

The data of the examined PV installations are monitored using OWL Intuition-PV monitoring unit. This monitoring unit transmits the data wirelessly to a local hub installed in the house. The hub logs and saves the data over a shared database with unique IP address. This unit has the following features:

- Transmission frequency: 433 MHz
- Operating range: 30 meters
- Transmitter battery life: 2 years
- Sensor suitable to monitor cable rated up to 71 amps

Additionally, the user is allowed to configure the settings of the PV data. Therefore, the daily, monthly, and yearly PV system data can be monitored. Also, it provides graphs showing both historical and peak values, allowing the user to identify when the solar panels have been generating the most energy, and therefore the best times to use power in a day.

3. Results

3.1.1 PV Site A

In order to investigate the difference in the output energy production for multiple PV systems installed at different azimuth angles. Firstly, Fig. 3(a), and (b) present the monthly irradiance and ambient temperature in the studied location (Huddersfield town). It is evident that the irradiance increases in the summer seasons, and has low averages in November, December, January, and February. In addition, according to Fig. 3(b), the average monthly temperature varies between +3.2 °C (February) and +16.3 °C (September).

A comparison between the PV systems shown previously in Fig. 2(a) installed at different azimuth angles was carried out. Fig. 3 shows the irradiance vs. output measured power in each of the PV installations analysed. A liner regression fit is presented for each dataset. Therefore, it is possible to compare the PV systems according to the obtained determination factor.

The determination factor, R^2, is a statistical measure of how close the data are to the fitted regression line. A determination factor of 100% indicates that the model explains all the variability of the response data around its mean, where in fact, this is hard to achieve in PV systems data sets because the measured data relies on the sensor efficiency, solar radiation, temperature variability, and many other factors, such as the delay in the data logging system, and the spectrum noise specially added when the PV installations are monitored wirelessly.

The determination factor was measured according to the data samples captured during 2017 for PV site A. It was found that the PV systems with azimuth angle of -4° attain the maximum determination factor of 85.23% as shown in Fig. 4(b), which means that this PV installation probably generates the maximum output power compared to all other PV systems with different azimuth angles. The minimum value of this parameter was measured for the PV system installed at azimuth angle +21°.

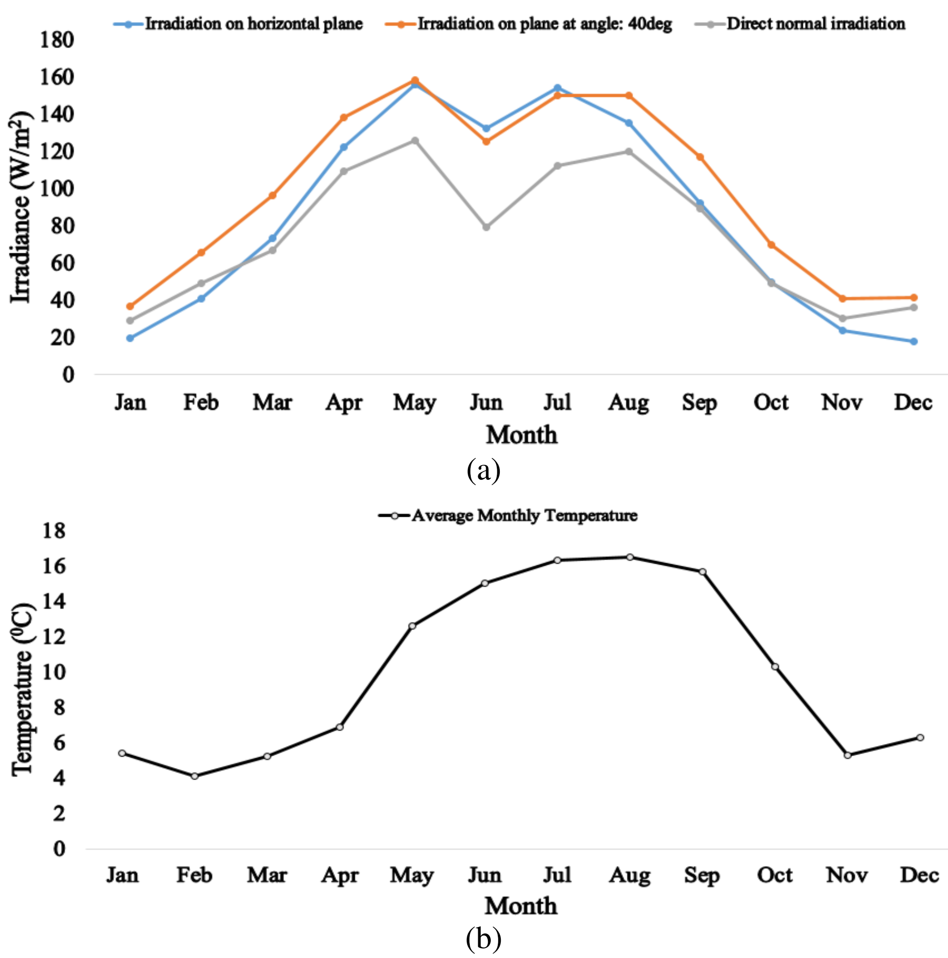


Fig. 3 (a) Monthly irradiance profile in Huddersfield town, (b) Monthly ambient temperature in Huddersfield town

For a better description, in the last six years the annual energy production of PV site A is measured and reported in Fig. 5. It is shown that the PV system installed at azimuth angle -4° shows the maximum energy production over the last six years, with an average value of 3537 kWh. The second highest energy production is found for the PV system installed at azimuth angle of -13° with an average energy production of 3521 kWh. The minimum energy production is observed for the PV system installed at azimuth angle of +21° with an average value of 3474 kWh, over the last six years.

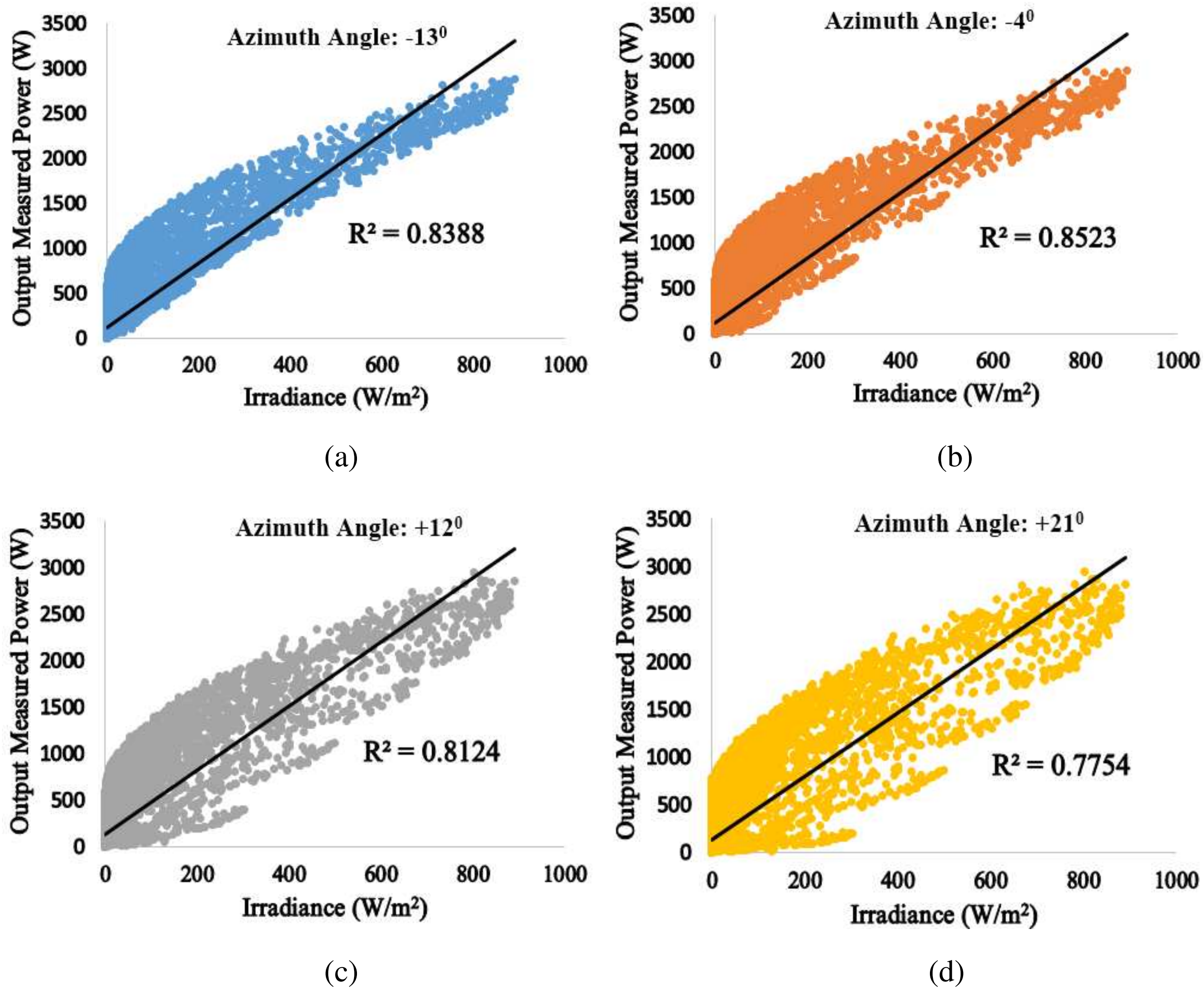


Fig. 4 Irradiance vs. output measured power obtained in PV site A. (a) PV system azimuth angle -13°, (b) PV system azimuth angle -4°, (c) PV system azimuth angle +12°, (d) PV system azimuth angle +21°

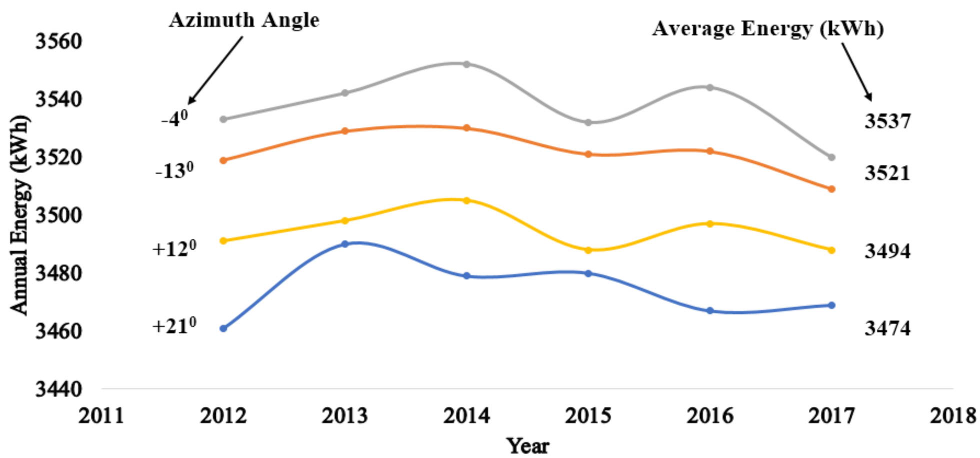


Fig. 5 Annual energy production for PV site A in the last six years (2012 – 2017)

3.2 PV Site B

This section describes the performance of PV systems in site B shown previously in Fig. 2(b). The PV installations have the following azimuth angles: -87°, -32°, +2°, and +17°. The data analysed corresponds to a period of 4 years between 2014 and 2017. The measured output power of the PV systems with various azimuth angles in year 2017 as a function of the irradiance for each observed PV system is presented in Fig. 6(a-d), whereas the overlap between all measured data is shown in Fig. 6(e). As it can be seen in the figures the PV system at azimuth angle of +2° shows the maximum determination factor of 86.11%. The minimum determination factor is observed for the PV system at azimuth angle of -87°. This occurred because at medium and high irradiance (>500 W/m2) levels, the PV system generates less output power compared to the PV systems installed at azimuth angles of either +2°, +17°, and -32°.

The measured data of the irradiance and output power in the interval: 2014 – 2016 is shown in Fig. 7. Obtained results indicate that in all the considered time interval, the determination factor of the PV systems from maximum to minimum are illustrated as follows:

- Azimuth angle +2°: average R^2 = 85.2 %, Maximum
- Azimuth angle +17°: average R^2 = 83.4 %
- Azimuth angle -32°: average R^2 = 77.3 %
- Azimuth angle -87°: average R^2 = 48.8 %, Minimum

Before moving to the analysis of the annual energy production for each PV installation, the determination factor values suggest that the PV installation at azimuth angle of +2° will generate more energy than the rest of PV installations, since the power production is almost linear with the irradiance profile among the last four years of the empirical data set.

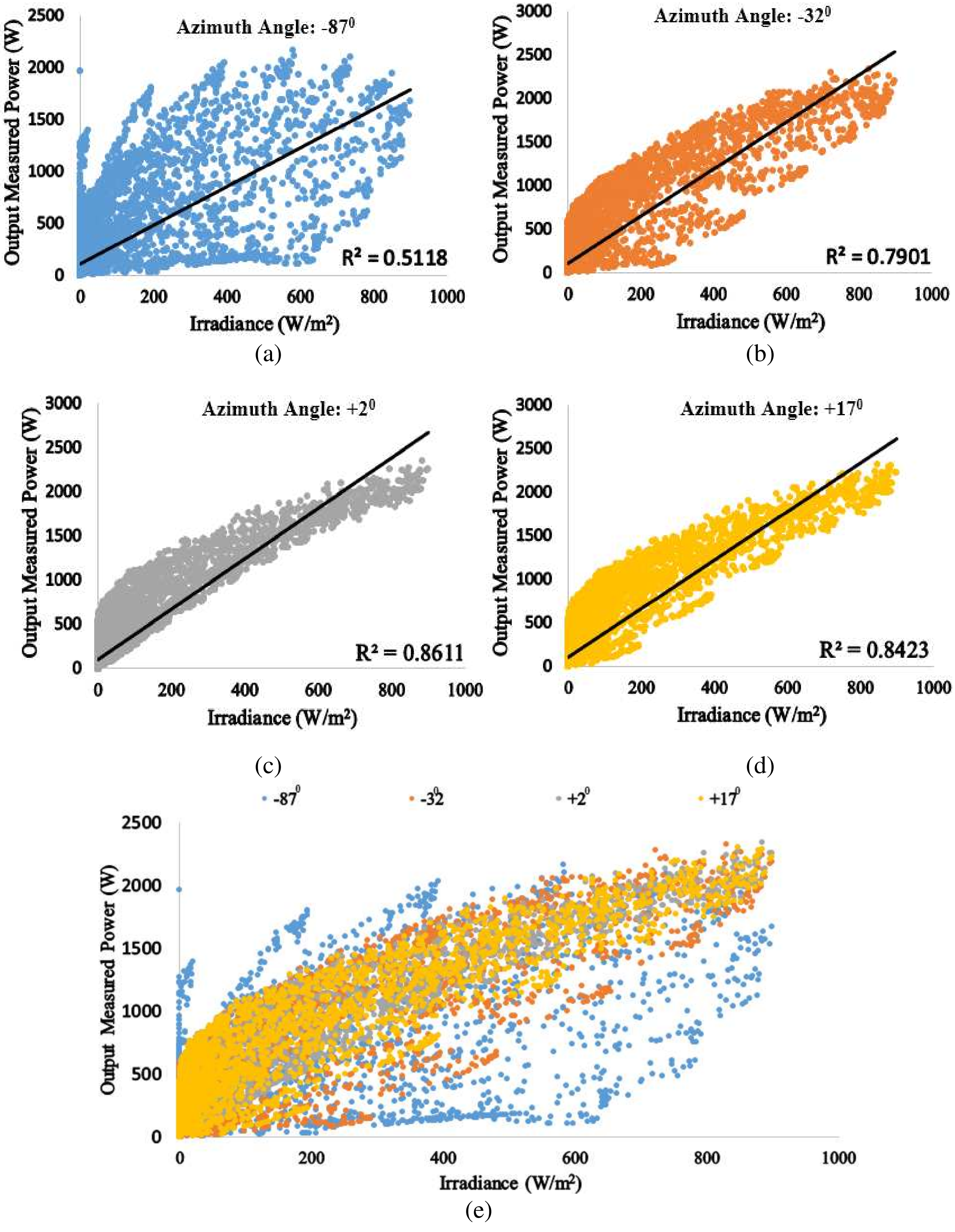


Fig. 6 Irradiance vs. output measured power obtained in PV site B. (a) PV system azimuth angle: -87°, (b) PV system azimuth angle: -32°, (c) PV system azimuth angle: +2°, (d) PV system azimuth angle: +17°, (e) Overlapping between all PV site B data

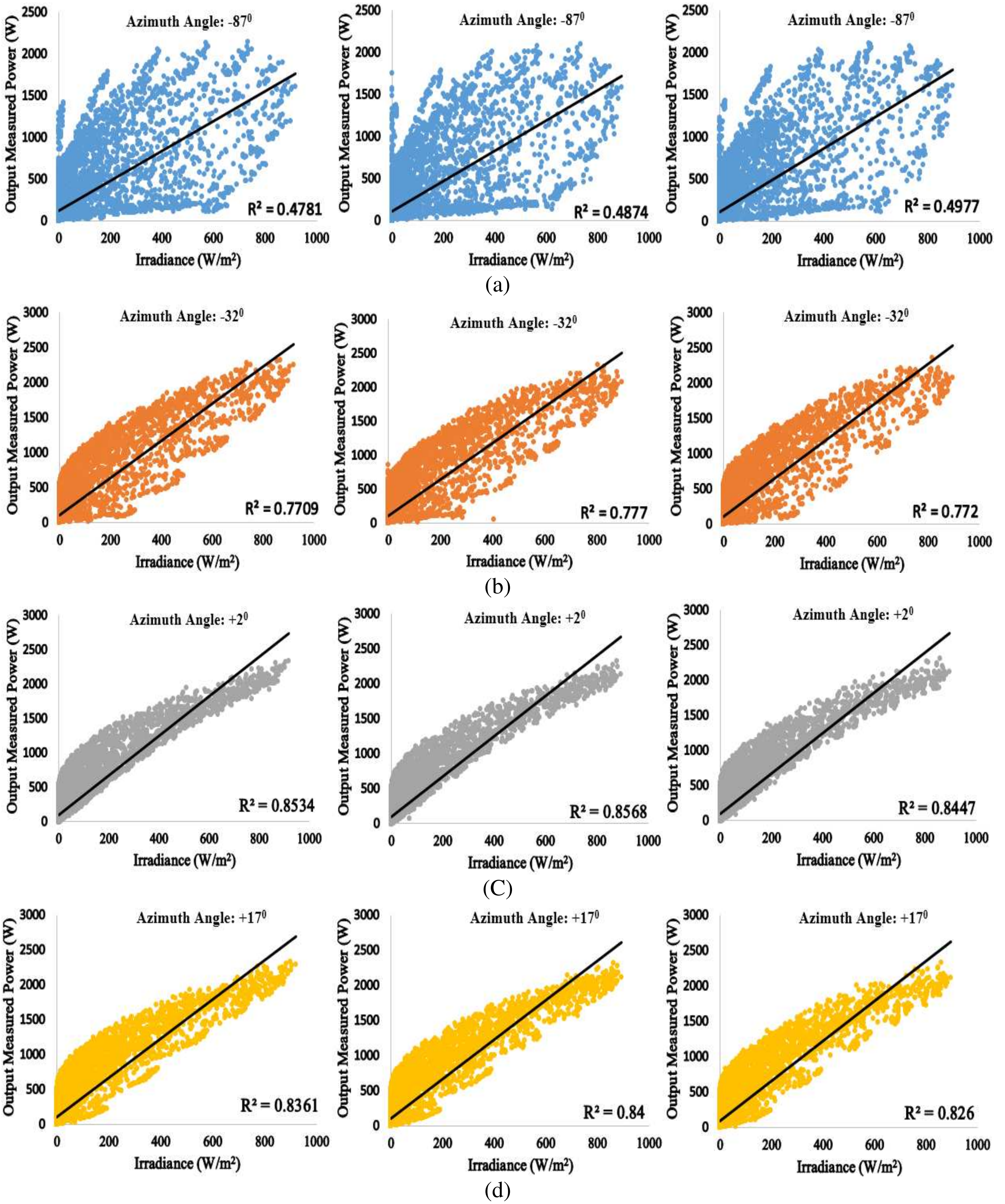
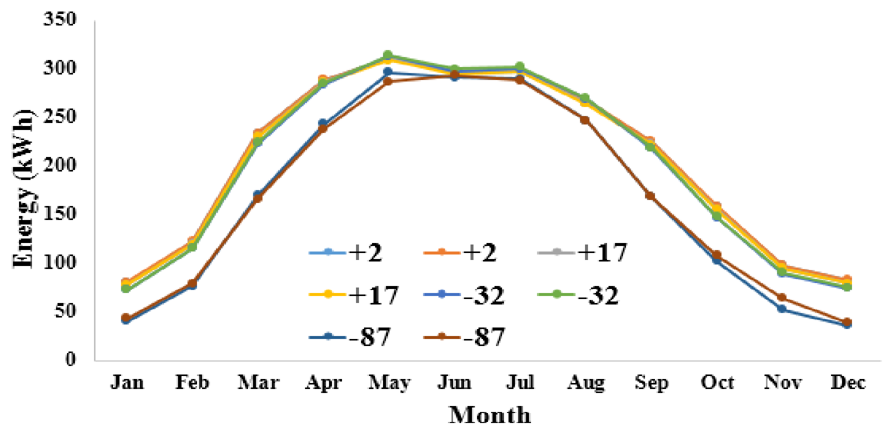


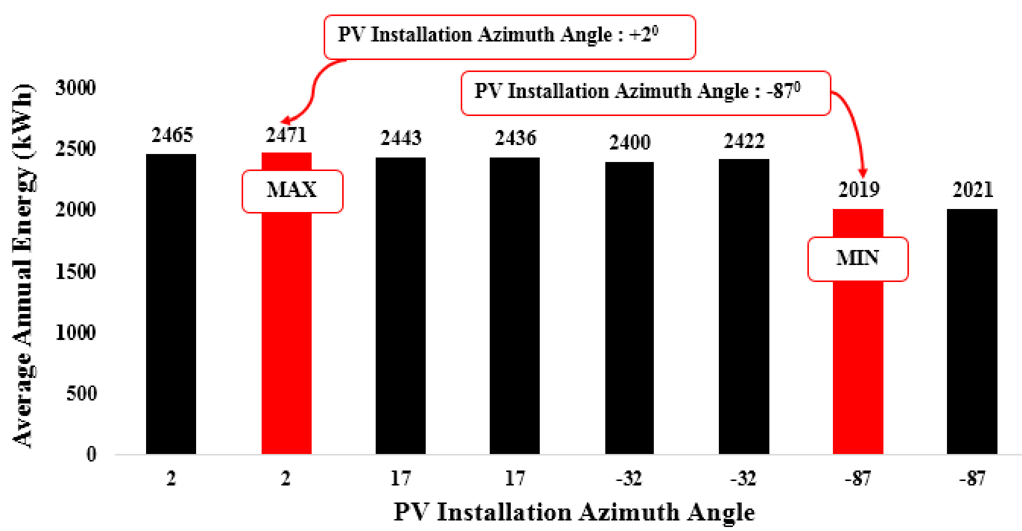
Fig. 7 Irradiance vs. measured power obtained in PV site B (2014, 2015, and 2016 left to right). (a) PV system azimuth angle: -87°, (b) PV system azimuth angle: -32°, (c) PV system azimuth angle: +2°, (d) PV system azimuth angle: +17°

The average monthly energy production by PV systems in site B is shown in Fig. 8(a). As it can be seen, the PV systems with azimuth angles of +2°, +17° and+-32° generate relatively equivalent energy. However, there is a large loss in the monthly energy produced by the PV systems installed at azimuth angle -87° relative to those with other azimuth angles.

The annual energy production in all considered PV systems for site B is given by Fig. 8(b). The maximum annual energy based on data observed over the last four years (2014 – 2017) is detected for PV systems with azimuth angles of +2°, in the range of 2471-2465 kWh. The second ideal azimuth angle was found to be of +17°, where the PV system generates 2443-2436 kWh yearly. The minimum energy production is detected in the PV systems installed at azimuth angle -87°. The average annual energy for the considered period of the study is between 2021-2019 kWh.



(a)

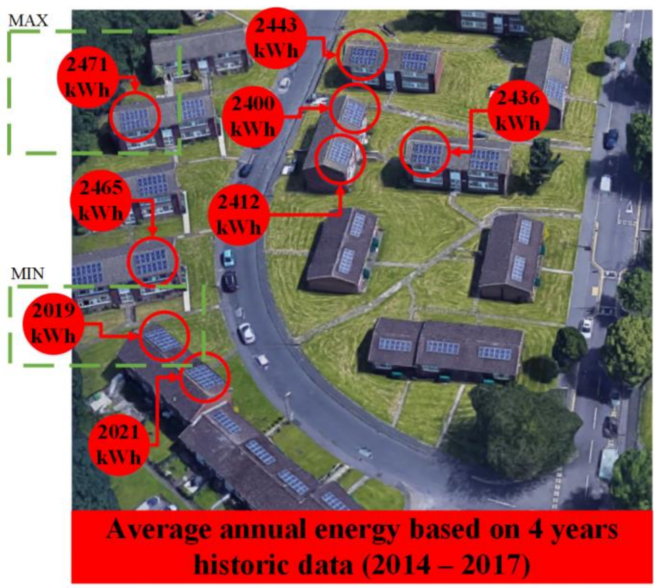


(b)

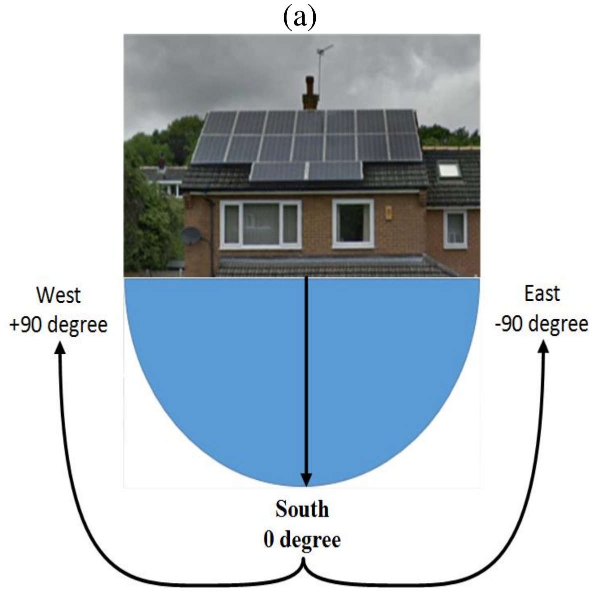
Fig. 8 (a) Average monthly energy production between 2014 and 2017 by PV systems in site B, (b) Average annual energy production between 2014 and 2017 generated by PV systems in PV site B

The distribution of the average annual energy production in all PV systems studied for site B is shown in Fig. 9. The maximum and minimum values observed are 2471 kWh, and 2019 kWh respectively. The optimum azimuth angle for the PV installations is observed to be between azimuth angles of +2° and -4°, whereas the minimum value of energy produced was observed for PV systems with azimuth angles of -87°.

A description of the azimuth angle variations between the south, east, and west is shown in Fig. 9(b). The probability of the energy production for the PV installations between the south-east and south-west will be described in the next section using the normal distribution function.



(a)



(b)

Fig. 9 (a) Average annual energy production for PV systems in site B, (b) Azimuth angle variations (South, East and West)

4. Probabilistic Modelling

In previous sections, the analysis of various azimuth angles was discussed, and it was found that the azimuth angle plays a major role in either decreasing or increasing the annual energy generation of a PV system. However, a probabilistic modelling incorporating the histogram of all measured energy at various azimuth angles will be evaluated using both normal density function (NDF), and the cumulative density function (CDF). As shown previously in Fig. 9(b) and as found in section 2 and 3, PV installations facing the south generates the peak annual energy. For that reason, the azimuth angle variations will be divided for two regions as follows: South-to-East: 0° to -90°, and South-to-West: 0° to +90°.

A histogram and a normal distribution function for South-to-East azimuth angle are illustrated in Fig. 10(a). As can be seen, the maximum mean energy is observed at 3383 kWh for 0°, whereas the minimum is detected at 2831 kWh for -90°. It is also noticeable that between the angles 0° to -20°, the annual energy yields are almost identical; between 3383 to 3353 kWh.

Remarkably, the histogram and the normal distribution of the annual energy for South-to-West azimuth angle are similar to South-to-East. This result is shown in Fig. 10(b). It is evident that there is a high correlation between the annual energy for PV systems installed at 0° to +20°; where the annual energy is always greater than 3300 kWh.

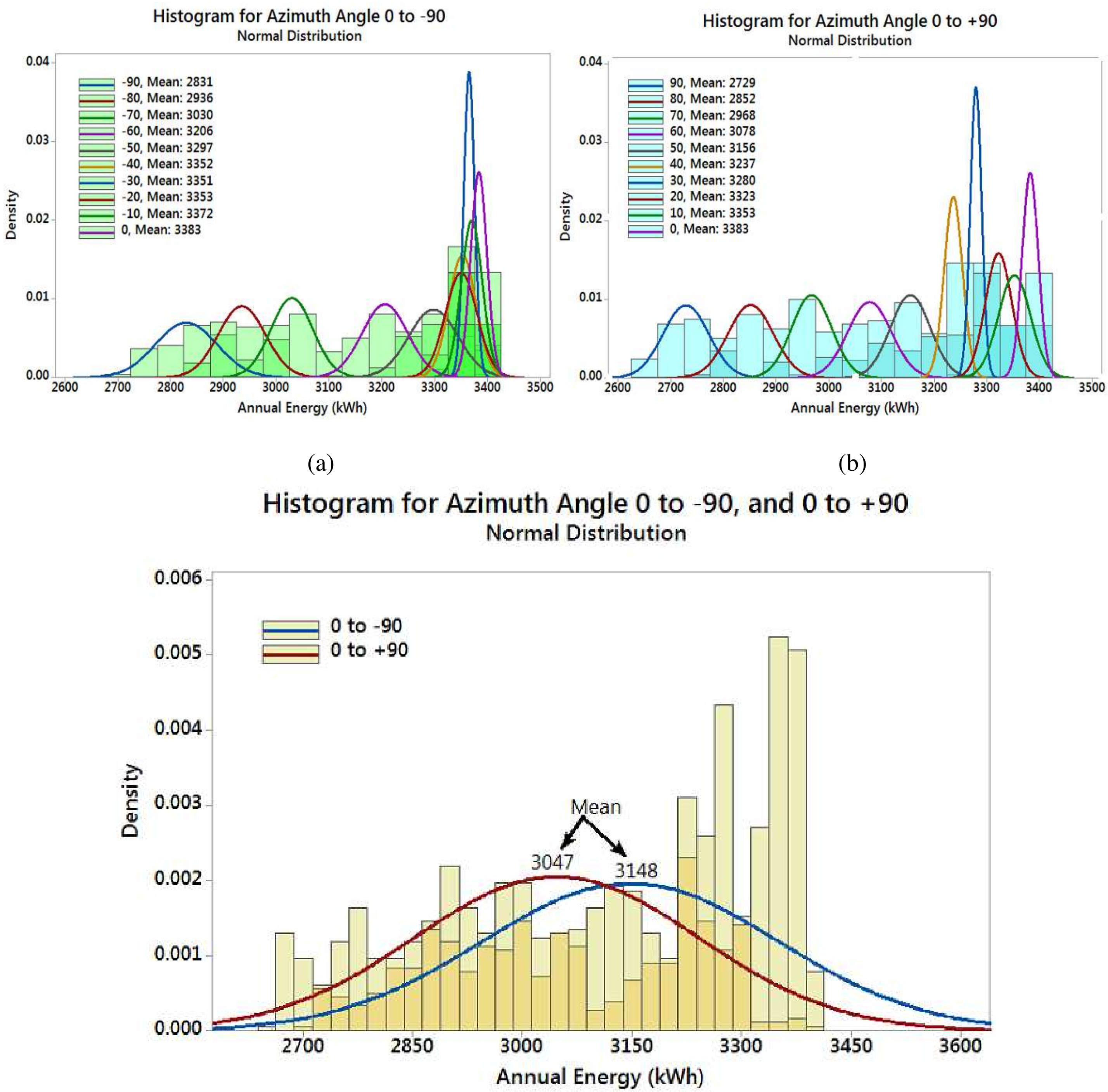
In order to compare between both azimuth angle categories (South-to-East and South-to-West), all observed samples were combined and plotted as shown in Fig. 10(c). This figure shows that the average annual energy for all azimuth angles between 0° to -90° is equal to 3148 kWh. There is slightly less output energy for all azimuth angles between 0° to +90° which is equal to 3047 kWh.

It is worthy noticing that this result does not change the fact that the annual energy yields between +20° to -20° are almost identical for all observed PV installations. However, which angle does perform at optimum probabilistic projection? The answer for this question will be evaluated using the CDF model for all data samples between azimuth angles of +20° to -20°. Therefore, it is possible to talk about how “likely” or “unlikely” a PV system at specific azimuth angle would generate energy at a specific threshold.

The output CDF plots are shown in Table 2. The CDF plots demonstrate the probability of a PV system installed at specific azimuth angle to maintain a specific annual energy. According Table 2, the CDF plots are shown at two specific projections 90% and 70%. Statistically sparking, 70% is a reasonable probability selection, sine it has been used as a rule of thumb in order to incorporate the data of a CDF model to actual representation of its findings, which is a practice that has been widely utilized [42-44].

According to the CDF models, there is 90% and 70% chance that PV systems installed at 0° would generate an annual energy of 3403 and 3391 kWh respectively. This annual energy projection is the highest among all other tested azimuth angles. The minimum projections are observed at azimuth angle of +20° at 3356 (90%) and 3337 (70%) kWh.

Remarkably, the second optimum azimuth angle is observed at -10°. There is 90% and 70% chance that a PV system installed at these azimuth would generate an annual energy of 3396 and 3381 kWh respectively.



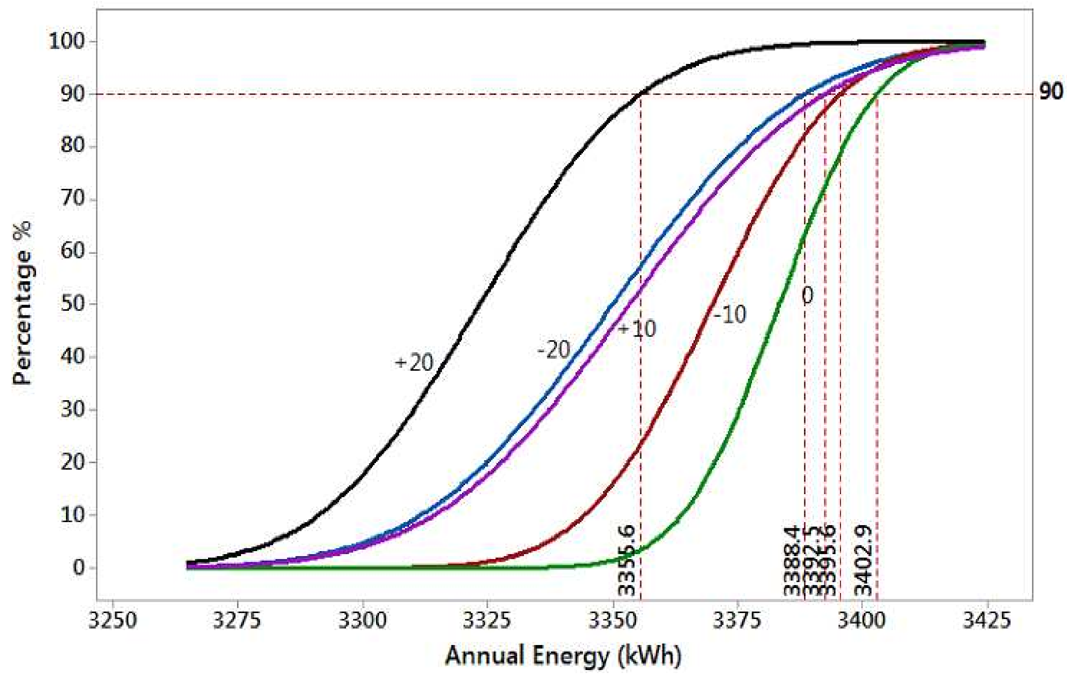
(c)

Fig. 10 Histogram and normal distribution density function for the PV annaual energy, all PV instllations capacity are equal to 3.6 kWp installted at tilt angle 41°. (a) Azimuth angle from 0° to -90°, (b) Azimuth angle from 0° to +90°, (c) Comparision between the normal distribution density function for PV azimuth angle from 0° to -90° and 0° to +90°

Table 2 CDF model output results at 90% and 70% projection rate

CDF 90%					
Azimuth Angle	+20°	+10°	0°	-10°	-20°
Output energy (kWh)	3356	3393	3403	3396	3388

CDF output Results



CDF 70%					
Azimuth Angle	+20°	+10°	0°	-10°	-20°
Output energy (kWh)	3337	3369	3391	3381	3367

CDF output Results

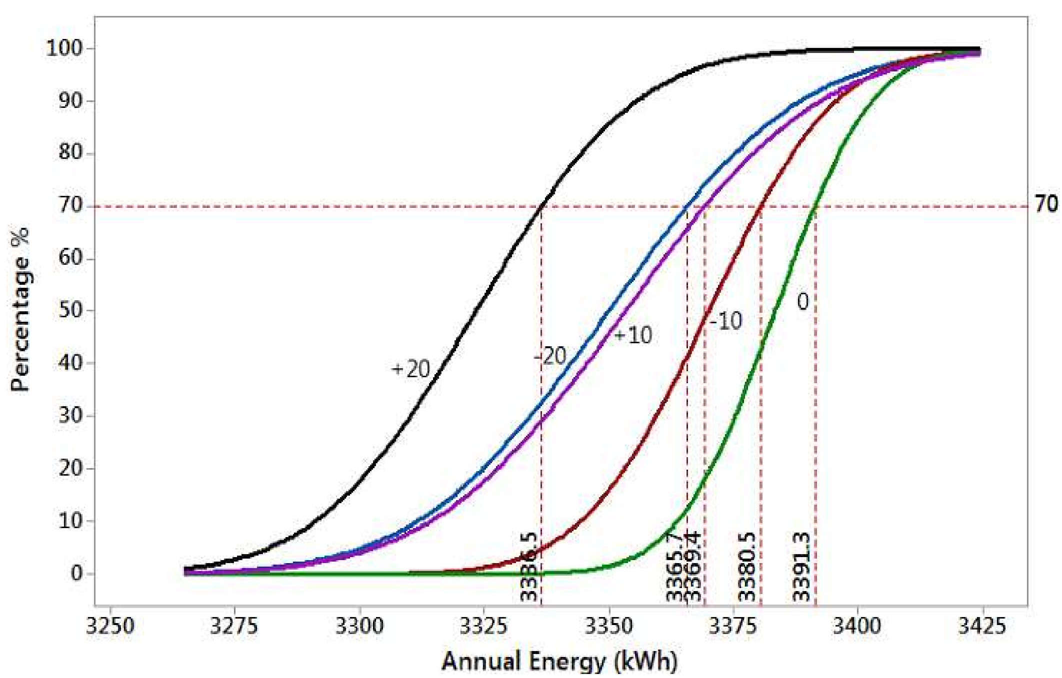
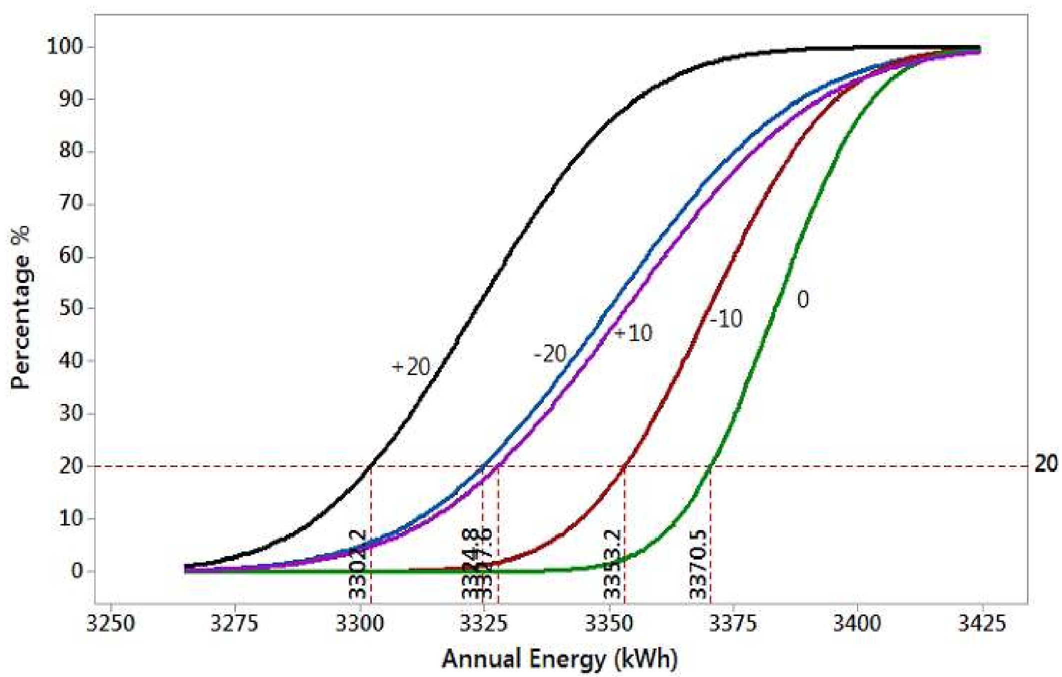


Table 2 illustrated that at 90% and 70% projection rate, the optimum azimuth angle remained at 0°. On the other hand, Table 3 shows the CDF plots projections at 20%. In this scenario, there is 20% chance that the PV systems installed at azimuth angle of 0° would generate 3371 kWh annually. Various results obtained for the observed azimuth angles as follows:

- -10° : 3353 kWh
- +10°: 3328 kWh
- -20° : 3325 kWh
- +20°: 3302 kWh

Table 3 CDF model output results at 20% projection rate

CDF 20 %					
Azimuth Angle	+20°	+10°	0°	-10°	-20°
Output energy (kWh)	3302	3328	3371	3353	3325
CDF output Results					

5. Conclusion

This paper analysed the impact of the azimuth angle on the energy production of PV installations. Two different PV sites, namely site A and site B were studied. Site A comprised PV Systems installed at: -13°, -4°, +12°, and +21° azimuth angles in different geographical locations, whereas the PV site B included adjacent PV systems installed at: -87°, -32°, +2°, and +17° azimuth angles.

In PV site A, the PV system installed at an azimuth angle of -4^0 generated the maximum energy production over the considered period (2012 – 2017), where its average energy was equal to 3537 kWh. The second highest energy production was found for the PV system installed at an azimuth angle of -13° with an average energy production of 3521 kWh. The minimum energy production was observed for the PV system installed at an azimuth angle of +21° with an average energy production of 3474 kWh over the studied period.

Results obtained for PV site B over the same period of 4 years showed a maximum annual energy production for PV systems installed at azimuth angles of +2° where the annual energy produced was in the range of 2471 - 2465 kWh. The second ideal azimuth angle was found to be at +17°, where the PV system generated a yearly energy production in the range of 2443 - 2436 kWh. The minimum energy production was observed in PV systems installed at an azimuth angle of -87°, with an average annual energy production in the range of 2021 - 2019 kWh.

6. References

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