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The Influence of Seasonal Cloud Cover, Ambient Temperature and Seasonal Variations in Daylight Hours on the Optimal PV Panel Tilt Angle in the United States

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Abstract: A variety of variables influence the optimal tilt angle of a PV panel, including the characteristics of the panel, the local seasonal weather variations, the number of daylight hours the panel is exposed to and the ambient temperature of the surroundings. In this study, the optimal PV tilt angle and maximum energy output of PV arrays was calculated for every county in the United States and compared against the practice of setting the PV tilt angle to be equivalent to the latitude angle of the PV geographic location. A PVWatts API, implemented through Python, was used in conjunction with the SciPy optimization package to find the optimal tilt angle for each county using a direct line search algorithm. Most counties (95.8%) showed a difference between the location latitude and the optimal tilt of more than one degree. Many counties showed a deviation of 2–6° lower than the location latitude. The variation of daylight hours had the largest influence on tilt angle and seasonal cloud cover and ambient temperature had varying levels of influence. Generally, winter cloud cover decreased the optimal tilt angle whereas high summer temperatures increased the tilt angle.

Keywords: photovoltaic tilt angle; optimization; weather

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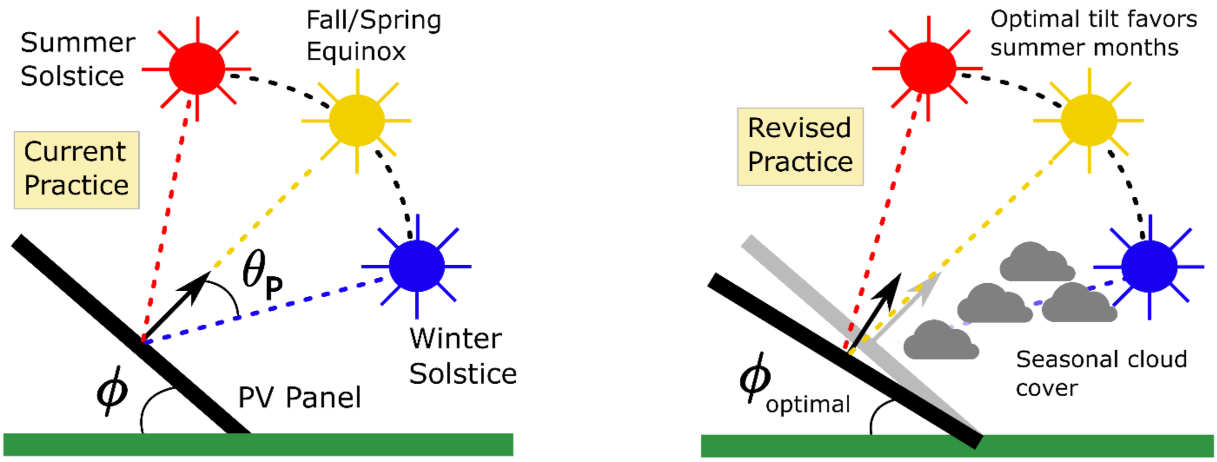
1. Introduction

Current research suggests that the number of PV installations will continue to grow globally due to lower costs, self-sufficiency and environmental impacts [1]. Given the rapid adoption of renewable energy that is required to contain climate change heating to within allowable levels [2], it is essential that every PV panel is deployed so as to collect as much solar energy as possible.

A fixed-tilt PV panel is installed to have a set tilt angle (ϕ as shown in Figure 1a), being the angle between the ground and the plane formed by the panel. The panel is also given a set azimuth angle, or the angle in the ground plane formed between the panel's normal vector and a normal vector pointing north. An azimuth of 180° indicates the panel is pointing directly south. Generally, a panel with a tilt angle of 0° or 90° will collect the least amount of energy over the course of one year as the panel's normal vector rarely aligns with the sun's position. For a PV panel having any tilt angle between the angles of 0° and 90°, it is found that a specific fixed tilt angle produces the most electrical energy over the course of the year. This is referred to as the optimal tilt angle. Likewise, an optimal azimuthal angle also exists.

Previous research of PV panels suggests the optimal tilt angle of the panel be equal to the latitude of the location to optimize the solar energy input into the panel [3]. At this angle, maximum energy output can be obtained from the PV panel [4], placing the panel perpendicular to the sun on the Fall and Spring equinoxes (as shown in Figure 1a) and minimizing the angle between the sun and the panel over the course of one year. Theoretically this would seem to maximize PV array production; however, this practice does not account for weather conditions or variation of daylight hours. For example, in certain locations where the weather may be subject to heavy cloud cover during the winter months, decreasing the tilt angle to favor summer months, as shown in Figure 1b, could result in an increase in energy collection. A lower PV tilt angle gives preferential treatment to summer energy collection, when the solar resource is most available, and decreases collection during winter months when the solar resource is limited.



(a) (b)

Figure 1. (**a**) A depiction of a commonly accepted practice for deploying PV panels, where the tilt angle is equivalent to the latitude of the PV panel geographic location. (**b**) A revised practice where the PV tilt angle is revised to reflect seasonal weather patterns and seasonal variations in daylight hours.

Several studies [1,3,5–11] have analyzed the effects of cloud cover and temperature on PV panel optimal tilt angle. Cloud cover affects the output of photovoltaic arrays because it determines the dominant type of radiation a solar module collects. Generally, beam radiation is the most significant, after that diffused radiation, and after that ground reflected radiation. When there is more cloud cover, less beam radiation and more diffused and ground-reflected radiation are available. This results in a lower energy output [12] and the total energy generation is decreased. Cloud coverage is one of the largest uncertainties with respect to solar energy collection [11]. Another study that investigated the effects of cloud coverage on fixed-tilt PV systems found that the optimal tilt can deviate by about 10° or more from latitude [3]. Likewise, high deviation of optimal tilt from latitude in certain locations around the world is mostly due to weather patterns and cloud coverage [3].

Photovoltaic panel efficiency is strongly correlated with the temperature of the panel cells, where elevated temperatures result in reduced panel efficiencies. However, few studies have looked at the effect that sustained high temperatures (and decreased efficiencies) have on the optimal PV panel tilt angle. One study observed how dust found in desert environments accumulates on PV panels and impacts performance negatively, but it did not investigate how extreme desert temperatures affect the PV panel tilt angle [4]. In the United States, several regions experience high summer temperatures, including the desert South-West and states touching the Gulf of Mexico. In these regions, it is expected that PV panel efficiency decline will influence the optimal tilt angle.

Finally, existing studies have calculated optimal tilt angles for a variety of locations throughout the world, such as: the United States [13,14] Taiwan [15], Nigeria [16], Japan [17], Saudi Arabia [18], Malaysia [19], Turkey [20], Canada [21], Pakistan [22] and many more. One study in particular performs a world-wide optimization [1]. Some of these studies indicate that cloud coverage plays a vital role in finding an optimal tilt angle to maximize the energy output of PV panels, and therefore determine that the optimal tilt angle is heavily dependent on local weather conditions. Notably, PV panel tilt optimization studies have not been completed for most United States locations.

In this work, the optimal PV tilt angle is determined for every county in the continental United States of America (USA), and the results provide insight regarding the influence of seasonal cloud cover, seasonal daylight hour variation and ambient temperatures on optimal PV tilt angle. The NREL PVWatts program is used to model energy production for each location using TMY3 data to account for transient cloud cover and ambient temperature variation. This work adds to existing PV panel research by explaining the process used to retrieve information with the PVWatts API and providing conclusions on how optimal tilt and maximum energy output rely on the ambient temperature, cloud coverage and seasonal daylight hour variation across the USA. Comparisons of optimal tilt angles against state-of-the-art practices and across locations with similar latitude locations but different weather patterns are included.

2. Materials and Methods

The energy collected by a PV panel at a given tilt angle in a specific geographic location is modeled using PVWatts, a toolset developed by NREL (National Renewable Energy Laboratory), which is accessed through an application programming interface (API) using the Python scripting language. The input parameters provided to PVWatts are given in Table 1. A Python script outputs the DC monthly energy generated for every tilt angle in increments of 1° from 0° to 90°. The highest annual DC energy production corresponds to the optimal tilt angle. This process is completed for every county in the United States, using the county seat to represent the county location. The coordinates for every county in the United States were derived from the United States Census Bureau.

Table 1. Parameters used in the PVWatts simulation software.

Input Parameter	Definition or Options	Value Used
System Capacity	System nameplate capacity in kW	5 kW
Module Type	0—Standard, 1—Premium, 2—Thin Film	0—Standard
System Losses	Generate derate factor in percent	10%
Array Type	Fixed: 1—open rack, 2—roof mounted	1 and 2
Tilt	Array tilt angle in degrees	0–90°
Azimuth	Array compass direction in degrees	180°
Latitude/Longitude	Location coordinates	Based on location
Timeframe	Hourly/Monthly	Monthly
Dataset	Weather data options include: NSRDB, TMY2, TMY3, INTL	TMY3

2.1. Model Inputs and Outputs

System-specific parameters used in the PVWatts simulation software are given in Table 1. As the target output is DC power, which is the energy produced before inverter losses are accounted for, specifying the inverter efficiency is not relevant for this study. The system capacity of 5 kW was selected randomly as the purpose of this study is to compare array output by location, meaning the results of each county are relative to each other. A value of 5 kW was used consistently for all tilt angles and locations.

Three different inputs for the module type are possible: standard, premium and thin film. In this case, a standard module was used throughout the whole study. The algorithm assumes an efficiency of 15 percent for the standard module, a temperature coefficient of −0.47%/°C, and a reference temperature of 25 °C. The cover is also assumed to be glass [23]. The module type was set to open rack, although optimal results were found to be independent of mounting type. The efficiency of the module varies as a function of cell temperature linearly, meaning that at 25 °C, the module efficiency is 15 percent, but the efficiency will decrease by 0.47 percentage points for every increase of one degree Celsius above the reference temperature.

The PVWatts model requires hourly data for the beam and diffused solar irradiance for a year. It also requires ambient temperatures and wind speeds. All these factors are considered when calculating the panel temperature by utilizing TMY3 data, which are average hourly weather data for the time period 1990–2010 [23]. TMY3 data are generally collected from airport weather stations, and use the closest airport weather station to the location latitude and longitude. The model provides monthly average values of DC power production, where DC values were selected since the inverter efficiency and losses were not accounted for.

2.2. Sun Position Calculations

The sun position was calculated every hour using the algorithm developed by Michalsky [24] at the midpoint of every hour, with special consideration for the sunrise and sunset hours [23]. The sun position was calculated using several equations starting with the equation of time.

$$\mathrm{EOT} = 9.87\sin(2\mathrm{B}) - 7.53\cos(\mathrm{B}) - 1.5\sin(\mathrm{B}) \tag{1}$$

$$\mathrm{B} = 360/365\,(\mathrm{d} - 81) \tag{2}$$

where d in Equation (2) is the number of days from the beginning of the year. Equation (3) calculates the local standard time meridian (LSTM) and is used in Equation (4), which is a time correction factor (TC). Equation (5) calculates the local solar time (LST) using the local time (LT), and Equation (6) calculates the hour angle (HRA). This a conversion from local solar time to the degrees the sun moves across the sky. Finally, Equations (7) and (8) calculate the elevation angle and the azimuth, respectively, including the latitude shown as φ and the declination shown as δ.

$$\mathrm{LSTM} = 15^\circ \cdot \Delta\mathrm{T_{GMT}} \tag{3}$$

$$\mathrm{TC} = 4(\mathrm{Longitude} - \mathrm{LSTM}) + \mathrm{EOT} \tag{4}$$

$$\mathrm{LST} = \mathrm{LT} + \frac{\mathrm{TC}}{60} \tag{5}$$

$$\mathrm{HRA} = 15^\circ(\mathrm{LST} - 12) \tag{6}$$

$$\mathrm{Elevation} = \sin^{-1}[\sin(\delta)\sin(\varphi) + \cos(\delta)\cos(\varphi)\cos(\mathrm{HRA}) \tag{7}$$

$$\mathrm{Azimuth} = \cos^{-1}\left[\frac{\sin(\delta)\cos(\varphi) - \cos(\delta)\sin(\varphi)\cos(\mathrm{HRA})}{\cos(\mathrm{Elevation})}\right] \tag{8}$$

The beam, diffused, and ground reflected irradiance is calculated using the Perez algorithm [24]. The total irradiance is the sum of all three as shown in Equation (9). TMY3 data include the hourly measurements for all three components of radiation.

$$\mathrm{I_{tot}} = \mathrm{I_b} + \mathrm{I_d} + \mathrm{I_g} \tag{9}$$

2.3. PV Power and Thermal Analysis

Given the total irradiance, the PVWatts model applies a correction to account for the reflection losses on the cover. This is done by using a "physical model of transmittance through a module cover" [25]. For the standard and thin film module, the model uses an index of refraction of 1.526. Additional equations are used to account for the anti-reflective coat for the premium module [23,25]. The thermal analysis and calculations of the operating cell temperature that the model uses are developed by Fuentes [26]. This model uses the total irradiance, wind speed and dry bulb temperature to calculate the cell temperature. The model assumes a nominal operating cell temperature (NOCT) of 45 °C for a ground-mounted array and 49 °C for a roof-mounted array. The difference is to account for restricted airflow around a roof-mounted array [23].

The PV panel DC output power is calculated using Equation (10) after the total irradiance ($\mathrm{I_{tot}}$) and the cell temperature ($\mathrm{T_{cell}}$) are calculated. In Equation (10), the reference cell temperature ($\mathrm{T_{ref}}$) is assumed to be 25 °C and γ is the temperature coefficient. $\mathrm{P_{DC,0}}$ is the nameplate DC rating of the array and the number 1000 in the denominator is the reference irradiance in units of W/m^2 [23]. As mentioned previously, the temperature coefficient is $-0.47\%/°C$.

$$P_{DC} = \frac{I_{tot}}{1000} P_{DC,0}(1 + \gamma(T_{cell} - T_{ref})) \quad (10)$$

2.4. Model Validation

The PVWatts model is validated by comparison to measured data. In a recent study [27], nine existing PV systems were compared against model results. The systems consisted of fixed-tilt and tracking arrays that were positioned in different parts of the United States and in different climates. When the annual AC energy was compared, the PVWatts Version 5 model under-predicted by 1.8% on average [23]. In this study, the PVWatts Version 6 model was used that is assumed to be similar in validation to Version 5.

2.5. Optimization

The optimization cost function, given by Equation (11), is the annual DC energy generated by the PV array and is a function of a single variable, the tilt angle of the PV panels. Since the time frame selected is monthly, Equation (10) will output monthly results. Summing the array of 12 months yields the annual DC energy generated by the array (Equation (11)). The tilt angles are constrained from 0° to 90°. The optimization problem and associated constraint are given in Equation (12). As a one-dimensional optimization problem, the minimal solution is easily resolved with a simple line search method implemented in the Python language.

$$E_{tot} = \sum_{1}^{12} P_{DC} = \sum_{1}^{12} \frac{I_{tot}}{1000} P_{DC,0}(1 + \gamma(T_{cell} - T_{ref})) \quad (11)$$

$$\text{Minimize}: \ -E_{tot}(\phi) \quad (12)$$

$$\text{Subject To}: \ 0° \leq \phi \leq 90°$$

3. Results

3.1. Seasonal Weather Variation

Figure 2 shows the average cloud cover during the winter months, and Figure 3 shows the average temperatures during the summer. During the winter season, the Pacific Northwest and some areas in the Midwest have the highest amount of cloud cover. Specifically, the coastal areas of Washington and Michigan. In the south, the coastal areas of Texas have more cloud cover than Florida, despite similar latitudes. In general, counties on similar latitude lines are compared to each other using the optimal PV panel tilt angle for that location. A lower tilt angle means that the array is tilted to favor the summer months when the sun is higher in the sky at solar noon. A higher optimal tilt angle means that the array is tilted to collect more towards winter where the sun is lower in the sky at solar noon. This terminology will be used throughout this paper.

3.2. PV Power and Optimal Tilt Angle

Figure 4 is a map of the maximum energy output for every county in the United States for PV panels with the optimal tilt angle for each location. Counties at southern latitudes produce more energy than counties at northern latitudes due to warmer weather, less cloud cover and a larger number of daylight hours. The Pacific Northwest exhibits the lowest energy production due to persistent cloud cover in that region.

Figure 5 is a map of the optimal PV panel tilt angle for every county in the continental United States of America, and Figure 6 is a map that displays the difference between the optimal tilt angle for a county and the latitude of that county. In Figure 5, three pairs of counties with similar latitudes but different tilt angles are indicated to be further analyzed in the next sections. In Figure 6, a negative value indicates an optimal tilt angle that is smaller than the latitude angle, or a panel that is tilted to favor collection during summer months over collection during winter months. A positive value indicates the opposite behavior, where a panel is tilted to favor collection during winter months. The magnitude of the difference displays the magnitude of the variation between the optimal tilt angle and the latitude angle. It is important to point out that in Figure 4 through 6, an error of 1.8% is expected as a result of using the PVWatts models. This error is expected to be approximately constant for each location and for all times of the year. A 1° variation in tilt angle above and below the optimal value varies the power by more than 1.8% for all locations. As such, the optimal tilt angles are expected to fall within 1° of the reported values here.

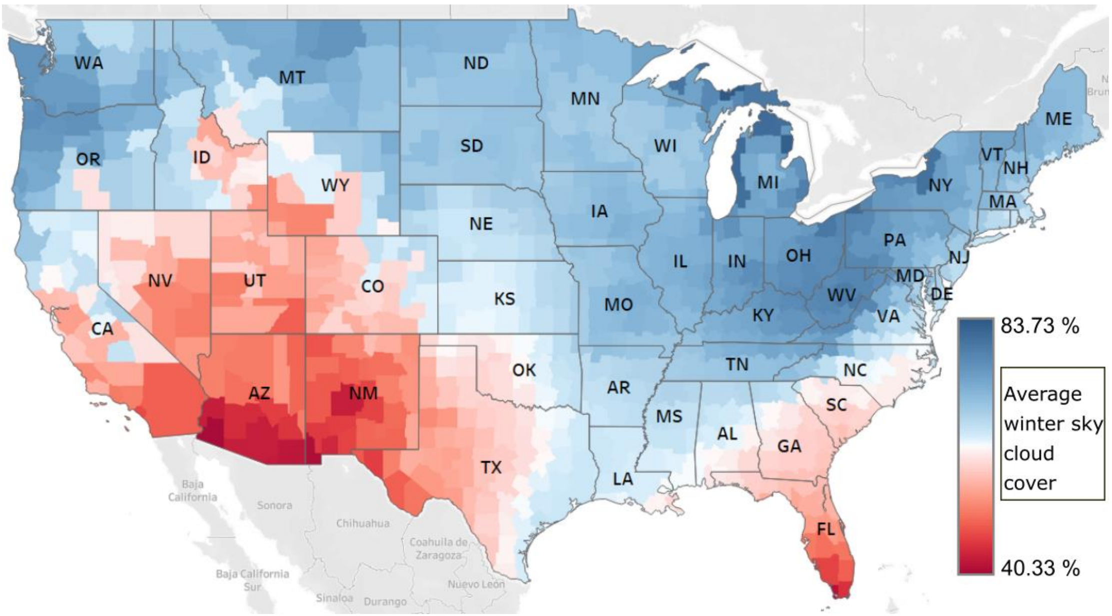


Figure 2. Average cloud cover during the winter in percent for every county in the continental United States.

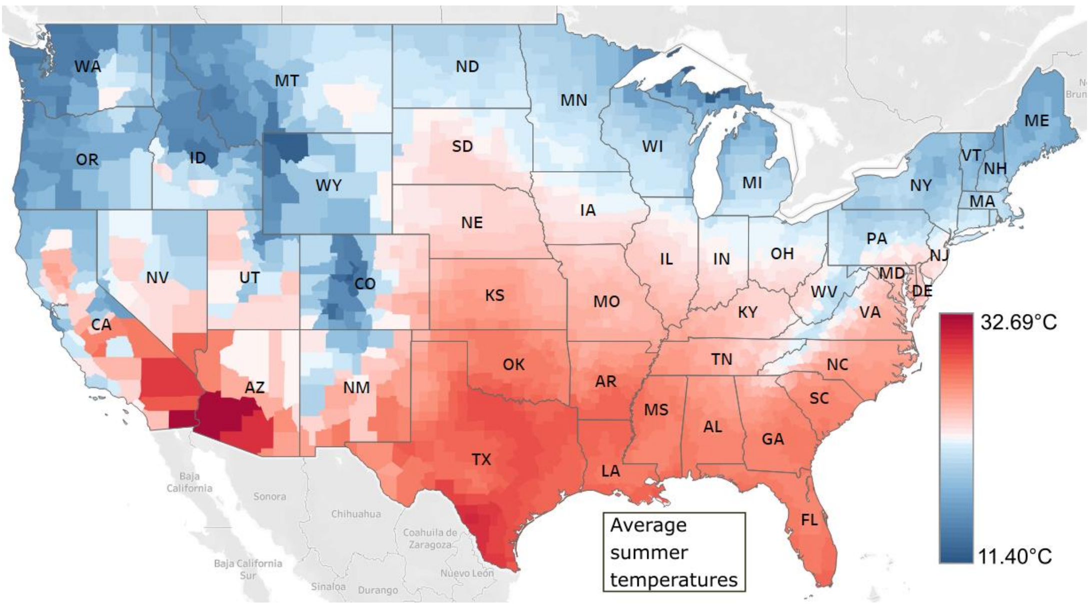


Figure 3. Average summer temperatures in °C for every county in the continental United States.

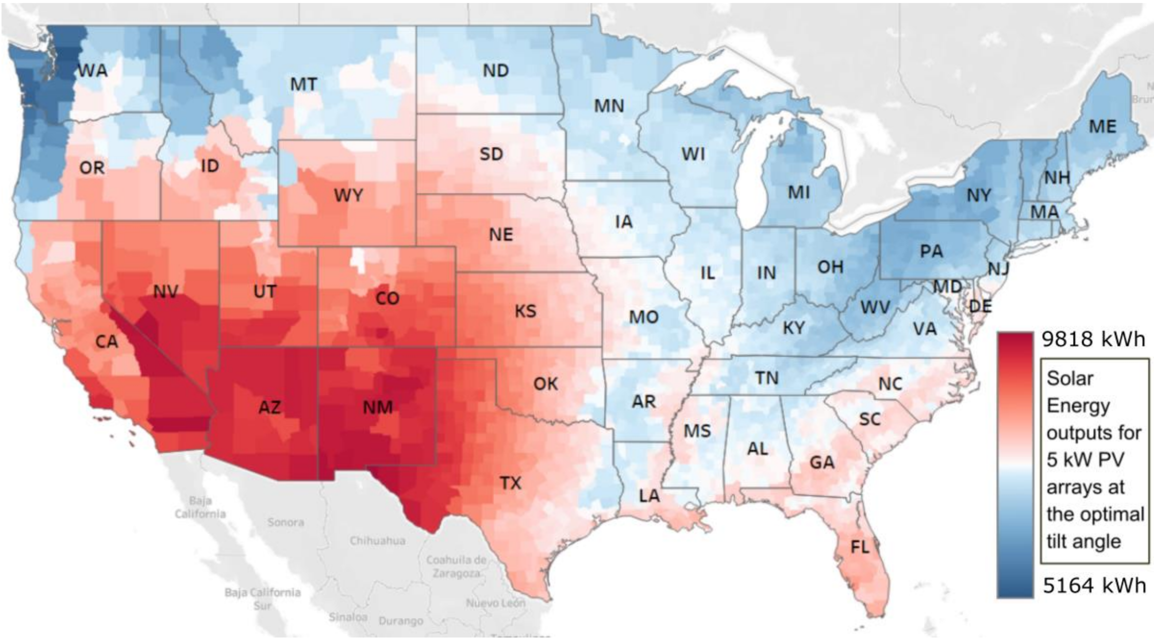


Figure 4. Solar energy output in kWh for 5 kW arrays in the continental United States.

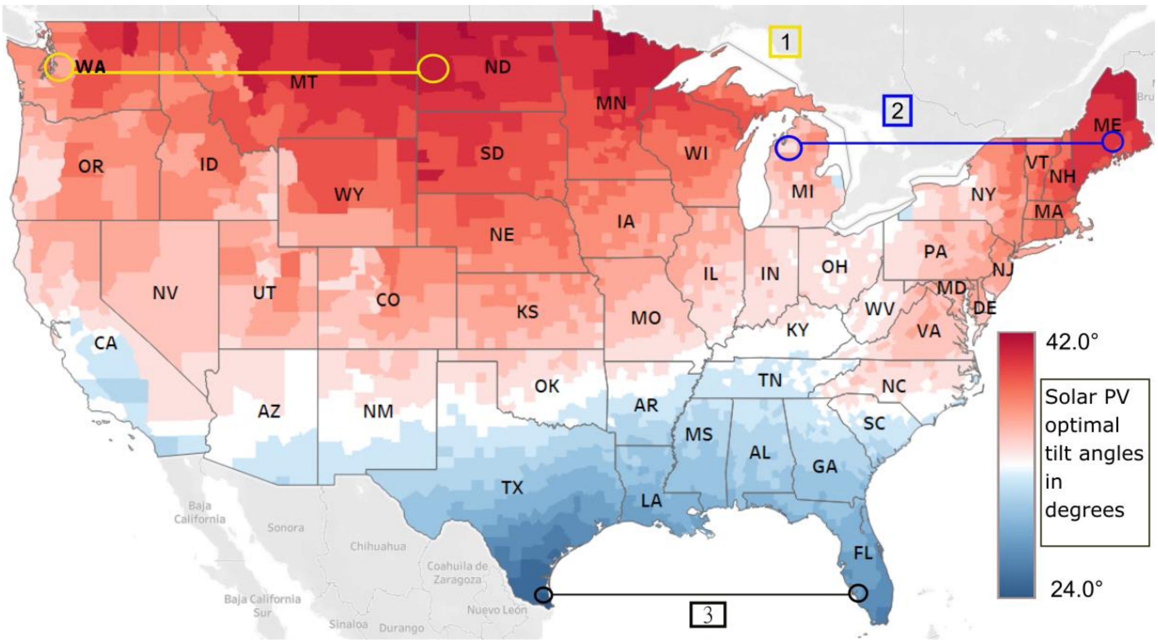


Figure 5. Solar PV optimal tilt angle in degrees for every United States county, showing locations of interest where optimal tilts differ at similar latitudes. The circles connected with lines, labeled with the boxed values 1, 2 and 3, indicate counties of similar latitude that are used for comparison cases.

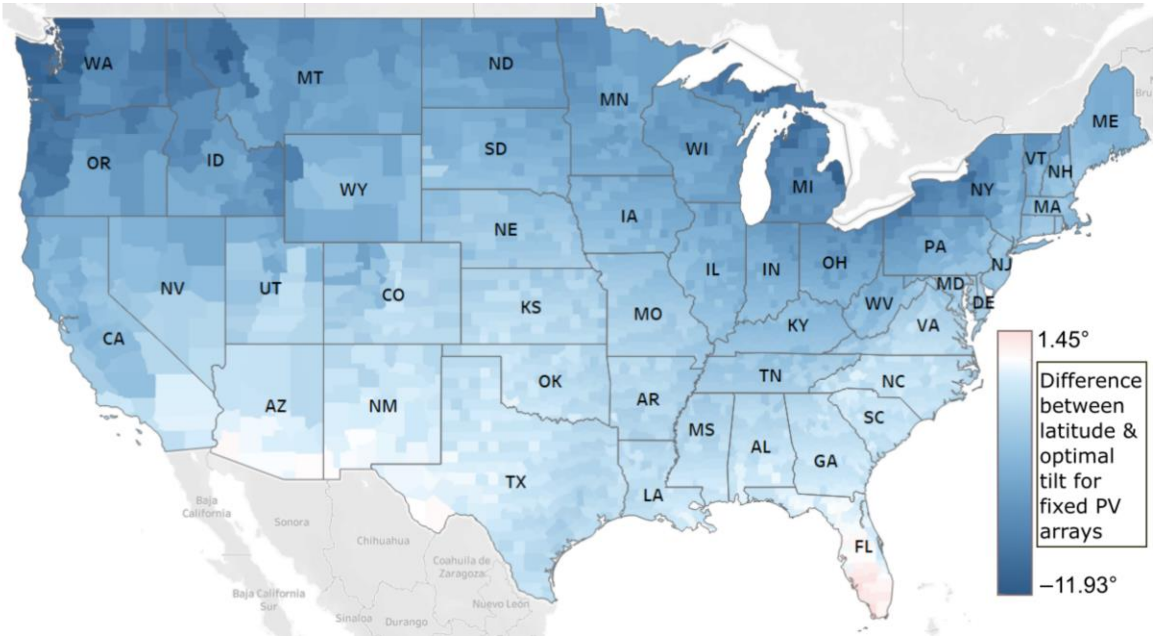


Figure 6. Calculated difference between optimal tilt angle and location latitude.

When comparing the obtained results with other published works, the studies by Jacobson [1] and Lave [28] offer comparable results. In Jacobson's study, optimal tilt angles are found for different locations globally, of which three are in the United States: Raleigh, North Carolina, Bakerfield, California, and Austin, Texas. The optimal tilts according to Jacobson are 32, 29 and 28, respectively. The results of this study show that the optimal tilts for those locations are 33, 30 and 29, respecitvely. The optimal tilt angles are very close and in this study the optimal tilt angles are consistently higher by 1°. Jacobson used a similar approach, implementing an optimization routine with the PVWatts software. The difference in results could be explained by different versions of PVWatts used for each respective study.

Lave's study is consistent with this study, exhibiting similar geographical trends. In both studies, the northern regions of Montana and Maine have the highest tilt angles at 42°. The locations with the lowest tilt angles are also the same, in the southern parts of Florida and Texas. However, the lowest tilt angle according to Lave is 26°, while the lowest tilt angles in this study are 24°. Both studies show counties in the state of Ohio have optimal tilt angles around 33°. Finally, both studies show a depression in the midwest around Ohio and Kentucky where the optimal tilt is not as high as areas on the same latitude.

3.3. Regional Comparison

Three different cases, labeled on Figure 5, will be used to explore the influence of cloud cover and ambient temperature on the optimal tilt angle. Figure 7 plots the average number of daylight hours throughout the year for each case. Figures 8–10 compare the monthly cloud cover, monthly ambient temperature and monthly PV panel efficiency for the three cases where two counties are on similar latitude lines but the optimal tilts differ. Case number one, shown in Figure 8, compares King County in Washington to Stark County in North Dakota. Figure 8a plots the temperature and cloud cover trends for both locations throughout the year, while Figure 8b shows the efficiency curves for both arrays throughout the year. The same data are plotted for all three cases, where Figure 9 compares Penobscot County in Maine and Charlevoix County in Michigan (case 2), and Figure 10 compares Willacy County in Texas to Lee County in Florida (case 3).

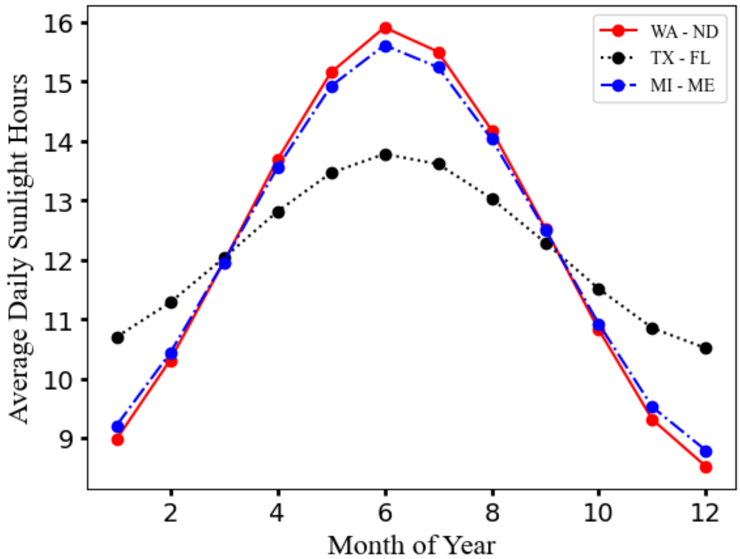


Figure 7. Daylight hours for three different latitudes as a function of month of the year.

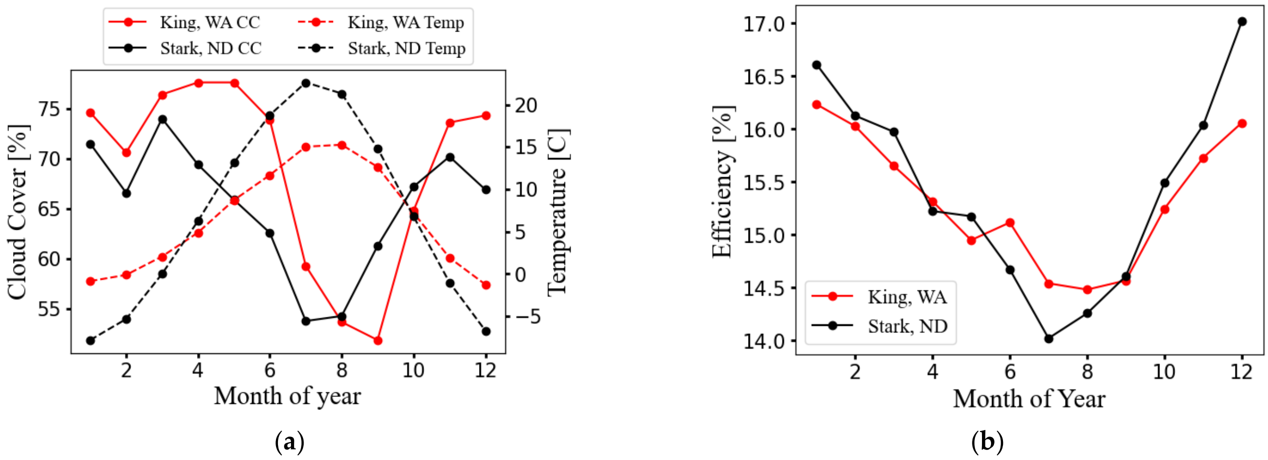


Figure 8. (**a**) Comparison of seasonal cloud cover and ambient temperatures for case 1 indicated in Figure 5. (**b**) The temperature-dependent efficiency of PV panels for case 1 locations.

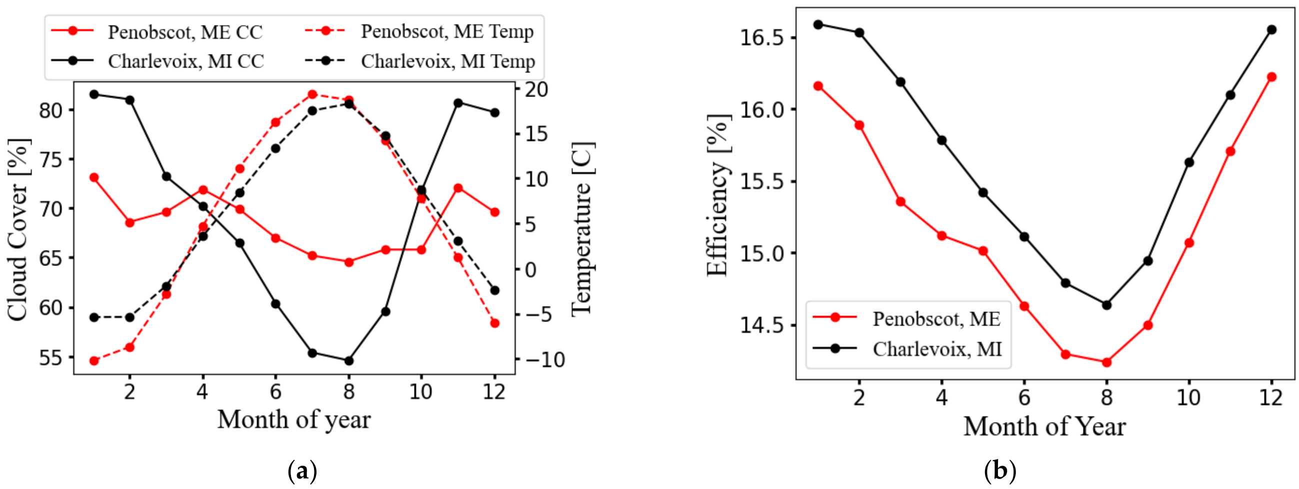


Figure 9. (**a**) Comparison of seasonal cloud cover and ambient temperatures for case 2 indicated in Figure 5. (**b**) The temperature-dependent efficiency of PV panels for case 2 locations.

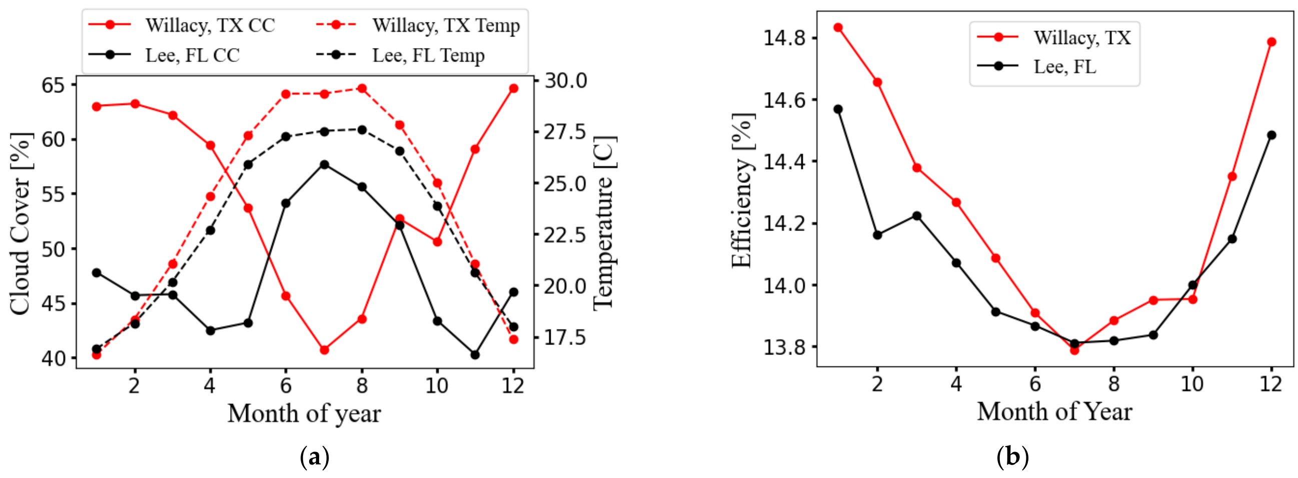


Figure 10. (**a**) Comparison of seasonal cloud cover and ambient temperatures for case 3 indicated in Figure 5. (**b**) The temperature dependent efficiency of PV panels for case 3 locations.

4. Discussion

Previous research suggests that the optimal tilt angle is equal to the latitude of the location [3]. However, Figures 5 and 6 illustrate a different story. As shown in Figure 5, multiple counties on approximately the same latitude line have optimal tilt angles varying by as much as 8°. Figure 6 shows that the difference between latitude and optimal tilt angle increases as the latitude increases, where the largest negative difference is in the Pacific Northwest, and the largest positive difference is in the southern states, mainly in Florida. This is likely due to the significant amount of cloud cover during the winter in the Pacific Northwest as shown in Figure 2, and the cooler temperatures during the summer in Figure 3.

Another observation to note is that almost all counties favor collection during the summer, meaning the optimal tilt is smaller than the latitude angle. Of 3143 counties, only 28 favor collection during the winter, while the remaining 3115 favor collection during the summer. Most of these counties are tilted 2–6° towards summer collection. All counties have an optimal tilt angle that is different than the latitude angle of the county seat location, where 2987 counties differ more than one degree. In Sections 4.1–4.3, the influence of three factors on the optimal tilt angle is explored.

4.1. Seasonal Variation in Daylight Hours

As seen in Figure 6, most locations favor collection during summer months. Further, Figure 6 indicates that the higher north a location is, the more it favors collection in the summer. Further, as shown in Figure 7, locations at higher latitudes have a large increase in the number of daylight hours when compared against winter daylight hours, going from 9 h in the winter to 16 h in June, gaining about 7 h of additional daylight. Lower latitude locations gain about 3 h during the summer, varying between 11 h in the winter and 14 h in the summer. Increased daylight hours provide additional solar irradiation for power production, causing the optimizer to favor collection during summer months.

Cases 1 and 2 in Figures 5 and 6 show that both locations, which are located at a high latitude, are heavily influenced towards summer collection by a near doubling of daylight hours in the summer months as compared to winter months. Unlike cases 1 and 2, case 3 is in the southern United States, where the optimal PV tilt angle is relatively close to the latitude angle as the summer daylight hours increase by only 18%. For case 1, however, the summer daylight hours are 77% larger than winter daylight hours, giving the summer a true advantage. The number of daylight hours has a clear influence on the optimal tilt angle.

4.2. Winter Cloud Cover

Examining case 1, King County Washington has an optimal tilt of 36° (latitude = 47.49°) and Stark County in North Dakota has an optimal tilt of 41° (latitude = 46.81°), indicating that Stark County does not favor the summer months as much as King County. Figure 8a shows that Stark County has less cloud cover during the winter months, and thus is tilted at a higher angle than King County to still utilize collection in the winter months while favoring the summer months. King County, on the other hand, experiences significant cloud cover for most of the year typical of the Northwest climate with a brief respite in the late summer. As such, the optimal tilt angle of King County heavily favors the summer months when compared against Stark County.

In case 2, Penobscot County in Maine is compared to Charlevoix County in Michigan. A visual location comparison is shown in Figure 5. The optimal tilt in Charlevoix is 35° (Latitude = 45.51°), where the optimal tilt in Penobscot is 40° (Latitude = 45.39°). A higher tilt angle corresponds to more solar collection during the wintertime, while a lower tilt angle corresponds to increased collection in the summertime. In this case, Michigan has lower cloud cover during the summer months, and higher cloud cover during the winter, as shown in Figure 9a, indicating a greater solar availability in the summer months when compared with Penobscot County. This would explain why the optimal PV tilt angle in Charlevoix County favors summer months more than Penobscot County. This is also shown in Figure 2, where the northern counties in Michigan have more cloud cover in the winter than the state of Maine. Figure 9b shows Charlevoix County is the more efficient location since there is much less cloud cover than Penobscot County.

In case 3, the optimal tilt in Willacy County is 24° (Latitude = 26.48°), while the optimal tilt in Lee County is 28° (Latitude = 26.55°). In this unique case, Willacy County is tilted below the latitude angle, whereas Lee County is tilted above the latitude angle. An array in Willacy County is tilted more towards the summer when compared to Lee County, due to the reduced cloud cover in Willacy County during the summer as compared to Lee County, which is tilted to favor collection during the clear winter months. Both counties have similar ambient temperatures throughout the year, but exhibit large differences in cloud cover.

As an interesting comparison, the tilt angles in King County, Washington, are compared against Lee County, Florida. Although these locations are not on the same latitude line, these counties exhibit the most extreme differences between tilt angle and latitude angle, with King County having the largest negative difference (tilt angle is smaller than latitude angle) of 11° and Lee County having the largest positive difference (tilt angle is larger than latitude angle) of 1.4°. Several factors play into the tilt angle for each location, but it is interesting to note the weather conditions at both locations. In King County, Washington, the cloud cover during the winter peaks at 75% and is significantly less during the summer at about 55%. In Florida, the opposite occurs, where the cloud cover peaks in the summer at 55% and is reduced to 40% during the winter. Likewise, King County is at a very high latitude location, indicating a large seasonal change in number of daylight hours and encouraging collection during summer months, whereas Lee County is located at one of the lowest latitude lines in the continental United States, indicating a small seasonal change in number of daylight hours.

4.3. Summer Ambient Temperature

Figure 8b shows the PV panel efficiency for the two locations in case 1. Stark County is significantly warmer in the summer, resulting in the summer month efficiency drop in Figure 8b. Likewise, Stark County is cooler than King County in the winter, and this corresponds with the higher efficiency shown in Figure 8b. It is more efficient for an array in Stark County to collect during the winter as compared to King County, contributing to the preferential winter tilt when compared to King County.

Figure 9b shows the efficiency plots for both locations in case 2 throughout the year. During the summer months, the efficiency is at its lowest due to hot ambient temperatures and generally non-cloudy conditions, resulting in the highest cell temperatures. Figure 9b shows Charlevoix County is the more efficient location since the weather is cooler in the summer, and there is much less cloud cover than Penobscot County. In Figure 10b, the efficiency plot for case 3 shows a decrease during the summer as expected; however, in Lee County the drop in efficiency is not a sharp as Willacy County. Again, considering the counties of Florida and Washington, the ambient temperature is significantly higher in Florida during the summer, causing efficiency to drop below 8% and causing the optimizer to prefer winter collection, while in King County the lowest efficiency ever reaches is 12.5%, resulting in preferential summer collection.

As an additional point of discussion, consider the states of Tennessee and North Carolina. The northern border of both states is the 36.55° latitude line, and the states are East–West neighbors. As such, the number of daylight hours is identical between the two states. As shown by Figures 2 and 3, the summer temperatures are similar although Tennessee is slightly cooler in the summer and has more cloud cover in the winter. The increased summer sunlight exposure and larger panel summer efficiency means that Tennessee PV panels are tilted lower to favor summer months when compared to North Carolina. This illustrates again the influence of ambient temperature and cloud cover on optimal tilt angle.

5. Conclusions

An optimization code accessed PVWatts to simulate energy production for a photovoltaic array at every discrete tilt angle between 0° and 90°. The optimal tilt angle was then calculated for every county in the continental United States to both provide a reference for solar array designers as well as to explore the influence of cloud cover, increase in sunlight hours in the summer months and ambient temperature on optimal tilt angle. In reviewing the results across a few example cases, it was evident that:

- The optimal tilt angle for any given location is almost never equal to the latitude, and in most cases it tilts to favor collection during the summer months.
- In the continental United States of America, latitude alone does not determine the optimal tilt angle of PV panels, but cloud cover, sunlight hours and ambient temperature play a role as well in the optimal tilt selection.
- The increase in cloud cover during the winter results in a shift for tilt angles to favor collection during the summer.
- Hot summer weather, especially in southern states, decreases panel efficiency and shifts tilt angles to favor collection in the winter.
- The increase in daylight hours during summer months has a significant influence, causing nearly all counties to tilt at an angle favoring collection in the summer.

In conclusion, the optimal tilt angle of an array depends on the location latitude as well as the local ambient temperature and cloud cover patterns. Discrepancies by as much as 12° are found between the optimal tilt angle and the latitude angle, with 77% of counties having a difference of 2° or more between the optimal tilt angle and the location latitude.

Regarding future work, optimization of both tilt angle and azimuth angle will be attempted while utilizing unique cost functions. For example, one cost function might be the total utility cost saved when the PV panel is used in a location with time-tiered utility billing. Future work will also consider the optimal tilt and azimuth angles for bifacial modules and the influence of weather on these unique PV modules.

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