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Seasonal Optimum Tilt Angle of Solar Panels for 100 Cities in the World

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ABSTRACT

Solar energy is the most abundant renewable energy source. This energy can be converted directly into electricity using solar panels. The fixed tilt solar panels are the most practical and the most widely installed throughout the world. Optimum tilt angle calculation has the advantage that it does not use expensive solar trackers. This research calculates the seasonal optimum tilt angle of solar panels for 17 cities in Iraq and 83 cities in 83 countries distributed around the world. Solar Panel Angle Calculator program was used in calculating the optimum tilt angles from vertical. The optimum tilt angle varies between 6˚ and 112˚ throughout the year. This angle for winter, spring/ autumn and summer seasons are found to be between 6˚ to 66˚, 30˚ to 89˚ and 54˚ to 112˚, respectively. All angles calculated from the calculator program are validated by comparing it with those obtained from equations. An excellent agreement was established. Cities which have approximately the same absolute values of the latitudes are have the same optimum tilt angles. Based on the results, adjusting angles four times a year is recommended. This work can serve as a guidance for installing solar panels.

KEYWORDS: Optimum tilt angle; renewable energy; solar panel angle calculator.

الخلاصة

الطاقة الشمسية هي أكثر مصادر الطاقة المتجددة وفرة. يمكن تحويل هذه الطاقة مباشرة الى كهرباء باستخدام الالواح الشمسية. الالواح الشمسية ذات الميل الثابت هي الاكثر عملية والاكثر تركيباً في جميع انحاء العالم. يتميز حساب زاوية الميل المثلى بميزة انه لا يستخدم متعقبات شمسية باهظة الثمن. يحسب هذا البحث زاوية الميل المثلى الفصلية للالواح الشمسية لـ 17 مدينة في العراق و83 مدينة في 83 دولة موزعة حول العالم. تم استخدام برنامج حساب زاوية الالواح الشمسية في حساب زوايا الميل المثلى من الوضع الرأسي. تتراوح زاوية الميل المثلى بين 6 درجات و112 درجة على مدار العام. وجدت هذه الزاوية لفصول الشتاء والربيع/ الخريف والصيف بين 6 درجات الى 66 درجة و30 درجة الى 89 درجة و54 درجة الى 112 درجة على التوالي. يتم التحقق من صحة جميع الزوايا المحسوبة من البرنامج من خلال مقارنتها مع الزوايا التي تم الحصول عليها من المعادلات. وتحقق اتفاقاً ممتازاً. المدن التي لها نفس القيم المطلقة تقريباً لخطوط العرض لها نفس زوايا الميل المثلى. بناءً على النتائج، يوصى بتعديل الزوايا أربع مرات في السنة. يمكن ان يكون هذا العمل بمثابة دليل لتركيب الالواح الشمسية.

INTRODUCTION

Energy forms the basis of human life [1]. Driving forces toward renewable sources are: increasing energy demand, decreasing conventional fossil fuels and worldwide environmental concerns. One of the most promising renewable energy sources is the solar energy [2]. It is clean, globally available and abundant in many locations around the world. Sunlight is the main energy source on earth [3]. Each year around 1500 million terawatt hours (TWh) of solar energy reaches the earth [4]. The main application fields of solar energy are residential, vehicular, naval, space and aircraft [2]. In the study conducted by Ozbay et al. [5], the optimum tilt angle for Bilecik city in Turkey was determined. They showed that the fixed tilt angle should be 20˚ or 40˚. Tlijani et al. [6] used MATLAB/SIMULINK model to determine the optimum tilt angle for Gafsa city in Tunisia. They concluded that 90˚ East represents the experimental optimum tilt angle. Salari and Javaran [7] developed a MATLAB code to calculate the optimum tilt angle for Yazd city in Iran. Morad et al. [8] carried out a study to predict the optimum tilt angle for three Iraqi cities (Baghdad, Diyala and

Tikrit). They showed that the optimum tilt angle is 31˚ for all these cities. Bailek et al. [9] determined the optimum tilt angle for Adrar city in Algeria. Asad Ullah et al. [10] developed the MATLAB code to calculate the optimum tilt angle for some of the major cities in Pakistan.

According to International Renewable Energy Agency (IRENA) reports [11–13], renewable power generation capacity increased by 176 gigawatts (GW) in 2019, 261 GW in 2020 and 257 GW in 2021. Solar power continued to lead capacity expansion, with an increase of 98 GW in 2019, 127 GW in 2020 and 133 GW in 2021.

The current work is the first which uses Solar Panel Angle Calculator to calculate seasonal optimum tilt angles of solar panels for 100 cities distributed around the world.

MATERIALS AND METHODS

Geographic Coordinates

Any location on the surface of earth is described by latitude and longitude. Latitude (ϕ) is an angle, north or south of the equator. It ranges from 0˚ (at the equator) to 90˚ (at the north pole) and –90˚ (at the south pole). Longitude is an angle, east or west of the prime meridian (Greenwich). It varies from 0˚ (at the prime meridian) to 180˚ (eastward) and –180˚ (westward) [14].

Equinoxes and Solstices

Each year, there are two days 21st March/ 21st September when the day is exactly 12 hours long. These are the spring/ autumn equinoxes, respectively. On these solar equinoxes, the sun will rise due east of the equator and will set due west of the equator. At solar noon (midday) on the equinox, the angle of the sun is [15]:

$$\beta = 90° - \phi \quad (1)$$

In the locations north of the equator, the shortest day (and longest night) of the year is 21st December and the longest day is 21st June. These two days are the winter and summer solstices, respectively. On the winter solstice, the angle of the sun is 23.5˚ lower than it is on the equinox:

$$\beta = 66.5° - \phi \quad (2)$$

On the summer solstice the angle is 23.5˚ higher than on the equinox:

$$\beta = 113.5° - \phi \quad (3)$$

where 23.5˚ is the axial tilt of the earth.

As an example, the latitude of London in the United Kingdom (UK) is (ϕ=51˚). On the equinox, the angle at noon will be (90˚–51˚=39˚). On the winter solstice, the angle will be (39˚–23.5˚=15.5˚) and on the summer solstice, it will be (39˚+23.5˚=62.5˚).

In the locations north of the equator, solar panel must be south facing and, in the locations, south of the equator, it must be north facing.

Solar Panels

Solar photovoltaic (PV) cells are the basic building blocks of solar PV panels. They convert sunlight directly into direct current (DC) electricity by the PV effect. The DC is converted to alternating current (AC) by a device called an inverter. An individual PV cell is capable of generating about 1 or 2 W of power. For higher power output of PV cells, they can be connected together to form larger units called solar PV modules [1, 2]. A solar panel, as illustrated in Figure 1, consists of several solar modules. Finally, a solar PV array consists of several solar panels [16]. By connecting the cells or modules in parallel, the output current can reach higher values. On the other hand, the output voltage can be increased by connecting in series [2]. Solar arrays can be ground or pole mounted, installed on building rooftops. The maintenance cost of a fixed PV array is negligible compared to conventional energy sources. A typical PV module has an economic life of more than 25 years [3]. Typical component costs are about 65% in modules, 15% in inverters, 10% in other parts and 10% in labor. The price of the renewable power would be falling as the technology advances, whereas the conventional power price would rise with inflation [17].

RESULTS AND DISCUSSION

In this work, optimum tilt angles from vertical of solar panels by season for 100 cities in 84 countries around the world have been calculated using an online Solar Panel Angle Calculator. This calculator can be used by selecting country and city from the list. The calculator will then show the optimum tilt angle.

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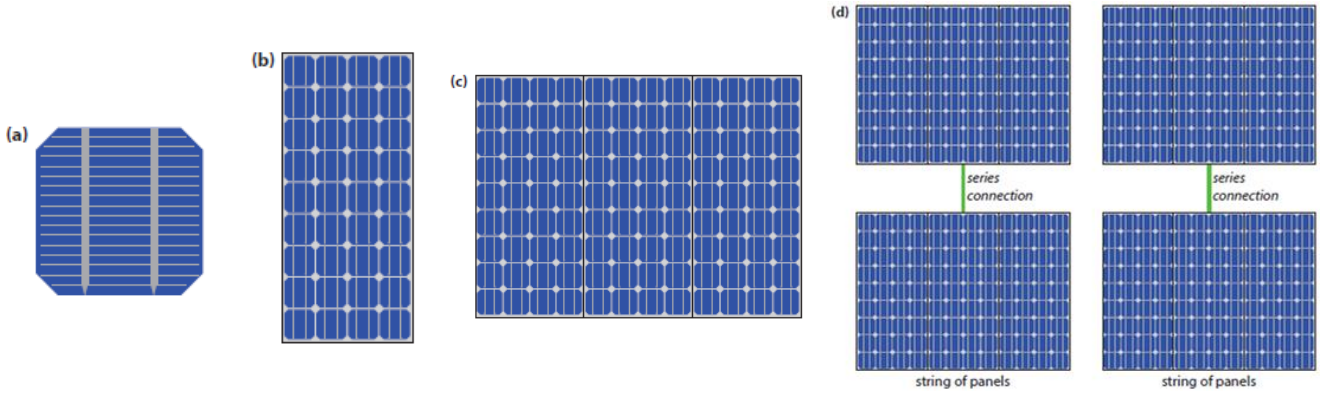

Figure 1. (a) a solar cell, (b) a solar module, (c) a solar panel and (d) a solar array [16].

Iraq and Neighboring Countries

Iraq is located north of the equator (i.e., in the Northern Hemisphere) and its capital city is Baghdad. Table 1 shows the seasonal optimum tilt angle of solar panels from Solar Panel Angle Calculator for 17 cities in the north, east, middle, west and south of Iraq. Northern cities have the lowest angles, while southern cities have the highest angles. For all cities, the minimum angle is for winter, the medium for spring/ autumn and the maximum for summer (more sun means more sunlight). The optimum tilt angle ranges from 30˚ to 36˚ in winter, 54˚ to 60˚ in spring/ autumn and 78˚ to 84˚ in summer. Figure 2 shows optimum tilt angles in degrees from vertical for Ramadi, Baghdad and Karbala'. This figure is obtained from Solar Panel Angle Calculator.

Table 1. Optimum tilt angle of solar panels in Iraq's cities.

City	Optimum tilt angle in degrees from vertical		
	Winter	Spring/ Autumn	Summer
Mosul	30˚	54˚	78˚
Arbil			
Sulaymaniyah			
Kirkuk			
Samarra'	32˚	56˚	80˚
Ba'qubah			
Ramadi	34˚	57˚	80˚
Baghdad			
Karbala'			
Kut	34˚	58˚	82˚
Hillah			
Najaf			
Diwaniyah			
Amarah			
Samawah	36˚	59˚	82˚
Nasiriyah			
Basrah	36˚	60˚	84˚

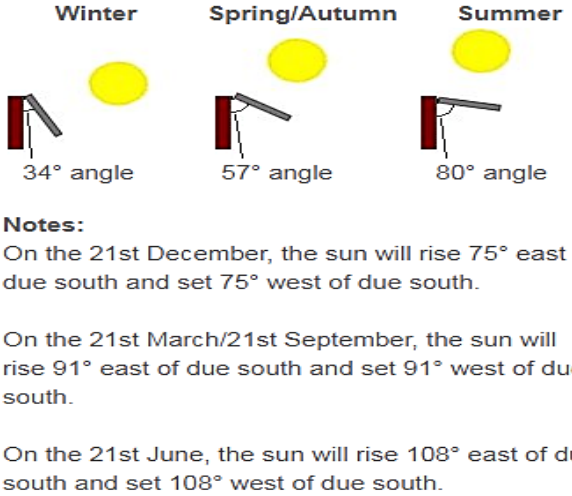

Figure 2. Optimum tilt angles for Ramadi, Baghdad and Karbala'.

Iraq is bordered to the north by Turkey, to the east by Iran, to the west by Syria, to the southwest by Jordan, to the southeast by Kuwait and to the south by Kingdom of Saudi Arabia (KSA). Table 2 shows optimum tilt angle of solar panels from Solar Panel Angle Calculator for six cities of Iraq's neighbor countries. The optimum tilt angle varies from 26˚ to 42˚ in winter, 50˚ to 65˚ in spring/autumn and 74˚ to 88˚ in summer.

Table 2: Optimum tilt angle of solar panels in Iraq's neighbor countries.

Country	City	Optimum tilt angle in degrees from vertical		
		Winter	Spring/ Autumn	Summer
Turkey	Ankara	26˚	50˚	74˚
Iran	Tehran	30˚	54˚	78˚
Syria	Damascus	32˚	56˚	80˚
Jordan	Amman	34˚	58˚	82˚
Kuwait	Al Wafrah	38˚	61˚	84˚
KSA	Riyadh	42˚	65˚	88˚

Other Countries in the World

Table 3 shows optimum tilt angle of solar panels from Solar Panel Angle Calculator for 77 capital cities in 77 countries. This angle lies in the range 6° to 66° in winter, 30° to 89° in spring/ autumn and 54° to 112° in summer.

Cities which have the same optimum tilt angles in Tables 1 to 3 are approximately have the same absolute values of latitudes as shown in Table 4. Optimum tilt angles in Tables 1 to 3 which calculated from Solar Panel Angle Calculator are in excellent agreement with those in Table 4 which calculated from Equations (1) to (3) depending on the latitude. The seasonal optimum tilt angle from vertical increases with decreasing absolute value of the latitude.

Table 3. Optimum tilt angle of solar panels in other countries.

Country	Capital	Optimum tilt angle in degrees from vertical			Country	Capital	Optimum tilt angle in degrees from vertical		
		Winter	Spring/ Autumn	Summer			Winter	Spring/ Autumn	Summer
Finland	Helsinki	6°	30°	54°	Libya	Tripoli	34°	57°	80°
Norway	Oslo				Egypt	Cairo	36°	60°	84°
Germany	Berlin	14°	38°	62°	India	New Delhi	38°	61°	84°
Netherlands	Amsterdam				Qatar	Doha	42°	65°	88°
Poland	Warsaw				Paraguay	Asuncion			
UK	London				Taiwan	Taipei			
Kazakhstan	Astana	16°	39°	62°	UAE	Abu Dhabi	42°	66°	90°
Belgium	Brussels				Bangladesh	Dhaka			
Austria	Vienna	18°	42°	66°	Oman	Muscat			
Slovakia	Bratislava				Haiti	Port-au-Prince	48°	72°	96°
Slovenia	Ljubljana	20°	44°	68°	Fiji	Suva			
Croatia	Zagreb				Mauritania	Nouakchott			
Kyrgyzstan	Bishkek	24°	47°	70°	Jamaica	Kingston			
Bulgaria	Sofia				Brazil	Brasilia	50°	74°	98°
Italy	Roma	24°	48°	72°	Sudan	Khartoum			
Georgia	Tbilisi				Yemen	Sanaa	52°	75°	98°
Albania	Tirana	26°	49°	72°	Eritrea	Asmara			
Uzbekistan	Tashkent				Senegal	Dakar			
New Zealand	Wellington				Philippines	Manila			
Spain	Madrid	26°	50°	74°	Thailand	Bangkok	52°	76°	100°
Azerbaijan	Baku				El Salvador	San Salvador			
Armenia	Yerevan				Chad	N'Djamena	54°	78°	102°
China	Beijing				Peru	Lima			
US	Washington	28°	51°	74°	Djibouti	Djibouti			
Portugal	Lisbon				Comoros	Moroni			
Tajikistan	Dushanbe	28°	52°	76°	Panama	Panama	58°	81°	104°
Greece	Athens				Ethiopia	Addis Ababa			
Turkmenistan	Ashgabat				Angola	Luanda			
South Korea	Seoul				Indonesia	Jakarta	60°	84°	108°
Tunisia	Tunis	30°	53°	76°	Tanzania	Dodoma			
Algeria	Algiers				Ghana	Accra			
Malta	Valletta	30°	54°	78°	Congo	Kinshasa	62°	86°	110°
Japan	Tokyo				Maldives	Male			
Australia	Canberra	32°	55°	78°	Cameroon	Yaounde			
Cyprus	Nicosia				Singapore	Singapore	66°	89°	112°
Uruguay	Montevideo				Kenya	Nairobi			
Argentina	Buenos Aires								
Afghanistan	Kabul	32°	56°	80°					
Morocco	Rabat								
Lebanon	Beirut								
Pakistan	Islamabad								

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Table 4. Geographic coordinates for 100 cities and corresponding optimum tilt angles.

City	Decimal Degrees (DD) coordinates [18]		Optimum tilt angle in degrees from vertical		
	Longitude	Latitude (ϕ)	Winter	Spring/ Autumn	Summer
			66.5˚–|ϕ|	90˚–|ϕ|	113.5˚–|ϕ|
Helsinki	24.938379	60.169856	6.3˚	29.8˚	53.3˚
Oslo	10.752245	59.913869	6.6˚	30.1˚	53.6˚
Berlin	13.404954	52.520007	14.0˚	37.5˚	61.0˚
Amsterdam	4.895168	52.370216	14.1˚	37.6˚	61.1˚
Warsaw	21.012229	52.229676	14.3˚	37.8˚	61.3˚
London	–0.127758	51.507351	15.0˚	38.5˚	62.0˚
Astana	71.470356	51.160523	15.3˚	38.8˚	62.3˚
Brussels	4.351721	50.850346	15.6˚	39.1˚	62.6˚
Vienna	16.373819	48.208174	18.3˚	41.8˚	65.3˚
Bratislava	17.107748	48.148596	18.4˚	41.9˚	65.4˚
Ljubljana	14.505751	46.056947	20.4˚	43.9˚	67.4˚
Zagreb	15.981919	45.815011	20.7˚	44.2˚	67.7˚
Bishkek	74.569762	42.874621	23.6˚	47.1˚	70.6˚
Sofia	23.321868	42.697708	23.8˚	47.3˚	70.8˚
Roma	12.496366	41.902783	24.6˚	48.1˚	71.6˚
Tbilisi	44.827096	41.715138	24.8˚	48.3˚	71.8˚
Tirana	19.818698	41.327546	25.2˚	48.7˚	72.2˚
Tashkent	69.240073	41.299496			
Wellington	174.776236	–41.286460			
Madrid	–3.703790	40.416775	26.1˚	49.6˚	73.1˚
Baku	49.867092	40.409262			
Yerevan	44.499103	40.179186	26.3˚	49.8˚	73.3˚
Ankara	32.859742	39.933363	26.6˚	50.1˚	73.6˚
Beijing	116.407396	39.904200			
Washington	–77.036871	38.907192	27.6˚	51.1˚	74.6˚
Lisbon	–9.139337	38.722252	27.8˚	51.3˚	74.8˚
Dushanbe	68.787038	38.559772	27.9˚	51.4˚	74.9˚
Athens	23.727539	37.983810	28.5˚	52.0˚	75.5˚
Ashgabat	58.326063	37.960077			
Seoul	126.977969	37.566535	28.9˚	52.4˚	75.9˚
Tunis	10.181532	36.806495	29.7˚	53.2˚	76.7˚
Algiers	3.058756	36.753768			
Mosul	43.164000	36.356648	30.1˚	53.6˚	77.1˚
Arbil	44.008870	36.206293	30.3˚	53.8˚	77.3˚
Valletta	14.514553	35.898908	30.6˚	54.1˚	77.6˚
Tokyo	139.691706	35.689487	30.8˚	54.3˚	77.8˚
Tehran	51.388974	35.689197			
Sulaymaniyah	45.435943	35.557045	30.9˚	54.4˚	77.9˚
Kirkuk	44.380392	35.465576	31.0˚	54.5˚	78.0˚
Canberra	149.130009	–35.280937	31.2˚	54.7˚	78.2˚
Nicosia	33.382276	35.185566	31.3˚	54.8˚	78.3˚
Montevideo	–56.164531	–34.901113	31.6˚	55.1˚	78.6˚
Buenos Aires	–58.381559	–34.603684	31.9˚	55.4˚	78.9˚
Kabul	69.207486	34.555349			
Samarra'	43.905515	34.166004	32.3˚	55.8˚	79.3˚
Rabat	–6.849813	33.971590	32.5˚	56.0˚	79.5˚
Beirut	35.501777	33.893791	32.6˚	56.1˚	79.6˚
Ba'qubah	44.606658	33.759641	32.7˚	56.2˚	79.7˚
Islamabad	73.229354	33.660036	32.8˚	56.3˚	79.8˚
Damascus	36.276528	33.513807	33.0˚	56.5˚	80.0˚
Ramadi	43.281158	33.435279	33.1˚	56.6˚	80.1˚
Baghdad	44.361488	33.312806	33.2˚	56.7˚	80.2˚
Tripoli	13.191338	32.887209	33.6˚	57.1˚	80.6˚
Karbala'	44.010392	32.606846	33.9˚	57.4˚	80.9˚

Kut	45.846961	32.516846	34.0°	57.5°	81.0°
Hillah	44.427621	32.477336			
Najaf	44.333116	32.027376	34.5°	58.0°	81.5°
Diwaniyah	44.906650	31.964143			
Amman	35.928372	31.945367	34.6°	58.1°	81.6°
Amarah	47.145960	31.849608	34.7°	58.2°	81.7°
Samawah	45.280618	31.318839	35.2°	58.7°	82.2°
Nasiriyah	46.266591	31.045234	35.5°	59.0°	82.5°
Basrah	47.783489	30.508103	36.0°	59.5°	83.0°
Cairo	31.235712	30.044420	36.5°	60.0°	83.5°
New Delhi	77.209021	28.613939	37.9°	61.4°	84.9°
Al Wafrah	48.104851	28.593025			
Doha	51.531040	25.285447	41.2°	64.7°	88.2°
Asuncion	–57.575926	–25.263740			
Taipei	121.565418	25.032969	41.5°	65.0°	88.5°
Riyadh	46.675296	24.713552	41.8°	65.3°	88.8°
Abu Dhabi	54.377344	24.453884	42.0°	65.5°	89.0°
Dhaka	90.412518	23.810332	42.7°	66.2°	89.7°
Muscat	58.405923	23.585890	42.9°	66.4°	89.9°
Port-au-Prince	–72.307433	18.594395	47.9°	71.4°	94.9°
Suva	178.450079	–18.124809	48.4°	71.9°	95.4°
Nouakchott	–15.958237	18.073530			
Kingston	–76.809904	18.017874	48.5°	72.0°	95.5°
Brasilia	–47.882166	–15.794229	50.7°	74.2°	97.7°
Khartoum	32.559899	15.500654	51.0°	74.5°	98.0°
Sanaa	44.191007	15.369445	51.1°	74.6°	98.1°
Asmara	38.925052	15.322877	51.2°	74.7°	98.2°
Dakar	–17.467686	14.716677	51.8°	75.3°	98.8°
Manila	120.984219	14.599512	51.9°	75.4°	98.9°
Bangkok	100.501765	13.756331	52.7°	76.2°	99.7°
San Salvador	–89.218191	13.692940	52.8°	76.3°	99.8°
N'Djamena	15.055742	12.134846	54.4°	77.9°	101.4°
Lima	–77.042754	–12.046373	54.5°	78.0°	101.5°
Djibouti	42.590275	11.825138	54.7°	78.2°	101.7°
Moroni	43.247315	–11.717216	54.8°	78.3°	101.8°
Panama	–79.519870	8.982379	57.5°	81.0°	104.5°
Addis Ababa	38.757761	8.980603			
Luanda	13.289437	–8.839988	57.7°	81.2°	104.7°
Jakarta	106.865039	–6.175110	60.3°	83.8°	107.3°
Dodoma	35.751607	–6.162959			
Accra	–0.186964	5.603717	60.9°	84.4°	107.9°
Kinshasa	15.266293	–4.441931	62.1°	85.6°	109.1°
Male	73.509347	4.175496	62.3°	85.8°	109.3°
Yaounde	11.502075	3.848032	62.7°	86.2°	109.7°
Singapore	103.819836	1.352083	65.1°	88.6°	112.1°
Nairobi	36.821946	–1.292066	65.2°	88.7°	112.2°

CONCLUSIONS

In this work, optimum tilt angles for non-tracking solar panels were calculated using Solar Panel Angle Calculator. These angles depend on seasons and locations. Cities with the same seasonal optimum tilt angles have approximately the same latitude. The higher the latitude, the lower the tilt angle. It has been concluded that adjusting angles once each season is recommended. This study can be extended to any city in the world.

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