Matching Photovoltaic Systems to Energy Loads

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ABSTRACT
Rather than orienting rooftop installation of photovoltaics (PV) to maximize power for the individual customer-generator, the design and performance of integrated PV were analyzed for two alternate objectives: 1.) maximizing the volume of grid sellbacks, and 2.) maximizing customer-generator revenue through net metering. These alternative orientation strategies attempt to maximize power output during times of peak demand on the grid, or when market prices are highest. Power output and PV system configurations were simulated using weather/radiation data specific to State College, PA. Given a system with no centralized storage capacity, we use hourly system loads and Locational Marginal Prices (LMP) from the PJM Interconnection to determine the specific orientations required to integrate intervals of energy gains from the PV system with periods of high demand for electricity in a building. We also determined optimal orientation of PV systems for a time-of-use purchasing scenario, matching orientations and electrical gains with periods in the day when it is economically beneficial to sell to the grid. Given a net-metered PV system with no storage capacity, altering the PV panel orientations allows one to design peak solar energy production times to match any set of energy demands.

1. INTRODUCTION
Restructuring of the electric power industry in many US states has reduced the barriers for distributed energy sources (including PV) to sell excess power back to the grid through “net metering” provisions. Traditional design criteria for building mounted photovoltaics orient rooftop panels for maximum southern exposure. The underlying objective of such an installation strategy is to maximize the peak power production from the installation over a 24-hour period. However, time of peak electricity demand does not coincide with peak electric gains from a PV array of southern azimuth (γ).

The first stage in integrating photovoltaics with a building project involves energy integration to reduce the building energy loads (demand) as much as possible. By reducing the energy loads, we can open our decision process to fulfill the energy needs of the home or building residents while permitting new orientations of the PV modules. In addition to fulfilling the needs of the localized resident, we shall demonstrate that there is opportunity for pushing electricity back onto the power grid at times of high pricing. This study includes an analysis of the energy cost trends as well as detailed energy analyses of the PV configurations and energy outputs.

FIGURE 1: Cartoon of tracking PV (horizontal mount, E-W azimuths) to standard fixed axis PV with South azimuth. Adapted from Duffie & Beckman.

As shown in Figure 1, the impetus for studying alternative panel orientations arose from comparing power outputs between single axis tracking systems and fixed axis systems. A collector rotating from East to West (along a N-
S axis) tracks the Sun throughout the course of each day, minimizing the angle of incidence between the panels and the Sun. This increases the contribution of beam radiation to the collector and increases the power produced by the PV array.2

For a fixed axis array, the time of peak solar gain can be altered similarly by selecting a different azimuth (\(\gamma\)) and slope (\(\beta\)) for the panels. In this study, we have selected the scenario where the simulated array of panels are split, such that half of the panels are oriented due east (\(\gamma = -90^\circ\)) and half are oriented due west (\(\gamma = +90^\circ\)). In doing so, one establishes a bimodal distribution of power output from the collection of panels. Alteration in slope affects the time of day at which the radiation on the panels will peak, providing power gains for a wide variety of times. The E-W array is compared against a standard fixed axis array with all modules facing due south (\(\gamma = 0^\circ\)) and a tilt near optimal for summer demand (\(\beta = 25^\circ\)).

2. NOMENCLATURE

*azimuth* (\(\gamma\)) angle of collector from South (-/+: E/W)
*slope* (\(\beta\)) angle of collector from horizontal
hourly integrated irradiance (I\(_{\text{meas}}\): Wh/m\(^2\))
hourly extraterrestrial irradiance (I\(_{E}\): Wh/m\(^2\))
clearness index (\(k_T = \frac{I_{\text{meas}}}{I_0}\))
avg. hourly clearness index (\(k_T\))
*hourly electric power* (\(P\)) withdrawn from the grid or supplied to the grid (+/-: supplied/withdrawn)
*hourly market price* (LMP) paid for power withdrawn from the grid, or received for power supplied to the grid

2. METHODS

2.1 Data Collection: Insolation and Weather

Data were gathered from the Rock Springs station in the SURFRAD Network (Surface Radiation Budget Network; 40.72°N 77.93°W, 337 m elev.), operated and maintained by the Dept. of Meteorology at the Pennsylvania State University. The site is located about 10 km from State College, PA, and is supported by NOAA’s Office of Global Programs. The data were collected in 3-minute time steps and downloaded from the SURFRAD site for processing by TRNSYS simulation (temperature, relative humidity, direct and diffuse irradiance and total irradiance on the horizontal).

2.2 Data Collection: Electricity Demand and Wholesale Electricity Prices

Hourly data on wholesale market prices for electricity were gathered from the PJM Interconnection (www.pjm.com).3 PJM is the Regional Transmission Organization (RTO) responsible for ensuring transmission-grid reliability in much of the Mid-Atlantic and parts of the Midwestern US. PJM publishes hourly wholesale price data for a number of locations in its service territory; price differences between locations are a measure of transmission congestion or local supply/demand conditions. These wholesale prices are known as Locational Marginal Prices (LMP). In PJM’s market, power generators are paid the LMP in their geographic area for each megawatt-hour of electric energy supplied to the grid, and wholesale buyers (primarily electric utilities) pay the LMP in their geographic area for each megawatt-hour of electric energy purchased. For calculating net-metering revenue, we use hourly LMP data corresponding to the Allegheny Power zone in PJM. We choose this location since the residence we model is based on weather conditions in Centre County, Pennsylvania, which lies within Allegheny Power’s utility area.

2.3 PV Simulation

Power output and PV system configurations were simulated using the TRNSYS program, using State College, PA as a case study.4 The basic system components included the weather importer, radiation processor, photovoltaic panels and data plotter. Weather data were processed to PV power gains using a 4-parameter equivalent circuit model with maximum power point tracking.5–6 Calculations for solar radiation processing in TRNSYS used the tilted surface diffuse radiation model from Reindl et al.7 Simulations assumed working parameters from 10 SunPower SPR-225-BLK modules.8 Panels were split into: 5x East, 5x West and 10x due South. The model was simplified to exclude effects of diffuse shadowing, but collector tilts were selected to be less that 25° to minimize any contribution of shadowing in future models. Results were assumed to be grid-connected (no battery capacity included).

Power output (solar gain) was estimated for five separate days in the year of 2007 (May 2nd, March 5th, June 18th, July 31st, and October 21st). Hourly clearness indices were calculated for each day from the 3-minute data. Four days were selected to be representative of a clear midday where the contribution of solar gain from a solar noon conversion would be high. One day, June 18th, we selected to be representative of a cloudy midday, for significant expected difference between the power output from the East and West arrays, relative to the South array.

2.4 Economic Analysis

Since we assume that the residential PV system is completely grid-tied, with no storage, during any given hour the electric energy balance will determine whether the customer-generator earns revenue by selling excess power to the grid or must pay for grid-provided power. If the amount of electric energy produced by the PV system is greater than the demands of the customer-generator, in which case excess energy is supplied to the grid, then \(P>0\)
and the customer-generator is paid the LMP for each megawatt-hour of energy supplied to the grid. If the amount of electric energy produced by the PV system is less than the demands of the customer-generator, in which case the balance is withdrawn from the grid, then \( P < 0 \) and the customer-generator must pay the LMP for each megawatt-hour of energy withdrawn from the grid. Mathematically, in every hour, the customer’s revenue (or cost) during hour \( t \) is given by:

\[
Revenue_t = P_t \times LMP_t
\]

where a positive value for \( Revenue \), indicates that the customer is supplying power to the grid during hour \( t \), and a negative value indicates that the customer is withdrawing power from the grid during hour \( t \). Daily net revenue to the customer is calculated as:

\[
DailyRevenue = \sum_{t=1}^{24} (P_t \times LMP_t).
\]

The daily net revenue for a customer may be positive, negative or even perhaps zero depending on whether the customer provided power to the grid during hours with higher prices than the hours when the customer withdrew power from the grid.

3. RESULTS AND DISCUSSION

3.1 PV Power Gains

As seen in Figure 2, there are distinct possibilities for providing excess power in the morning when the E-W collector gains are summed over the day. With the exception of May 2, 2007, all data demonstrated solar gains in the morning, and earlier gains than for the South array. We attribute this peak to a substantial contribution from horizon brightening in the diffuse light component due to humidity in the morning.

In Figure 3, we note that an increase in the tilt of the array from \( \beta = 15^\circ \) to \( \beta = 25^\circ \) demonstrated a substantial increase in morning and evening surplus solar gains.

In Figure 4, we observe the special case of June 18 where the intermittent scattering of beam radiation has induced the effect (common in the Northeast) of a high diffuse light component at midday. In this case, integration of the differential data (relative to the 10x panel South array) demonstrates not only a displacement in peak solar gains, but also a surplus of energy (+272.4 Wh) beyond that of the “rule of thumb” array.

3.2 Insolation and Clearness Indices

The hourly clearness indices in Table 1 and Figure 5 were calculated using the horizontal irradiance from the SURFRAD data integrated over one hour \( (I_{max}) \) in Wh/m² and a calculated value of hourly extraterrestrial irradiation \( (I_h) \) in Wh/m². From analyzing the hourly clearness indices we observe an asymmetrical distribution throughout a day. On all dates the elevated clearness indices during the morning (relative to zero values at dusk) illustrate that the average hourly clearness index is a poor representation of a high radiation morning. This trend has a great impact on the performance of an east-facing array.

Net Revenue Analysis:

For each day that we analyze, and for each value of \( \beta \) and \( \gamma \) that we compared against the standard orientation \( (\gamma = 0^\circ \) and \( \beta = 25^\circ \), the net revenue of the PV orientation was calculated as discussed in Section 2.4. A summary of our results, as compared to the net revenue from the standard orientation, is shown in Figure 6. Generally, the East-West orientation produces revenue gains for the customer during the morning and evening peaks. The smaller power gains relative to the southern orientation produce smaller revenue gains during the afternoon peak. This, however, is when electricity prices tend to be highest.

Power gains during the morning and evening peak do not necessarily translate into economic gains over the course of a single day. Summer days in our sample (May 4, July 31) produced a net revenue gain for the customer. Our sample consists of days that represent a variety of demand conditions on the PJM electric grid, but prices on these days were not particularly high. Thus, while our analysis consists of “typical” load days for each season, the peakiness of annual electricity demand (particularly during the summer months) suggests that further analysis is needed to optimally match azimuth and tilt angles to economic signals from the transmission grid.

4. CONCLUSIONS

By splitting the orientation of panel arrays for an East-West azimuth orientation rather than a fixed Southern azimuth, significant power gains during the morning and evening demand peaks can be realized. This may be advantageous for residential customer-generators, since the East-West orientation is matched more closely to the customer’s demands. Such an orientation, however, assumes that the customer’s goal is to maximize power produced for local consumption. A customer orienting a rooftop PV array to maximize revenues from net metering (perhaps to offset the initial capital outlay for the system) would need to consider orienting the panels based on wholesale electric prices, which on an hour-to-hour basis may not perfectly correlate with local customer demands.

5. ACKNOWLEDGMENTS

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**Figure 2:** Relative power gains from fixed PV arrays of different orientations. The pink curve indicates the summation of E-W panels, each with $\beta=15^\circ$. The black curve indicates an equal number of modules all oriented south with $\beta=15^\circ$.

**Table 1:** Hourly Clearness Indices from [first data hour] to hour of sunset (solar time, no daylight savings correction). * indicates value outside $k_T$ range.

<table>
<thead>
<tr>
<th>Date (2007)</th>
<th>$k_T$</th>
<th>$\bar{k}_T$</th>
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</thead>
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<tr>
<td>March 2 [07:00]</td>
<td>[0.18], 0.08, 0.31, 0.45, 0.54, 0.53</td>
<td>0.297</td>
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<tr>
<td>May 4 [06:00]</td>
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</tr>
<tr>
<td>July 31 [06:00]</td>
<td>[0.21], 0.41, 0.46, 0.49, 0.51, 0.51, 0.50</td>
<td>0.372</td>
</tr>
<tr>
<td>October 21 [07:00]</td>
<td>[2.09*], 0.71, 0.58, 0.53, 0.49, 0.44, 0.38, 0.30, 0.19</td>
<td>0.476</td>
</tr>
</tbody>
</table>

**Figure 3:** Differential power gains from split E-W PV arrays relative to South orientation (tilt indicated). The top pink curves indicates the summation of E-W panels, each with $\beta=15^\circ$.

**Figure 4:** Hourly clearness indices for the data. Peak $k_T$ indicated with dot and label (within bounds of 0-1).
Figure 5: June 18, 2007: Differential power gains from split E-W PV arrays relative to South orientation ($\beta=15^\circ$).

Figure 6: Hourly revenue gains and losses from a split E-W PV array, relative to South orientation ($\beta=25^\circ$). Hourly revenues are calculated using units of Cents ($0.01$).

6. REFERENCES


