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Tilt Angle of Solar Panels for Best Winter, Summer and Year-Round Performances for Different Regions of the World

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زاوية ميل الالواح الشمسية لأفضل اداءات الشتاء والصيف وعلى مدار العام لمناطق مختلفة من العالم

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ABSTRACT

Background:

In recent years, solar energy has gained increased attention. The energy from the sun is unlimited and environment friendly. It is useful in decreasing the carbon dioxide emission that comes from the burning of fossil fuels and leads to global warming.

Materials and Methods:

The tilt angle of a solar panel is an important parameter that affects its performance. This paper provides the tilt angle of solar panels for 90 capital cities in 90 countries in the northern and southern hemispheres. Solar Irradiance Calculator is used to calculate the tilt angles from vertical.

Results:

The tilt angle for the studied capital cities ranges from 11° to 90° in winter, 41° to 105° in summer and 26° to 90° for year-round. The output results obtained from the calculator are very close to those calculated from equations and agree with previous studies.

Conclusions:

According to the results of the current work, only the latitude is required to calculate the tilt angle at any location worldwide. These results can be generalized to any location on the earth. The results of this work are expected to give valuable information to the users of solar panels.

Keywords:

Tilt angle, Solar panels, Solar Irradiance Calculator, Solar energy.

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الخلاصة

مقدمة:

في السنوات الاخيرة، اكتسبت الطاقة الشمسية اهتماماً متزايداً. الطاقة من الشمس غير محدودة وصديقة للبيئة. فهي تفيد في تقليل انبعاث ثنائي اوكسيد الكربون الناتج عن احتراق الوقود الاحفوري ويؤدي الى الاحتباس الحراري.

طرق العمل:

تعد زاوية ميل اللوح الشمسي عاملاً مهماً تؤثر على ادائه. يوفر هذا البحث زاوية ميل الالواح الشمسية لـ 90 عاصمة في 90 دولة في النصفين الشمالي والجنوبي من الكرة الارضية. تم استخدام برنامج حساب الاشعاع الشمسي لحساب زوايا الميل من الوضع العمودي.

النتائج:

تتراوح زاوية الميل للعواصم المدروسة من 11 درجة الى 90 درجة في الشتاء، ومن 41 درجة الى 105 درجة في الصيف ومن 26 درجة الى 90 درجة على مدار العام. نتائج المخرجات التي تم الحصول عليها من البرنامج الحسابي قريبة جداً من تلك المحسوبة من المعادلات وتتفق مع الدراسات السابقة.

الاستنتاجات:

وفقاً لنتائج العمل الحالي, فقط دائرة العرض مطلوبة لحساب زاوية الميل في اي مكان في جميع انحاء العالم. يمكن تعميم هذه النتائج على اي مكان على وجه الارض. من المتوقع ان تعطي نتائج هذا العمل معلومات قيّمة لمستخدمي الالواح الشمسية.

الكلمات المفتاحية:

زاوية الميل, الالواح الشمسية, برنامج حساب الاشعاع الشمسي, الطاقة الشمسية.

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INTRODUCTION

The use of fossil fuels like oil, natural gas and coal to generate energy gives rise to several pollutants that have a harm impact on human health and the environment [1]. Solar energy is the most important renewable energy source available to the earth [2]. For many years, solar energy technologies have been dominating the renewables industry [3]. Solar technologies use the energy contained in sunlight directly to generate energy as well as electricity for general consumption in buildings, industrial processes and transportation [4].

Many previous studies were carried out to determine the optimum tilt angle of solar panels. Al-Sayyab et al. [5] used a mathematical model to find the optimum tilt angle for Basra city in the south of Iraq. They showed that the yearly optimum tilt angle is 28°. This angle is not equal to the latitude of the city. Nicolás-Martín et al. [6] proposed global models to estimate the yearly optimum tilt angle at any location worldwide without using local meteorological data. Mansour et al. [7] estimated the yearly optimum tilt angle for five cities of the Kingdom of Saudi Arabia (KSA). These cities are Abha, Arar, Dhahran, Jeddah and Riyadh. They obtained that the tilt angle is approximately equal to the latitude. Ibrahim and Ibrahim [8] presented that the yearly optimum tilt angle for Duhok city in the north of Iraq is 25° which is not equal to the latitude. Sarr et al. [9] used a mathematical model to determine the optimum tilt angle in four typical climatic zones in Senegal. These sites are Dakar, Saint Louis, Tambacounda and Ziguinchor. They showed that the yearly tilt angle is close to the latitude. Buzra et al. [10] determined the optimum tilt angle for three Albanian cities by using a mathematical model. They showed that the yearly optimum tilt angle for the cities of Vlora, Tirana and Kukes are respectively 37°, 38°and 39°. They noted that the tilt angle is almost equal to the latitude of the city.

In 2021, the total solar energy generation was 581.5 terawatt hours (TWh) in Asia Pacific, 195.6 TWh in Europe, 182.4 TWh in North America, 37.2 TWh in South & Central America, 16.5 TWh in Africa, 15.2 TWh in the Middle East and 4.1 TWh in Commonwealth of Independent States (CIS) [11].

In my previous work [12], Solar Panel Angle Calculator was used for calculating seasonal optimum tilt angles for seventeen cities in Iraq and eighty-three cities in other countries. The present work is the first which determines the tilt angles to get the best performance of solar panels for 90 countries using an online Solar Irradiance Calculator which covers every country in the world.

Materials and Methods

Solar energy is a combination of the hours and the strength of sunlight. This combination is called solar irradiance. This changes throughout the year and varies significantly from one place to another [13]. The yearly solar energy reaching the earth is about 5.46 million exajoules (EJ) [14]. A solar cell is a semiconductor device that directly converts solar energy into electricity [15]. Solar cells with more than 47% solar-to-electricity conversion efficiency were developed at National Renewable Energy Laboratory (NREL) [16]. In Figure 1, solar cells are packed into solar modules that produce a specific current and voltage when illuminated. Solar modules can be connected in parallel or in series to produce larger currents or voltages [17]. A collection of solar modules is called a solar panel, and a system of solar panels is called a solar array [18].

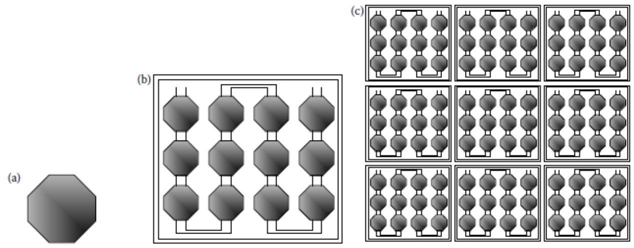

Figure 1. (a) solar cell, (b) solar module and (c) solar array [19].

There are three different solar panel technologies used to produce panels that are available commercially. The cheapest technology is amorphous (thin-film) solar panels. These are the least-efficient, with conversion efficiency around 6–8%. They have the benefits of high temperature performance and improved shade. Polycrystalline solar panels are expensive and have efficiency levels of 12–17%. Monocrystalline solar panels are the most expensive and the most efficient, with efficiency levels of 15–20%. They offer the best solution for most applications [13].

Solar panels must be directed for maximum solar energy capture. In the northern hemisphere, the best direction is true south (not magnetic south). In the southern hemisphere, solar panels must be directed to the true north [20].

The irradiance from the sun reaches its peak in the middle of the day. The tilt angle for best winter performance is [13]:

$$\beta=74.4^{\circ}-L \quad (1)$$

For best summer performance:

$$\beta=105.6^{\circ}-L \quad (2)$$

For best year-round performance:

$$\beta=90^{\circ}-L \quad (3)$$

where L is the local latitude. The positive latitudes are at north of the equator ($L=0^{\circ}$), while the negative ones are at the south [21].

Results and Discussion

In this study, tilt angles of solar panels for 90 capital cities in 90 countries were calculated by using a free Solar Irradiance Calculator which can be used by selecting the country from the list of countries, the city from the list of cities and solar panel direction from the list of directions. The calculator will calculate the tilt angle from vertical. Figure 2 shows different tilt angles for Baghdad in the middle of Iraq.

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Figure 2. Tilt angles for Baghdad.

Table 1 shows the tilt angle of solar panels for 50 capital cities in both hemispheres obtained from the Solar Irradiance Calculator. The tilt angle lies in the range 11° to 59° in winter, 41° to 89° in summer and 26° to 74° for year-round. All angles are from vertical. Hours of daylight have an obvious effect on a solar panel. During the summer, the solar panel receives the maximum solar irradiance, therefore tilt angle reaches maximum and during the winter, tilt angles attain low values. The tilt angle for winter is less than the tilt angle for summer by 30°. The year-round tilt angle is the average value of winter and summer tilt angles.

Table 1. Tilt angle of solar panels for 50 capital cities in the world.

No.	Country	Capital City	Tilt Angle		
			Winter	Summer	Year-round
1	Greenland	Nuuk	11°	41°	26°
2	Iceland	Reykjavik			
3	Estonia	Tallinn	16°	46°	31°
4	Sweden	Stockholm			
5	Latvia	Riga	18°	48°	33°
6	Russia	Moscow	19°	49°	34°
7	Denmark	Copenhagen			
8	Lithuania	Vilnius	20°	50°	35°
9	Belarus	Minsk	21°	51°	36°
10	Ireland	Dublin	22°	52°	37°
11	Ukraine	Kiev	25°	55°	40°
12	Czech	Praha			
13	France	Paris	26°	56°	41°
14	Mongolia	Ulaanbaatar	27°	57°	42°
15	Hungary	Budapest			
16	Liechtenstein	Vaduz	28°	58°	43°
17	Moldova	Chisinau			
18	Switzerland	Bern			
19	Canada	Ottawa	30°	60°	45°

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20	**Romania**	**Bucuresti**	31°	61°	46°
21	**San Marino**	**San Marino**			
22	**Andorra**	**Andorra la Vella**	33°	63°	48°
23	**Macedonia**	**Skopje**			
24	**Albania**	**Tirana**	34°	64°	49°
25	**North Korea**	**Pyongyang**	36°	66°	51°
26	**Gibraltar**	**Gibraltar**	39°	69°	54°
27	**Chile**	**Santiago**	42°	72°	57°
28	**Iraq**	**Baghdad**			
29	**Bermuda**	**Hamilton**	43°	73°	58°
30	**Lesotho**	**Maseru**	46°	76°	61°
31	**Nepal**	**Kathmandu**	47°	77°	62°
32	**Bhutan**	**Thimphu**			
33	**Bahrain**	**Manama**	49°	79°	64°
34	**Mozambique**	**Maputo**			
35	**Bahamas**	**Nassau**	50°	80°	65°
36	**KSA**	**Riyadh**			
37	**Botswana**	**Gaborone**			
38	**Cuba**	**Havana**	52°	82°	67°
39	**Namibia**	**Windhoek**			
40	**Viet Nam**	**Ha Noi**	54°	84°	69°
41	**Reunion**	**Saint-Denis**			
42	**Mauritius**	**Port Louis**	55°	85°	70°
43	**Mexico**	**Mexico City**	56°	86°	71°
44	**Niue**	**Alofi**			
45	**Madagascar**	**Antananarivo**			
46	**Anguilla**	**The Valley**	57°	87°	72°
47	**Zimbabwe**	**Harare**			
48	**Vanuatu**	**Port-Vila**			
49	**Belize**	**Belmopan**	58°	88°	73°
50	**Guadeloupe**	**Basse-Terre**	59°	89°	74°

Table 2 shows the tilt angle of solar panels for 40 capital cities in both hemispheres calculated from the Solar Irradiance Calculator. The tilt angle lies in the range of 74° to 90° in winter/ year-round and 89° to 105° in summer. Both winter and year-round tilt angles are less than summer tilt angle by 15°.

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Table 2. Tilt angle of solar panels for 40 capital cities in the world.

No.	Country	Capital City	Tilt Angle	
			Winter/ Year-round	Summer
1	Brazil	Brasilia	74°	89°
2	Zambia	Lusaka	75°	90°
3	Cape Verde	Praia		
4	Senegal	Dakar		
5	Guatemala	Guatemala City		
6	Martinique	Fort-de-France		
7	Honduras	Tegucigalpa	76°	91°
8	Malawi	Lilongwe		
9	Niger	Niamey		
10	Guam	Hagatna		
11	Barbados	Bridgetown	77°	92°
12	Mali	Bamako		
13	Aruba	Oranjestad	78°	93°
14	Burkina Faso	Ouagadougou		
15	Nicaragua	Managua		
16	Grenada	Saint George's		
17	Cambodia	Phnom Penh		
18	Venezuela	Caracas	80°	95°
19	Guinea	Conakry		
20	Nigeria	Abuja	81°	96°
21	Tuvalu	Funafuti	82°	97°
22	Sierra Leone	Freetown		
23	Marshall Islands	Majuro	83°	98°
24	Micronesia	Palikir		
25	Guyana	Georgetown		
26	Benin	Porto-Novo	84°	99°
27	Liberia	Monrovia		
28	Suriname	Paramaribo		
29	Brunei	Bandar Seri Begawan	85°	100°
30	Seychelles	Victoria		
31	Colombia	Bogota		
32	Equatorial Guinea	Malabo	86°	101°
33	Malaysia	Kuala Lumpur	87°	102°
34	Somalia	Mogadishu	88°	103°
35	Rwanda	Kigali		

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36	**Kiribati**	**Tarawa**	89°	104°
37	**Kenya**	**Nairobi**		
38	**Gabon**	**Libreville**	90°	105°
39	**Uganda**	**Kampala**		
40	**Ecuador**	**Quito**		

The results obtained from Solar Irradiance Calculator (shown in Tables 1 and 2) are very close to those in Tables 3 and 4 which are calculated by using Equations (1) to (3). Table 3 shows the tilt angle of solar panels for best winter, summer and year-round performances where the absolute value for the latitude is more than 15.8°. Capital cities which lie far from the equator have the lowest tilt angles. All angles increase with decreasing latitude absolute value (Figure 3). It should be noted that if the tilt angle for year-round is calculated horizontally instead of vertically, this angle is equal to the absolute latitude angle of the studied capital cities as shown in many previous studies.

Table 3. Tilt angle for 50 capital cities with absolute latitudes more than 15.8°.

No.	Capital City	L [22]	β		
			Winter	Summer	Year-round
			74.4°–|L|	105.6°–|L|	90°–|L|
1	**Nuuk**	64.1835°	10.2°	41.4°	25.8°
2	**Reykjavik**	64.1355°	10.3°	41.5°	25.9°
3	**Tallinn**	59.4370°	15.0°	46.2°	30.6°
4	**Stockholm**	59.3326°	15.1°	46.3°	30.7°
5	**Riga**	56.9460°	17.5°	48.7°	33.1°
6	**Moscow**	55.7550°	18.6°	49.8°	34.2°
7	**Copenhagen**	55.6759°	18.7°	49.9°	34.3°
8	**Vilnius**	54.6892°	19.7°	50.9°	35.3°
9	**Minsk**	53.9000°	20.5°	51.7°	36.1°
10	**Dublin**	53.3331°	21.1°	52.3°	36.7°
11	**Kiev**	50.4454°	24.0°	55.2°	39.6°
12	**Praha**	50.0880°	24.3°	55.5°	39.9°
13	**Paris**	48.8534°	25.5°	56.7°	41.1°
14	**Ulaanbaatar**	47.9077°	26.5°	57.7°	42.1°
15	**Budapest**	47.4980°	26.9°	58.1°	42.5°
16	**Vaduz**	47.1415°	27.3°	58.5°	42.9°
17	**Chisinau**	47.0056°	27.4°	58.6°	43.0°
18	**Bern**	46.9481°	27.5°	58.7°	43.1°
19	**Ottawa**	45.4166°	29.0°	60.2°	44.6°
20	**Bucuresti**	44.4328°	30.0°	61.2°	45.6°

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21	**San Marino**	43.9333°	30.5°	61.7°	46.1°
22	**Andorra la Vella**	42.5078°	31.9°	63.1°	47.5°
23	**Skopje**	42.0000°	32.4°	63.6°	48.0°
24	**Tirana**	41.3275°	33.1°	64.3°	48.7°
25	**Pyongyang**	39.0339°	35.4°	66.6°	51.0°
26	**Gibraltar**	36.1447°	38.3°	69.5°	53.9°
27	**Santiago**	–33.4569°	40.9°	72.1°	56.5°
28	**Baghdad**	33.3406°	41.1°	72.3°	56.7°
29	**Hamilton**	32.2915°	42.1°	73.3°	57.7°
30	**Maseru**	–29.3167°	45.1°	76.3°	60.7°
31	**Kathmandu**	27.7017°	46.7°	77.9°	62.3°
32	**Thimphu**	27.4661°	46.9°	78.1°	62.5°
33	**Manama**	26.2154°	48.2°	79.4°	63.8°
34	**Maputo**	–25.9653°	48.4°	79.6°	64.0°
35	**Nassau**	25.0582°	49.3°	80.5°	64.9°
36	**Riyadh**	24.6905°	49.7°	80.9°	65.3°
37	**Gaborone**	–24.6545°			
38	**Havana**	23.1195°	51.3°	82.5°	66.9°
39	**Windhoek**	–22.5594°	51.8°	83.0°	67.4°
40	**Ha Noi**	21.0245°	53.4°	84.6°	69.0°
41	**Saint-Denis**	–20.8823°	53.5°	84.7°	69.1°
42	**Port Louis**	–20.1619°	54.2°	85.4°	69.8°
43	**Mexico City**	19.4273°	55.0°	86.2°	70.6°
44	**Alofi**	–19.0585°	55.3°	86.5°	70.9°
45	**Antananarivo**	–18.9137°	55.5°	86.7°	71.1°
46	**The Valley**	18.2170°	56.2°	87.4°	71.8°
47	**Harare**	–17.8294°	56.6°	87.8°	72.2°
48	**Port-Vila**	–17.7338°	56.7°	87.9°	72.3°
49	**Belmopan**	17.2500°	57.2°	88.4°	72.8°
50	**Basse-Terre**	15.9985°	58.4°	89.6°	74.0°

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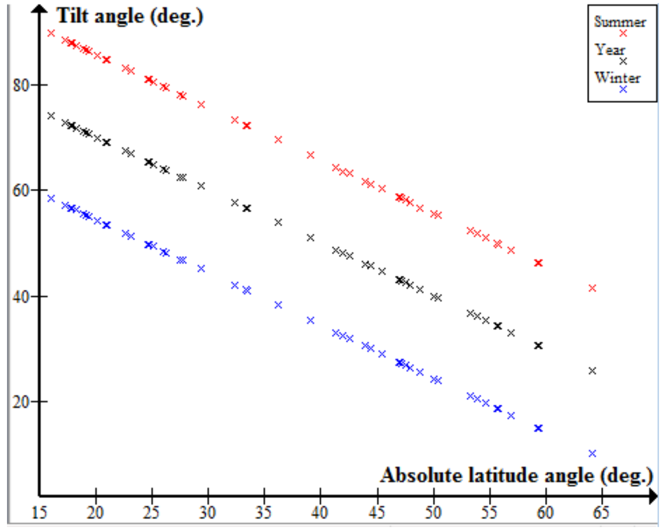

Figure 3. Tilt angle for 50 capital cities.

Table 4 shows the tilt angle of solar panels where the absolute value for the latitude is less than 15.8°. Decreasing the latitude absolute value leads to an increase in tilt angle (Figure 4). Capital cities which lie near the equator have the highest tilt angles.

Table 4. Tilt angle for 40 capital cities with absolute latitudes less than 15.8°.

No.	Capital City	L [22]	β	
			Winter/ Year-round	Summer
			90°–|L|	105.6°–|L|
1	Brasilia	–15.7797°	74.2°	89.8°
2	Lusaka	–15.4134°	74.6°	90.2°
3	Praia	14.9215°	75.1°	90.7°
4	Dakar	14.6937°	75.3°	90.9°
5	Guatemala City	14.6127°	75.4°	91.0°
6	Fort-de-France	14.6089°		
7	Tegucigalpa	14.0818°	75.9°	91.5°
8	Lilongwe	–13.9669°	76.0°	91.6°
9	Niamey	13.5137°	76.5°	92.1°
10	Hagatna	13.4757°		
11	Bridgetown	13.1000°	76.9°	92.5°
12	Bamako	12.6500°	77.4°	93.0°
13	Oranjestad	12.5240°	77.5°	93.1°
14	Ouagadougou	12.3642°	77.6°	93.2°
15	Managua	12.1328°	77.9°	93.5°

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16	**Saint George's**	12.0564°		
17	**Phnom Penh**	11.5625°	78.4°	94.0°
18	**Caracas**	10.4880°	79.5°	95.1°
19	**Conakry**	9.5716°	80.4°	96.0°
20	**Abuja**	9.0574°	80.9°	96.5°
21	**Funafuti**	–8.5189°	81.5°	97.1°
22	**Freetown**	8.4840°		
23	**Majuro**	7.0897°	82.9°	98.5°
24	**Palikir**	6.9174°	83.1°	98.7°
25	**Georgetown**	6.8045°	83.2°	98.8°
26	**Porto-Novo**	6.4965°	83.5°	99.1°
27	**Monrovia**	6.3005°	83.7°	99.3°
28	**Paramaribo**	5.8664°	84.1°	99.7°
29	**Bandar Seri Begawan**	4.9403°	85.1°	100.7°
30	**Victoria**	–4.6167°	85.4°	101.0°
31	**Bogota**	4.6097°		
32	**Malabo**	3.7500°	86.3°	101.9°
33	**Kuala Lumpur**	3.1412°	86.9°	102.5°
34	**Mogadishu**	2.0416°	88.0°	103.6°
35	**Kigali**	–1.9474°	88.1°	103.7°
36	**Tarawa**	1.3272°	88.7°	104.3°
37	**Nairobi**	–1.2833°		
38	**Libreville**	0.3925°	89.6°	105.2°
39	**Kampala**	0.3163°	89.7°	105.3°
40	**Quito**	–0.2299°	89.8°	105.4°

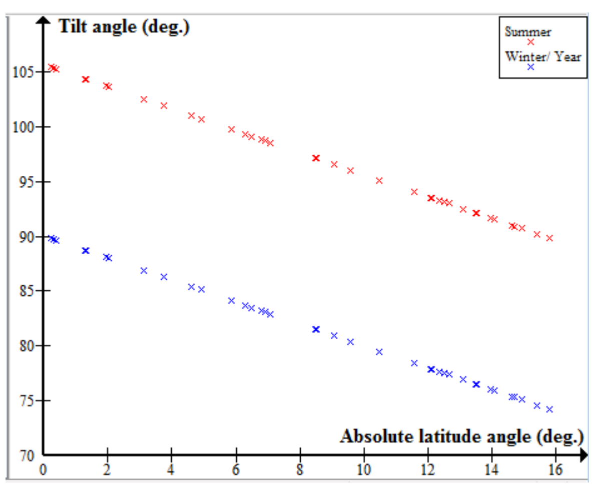

Figure 4. Tilt angle for 40 capital cities.

Conclusions

The performance of a solar panel is highly affected by its tilt angle and its direction to get the best out of the system. In this paper, tilt angles for fixed solar panels have been calculated by using Solar Irradiance Calculator. The calculated angles have been verified by comparison with those calculated from equations. For all capital cities located at about the same geographic latitude angle, the tilt angles are the same. According to this study, only the latitude is necessary to determine the tilt angle at any location in the world. To get the best performance, the solar panels must be adjusted according to the angles in this work.

Conflict of interests

There are non-conflicts of interest.

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