OPTIMUM FIXED ORIENTATIONS CONSIDERING DAY-AHEAD MARKET ENERGY PRICING IN CALIFORNIA

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ABSTRACT

Optimum orientations for mounting solar PV panels considering energy prices were found for California using irradiance data from the SolarAnywhere database and day-ahead market prices from the California Independent Service Operator (CAISO) Open Access Same-time Information System (OASIS). Results show that the optimum azimuth based on revenue is up to over 10° west of the optimum azimuth based on maximum energy output. However, the revenue is not very sensitive to changes in tilt and azimuth, and installing a panel within 10° of optimum generally results in 95% of the maximum revenue for most sites.

1. INTRODUCTION

Widespread implementation of solar energy has been hindered greatly by the high start-up costs of photovoltaic (PV) systems and the long return on investment time. Thus, it is not necessarily most important to optimize a PV system for energy output but rather it is crucial that PV systems are installed at the optimum tilt and azimuth such that they produce the maximum revenue. Previous convention called for installing solar panels at an azimuth of due south and a tilt equal to the latitude (e.g., a panel at 40°N should have a 40° tilt from horizontal) to achieve maximum power output over the course of a year. Recent studies have shown that optimum tilt and azimuth is not solely a function of latitude but also a function of cloudiness ([1], [2]). For example, in regions like the west coast of the United States, the optimum azimuth for maximum energy production would be west of due south because of morning fog. The optimum tilt and azimuth considering energy pricing should also deviate from the previous convention as the price for which power is sold varies as a function of time of day and time of year, with a daily peak in the afternoon and evening hours and a seasonal peak in the late summer months, when demand for power is highest.

We compare the optimal tilt and azimuth maximizing revenue considering time of day energy pricing to the optimal tilt and azimuth maximizing energy output and the previous convention of latitude tilt. Additionally, we investigate the advantages of using a dual-axis tracking PV system over fixed orientations.

2. METHODS

Satellite derived global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) were obtained from the high-resolution SolarAnywhere database for 2010. The high-resolution SolarAnywhere data is available on a 1 km x 1 km grid for California with 30 minute temporal resolution and uses an updated version of the Perez model [4] to derive GHI, DNI, and DHI. The Page [3] model uses GHI, DNI, DHI, time, latitude, and longitude as inputs to calculate global irradiation (GI, Eq. 1) for a panel of any tilt and azimuth.

$$GI = B + D + R_g \tag{1}$$

The direct (beam) radiation, B, on the titled surface is a function of tilt β and azimuth α (Eq. 2)

$$B(\beta, \alpha) = B_n \cos v(\beta, \alpha) \tag{2}$$

B_n is the beam normal irradiation (DNI) and $v(\beta, \alpha)$ is the solar incidence angle on the tilted panel.

The diffuse component of irradiation on a tilted surface, D, is calculated in conjunction with the equations used by Page [4]:

$$\frac{D(\beta, \alpha)}{D_h} = f(\beta)(1 - K_b) + \frac{K_b \cos v(\beta, \alpha)}{\sin \gamma_s} \tag{3}$$

where γ_s is the mid-hour solar altitude angle, K_b accounts for cloud cover and is calculated by $K_b=(G_h - D_h)/\{\epsilon*(1367 \text{ Wh m}^{-2})\sin \gamma_s\}$, where ϵ is a correction to the mean solar distance from earth, and $f(\beta)$ is an empirical function found by Page for Southern Europe (which was validated for the United States by Lave [1]) to relate the directionality of diffuse irradiation to the panel tilt angle and clearness index:

$$f(\beta) = (0.00263 - 0.7120K_b - 0.6883K_b^2) \times \left[\sin\beta - \beta\cos\beta - \pi\sin^2\left(\frac{\beta}{2}\right)\right] + \cos^2\left(\frac{\beta}{2}\right) \tag{4}$$

The reflected irradiation, R_g, is modeled by:

$$R_g = r_\beta \rho_g G_h \tag{5}$$

Where G_h is GHI, r_β is the reflection coefficient and is solely a function of panel tilt ($r_\beta=(1 - \cos\beta)/2$), and $\rho_g=0.2$ was used as an average ground surface albedo for land. Additionally, GI was calculated for a dual-axis tracking panel, in which $B=B_n$.

Energy pricing data was obtained from the California Independent Service Operator (CAISO) Open Access Same-time Information System (OASIS) for 602 price nodes for 2010. These nodes represent locations in the CAISO power network in which power can be sold into the energy market at a given Location Marginal Price (LMP). We assumed that energy was bid into the Day-ahead market (DAM) using a perfect forecast. Power bids must be made in the DAM before 12:00 the day before the operating. Nearest neighbor interpolation was used to convert the discrete price node locations to 1 km x 1 km resolution, and hourly price values were linearly interpolated to 30 min resolution.

Optimum tilt and azimuths were calculated for which the yearly sum of the product of GI and DAM LMP was maximized.

3. RESULTS

The largest DAM LMPs occur throughout the entire day in January and February and the afternoon to evening hours in June through September (Fig 1a). The typical locational variation of DAM LMP is shown in Fig 2a, where nearest neighbor interpolation between discrete DAM LMP locations (black dots) was used to map pricing data across the whole state. Optimum azimuth changes significantly in going from irradiance optimized orientation (Fig. 2a) to irradiance combined with DAM optimized orientation (Fig. 2b).Tilts increase slightly in going from irradiance optimized orientation (Fig. 2c) to irradiance combined with DAM optimized orientation (Fig. 2d), presumably to take advantage of more afternoon irradiance when the sun angle is low but prices are high. Though changes in azimuth and tilt can be up to 10° when considering DAM pricing, the increase in revenue for DAM optimized tilt versus latitude tilt is quite small and is almost never greater than 1% (Fig. 2e). A 2-axis tracking panel with DAM optimized orientation yields a big improvement in revenue over latitude tilt (30-40%), but this is similar to the improvement found for 2-axis tracking versus optimum tilt when considering only irradiance (Fig. 2f) [1].

Changes in revenue are small when comparing the DAM optimized orientation to latitude tilt because there is very little sensitivity to tilt or azimuth when within approximately +/- 10° to the DAM optimized orientation (Fig. 3).

4. CONCLUSIONS

Optimum orientations considering DAM prices differed by up to 10° from optimum orientations considering irradiance. Improvements in total yearly revenue were less than 1% from total yearly revenue using latitude tilt due to low sensitivity of the optimum orientation under DAM prices. Installing PV systems within approximately +/- 10° to the DAM optimized orientation will generally result in 95% of the optimum revenue.

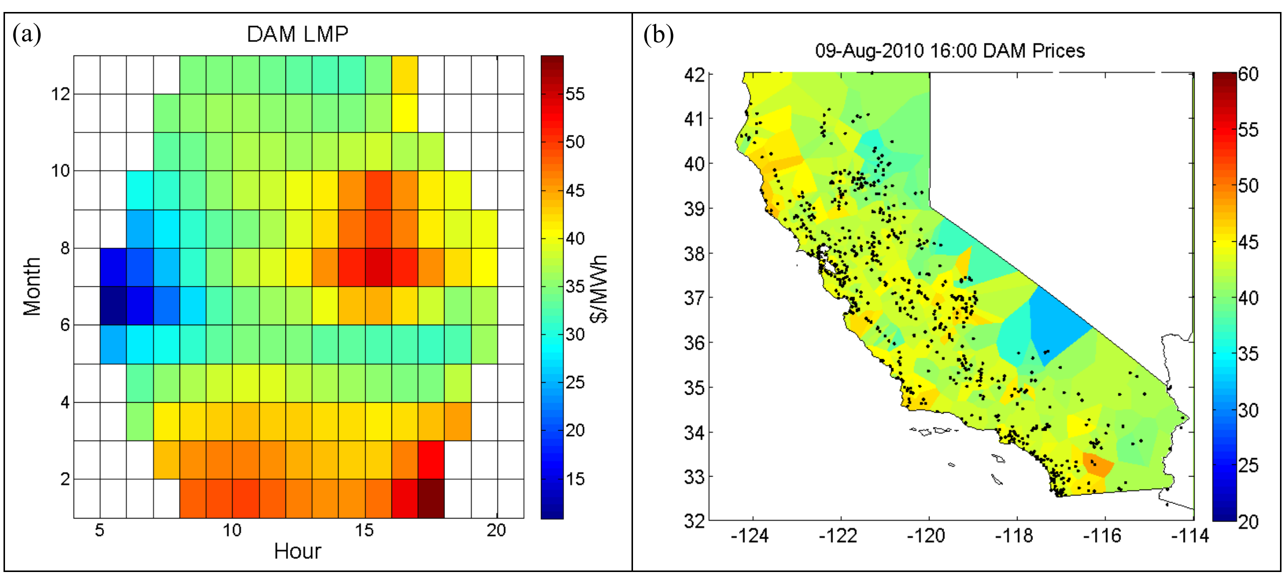

Figure 1: (a) Averaged DAM LMP for all sites by time of day and month of year. (b) Plot of DAM LMP locations (black dots) and DAM prices for August 9, 2010 at 16:00.

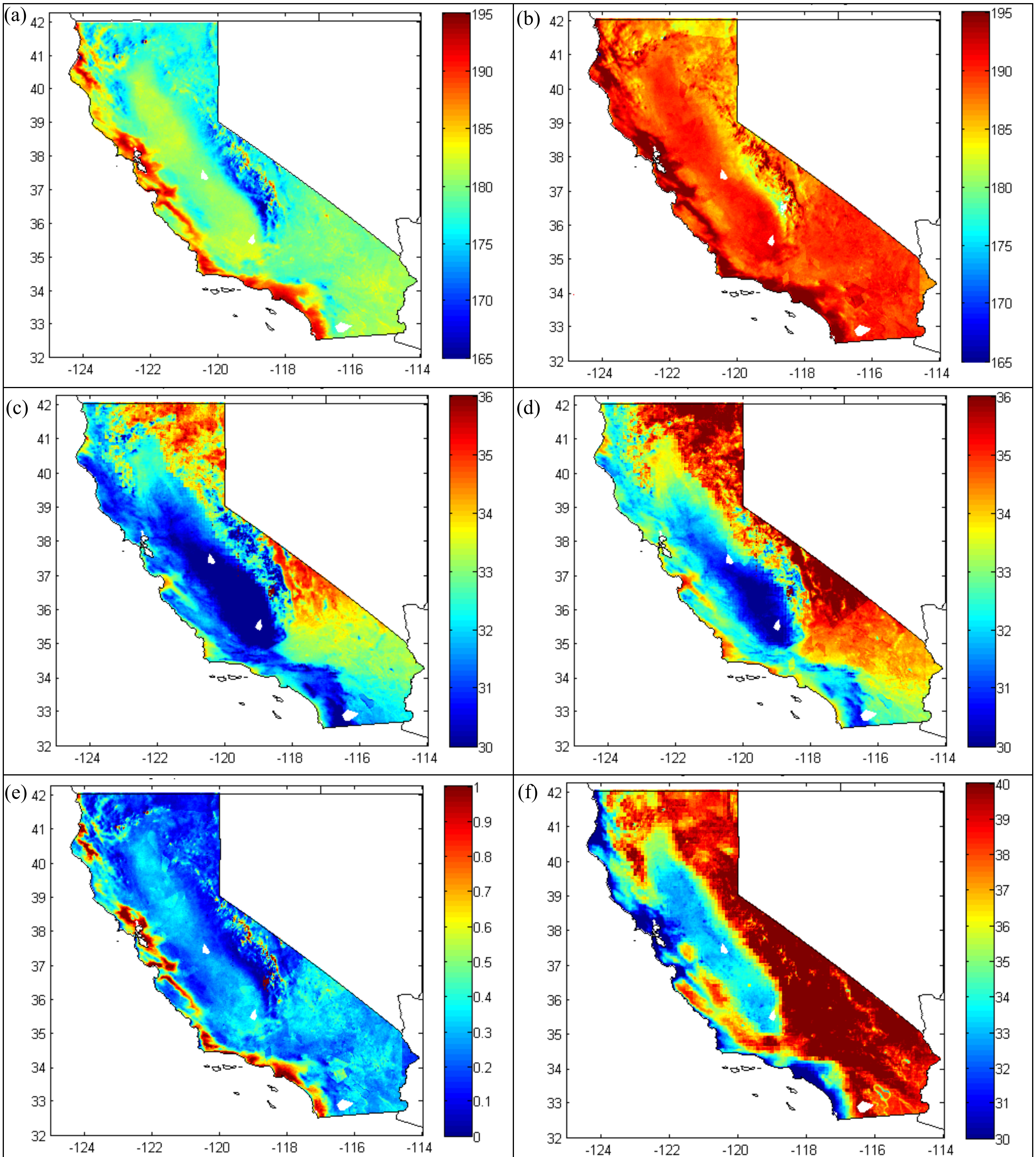

Figure 2: Optimum azimuth considering irradiance (a) and DAM prices (b). Optimum tilt considering irradiance (c) and DAM prices (d). Percent increase in revenue from latitude tilt to

optimimum oreientation considering DAM prices and from latitude tilt (e) to dual-axis tracking system (f).

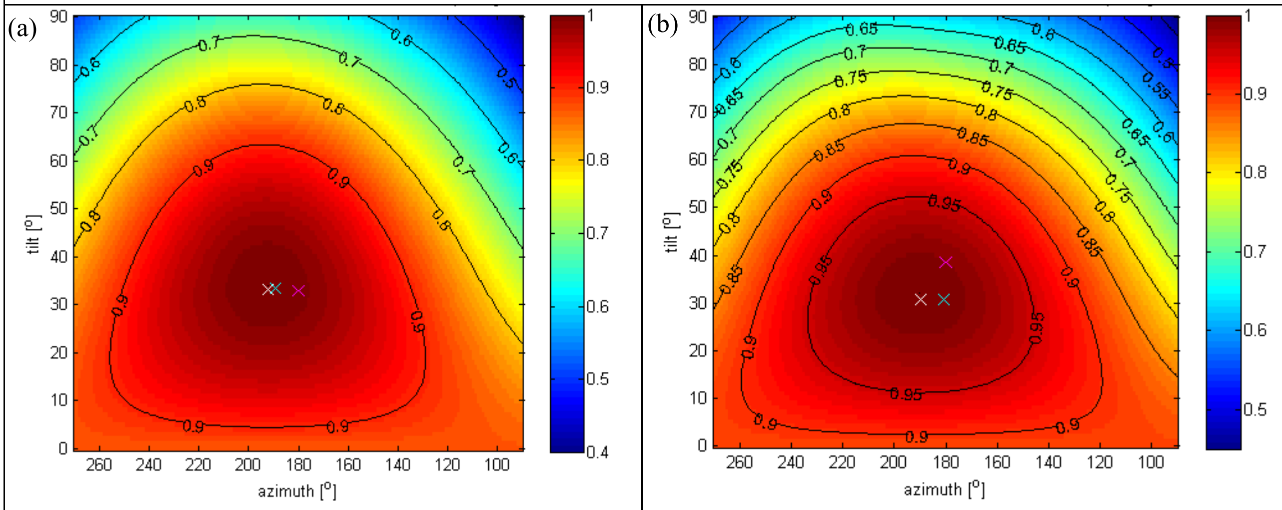

Figure 3: Sensitivity plots for San Diego (a) and Davis (b) show the ratio of revenue at a given tilt to the revenue using the optimum orientation with DAM prices. Also shown are the optimum orientation with DAM prices (white ‘x’), the optimum orientation considering irradiance (blue ‘x’), and latitude tilt (magenta ‘x’).

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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