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Determining the Optimum Tilt Angle for Solar Applications in Northern Jordan

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Abstract

Determining the optimum tilt angle for PV system based power plants is crucial to be considered when fixing the PV systems. Although the optimum tilt angle is normally close to the latitude value of the location, lots of other factors affect this. So when designing a power plant, it is necessary to take these factors into consideration to maximize the output of those plants. The present paper reviews the main scientific concepts related to solar radiation, the models used to describe the solar radiation properties, and the methods of calculating the optimum tilt angle. The optimum tilt angle for northern Jordan and, as a case study, Jordan University of Science and Technology (JUST) Campus is then calculated by applying the appropriate methods and models. In addition to that, simulation software is used to calculate the optimum tilt angle and the yield of the power station. Other factors affecting the tilt angle of a PV array are reported and relevant recommendations are given.

Keywords: *Solar Radiation, Tilt Angle, Photovoltaic, Optimum Tilt, PV Power Plants*.

1. Introduction

The lack of energy resources is one of the most challenging problems that face the economic development in Jordan; the situations are worsened even by the overall regional political disturbances around Jordan, which resulted in cutting the energy supply lines (Egyptian gas and Iraqi oil), raising the fears of energy security and causing tremendous losses in the sector of electricity generation.

Renewable energy is widely looked at as a sustainable solution that can push the wheel of development; Jordan has a good potential for renewable and solar resources in particular [1-13]. It has plans to increase the share of renewable energy in its energy mix up to 15% by 2020. Solar energy and, particularly, photovoltaics are among the main technologies that Jordan relies on to achieve its renewable energy targets [14] and to meet the increasing demand on electrical energy, especially at the northern part of Jordan.

Jordan University of Science and Technology (JUST) is located near to Irbid, north of Jordan, at (32°29' N 35°59' E). It is one of the leading universities in Jordan and the Middle East in academic and technology transfer fields. It was ranked 49th by UI Green Metric World University Ranking in 2013[18] and the 1st among the Arab universities. JUST is planning to build a 5 MWp PV power station as part of its continuous efforts toward a sustainable and green campus, besides lowering the electricity bill bought from the national grid. The station will serve the educational purposes of the university by providing practical training to the students on actual utility scale PV systems. [20]

There are many factors that affect the Levelized Cost of Electricity (LCE) that is generated from PV source; some of these factors are installation conditions, including the orientation of the PV array, distance between strings, and, most importantly, the tilt angle. [16,17,19]

The tilt angle of the solar panel affects the output of the PV array as it changes the amount of solar radiation incident on the panel; therefore, installing PV panels at an optimum angle helps reducing the LCE by increasing the energy production for the same installation. Furthermore, understanding the effect of the tilt angle and the orientation helps in predicting the yield of a specific system where the panel's tilt angle or orientation is fixed, such as rooftops applications in which the orientation and slope of the roof determine the tilt angle and the orientation of the panel.

The present paper reviews the main scientific concepts related to solar radiation, in addition to the methods used in predicting the solar radiation to be applied for obtaining the optimum tilt angle. Finally, some recommendations

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will be suggested regarding the optimum tilt angle for northern part of Jordan.

2. Solar Radiation

Solar radiation can best be approximated to the radiation of a black body with a temperature of 5780 K in both intensity and spectrum. Taking this into consideration, the extraterrestrial solar radiation falling on a surface normal to the sun's rays at the mean sun earth distance, which is also called the solar constant, can be calculated using equation 1:

$$G_{sc} = \sigma T^4 . \frac{r_s^2}{r_{se}^2} \quad (1)$$

The solar constant is approximately equal to 1367 W/m2; this value is an approximation based on the distance between the earth and the sun, which is equal to 1AU. And since the earth's orbit around the sun is elliptical, then the Gsc value may change slightly (about +3.3%) due to the change in the distance between the earth and the sun. This value was verified experimentally and the World Meteorological Organization (WMO) chose the average value 1367 W/m2 as the solar constant.

2.1. Diffusion of Solar Radiation

The solar radiation is subjected to several radiation attenuating effects when it travels across the atmosphere. There are two general cases of attenuating effects: absorption and scattering (reflection is a special case of scattering). The radiation that is neither scattered nor absorbed and reaches the surface directly from the sun disk is called direct radiation, while the scattered radiation that reaches the ground is called diffused radiation.

The radiation extinction depends on different factors, such as: humidity, cloud coverage, other residual particles; those factors can only be determined by measurements, while others can be calculated (such as the path length of the solar beam from the top of the atmosphere to a given location on the earth's surface, which is called the air mass), and it is a function of the geographic altitude of a certain location and the solar zenith angle Θ_z at that location, but it can be simplified using Eq. 2. [21]:

$$AM = \frac{1}{\cos\theta_z} \quad (2)$$

2.2. Solar Radiation on Tilted Surfaces and Radiance Distribution over the Sky

In order to determine the incident radiation on a tilted surface, the measured value of radiation on a horizontal surface can be used in addition to the direction of the beam and the diffused radiation component.

The distribution of the solar diffused radiance over the sky is shown in Figure 1. It consists of three components: isotropic dome, where the diffused radiation is uniform over the sky dome, circumsolar brightening [22], which is concentrated at the center of the sun, and horizon brightening, which is assumed to be a line source concentrated at the horizon; the latter results from radiation reflected from the ground, thus the horizontal brightening is a function of ground reflection (albedo). Clear sky diffused radiation is maximized at the horizon and decreases when moving away from the horizon and the radiance increases away from the horizon at the overcast skies, specific solar angles on tilted surfaces are shown in Figure 2.

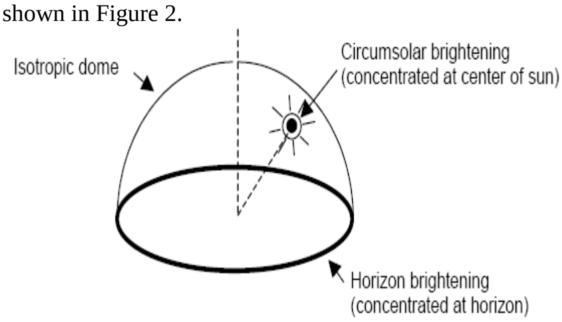

Figure 1. Distribution of diffused radiance [22]

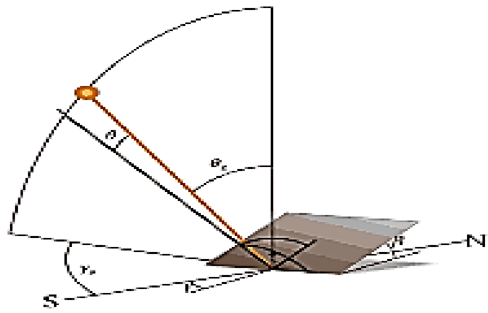

Figure 2. Solar radiation angles [21]

The isotropic model, which assumes that the diffused radiation is uniform over the sky dome, can describe the overcast or cloudy sky, while the anisotropic model, which includes diffused sky radiation in the circumsolar and horizon brightening components of the solar radiation, is more accurate in describing clear sky. Isotropic diffused solar radiation can be obtained by the following equations:

$$G_T = G_{T,b} + G_{T,d} + G_{T,ref} \quad (3)$$

$$G_{T,d} = G_d \left(\frac{1+\cos\beta}{2}\right) \quad (4)$$

$$G_{T,ref} = G_{ref} \left(\frac{1-\cos\beta}{2}\right) \quad (5)$$

$$G_{T,b} = G_b . R_b \quad (6)$$

$$R_b = \frac{\cos(\varphi-\beta)\cos\delta\sin\omega_s + \left(\frac{\pi}{180}\right)\omega_s'\sin(\varphi-\beta)\sin\delta}{\cos(\varphi)\cos\delta\sin\omega_s + \left(\frac{\pi}{180}\right)\omega_s\sin(\varphi)\sin\delta} \quad (7)$$

$$\omega_s' = \cos^{-1}(-tan(\varphi-\beta).tan\delta) \quad (8)$$

The previous equations are based on Liu and Jordan model which is one of the simplest and earliest models. Anisotropic models should take into consideration two more components, as the following equation shows:

$$G_T = G_{T,b} + G_{T,d,iso} + G_{T,d,os} + G_{T,d,hc} + G_{T,ref} \quad (9)$$

where,
G_T is the global radiation
$G_{T,b}$ is the beam radiation
$G_{T,d,iso}$ is the isotropic component
$G_{T,d,cs}$ is the circumsolar component

$G_{T,d,hz}$ is the Horizontal brightening component

$G_{T,d,ref}$ is the reflected radiation component

Researchers have introduced a variety of isotropic and anisotropic models, suggesting relations to determine the ratio of the average daily diffused radiation incident on an inclined surface to that on a horizontal surface (R_d). A. K. Yadav and S. S. Chandel conducted a review of the solar radiation models, where each model had its own limitations and conditions [23]. Nooriana *et al.* made an evaluation in which 12 models where investigated to estimate the hourly diffused radiation on inclined surfaces and compared the results to actual measured data [24]. If one of those models can be validated for a certain place and atmospheric conditions, an optimum tilting angle can be reached by varying tilt angle (β) from 0 to 90 until the solar radiation on the tilted surface is maximized.

3. Optimum Tilt Angle Calculation

Failing to install PV panels at its optimum tilt angle leads to the loss of the potential solar power. The optimum tilt angle calculations are based on maximizing the solar radiation falling on a sloped surface using different optimization techniques. In [23], the authors summarized some of the relations between the latitude and the optimum tilt angle.

This section shows the work of different researchers who have determined optimum tilt angles analytically or experimentally for a number of locations.

Skeiker [26] used a mathematical model to estimate the daily optimum tilt angle according to equation (10), and a monthly optimum tilt angle according to equation (11) for many locations in Syria, and, in addition to that, the seasonal and annual optimum tilts angles. The annual optimum tilt angle for Daraa (on the northern border of Jordan – 32°37′N 36°6′E) was *ß* = 30.13°, monthly, and the seasonal tilt angles energy gains were 28% and 26%, respectively. A major concern regarding this model was that it took into consideration the varying tilt angle to the maximize extraterrestrial radiation but disregarded the attenuation effects that changes the properties of the solar radiation. Soulayman [27] commented on Skeiker work and set all the negative values of the tilt angles to zero, identifying some other errors in his methodology.

$$\beta_{opt,d} = \emptyset - \tan^{-1}\left[\frac{h_{ss}}{\sin(h_{ss})}\tan(\delta)\right] \tag{10}$$

$$\beta_{opt,m} = \emptyset - \tan^{-1}\frac{X}{Y}$$

$$X = \sum_{n=n1}^{n=n2}\frac{24}{\pi}I_0\left[1+0.034\cos\left(\frac{2\pi n}{365}\right)\right]\sin(\delta)h_{ss} \tag{11}$$

$$Y = \sum_{n=n1}^{n=n2}\frac{24}{\pi}I_0\left[1+0.034\cos\left(\frac{2\pi n}{365}\right)\right]\cos(\delta)\sin(h_{ss})$$

Agha and Sbita [28] conducted a study for four different locations in Libya to determine the optimum tilt angle for the solar systems using an accurate simple sizing method rather than numerical methods. The selection criterion for the optimum tilt angle was based on an optimization factor (F_{opt}) as shown in equation (12):

$$F_{opt}(\beta) = H_{avg}(\beta)/SDEV(\beta) \tag{12}$$

where H_{avg} is the monthly average of the daily total of the solar irradiation (kWh/m^2.day), SDEV is the standard deviation of the curve that represents the divergence between the normalized load curve and normalized solar irradiation curve at a certain angle.

One of the cities, included in this study, is Tripoli, *Lat.*=32.87° which is close to that of the northern part of Jordan. The optimum tilt angle for Tripoli is about 25°. One of the assumptions of the present study is, excluding the cloudy days, even though Tripoli is a coastal city, both Tripoli and Jordan have a near latitude but concerning other factors, like the weather conditions and temperature variation, solar radiation, etc., which affect the optimum tilt angle, they are different.

Moghadam *et al.* [29] conducted a study to determine the optimum tilt angle of the solar collectors in Iran by making a simulation using MATLAB program. Iran is located on the sun belt of the world and has a high value of solar radiation; it is mostly sunny all year around. Moghadam *et al.* [29] calculated the monthly, seasonal, semi-annual and annual optimum tilt angles for Zahedan city (*latitude* = 29.49°). The annual optimum tilt angle for Zahedan was equal to 28°. The study also found that the tilt angle was equal to 5° in the first half of the year and 50° in the second half and if the tilt angle is adjusted two times in a year, the total annual extra received energy will be more than 8% .

Talebizadeh [30] developed new correlations to calculate the monthly, seasonal, and yearly optimum slope angles for latitudes of 20° to 40° north, suggesting that the annual optimum tilt angle was $\beta_{opt} = 0.6804\emptyset + 7.203$. Therefore, the optimum for locations in northern Jordan equals 29.17°. The correlations were obtained according to the optimum slope angles predicted by the researcher and using the optimum slope angles achieved by other researchers at locations out of Iran but in the same range of latitudes; the results showed that the optimum azimuth angle is zero for receiving maximum solar energy.

It can be noticed that the previous results are consistent with the simple and general correlations to determine the optimum tilt angle depending only on the latitude that can be used as a rule of thumb, such as Heywood [31] who came up with the following equation:

$$\beta_{opt} = \emptyset - 10^{\circ} \tag{13}$$

According to equation 13, the optimum tilt angle in the northern part of Jordan is equal to 22.29 degree. Or Lunde [32] suggested the following equation:

$$\beta_{opt} = \emptyset \pm 15^{\circ} \tag{14}$$

The optimum tilt angle for the northern part of Jordan, according to equation 14, is equal to 17.5 in summer, 47.5 in winter, where the plus and minus signs are used for the winter and summer seasons.

Duffie and Beckman [33] suggested that the optimum tilt is in the range of the latitude plus 10° to the latitude plus 20°, and the variation of 10° either way outside of this range, so, accordingly, the optimum tilt angle (*ß*) is equal to 52.29° - 62.29°, in winter, and from 32.29° to 42.29°, in summer. That was determined to insure the visibility of a thermal system recommendation but is not expected to be accurate within the view of a PV system.

4. PV System Simulation

PVSYST is a simulation tool that can be used to calculate all the design parameters for a PV system; it uses an anisotropic model (transposition: Perez, Diffuse: Erbs) and uses Meteonorm solar radiation data with long-term solar radiation measured values. Figure 3 represents the main parameters that are entered into the simulation software. The simulation is based on hourly values, using PVSYST, the optimum tilt angle all over the year is about 30°, as shown in Figure 4. Meanwhile, the seasonal tilt angle is about 10°, in summer, and 50°, in winter, as shown in Figure 5 and 6.

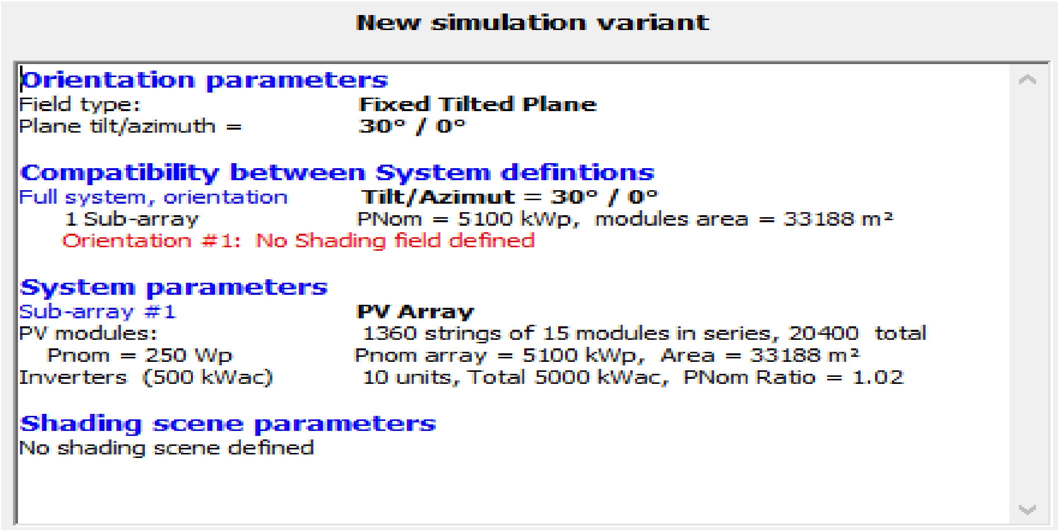

Figure 3. Parameters of the Simulation

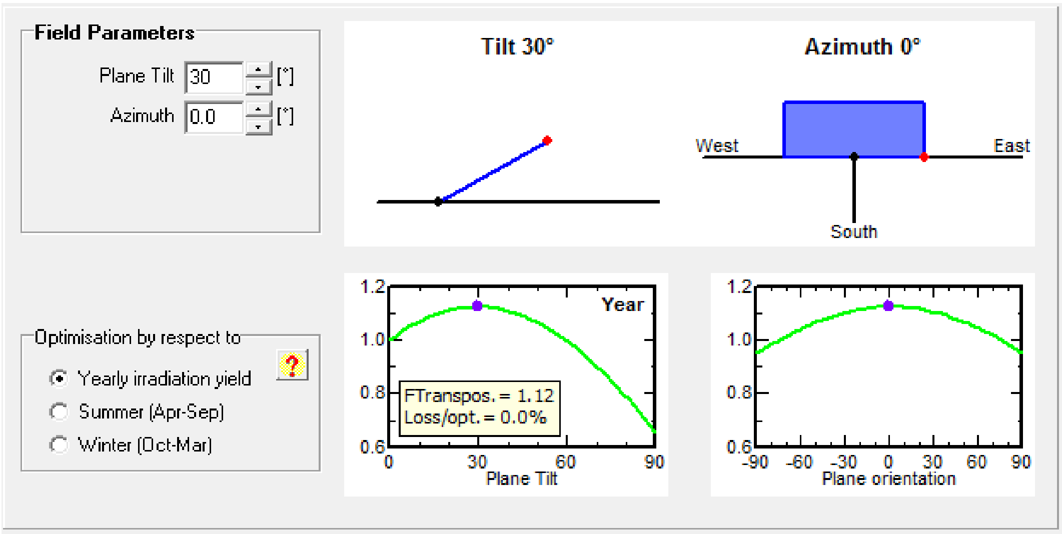

Figure 4. Year optimized angle

The yield of the 5 MWh PV solar system was also simulated using the software and meteorological data of Jerusalem city (31.8°N , 35.2°E). The main simulation results are shown in the Figure 7:

5. Applying Results to JUST Station

Most of the relations from the literature lead to an optimum angle between 22° and 30°, though other factors should be taken into consideration in order to get a practical result. Those factors can be summarized as follows:

- The above relations do not take the altitude into consideration.
- The above relations rely only on the idea of maximizing radiation, that might be the general case, but in winter the threshold of the inverter might not be satisfied in a few days due to small radiation; if such days are excluded from the calculations, the result may shift toward the summer optimum angle.
- There might be some weather conditions occurring over parts of the day during the year, such as a summer cloud cover in the afternoon, which might change the results depending on its frequency.
- Some geographic features may play a role in determining the optimum tilt angle and the orientation of the array.
- Land usage and the PV array shading losses are also important issues in a multi-line array.

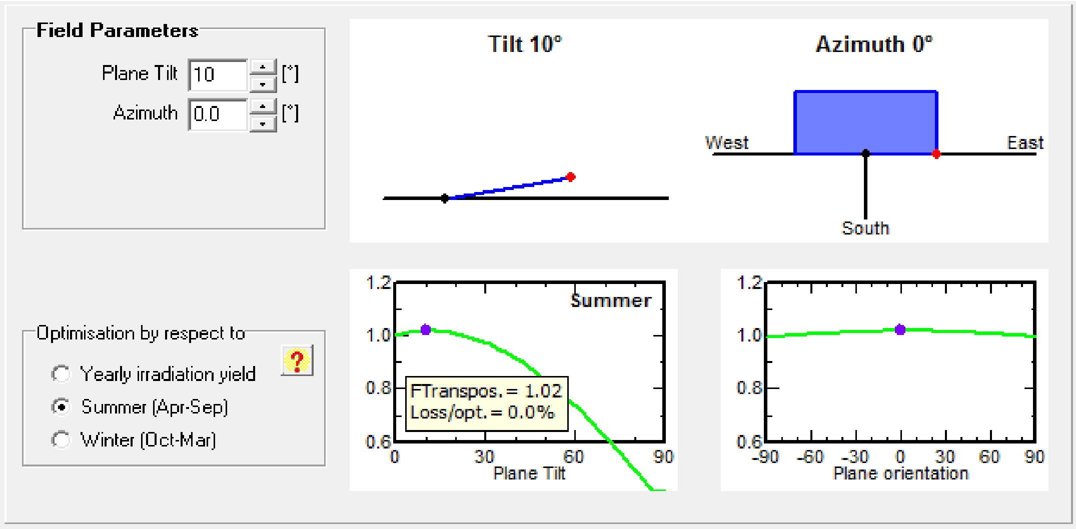

Figure 5. Summer optimized angle

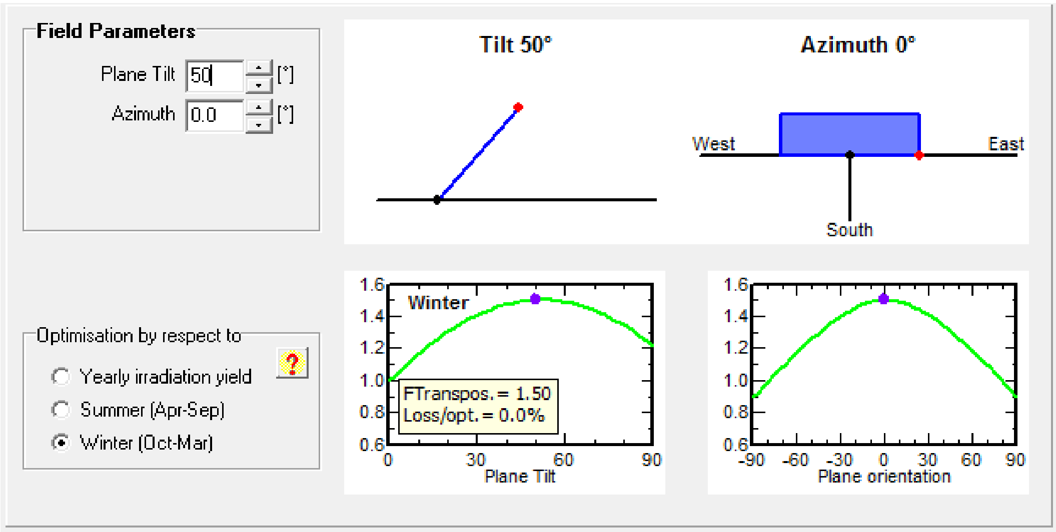

Figure 6. Winter optimized angle

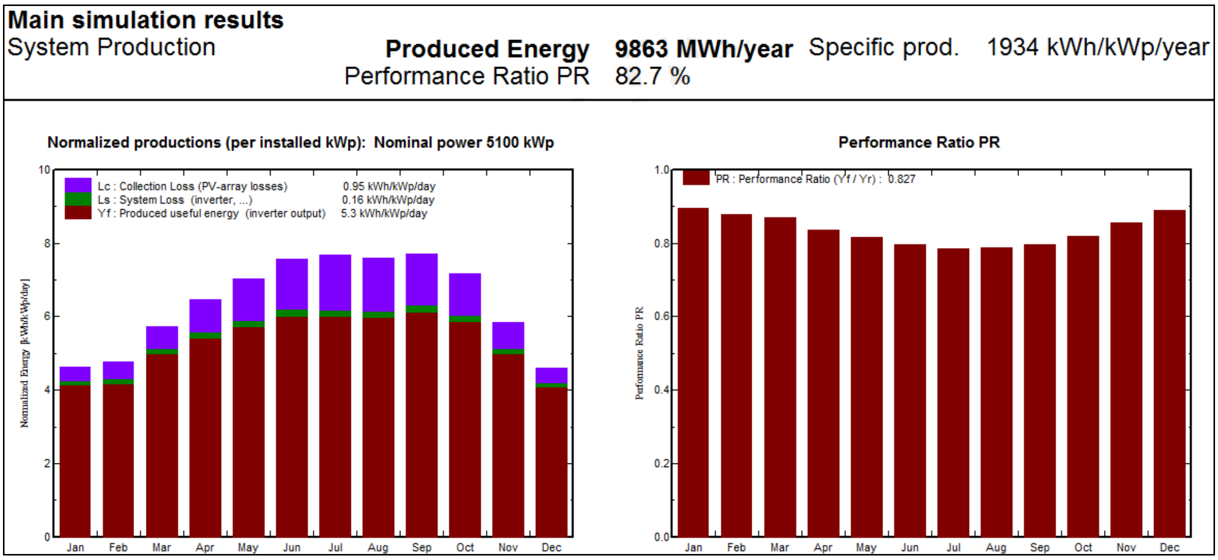

Figure 7. Main simulation results

Table 1. The different results based on references

Author	Result for JUST (32.29oN)
Etier [4]	30° @ 32.05°N
Skeiker[26]	30.56o @32.37oN
Agha and Sbita[27]	25o @32.87oN
Moghadam [28]	28o @29.49N
Talebizadeh [29]	29.17o
Heywood [30]	22.29o
Lunde[31]	32.29o
PVSYST	@ 31.8N

Based on the result of the simulation of the optimum tilt angle is 30° and Summer optimum tilt angle 10° and winter optimum tilt angle 50° as Table 2 shows:

Table 2. The yield of the 5MWp System in MWh per deferent tilt angle

Month	tilt=10°	tilt=30°	tilt=50°	best tilt	best value
January	527	655.8	714.7	50	714.7
February	517	596.4	617.7	50	617.7
March	735	788.3	769.8	30	788.3
April	830	829.2	755.7	10	830
May	965	904.5	766.1	10	965
June	1024	920.2	738.1	10	1024
July	1040	949.6	775.5	10	1040
August	974	944.9	831.5	10	974
September	892	938	897.6	30	938
October	804	926.7	957.9	50	957.9
November	617	764	829.6	50	829.6
December	508	645.7	731.5	50	731.5
Year	9433	9863.3	9385.7	30	10410.7

The simulation shows that if the variable tilt angle is adopted the yield of the system will increase decently; Table 3 demonstrates the cases simulated and provides a summary of the results. The result is consistent with other results obtained by other researchers in the literature; though the results are not identical due to the different location [15, 26 and 27]. The result obtained by 26 and 27 are the yield solar radiation, not the electric yield. And the value of the additional yield was calculated based on 0.20 JD/kWh.

Table 3. The yield of the 5MWp System with different cases

Case	Year optimum tilt	Simi annually tilt	quarter annually tilt	Monthly tilt
Yield (MWh)	9863.3	10328	10410.7	10465.8
Increment (%)	0	4.71	5.55	6.11
Value of the Additional energy (JD)	0	92940	109480	120500

6. Conclusions

Using the correlation and data available in the literature, an optimum angle was found to be around 30°; this result was verified by PV SYS software. To get an accurate and a confirmed value, we need to study the different radiation models and decide which one applies best to JUST site and, then, run our own simulation based on an hourly measured direct and diffused solar radiation. A system with a changeable tilt angle, on a monthly basis or seasonal basis, may increase the yield of the system to about 6%, 5.5%, respectively. For the case of the monthly optimum angle that can be about 600 MWh per year for JUST site, this result is consistent with other results from the literature with a small difference due to the variance in latitude [15].

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