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Optimal Winter and Summer Settings of Solar Photovoltaic Panels for Many Locations in the World

Aqeel R. Salih

Department of Physics, College of Education for Pure Science (Ibn Al-Haitham), University of Baghdad, Iraq

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Corresponding Author:

Name: Aqeel R. Salih

E-mail:

aqeel.r.s@ihcoedu.uobaghdad.edu.iq

Tel: + 964 7705841971

ABSTRACT

An increasing interest in the use of solar energy to generate electricity for several applications has stimulated a need for studying optimal settings of photovoltaic panels. The photovoltaic panel performance is highly affected by its direction and its tilt angle. This research calculates the optimal tilt angles of photovoltaic panels for 60 locations in 60 countries around the world. These angles are calculated from vertical using Solar Irradiance Calculator. The optimal tilt angle for the studied locations ranges from (15°) to (57°) and (45°) to (87°) in winter and summer, respectively. It is shown that the angles that are obtained from equations are very close to those calculated from the calculator. This study is very useful to find the optimal tilt angle at any location by knowing only its latitude. The results can be extended to any location in the world. This research is intended to be used as a guidance for using photovoltaic panels.

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إعدادات الشتاء والصيف المثالية للألواح الشمسية الكهروضوئية للعديد من المواقع في العالم

عقيل رزاق صالح

قسم الفيزياء، كلية التربية للعلوم الصرفة (ابن الهيثم)، جامعة بغداد، بغداد، العراق

الملخص

أدى الاهتمام المتزايد باستخدام الطاقة الشمسية لتوليد الكهرباء للعديد من التطبيقات إلى زيادة الحاجة إلى دراسة الإعدادات المثلى للألواح الكهروضوئية. يتأثر أداء اللوح الكهروضوئي بشكل كبير باتجاهه وزاوية ميله. يحسب هذا البحث زوايا الميل المثالية للألواح الكهروضوئية في 60 موقعاً في 60 دولة حول العالم. يتم حساب هذه الزوايا عمودياً باستخدام برنامج حساب الإشعاع الشمسي. تتراوح زاوية الميل المثالية للمواقع المدروسة من (15°) إلى (57°) ومن (45°) إلى (87°) في الشتاء والصيف على التوالي. وتبين أن الزوايا التي يتم الحصول عليها من المعادلات قريبة جداً من تلك المحسوبة من البرنامج الحسابي. هذه الدراسة مفيدة جداً لإيجاد زاوية الميل المثالية في أي موقع من خلال معرفة دائرة العرض فقط. يمكن تعميم النتائج إلى أي موقع في العالم. يستفاد من هذا البحث كدليل لاستخدام الألواح الكهروضوئية.

1. Introduction

Energy is central for the life quality, productivity and society prosperity [1]. Energy need and environmental concerns are the driving forces toward renewable sources [2]. Renewable energy sources do not vanish in nature as they are transformed to other forms. Light from the sun is the principal energy source on earth. It can be directly converted to electricity [1]. The energy emitted by the sun is around (47%) visible light, (46%) infrared and (7%) ultraviolet [3]. The earth-sun distance varies throughout the year, the minimum being (147.1×10^{6} km) at winter solstice (December 21) and the maximum being (152.1×10^{6} km) at summer solstice (June 21). Therefore, the amount of solar energy intercepted by the earth changes throughout the year, the maximum being on the 21st December and the minimum being on the 21st June [4]. In the literature, different authors determined the optimal tilt angle for many locations. Zhou and Yang [5] optimized the installing angles of photovoltaic (PV) panels in Wuhan city, China. They showed that the yearly optimized tilt angle was (15°) (about 15.52° less than the latitude). Al Garni et al. [6] investigated the optimal angles for solar PV modules at 18 cities in Saudi Arabia. They found that the yearly optimal tilt angle for the six cities: Albaha, Arar, Hail, Riyadh, Tabuk and Taif was only slightly higher than the location latitude. Dogaheh and Puig [7] showed that the yearly optimal tilt angle of PV panels for Barcelona city, Spain was (36.87°).

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Nfaoui and El-Hami [8] used MATLAB to extract the optimal tilt angle for PV arrays in Settat city (latitude 33.029°) in Morocco. They found that the optimal angle for the whole year was (29°). Hua et al. [9] optimized tilt angles of PV panels for seven sites in Gansu province, China. Barbón et al. [10] presented a method for computing the optimal tilt angle for 39 cities around the world for latitudes between about (6°) and (60°). Khan et al. [11] used the stacking ensemble learning model to predict the optimal tilt angle for the PV panel. Al-Shohani et al. [12] showed that the yearly optimal tilt angle of PV modules which are installed in Baghdad city, Iraq was (30.6°). Abdelaal and El-Fergany [13] computed the optimal tilt angle for PV panels in some Egyptian cities. They found that the yearly optimal tilt angle was nearly equal to the latitude. Mahmood et al. [14, 15] and Salim [16] studied the effect of some factors on the efficiency of solar cells. In 2023, the world added (473 GW) of renewables. Solar power alone accounted for (346 GW) (about three-quarters of renewable additions) [17]. In the current work, the optimal settings for both winter and summer seasons to get the best output of PV panels for 60 locations in 60 countries are obtained from Solar Irradiance Calculator and then compared with those calculated from equations.

2. Background Information

2.1 Solar PV Panels

Solar energy is the most abundant permanent energy source [18]. A measure of how much solar power is getting at a specific location is called solar insolation or solar irradiance. It changes throughout the day depending on the sun position in the sky and the weather. It also changes throughout the year depending on the seasons [19]. A PV cell is a device that directly converts solar energy into electrical energy through the PV effect [20]. The typical output voltage of the PV cell is approximately (0.6 to 0.8 V). For higher output voltage and power generation, PV cells are combined in a series and parallel configuration to form PV modules and PV panels. A combination of PV panels forms a PV array, as shown in Figure 1. The actual electric generation of an array depends on the solar irradiance at the location, direction, tilt angle and shading [1].

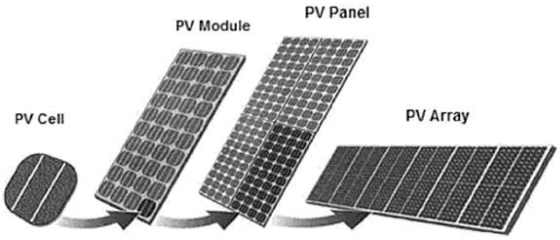

Fig. 1: PV cell, module, panel and array [21].

The major materials for the solar cells are crystalline types and thin-film, varying from each other in terms of manufacturing technology, production cost, light absorption efficiency and energy conversion efficiency. Table 1 shows the three major types of solar panels.

Table 1: Comparison of three types of solar panels [22].

Specifications	Monocrystalline panels	Polycrystalline panels	Thin-film panels
Type			
Life span	25–30 years	20–25 years	15–20 years
Tolerance of temperature	0 to +5%	−5 to +5%	−3 to +3%
Efficiency	10% to 15%	9% to 12%	9% to 12%

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Solar panels should be directed towards the equator, i.e. to the south when installed in the northern hemisphere and to the north when installed in the southern hemisphere [23].

At any location, the sun always rises in the east and sets in the west. The solar irradiance reaches its peak at noon. The optimal winter tilt for solar panels is [24]:

$\beta = 90^\circ - \phi - 15.6^\circ$ …..(1)

and the optimal summer tilt is:

$\beta = 90^\circ - \phi + 15.6^\circ$ ….(2)

where ϕ is the absolute latitude. Latitude values are positive in the northern hemisphere, and negative in the southern hemisphere [25].

2.2 Correlation Coefficient

If there is a significant relationship between two variables x and y, then they are correlated. The most widely used correlation coefficient is the Pearson correlation coefficient [26, 27]:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad \text{….. (3)}$$

where n is the sample size, $\bar{x}$ and $\bar{y}$ are the mean values of x and y, respectively.

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \quad \text{…..(4)}$$

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} \quad \text{… (5)}$$

This coefficient is a measure of the strength of a linear relationship between two variables and it ranges from (–1 to 1). The value $(r = -1)$ suggests a perfect negative linear relationship. When $(r = 1)$, it reflects a perfect positive linear relationship, whereas the value $(r = 0)$ indicates that there is no linear relationship between x and y.

In this work, x and y represent ϕ and β, respectively.

3. Results and Discussions

In this paper, optimal tilt angles for 60 locations were obtained from Solar Irradiance Calculator. After selecting the country, the name of town or city and direction of solar panel from a list, this calculator will show the optimal tilt angle from vertical. Figures 2 and 3 show solar irradiance figures for a solar panel set at two different angles in Baghdad, Iraq which is located in the northern half of the earth, so the best solar panel direction is the south. The best winter tilt is (42°) and the best summer tilt is (72°). In Figure 2, it can be seen that in June (the first month of summer) we get the equivalent of (5.57 hours) of midday sunlight, whilst in December (the first month of winter) we get the equivalent of (4.25 hours) of midday sunlight. The monthly solar irradiance figure can be multiplied by the wattage of the solar panel to calculate how much energy a solar panel will generate per day. In Figure 3, it can be seen that in June we get the equivalent of (7.22 hours) of midday sunlight, whilst in December we get the equivalent of (3.45 hours) of midday sunlight.

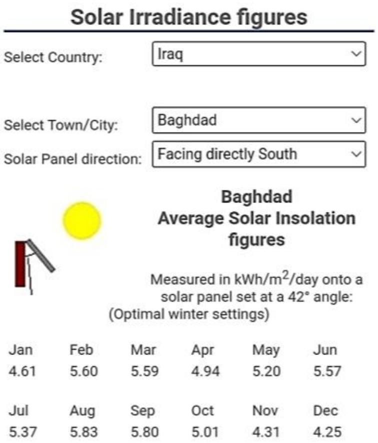

Fig. 2: Baghdad solar irradiance figures for a solar panel set at a (42°) angle: (optimal winter settings).

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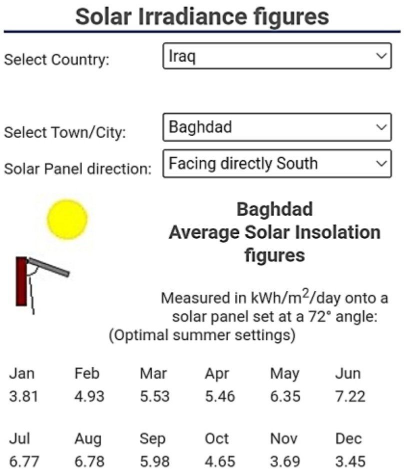

Fig. 3: Baghdad solar irradiance figures for a solar panel set at a (72°) angle: (optimal summer settings).

Optimal tilt angles for 60 locations obtained from the calculator are presented in Table 2. During winter, the PV panel receives minimum solar irradiance, therefore its tilt angle reaches minimum value and ranges from (15°) to (57°). During summer, tilt angles reach high values and range from (45°) to (87°) or more than those for winter by (30°).

Table 2: Tilt angle for 60 locations in the world.

Number	Location	Tilt Angle (deg.)	
		Winter	Summer
1	Helsinki (Finland)	15	45
2	Oslo (Norway)	15	45
3	Berlin (Germany)	23	53
4	Amsterdam (Netherlands)	23	53
5	Warsaw (Poland)	23	53
6	London (United Kingdom)	23	53
7	Astana (Kazakhstan)	24	54
8	Brussels (Belgium)	24	54
9	Vienna (Austria)	27	57
10	Bratislava (Slovakia)	27	57
11	Ljubljana (Slovenia)	29	59
12	Zagreb (Croatia)	29	59
13	Bishkek (Kyrgyzstan)	32	62
14	Sofia (Bulgaria)	32	62
15	Roma (Italy)	33	63
16	Tbilisi (Georgia)	33	63
17	Wellington (New Zealand)	34	64
18	Tashkent (Uzbekistan)	34	64
19	Madrid (Spain)	35	65
20	Baku (Azerbaijan)	35	65
21	Yerevan (Armenia)	35	65
22	Ankara (Turkey)	35	65
23	Beijing (China)	35	65
24	Washington (United States)	36	66
25	Lisbon (Portugal)	36	66
26	Dushanbe (Tajikistan)	37	67
27	Athens (Greece)	37	67
28	Ashgabat (Turkmenistan)	37	67
29	Seoul (South Korea)	37	67
30	Tunis (Tunisia)	38	68
31	Algiers (Algeria)	38	68
32	Valletta (Malta)	39	69
33	Tehran (Iran)	39	69
34	Tokyo (Japan)	39	69
35	Canberra (Australia)	40	70

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36	Nicosia (Cyprus)	40	70
37	Montevideo (Uruguay)	40	70
38	Buenos Aires (Argentina)	40	70
39	Kabul (Afghanistan)	41	71
40	Rabat (Morocco)	41	71
41	Beirut (Lebanon)	41	71
42	Islamabad (Pakistan)	41	71
43	Damascus (Syria)	41	71
44	Baghdad (Iraq)	42	72
45	Tripoli (Libya)	42	72
46	Amman (Jordan)	43	73
47	Cairo (Egypt)	45	75
48	New Delhi (India)	46	76
49	Asuncion (Paraguay)	50	80
50	Doha (Qatar)	50	80
51	Taipei (Taiwan)	50	80
52	Riyadh (Saudi Arabia)	50	80
53	Abu Dhabi (Emirates)	51	81
54	Dhaka (Bangladesh)	51	81
55	Muscat (Oman)	51	81
56	Port-au-Prince (Haiti)	57	87
57	Santo Domingo (Dominican)	57	87
58	Suva (Fiji)	57	87
59	Nouakchott (Mauritania)	57	87
60	Kingston (Jamaica)	57	87

Optimal tilt angles shown in Table 2 which obtained from the calculator are in good agreement with those in Table 3 which calculated from Equations (1) and (2). Table 3 shows tilt angle for optimal winter and summer settings. It can be noted that away from the equator (which is located at zero latitude), the capital cities have the lowest tilt angles.

Table 3: Tilt angle for 60 capital cities as calculated from equations.

Number	**Capital City**	**Latitude (deg.) [28]**	**Tilt Angle (deg.)**	
			Winter From Eq. (1)	**Summer From Eq. (2)**
1	Helsinki	60.1692	14.2	45.4
2	Oslo	59.9127	14.5	45.7
3	Berlin	52.5244	21.9	53.1
4	Amsterdam	52.3740	22.0	53.2
5	Warsaw	52.2298	22.2	53.4
6	London	51.5085	22.9	54.1
7	Astana	51.1801	23.2	54.4
8	Brussels	50.8467	23.6	54.8
9	Vienna	48.2064	26.2	57.4
10	Bratislava	48.1482	26.3	57.5
11	Ljubljana	46.0511	28.3	59.5
12	Zagreb	45.8144	28.6	59.8
13	Bishkek	42.8700	31.5	62.7
14	Sofia	42.6975	31.7	62.9
15	Roma	41.8947	32.5	63.7
16	Tbilisi	41.6941	32.7	63.9
17	Wellington	–41.2866	33.1	64.3
18	Tashkent	41.2647	33.1	64.3
19	Madrid	40.4165	34.0	65.2
20	Baku	40.3777	34.0	65.2

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21	Yerevan	40.1820	34.2	65.4
22	Ankara	39.9199	34.5	65.7
23	Beijing	39.9075	34.5	65.7
24	Washington	38.8951	35.5	66.7
25	Lisbon	38.7169	35.7	66.9
26	Dushanbe	38.5358	35.9	67.1
27	Athens	37.9534	36.4	67.6
28	Ashgabat	37.9500	36.5	67.7
29	Seoul	37.5683	36.8	68.0
30	Tunis	36.8190	37.6	68.8
31	Algiers	36.7525	37.6	68.8
32	Valletta	35.8997	38.5	69.7
33	Tehran	35.6944	38.7	69.9
34	Tokyo	35.6895	38.7	69.9
35	Canberra	–35.2835	39.1	70.3
36	Nicosia	35.1595	39.2	70.4
37	Montevideo	–34.8335	39.6	70.8
38	Buenos Aires	–34.6051	39.8	71.0
39	Kabul	34.5289	39.9	71.1
40	Rabat	34.0133	40.4	71.6
41	Beirut	33.9000	40.5	71.7
42	Islamabad	33.7035	40.7	71.9
43	Damascus	33.5086	40.9	72.1
44	Baghdad	33.3406	41.1	72.3
45	Tripoli	32.8752	41.5	72.7
46	Amman	31.9552	42.4	73.6
47	Cairo	30.0392	44.4	75.6
48	New Delhi	28.6667	45.7	76.9
49	Asuncion	–25.3007	49.1	80.3
50	Doha	25.2747	49.1	80.3
51	Taipei	25.0470	49.4	80.6
52	Riyadh	24.6905	49.7	80.9
53	Abu Dhabi	24.4648	49.9	81.1
54	Dhaka	23.7104	50.7	81.9
55	Muscat	23.6139	50.8	82.0
56	Port-au-Prince	18.5392	55.9	87.1
57	Santo Domingo	18.4896	55.9	87.1
58	Suva	–18.1416	56.3	87.5
59	Nouakchott	18.0858	56.3	87.5
60	Kingston	17.9970	56.4	87.6

Table 4 shows calculating the Pearson correlation coefficient from data in Table 3 using Equation (3). The Pearson correlation coefficient is (–1). This implies a perfect negative linear relationship between absolute latitude and tilt angle. In other words, they are inversely related.

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Table 4: Calculation of the Pearson correlation coefficient.

Details	$(x, y) = (\phi, \beta)$ Winter	Summer
n	60	60
$\sum_{i=1}^{n} x_i$	2211.7193	2211.7193
$\bar{x}$	36.862	36.862
$\sum_{i=1}^{n} y_i$	2252.3	4124.3
$\bar{y}$	37.5383	68.7383
$\sum_{i=1}^{n} (x_i - \bar{x})^2$	6076.009	6076.009
$\sum_{i=1}^{n} (y_i - \bar{y})^2$	6077.1418	6077.1418
$\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})$	–6076.5534	–6076.5534
r	–1	–1

The relationship between tilt angle and absolute latitude angle is shown graphically in Figure 4 for locations with absolute latitudes between about (18°) and (60°). Increasing latitude absolute value (away from the equator) corresponds to decrease both winter and summer tilt angles.

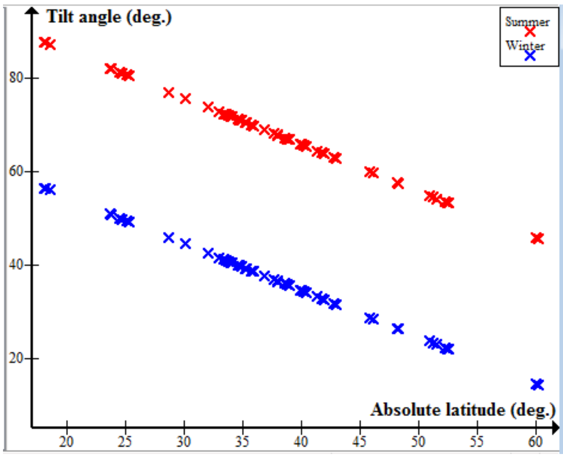

Fig. 4: Winter and summer tilt angles for 60 capital cities.

4. Conclusions

The optimal tilt of solar panels varies throughout the year depending on the season. Using Solar Irradiance Calculator, tilt angles for solar panels were obtained and then compared with those calculated from equations. In this work, the optimal tilt angle can be determined by taking only the geographic latitude angle of the location. The tilt angles are the same, for all locations located at about the same latitude. The less tilt angles are observed for the locations farther from the equator. To obtain the best output, PV panels must be tilted at an angle determined by the local latitude.

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Author contribution: One author contributed in the study.

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