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SIMULATION OF AN ENERGY-GENERATING HOME CANOPY USING PHOTOVOLTAIC PANELS WITH MULTIPLE TILT ANGLES

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ABSTRACT

Due to the effect of changing the angle of incidence of solar radiation on the surface of the photovoltaic panel in determining the amount of electrical production, the world is heading today to study this effect and work to achieve the optimal position of the panel to increase its efficiency. This includes studying and analyzing the angles of PV panel tilting, taking into consideration the change in the position of the sun (altitude angle). In this article, a system has been designed using MATLAB/SIMULINK software to simulate the work of a home canopy that exploits photovoltaic panels to generate electrical energy. The system is designed to process multiple data at the same time, ten tilt angles of panels are adopted, in addition to taking into account the change in the position of the sun (from 40° to 80°) in winter and summer respectively, every second over a whole year. The curves of the proposed model showed that the high solar elevation angle in summer of Iraq (which did not require significant tilting of the panels to obtain vertical radiation (only 10°-20°) allows for the benefit of panels installed on a flat surface, at least if the panels cannot be oriented at the required tilt angle. However, flat panels are not effective in the winter due to the need to orient them at a relatively high tilt angle (50°) to obtain vertical radiation. It is also possible to design a fixed canopy throughout the year with panels tilted at an angle close to the latitude of the station's geographic area, given the relatively high radiation values in Iraq throughout the four seasons. these results show realistic behavior with excellent accuracy, by reaching the required monthly and seasonally tilt angles, which confirm the importance of having accurate models that enable the users to estimate angles and production quantities under different conditions and locations.

KEYWORDS

Tilt angle, simulation, optimum tilt, home canopy, solar altitude.

1. INTRODUCTION

Residents in Iraq tend to seek viable alternatives to the deteriorating main network, ensuring continuous power supply throughout the day as much as possible. Given that solar energy sources in Iraq are among the most sustainable due to the country's high irradiation levels Fig.1, photovoltaic panels represent an attractive option for many local residents (Ghazi et al., 2021). To harness this clean, safe, and sustainable solar energy, residents typically use the roofs of their homes to install solar panels and harness the generated energy to power various household appliances. As is well known, the amount of energy produced by panels is directly proportional to the area of the panels installed. Therefore, to increase the number of panels and increase generation capacity, residents seek to invest in other suitable spaces. An example of this is the outdoor patio umbrellas (canopy) found in most Iraqi homes, which protect them from the heat of the sun and dust in the summer, and from rain and wind in the winter Fig. 2.

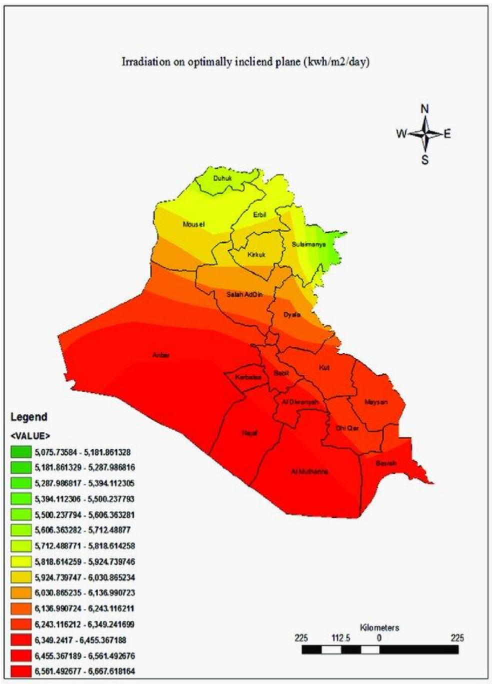

Fig.1. The potential of irradiation on horizontal plane (kwh/ m2 /day) (Hussain and Mahdi, 2018)

Fig.2. A canopy in the front yard of the house

In a photovoltaic system, solar radiation is directly converted into electrical energy (Syed et al., 2013;Ahmed S. F., 2007;Mia et al., 2024). This energy is generated depending on several factors, including radiation intensity, energy conversion efficiency, system location, panel installation orientation, tilt angle, and other weather conditions.

It is well known that one of the most important factors influencing increased solar panel production is the continuous incidence of sunlight on the photovoltaic panel to ensure continuous electrical energy generation (Al-Jabari et al., 2022). However, the continuous incidence of sunlight on the panel alone is not sufficient to achieve optimal production. The angle of incidence of sunlight on the photovoltaic panel plays a major role in determining the amount of electrical production generated (Manowska et al., 2023). Radiation on Earth is most intense at points directly facing the sun. Therefore, the more perpendicular the rays are to the panel, the greater the production efficiency. This causes the generation level to change throughout the day and throughout the seasons, due to the changing position of the sun during the day and seasons, respectively, which changes the angle of incidence on the photovoltaic panels (Abed & ghaydh, 2023), Fig.3.

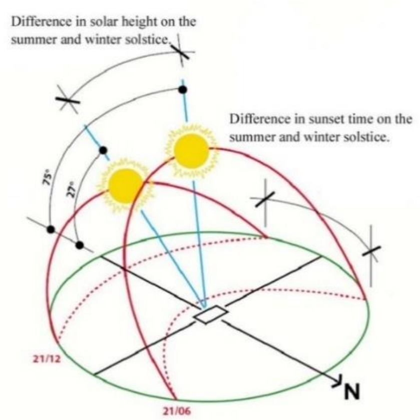

Fig.3. The altitude solar angles during winter and summer solstice shows the change in position of the sun during the day and seasons

Therefore, many studies focus on studying the effect of photovoltaic cell orientation and tilt on the solar panel performance to reach the optimum angle which generate the maximum amount of energy comparing with other angles. Study (Jain & Kaur, 2015) changed the tilt angles of the panels to make them perpendicular to the solar radiation to achieve optimal energy production in a solar power plant in a remote village in India. Meanwhile, Study (Mufti et al., 2022) relies on changing the orientation of the panels based on the azimuth angle.

While some researches found a preference for changing the angle of the panel's tilt monthly (Ahmed, B. et al., 2021) as well as (Benghanem M., 2011) which was conducted in Medina in Saudi Arabia, which is characterized by weather conditions similar to those of the city of Najaf (the site of the current study). While some researches recommended changing the direction of photovoltaic panels seasonally (Ali F., 2018) as well as (Singh et al., 2021) which conducted the research in the cities of New Delhi and Nagpur in India, taking into account optimization techniques based on available theoretical models.

Also in Study (Prunier et al., 2023), the optimal dates and the optimal angles have been calculated for PV panels located at Reykjavik (Iceland), Sherbrooke (Canada), Quito (Ecuador), and Brasília (Brazil). It was found that twice-annual reorientation was the most suitable option for all locations, resulting in a 3% to 4.8% increase in annual energy production compared to no reorientation. For short-term installations, using optimal orientation can improve energy production, for example, by 13% for a monthly installation in Brasilia.

It was mentioned in (Torres and Crichigno, 2015) relationships to calculate the approximate optimum angles of inclination at any latitude between 25° and 50° north of the equator for the seasons, summer (30-April) and winter (12-September), as in the relationships below:

$$\theta_{summer} = \text{latitude} \times 0.93 - 21 \quad (1)$$

$$\theta_{winter} = \text{latitude} \times 0.875 + 19.2 \quad (2)$$

This is what Suleiman et al. (Soulayman S., 1991) also showed, that the optimal inclination angle is approximately equal to the latitude.

In (Alam et al., 2024), a model based on the MacCormach explicit finite difference technique was used to predict the optimal tilt angle for south-facing solar panels in India. For the analysis, 23 Indian locations with diverse climatic conditions were selected to estimate the monthly, seasonal, and annual values of the optimal tilt angles. The estimated monthly optimal tilt angles were compared with those obtained by other researchers, with the maximum increase being 4.35% in Sri Nagar during August and 7.6% in Sri Nagar during the second season.

Study (Gwesha & Alfulayyih, 2020), conducted in Arizona, USA, considered the availability of sunlight or sky coverage conditions for short enough periods throughout the year in the modeling to calculate solar power on photovoltaic panels and optimize the panel tilt angles to achieve optimal tilt angles. The analysis calculates the instantaneous sun rays vectors and the vertical orientation of the solar panels to account for the cosine effect. However, the analysis is performed by adding up the energy harvested by the photovoltaic panels every 6 minutes. The study results showed an increase in the annual solar energy production received by a solar panel tilted at a fixed angle equal to the local latitude, taking into account the ten-year average sky coverage every 6 minutes. Further increases of 7.59%, 7.60%, and 9.19% were achieved if the panels were tilted at the optimal angles discovered with adjustments twice, four seasons, and monthly, respectively, compared to a fixed angle equal to the local latitude.

In (Sırdaş & Kaynaklı, 2024), the most suitable solar panel angles for Bursa city center and Uludağ were investigated, focusing on determining the optimal panel angles on a monthly, seasonal, and annual basis. The calculation method involved mathematical simulation of the panel angles for both regions using MATLAB. Angle values were determined for each degree in the range of 0-90 degrees for 365 days, based on the maximum irradiance, taking into account the effects of elevation and snow surface reflectance. The results showed that the annual optimal panel angle is 34 degrees for the city center and 39 degrees for Uludağ. It was observed that the effects of elevation and snow surface reflectance lead to higher panel efficiency, and that the angle values are higher in winter and lower in summer, but the annual total irradiance values are the same due to seasonal gains.

As it is evident from previous studies that they focused on optimization techniques or theoretical analysis to select the optimal angles monthly, seasonally or annually, but they did not provide an accurate analysis of the behavior of panels at all tilt angles, an analysis that can be monitored and changed to observe the effect of changing parameters instantly, as in the current study. Also, most studies analyzed the effect of parameters separately rather than combined. It is true that study (Gwesha & Alfulayyih, 2020) studied the effect of panel tilt angles and the sun elevation angle, but it used another methodology to analyze the data, since it developed a program in MATLAB using mathematical equations to calculate the average daily/monthly total radiation on an equatorial surface with tilt angles varying from 0 to 90 degrees. Using the MATLAB software package, graphs were drawn of the total radiation versus tilt angle for each month. Second-order polynomial equations were developed to fit the curves, also this study was not conducted under the special conditions of Iraq.

The current paper adopts simulation to develop an integrated model that accepts changing a set of parameters to provide a clear and accurate view of the behavior of panels when changes occur instantly, for Iraqi conditions specifically.

This paper study the design of a model that simulates the operation of a home's canopy to generate electricity using photovoltaic panels, as a feasible and widespread home option. The model, developed in MATLAB/Simulink, analyzes the behavior of this plant when the tilt angles of the panels change with the sun's elevation angles, in addition to the possibility of modifying some other parameters, such as the area of the panels used and their efficiency.

The model does not aim just to find the best angle monthly, seasonally, or annually, as most previous studies have focused on, rather, it provides a design that allows for monitoring and analysis every second throughout the year, observing the effect of changing panel tilt angles and changing sun elevation on the amount of energy generated. It also allows for changes in any of the design parameters, providing an accurate model for simulating, monitoring, and analyzing reality.

2. METHODOLOGY

To observe the impact of the angle of incidence of solar radiation on the panels and monitor their performance during the year to reach an optimal design for the canopy invested to generate energy, the MATLAB program has used to design a model that simulates the work of a home canopy in the city of Najaf in Iraq, which invests PV panels to supply the house with electrical energy.

In the model, the movement of the sun was taken into account every day throughout the year, in addition to changing the tilt angle of the PV panels directed towards the south to capture the greatest amount of radiation intensity and trying to obtain the largest amount of the perpendicular radiation, which is an improvement of the model used in paper (Abdulridha et al. 2020). Where the tilt angles of the panels (β) has changed from (0-90°) with a step of 10 degrees, while the altitude angles of the sun (δ) has represented for every second over a whole year.

Fig.4 shows the relationship between the incident radiation (H) on the Earth's surface at the altitude angle of the sun (δ) and the effective radiation ($H_{effective}$) perpendicular to a solar panel, the panel tilted with an angle (β). This relationship can be represented as following:

$$H_{effective} = H \cdot \sin(\delta + \beta) \tag{3}$$

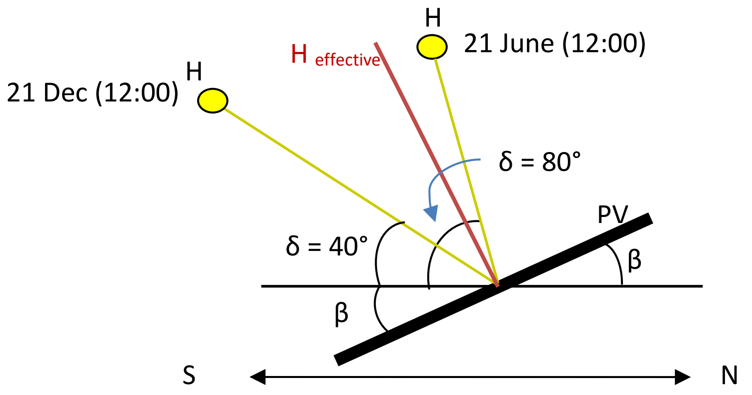

Fig. 4. The tilt angle of the PV panel (β), the altitude angle of the sun (δ), incident radiation (H) and perpendicular radiation (Heffective)

The performance of the panels has monitored by calculating the electrical energy produced by the solar panels Equ.4 and comparing the results for all angles.

$$E = H_{effective} \times A \times \eta \times t \tag{4}$$

where, E: Electrical energy (Wh); H: Solar irradiance (W/m²); A: Panel area (m²); η: Panel efficiency; t: Time (h).

Fig. 5 illustrates a dynamic Simulink model that calculates the energy produced based on the relationship (3) which analyzes the behavior of the panel tilt angles (10 values) along with the changes in radiation values (due to changes in the altitude of the sun).

In the designed model, the average intensity of radiation falling on the horizontal surface was taken as a constant value (1380 W/m^2). The dimensions (5 x 3) m^2 were adopted as the area of the canopy carrying the panels, taking into account the efficiency of the panels (which represents the percentage of solar energy falling on the surface of the panel that is converted into usable electrical energy) at a value of 20% Fig. 6.

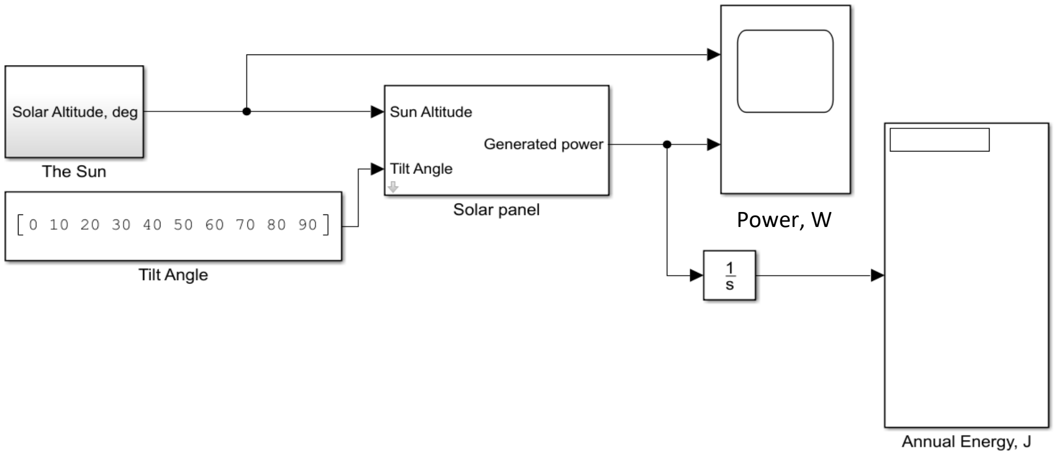

Fig. 5. Simulation model of the operation of the home energy-generating canopy at different tilt angles throughout the year

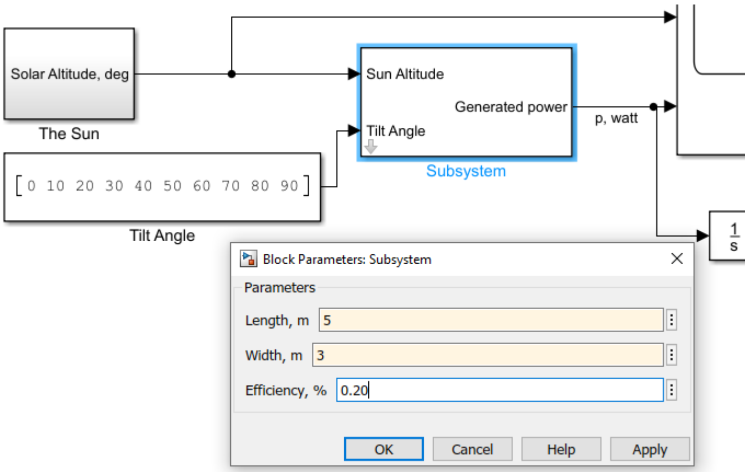

Fig. 6. Window of system inputs

In the first part of the system (solar altitude, deg), the sun altitude angles (δ) has been represented as an approximate curve starts at (40°) and reaches the highest value (80°) approximately, this curve also consists of pulsations representing the change in the position of the Sun during day every second throughout the year Fig. 7 a & b. The values of the angles (δ) above represent the lowest and highest value reached by the sun altitude at the winter and summer solstice, respectively. Fig.8 taken from application SunCalc (application SunCalc, 2022) shows how to get the value of the sun altitude at winter and summer solstice according to the geographical location chosen.

3. RESULTS AND DISCUSSION

Fig.9 a & b shows the curves represented for the purpose of implementing relationship (3). By representing this relationship in the designed model, the resulting power curves look as in Figs10 a & b, where it can be observed that the behaviour of the produced power change between winter and summer with the change in the values of the altitude angle of the sun (δ).

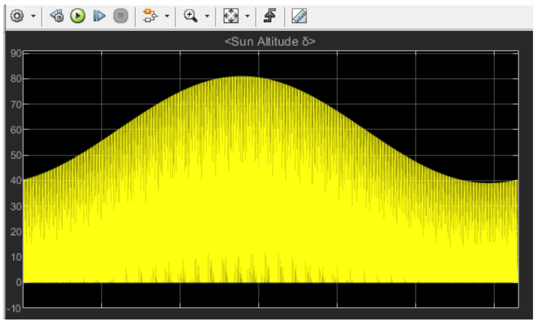

Fig. 7 a. Representation the altitude angle of the sun each second throughout the year

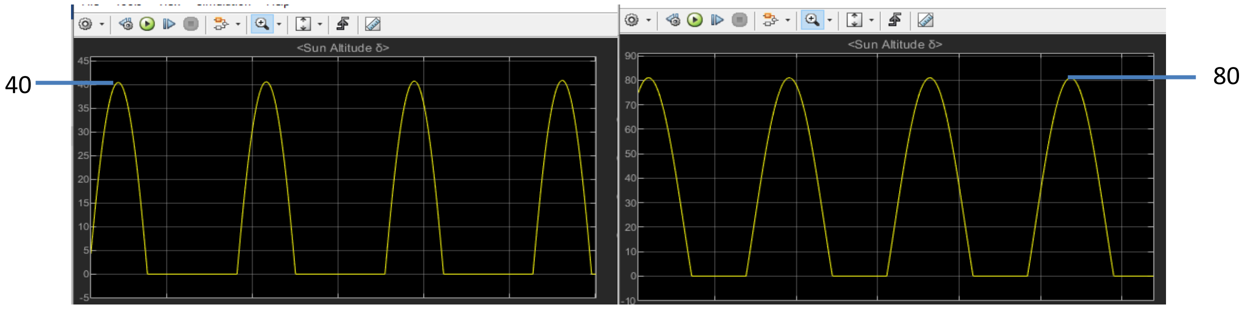

Fig. 7 b. Maximum (right) and minimum (left) altitude angle of the sun each second

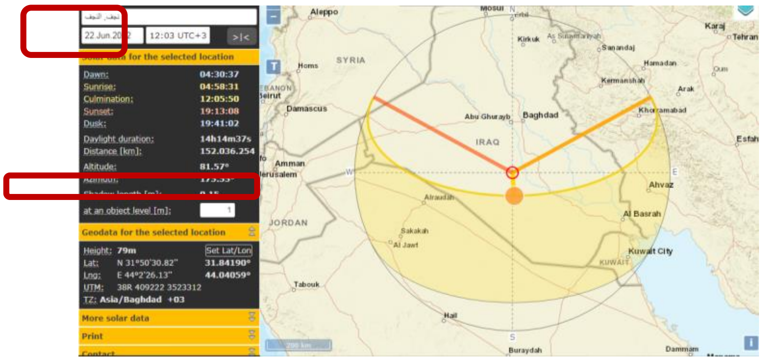

Fig. 8. The application interface of (SunCalc) shows the data of the geographical location chosen in this research

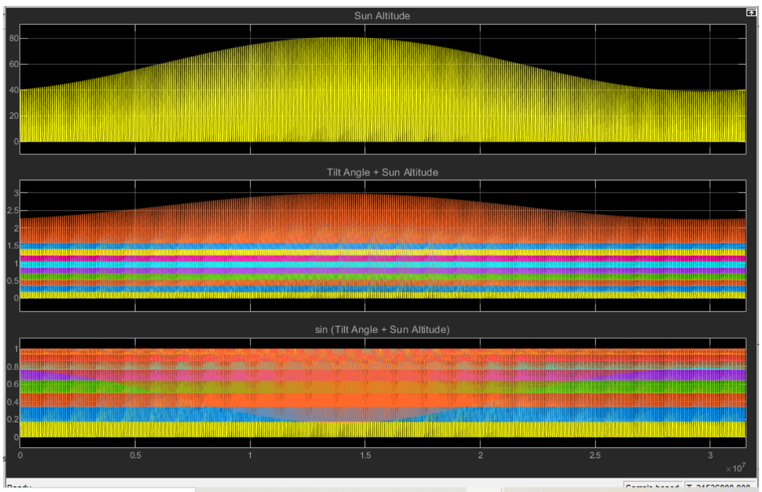

Fig. 9 a. Representation of the tilt angles of the panels and the altitude angle of the sun in the designed model

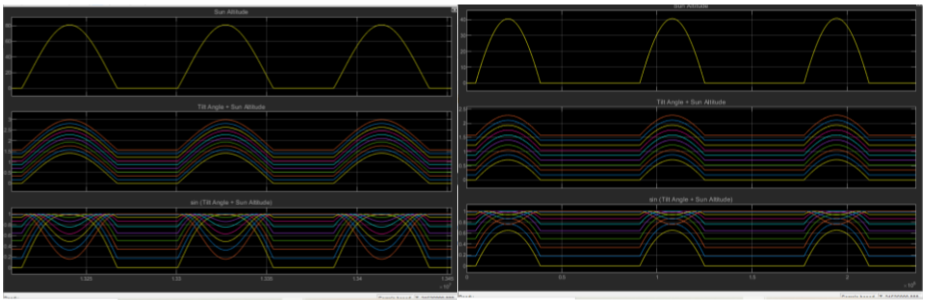

Fig. 9 b. An enlarged figure of the curve representing an approximate behaviour of the angles every second for summer and winter

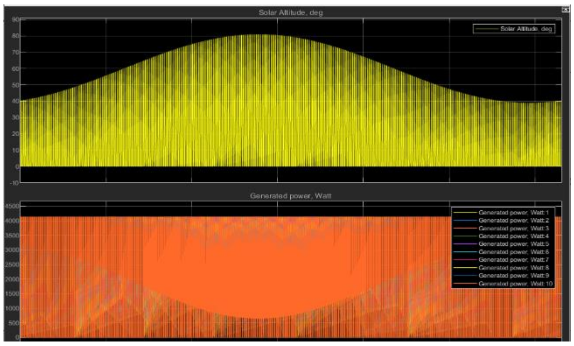

Fig. *10* a. Altitude angle and output power throughout the year

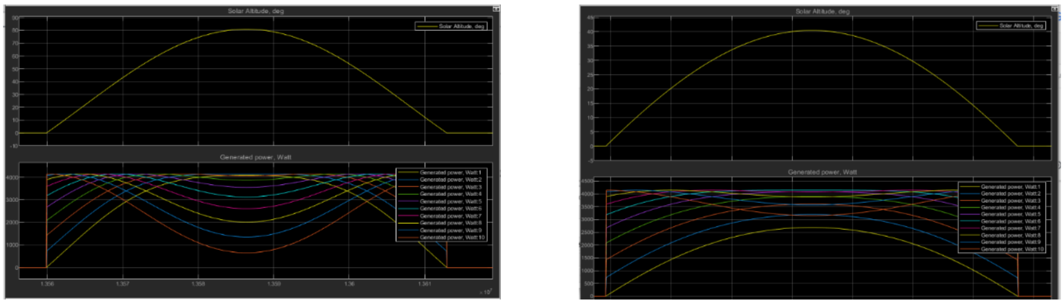

Fig. 10 b. The effect of changing the altitude angle of the sun on the behavior of the produced power for each tilt angle of panels, for summer (left) and winter (right)

It is noted from the curves data box in Fig.10 b that the highest value of the output power reached approximately (4 kw) at a tilt angle (10° - 20°) in summer, and (50°) in winter.

It is worth noting that the radiation intensity was taken as constant in the designed model, so by using the monthly radiation values for the chosen geographical area, the results will be more accurate and realistic. Figs.11a & b shows closely the behaviour of the resulting power at each angle of inclination of the panels.

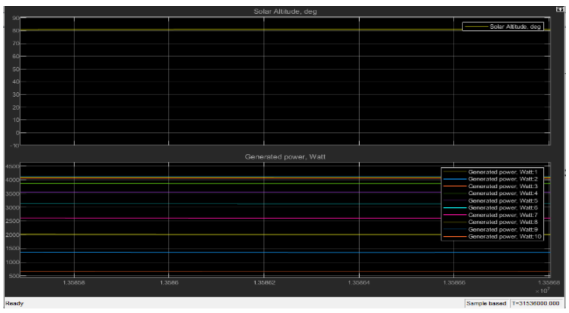

Fig. 11 a. The highest power values generated by the tilt angles of the ten photovoltaic panels for the summer season

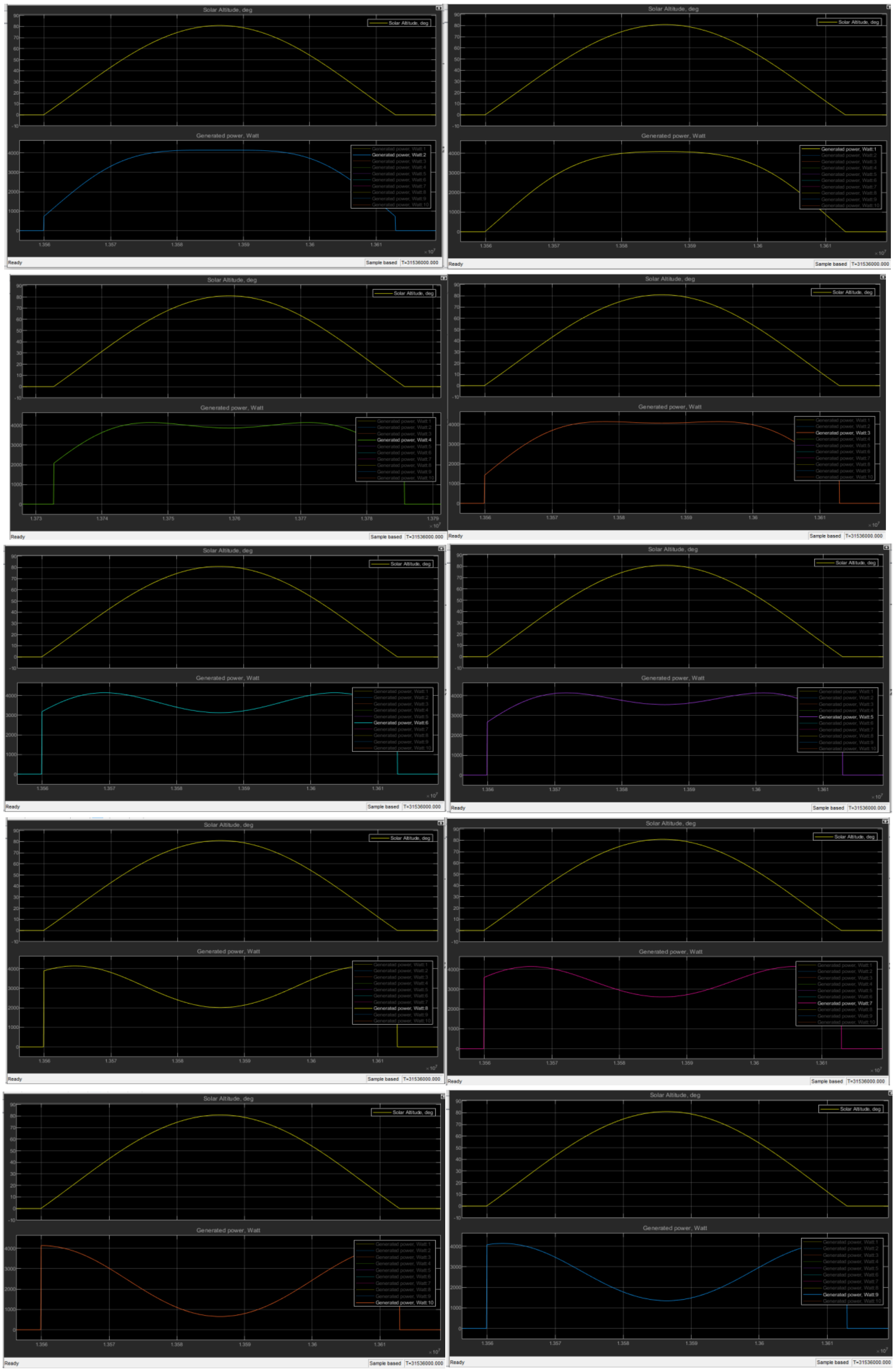

Fig. 11b The highest power values for each tilt angle of PV panels separately

It can also be observed the effect of changing the tilting angles on the annual energy value as in Fig. 12, where the highest annual energy values were (10,687 * 10^3 kWh) at the tilt angle (50°), other power generated values are listed in Table 1.

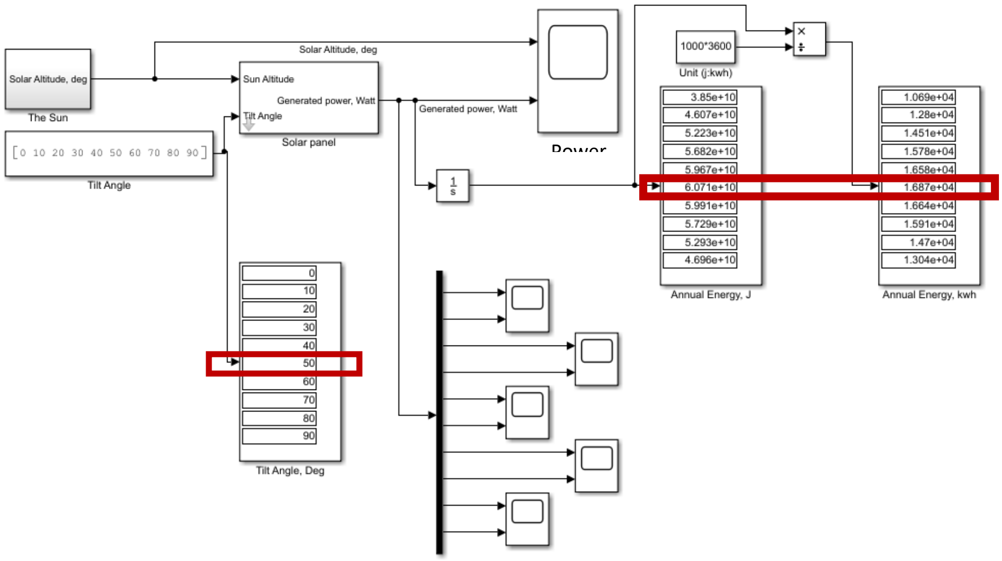

Fig. 12. Annual energy measurements generated by the designed model

Table 1. Power delivered with each angle

Tilt angle (°)	0	10	20	30	40	50	60	70	80	90
Power (kw)	2.97	3.56	4.03	4.38	4.61	4.69	4.62	4.42	4.08	3.62

(Ahmed B. et al., 2021) found that the average optimum tilt angle for Baghdad (latitude 33° 21': close to the geographical location of the current study site) equal to 33°, while summer tilt angle is 15° and winter angle 51°. Also (Abbood et al., 2017) reached the values shown in Table 2 for all months of the year in Baghdad, where the average angles for the summer months (May-August) is 18°, and the average of winter months (November-February) is 48° and the average angle for all months of the year is 33° which is preferred to be chosen if the fixed panel system is used throughout the year.

It is also clear that the results of the proposed model are very close to the above results.

Table 2. Monthly and seasonally optimal tilt angle panel for Baghdad

Season			**Summer**						**Winter**			
Month	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
Optimal tilt angle	23°	14°	10°	12°	20°	31°	43°	52°	56°	54°	47°	36°
Average			18°						48°			

From Tables 1 and 2, the monthly power generated by the umbrella when its panels are tilted at the optimal angle for that month can be estimated. Also, the results of the model designed in this research are close to the theoretical calculations in relationships 1 and 2 proposed for calculating the tilt angles of the panels in summer and winter.

$$\theta_{summer} = \text{latitude} \times 0.93 - 21 = 31.8 \times 0.93 - 21$$

$$\approx 9^o \text{ (for Najaf lat. =31.8)} \approx 10^o \text{ (for Baghdad lat. =33)}$$

$$\theta_{winter} = \text{latitude} \times 0.875 + 19.2 = 31.8 \times 0.875 + 19.2$$

$$\approx 47^o \text{ (for Najaf lat.} = 31.8) \approx 48^o \text{ (for Baghdad lat. =33)}$$

4. CONCLUSIONS

The most influential factor in determining the amount of electricity production is harvesting vertical radiation for the longest possible period of the day. This is achieved by varying the tilt angles of solar panels to keep them perpendicular to the incident radiation.

The model successfully represented the behavior of the panels under the conditions adopted in the current study. This was achieved by simulating the effect of the two parameters: solar panel tilt angles and solar elevation angles (altitude) together every second over the course of a year, simulating the reality of daily, monthly, and seasonal changes in energy production levels.

The curves of the designed model showed results that are very close to the results of previous researches. The resulting curves also allowed an accurate observation of the behavior of the energy produced throughout the year and per second, coinciding with the change in the system inputs represented in the PV tilt angles and the altitude angles of the sun. This allows an easy possibility to change the inputs of the designed model to find the most suitable conditions for generation.

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