Optimal Installation of PV Solar Panels: Optimum Tilt Angles and Incident Solar Radiation as Solutions of the Annual Electric Power Peak Demands in Palestine

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Abstract: An important parameter that affects the performance of fixed solar panels and flat plate solar collectors is their tilt angle with horizontal. In fact, variation of tilt angle changes the top loss coefficient of solar panels and the amount of solar radiation reaching the absorber plate. A mathematical model is developed and used for calculating the absorbed energy for a typical solar panel in Palestine Capital City; Jerusalem (N 31° 47', E 35°14'), on the daily, monthly, and seasonal basis. The optimal tilt angle (β) for a solar panel oriented to the south is also obtained for two periods: the first is named Cold-Weather or Winter optimal installation tilt angle for the period (September 23 – to – March 21) and the other is named Hot-Weather or Summer optimal installation angle for the period (March 22 – to – September 22). The annual optimal average installation tilt angle is (β_{Avg} = 31.69°), the average optimal cold- weather installation tilt angle is (β_{Avg} = 46.36°) and the average optimal hot-weather installation tilt angle is (β_{Avg} = 17.43°). The obtained results show that using two annual installation tilting angles is more efficient than using the annual average installation tilting angle and the obtained direct solar radiation is very close to that obtained by using single axis auto tracking solar panels.

Key words: solar photovoltaic, optimum tilt angle, model evaluation, maximum power, solar panel orientation.

1. Introduction

Since the seventies of the previous century, there is an ongoing research both at Palestinian universities and local communities for the purpose of utilizing solar energy for water heating until almost every roof in Palestinian residential areas becomes containing flat plate solar water heaters. An evaluation of what was achieved was done immediately after the establishment of the Palestinian National Authority; in the year 1994. The results of that evaluation was: Palestine is ranked as the third country in the world (Japan is the first, and USA is the second) in utilizing solar domestic water heater (SDWH, total glazed collector area installed is about 2,800000 m^2 in the year 1994), and ranked as the second producer (the first is China) of glazed solar collectors (annual production is about 300,000 m^2 in the year 1994), [1].

In Palestine, the main reason stands behind the choice of solar energy is that Palestine is considered as a poor country in the sources of fossil fuel (power), nowadays this fossil power prices as escalating to unprecedented levels, which is not affordable by Palestinian economy especially that the demand on fossil fuel is increasing, that makes the prices of oil increasing rapidly and becomes the highest in all over the world, where Palestine citizens cannot withstand; Palestinian households spend about 8.5 percent of their income on electric power and liquid gas, [2].

In Palestine, the demand on electric power is increasing rapidly and it is expected to reach 12850 GWh in the year 2030 and the electric power generation must reach 2335 MW; [3,4].

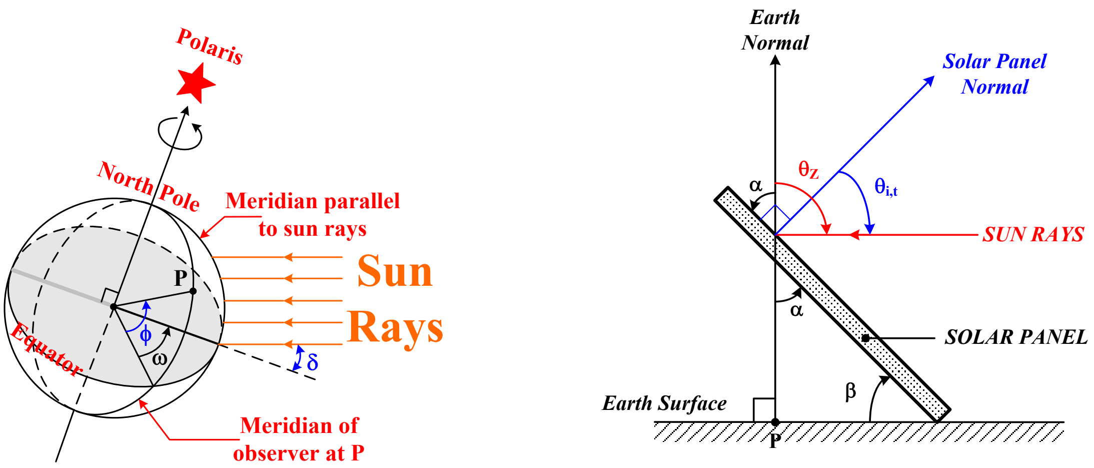
This research aims for the determination of the monthly, seasonally, and annual optimal installation tilting angle (β) for photovoltaic (PV) solar panels and flat plate solar water heaters in Palestine for the purpose of minimizing the catchment area of PV solar panels and maximizing the electric power production of the PV-solar power stations.

2. Radiation Models: Comparisons and Evaluations

The amount of solar energy that reaches the earth's surface at a particular time depends upon a number of factors namely: air mass, angle, cloud and haze, and diffuse radiation factors.

The air mass factor is defined as the length of path that the radiation beam travels through the atmosphere. It is a function of the zenith distance and the angle between the zenith and the direction of the sun. The zenith angle (θ_Z) varies throughout the day and from day – to – day as a function of the latitude (ϕ), the solar declination angle (δ), and the hour angle (ω) of the sun, see Figure 1.

The direct radiation $\dot{\mathbf{E}}_{\mathbf{n}}$ incident upon a surface located on the earth and oriented in a direction normal to the rays of the sun is given and approximated by the equation: $\dot{\mathbf{E}}_{\mathbf{n}} = \dot{\mathbf{E}}_{\mathbf{o}}\, \boldsymbol{\tau}_{\mathbf{a}}^{\mathbf{m}}$



a) Solar angles.

b) Collector or solar panel geometry with installation angles.

Figure 1: Solar Angles and solar panel geometry with installation location and angles.

Where: $\dot{E}_o$ is the solar constant (1366.1 W/m^2), τ_a is the transmission coefficient for unit air mass; its value varies with the condition of the sky and ranges from about 0.8 on a clear sunny day to less than 0.10 on a heavy over cast day. At a particular location, the appropriate value of τ_a is predicted from meteorological data. Andthe superscript (**m**) is the relative air mass; defined as the ratio of the length of the actual path to the length of the shortest possible path (m = sec θz for θz < 80°). The direct radiation incident upon a surface which is not normal to the direction of the sun is determined by the equation: $\dot{E}_i = \dot{E}_n \cos\theta_i$

Where: θ_i is the angle of incidence; measured between the sun's direction and the normal to the surface (solar panel).

3. Solar Angles & Collector Geometry For Calculations of Tilt angle

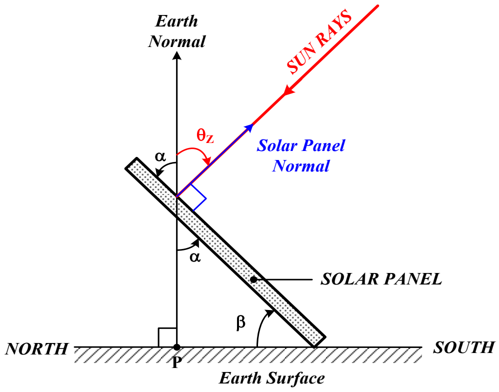


Figure 2: Optimal installation of a solar panel.

Figure 1-a presents the solar angles and the location place (P) of a solar collector or panel on the earth's surface, and Figure 1-b presents the collector geometry. With the aid of Figure 1 and using trigonometric relations, one can easily drive the zenith angle (θz) in function of the solar angles (ϕ, δ, and ω and obtain the equation:

$$\cos\theta_Z = \sin\emptyset \sin\delta + \cos\emptyset \cos\omega \cos\delta$$

The angle (ω) is defined as the hour angle of the sun (15 degrees/hour). The time of day can be expressed by the hour angle, which is indicative of the apparent rotation of the sun about the earth's axis. The rotation is measured with respect to the time (solar noon) when the sun crosses the south meridian of a particular location on the earth. The value of ω varies from zero at local noon to a maximum at sunrise or sunset. In Jerusalem, the longest day of the year is the 21 of June, where the sun rise time is at 4:31 AM, the sunset time is at 6:52 PM and the length of this day is 14 hours and 21 minutes.

$$\cos\beta = \sin\emptyset \sin\delta + \cos\emptyset \cos\delta$$

Applying the trigonometric relations to the Equation yields: $\beta = \emptyset - \delta$

The optimal annual or seasonal average tilting angle (β_{Avg}) can be calculated by: $\beta_{Avg} = \frac{\sum_{i=1}^{n} Nd_i \times \beta_i}{\sum_{i=1}^{n} Nd_i}$

Where: β_{Avg} (degrees) is the optimal average tilting angle that is calculated over a period of time (days) in a year, Nd_i indicates the number of days in a month or a season that are associated with the optimal tilting angle (β_i) and the subscript (i) indicates the number of the month or season.

4. Calculated Results, Conclusions and Recommendations of Solar Energy

In Palestine, the majority of the people use thermo-siphon flat plate solar water heaters with storage tank ranging 150 to 200 liters in volume and usually the storage tank is supplied with electric heater to be used in winter

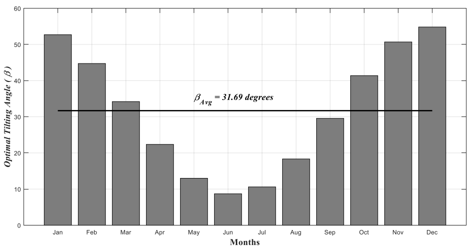


Figure 3: Optimal tilting angle (β) for each month in Jerusalem (N 31° 47’, E 35°14’), and the annual average tilting angle (β_{Avg} = 31.69°)

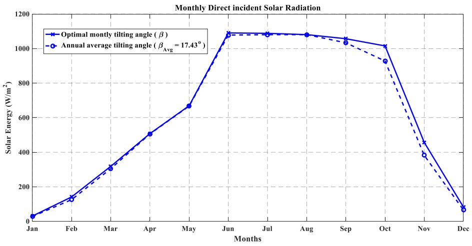


Figure 5: Monthly direct solar radiation on PV solar panels tilted by optimal monthly tilting angle (solid-line) and hot-weather period annual average tilting angle (β_{avg} = 17.43°, dashed-line).

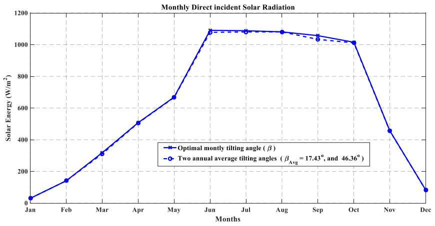


Figure 7: Monthly direct solar radiation on PV solar panels tilted by optimal monthly tilting angle (solid-line) and two annual sittings: Cold-Weather or Winter optimal installation tilt angle (β_{avg} = 46.36°, dashed-line) for the period (September 23 – to – March 21) and Hot-Weather or Summer optimal installation angle (β_{avg} = 17.43°, dashed-line) for the period (March 22 – to – September 22).

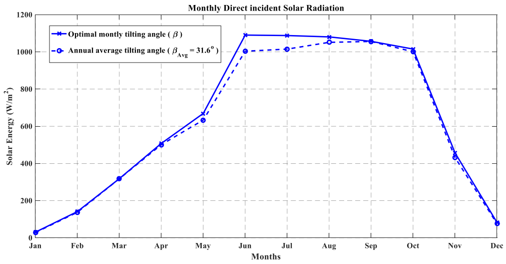


Figure 4: Monthly direct solar radiation on PV solar panels tilted by optimal monthly tilting angle (solid-line) and annual average tilting angle (β_{avg} = 31.6°, dashed-line).

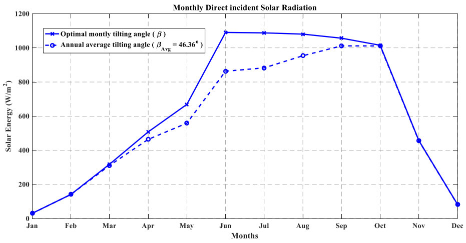


Figure 6: Monthly direct solar radiation on PV solar panels tilted by optimal monthly tilting angle (solid-line) and cold-weather period annual average tilting angle (β_{avg} = 46.36°, dashed-line).

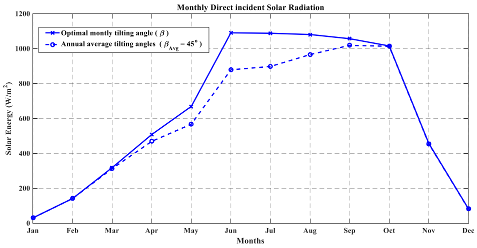


Figure 8: Monthly direct solar radiation on PV solar panels tilted by optimal monthly tilting angle (solid-line) and annual sitting technical tilting angle (β_{avg} = 45°, dashed-line).

where there is no sun shine or for rising the temperature of water when it is less than 70°C. More than 99.7% of the Palestinian people are connected to the electric power grid [3]; and the majority of PVs are on grid solar power stations where no electric power storage (batteries) is used. These two main points serves as the key issues of solving the excessive peak demand.

In Palestine, there are mainly two annual peak demands that the electric power supply should cover. Firstly, the main peak demand occurs in summer period due to intensive use of air conditioning systems that cause shortages and sometimes shutdown of electric power for about two or three hours during hot days depending on the weather conditions and the individual peak loads of the region. Secondly, Peak demands in winter period due to water heating for domestic needs specially when the atmospheric temperature drops to minimum ranges (0 - 8°C). Note that, Palestine such as European countries and United states has liquid gas (used mainly for house heating) peak demand in winter. If there is shortages in Liquid gas, the Palestinian people use electric power for heating that cause a rapid increase in the electric power peak demand in winter.

Figure 4 presents graphically the obtained results and compares the maximum direct incident solar radiation ($\dot{\mathbf{E}}_{\mathbf{n}}$) on a PV panel directed normally to sun rays with the incident solar radiation ($\dot{\mathbf{E}}_{\mathbf{i,t}}$) on a PV panel tilted by the annual average tilting angle (β_{avg} = 31.6°) and shows that there is measurable deviation in the incident solar radiation in spring and summer periods that means using the annual average tilting will increase the total area of the PV solar power station to produce a certain electric power.

Figure 5 presents graphically the obtained results and compares the maximum direct incident solar radiation ($\dot{\mathbf{E}}_{\mathbf{n}}$) on a PV panel directed normally to sun rays with the incident solar radiation ($\dot{\mathbf{E}}_{\mathbf{i,t}}$) on a PV panel tilted by the hot-weather (summer period) annual average tilting angle (β_{avg} = 17.43°) and shows that there is small deviation in the incident solar radiation in autumn period that means using the hot weather annual average tilting will minimize the total area of the PV solar power station and will be able to solve excessive peak demand in summer. Figure 6 presents graphically the obtained results and compares the maximum direct incident solar radiation ($\dot{\mathbf{E}}_{\mathbf{n}}$) on a PV panel directed normally to sun rays with the incident solar radiation ($\dot{\mathbf{E}}_{\mathbf{i,t}}$) on a PV panel tilted by the Cold-Weather (Winter-Period) annual average tilting angle (β_{avg} = 46.36°) and shows that there is a very large deviation in the incident solar radiation in spring and summer (Hot-Whether) period that means using the Cold- Weather annual average tilting cannot be used due a very large total area of the PV solar power station and will not be able to solve excessive peak demand in summer. Figure 7 presents graphically the obtained results and compares the maximum direct incident solar radiation ($\dot{\mathbf{E}}_{\mathbf{n}}$) on a PV panel directed normally to sun rays with the incident solar radiation ($\dot{\mathbf{E}}_{\mathbf{i,t}}$) on a PV panel tilted by the Cold-Weather (Winter-Period, sep. 23 - Mar. 21) average tilting angle (β_{avg} = 46.36°) and then tilted by Hot-Weather (Summer-Period, Mar. 22 - Sep. 22) average tilting angle (β_{avg} = 17.43°) shows that the incident solar radiation ($\dot{\mathbf{E}}_{\mathbf{i,t}}$) is very close to maximum direct incident solar radian ($\dot{\mathbf{E}}_{\mathbf{n}}$) . Using two annual settings for the tilting angle will minimize the total area of the PV solar power station and maximize the electric power generation that serves as the key solution of solving the excessive peak demand in Palestine. Figure 8 presents graphically the obtained results and compares the maximum direct incident solar radiation ($\dot{\mathbf{E}}_{\mathbf{n}}$) on a PV panel directed normally to sun rays with the incident solar radiation ($\dot{\mathbf{E}}_{\mathbf{i,t}}$) on a PV panel tilted by the annual technical tilting angle (β_{avg} = 5°) and shows that there is measurable deviation in the incident solar radiation in most of the year that means the annual technical tilting angle cannot be used due a very large total area of the PV solar power station is needed and will not be able to solve excessive peak demand in most of the year.

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