Optimization of Commercial Rooftop PV Systems in the Continental United States Using Angle-and-wavelength-resolved Solar Irradiance Data

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***Abstract* — This paper presents a systematic approach for optimizing commercial rooftop PV system installations, estimating energy yields using more realistic angle-and-wavelength-resolved clear sky solar irradiance data and quantifying the economic benefits. In this paper's case study of Berkeley, the proposed semiannually-fixed tilt configuration of solar panels is found to increase the energy yield by 5.8% over the year and up to 15.6% during peak summer days. This study attempts to quantify both the energy yield and economic benefits of improved angular and spectral response of solar cells. We believe that these sets of information would be important for manufacturers to assess the cost-effectiveness of a certain technological improvement, and for developers to choose the more cost-effective products for installations at a given geographic location. 3 cities varying from N30° to N45° in latitude are covered in this study to represent the typical geographic variations in the lower continental United States. The north-south difference in energy yield due to geographic locations is most significant in winter by about 15%.**

***Index Terms* — economic indicators, maintenance, optimization, photovoltaic systems, simulation, solar energy.**

I. INTRODUCTION

Measured efficiency under AM1.5G spectra has been the widely accepted standard to quantify the performance of solar cells. However, the test is carried out at normal incidence of light, while the installed solar panels are subjected to solar irradiation with different Angle of Incidences (AOI) and spectra most of the time. Especially when evaluating the performance improvement of different antireflection coatings on solar cells, one might need solar irradiation data including these angular and spectral variations [1]. Optical losses from surface reflection and poor infrared absorption remain as the main bottlenecks in further improving the cost-effectiveness of today's crystalline-silicon solar cells, and considerable amount of research efforts have been devoted into light management for photovoltaic applications [2]. The yearly solar irradiation data, which is resolved in both angle and wavelength, presents an effective and a more realistic approach to quantify the measured improvement in optical properties, such as angle-resolved reflectance spectroscopy data from new antireflection coatings.

From the economics perspectives, installations of PV systems on residential and commercial rooftops in good sunlight locations may represent the largest PV market potential in the next 10 years, according to a recent McKinsey study [3]. Optimizing the installation of a given PV system can help reduce the Levelized Cost of Electricity (LCOE) with higher energy yield. To improve the energy yield under solar irradiation with daily variations in AOI, single-axis tracking has been used in PV power plants. While the PV systems installed on residential and commercial rooftops normally opt for fixed-tilt panel configuration, due to constrained area and maintenance concerns. Simulations and observations both show that the tracking can yield 18% to 25% more in energy output and capacity factor, compared with fixed-tilt panel configurations [4, 5]. As a compromise between maintenance cost and energy yield, the tilt angle in a semiannually-fixed tilt configuration changes twice every year, which is optimized for summer (Apr to Sep) or winter (Oct to Mar) respectively [6]. Recognizing the necessity for regular maintenance to clean dust off solar panels, these changes in tilt angle have the potential to be integrated with other regular maintenances with little increase in operating costs. This study finds that the semiannually-fixed tilt configuration can improve the capacity factor by more than 15% in July, when the electricity typically is in stronger demand and has a higher value. The added value presents a market potential for such Balance of Systems (BOS) which allows semiannually-fixed tilt configuration.

II. SIMULATION SETUP

The AM1.5G spectra, also known as the ASTMG173 terrestrial reference spectra for evaluating photovoltaics performance, are derived from the NREL's SMARTS model for a south-facing 37^0 tilted flat surface, which receives sunlight with air mass (AM) of 1.5 [7]. This study uses the SMARTS 2.9.5 model to obtain daily solar irradiance data resolved in both angle of incidence and wavelength over a whole year (see Fig. 1). All the parameters are chosen according to the ASTMG173 spectra, except for the latitude and tilt angle. The resolution of the irradiance data is 1 degree in AOI and 10nm in wavelength.

To investigate the effect of spectral variations in solar irradiance on energy yield, 2 sets of PV External Quantum Efficiency (EQE) data of hypothetical PV systems, also

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resolved in both angle of incidence and wavelength, are obtained by combining Internal Quantum Efficiency (IQE) data from literature [8, 9] and angle-resolved transmittance data from modeling glass/EVA/silicon interfaces [10, 11] by ray tracing technique in multilayers [12, 13]. The difference in optical response between cell and module is accounted mainly by the strong angular dependence of reflection at the air/glass interface and strong UV absorption by the encapsulant (see Fig. 2). Both sets of EQE data (labeled A and B) are normalized to a power output of 182 W/m2 under normal incidence of sunlight with AM1.5G spectrum.

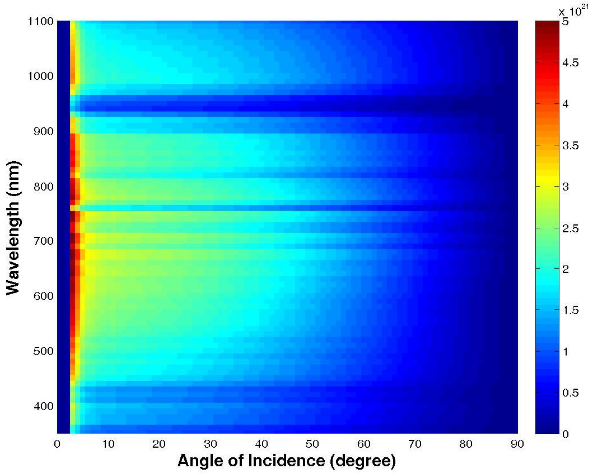

Fig. 1. Average daily solar irradiance data for a surface tilted at 37.73^0 in Berkeley in March.

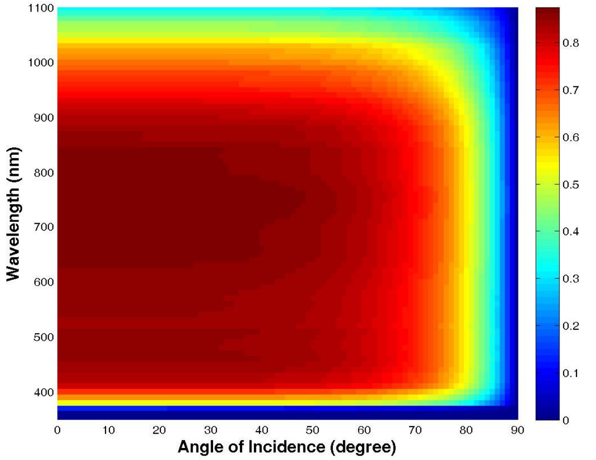

Fig. 2. EQE map for the PV module A.

The total number of electrons collected in one day is obtained by multiplying the daily solar irradiance (as in Fig. 1) with the EQE data (as in Fig. 2), both of which are resolved in Angle of Incidence θ and wavelength λ. In order to present the energy output results in a more meaningful form (kWh/m^2), the presented daily energy yield is the product of total collected charges and a working voltage V_{op} of 0.527 Volts [8].

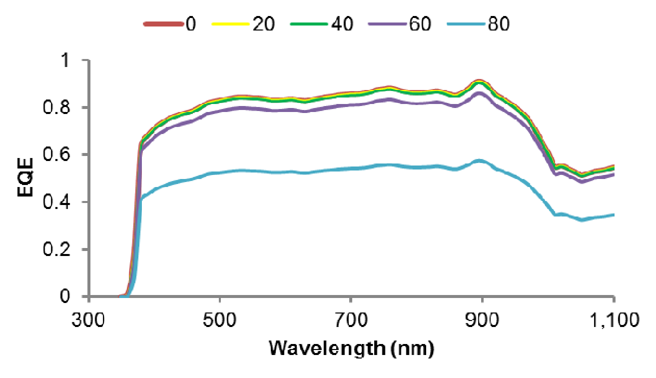

Fig. 3. EQE profiles for PV module A at various AOIs.

III. RESULTS AND DISCUSSIONS

A. Comparison with standard test spectrum

The AM1.5G standard spectra are considered to be a reasonable average for the lower 48 continental U.S. states. However, there are clear seasonal variations in the daily average solar spectra as shown in Fig. 4. For the same power density in the interested wavelength range (350nm – 1100nm), winter spectrum (Dec) is significantly red shifted with a higher weightage of long-wavelength photons; while summer spectrum (Jun) is somewhat blue shifted with a higher weightage of short-wavelength photons.

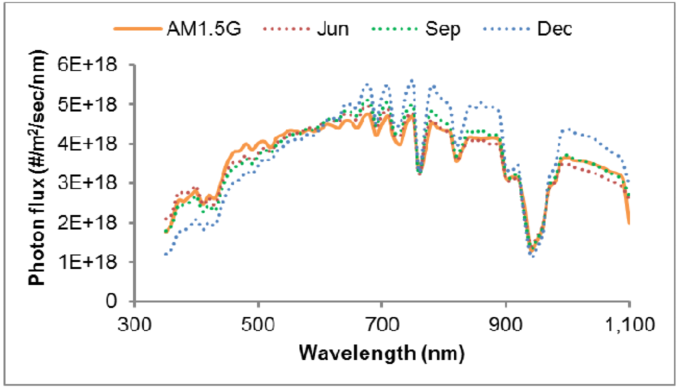

Fig. 4. Seasonal variations in normalized solar spectra for a surface tilted at 37.73^0 in Berkeley.

The angle-and-wavelength-resolved solar irradiance captures both the angular and spectral influences on power output, compared with using standard testing spectrum. Table 1 compares the power output of PV module A tilted at Latitude Angle in Berkeley between these two approaches. Accounting for only the spectrum difference, power output under the normalized Dec spectrum could be 4.7% higher than using the AM1.5G spectrum, as the Dec spectrum is significantly red shifted (see Fig. 4). The normalized Dec spectrum turns out to produce more power than the normalized Jun spectrum, because the lower weightage of short-wavelength photons reduces thermalization losses.

TABLE 1.
ANGULAR AND SPECTRAL EFFECTS ON POWER OUTPUT

(W/m^2)	**Jun**	**Sep**	**Dec**
Angular & Spectral	174.1	179.4	188.5
Spectral	181.3	184.0	190.6
AM1.5G	182	182	182

Comparing "Angular & Spectral" and "Spectral" in Table 1, the power output could be 1.1% - 4% less after accounting for angular dependence of EQE. The angular effects of solar irradiation and EQE are observable but not very significant. The main reason is that due to the light refraction in the glass and EVA layers, the angular dependence of the module's EQE (see Fig. 3) is only significant at large AOIs (>60^0). While only 4% - 16% of the solar irradiance is at these large AOIs (see Fig. 5), depending on the season.

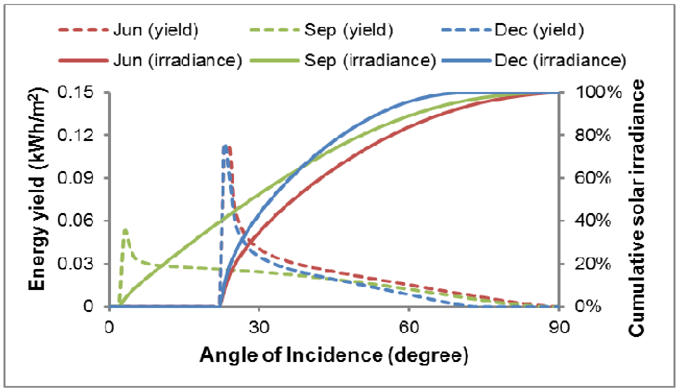

Fig. 4. Angular distributions of energy yield and incident solar irradiance for a surface tilted at 37.73^0 in Berkeley.

B. Energy yield from different tilt configurations

The NREL SMARTS 2.9.5 is used to generate angle-and-wavelength-resolved solar irradiance data for the 3 U.S. cities covered in this study and for a combination of tilt angles. The selections of tilt angles are based on the results from previous studies [4, 6]. Shown in Table 2, the rule-of-thumb for PV panel orientation (tilted at an angle equals to the latitude and facing south) is neither optimized for summer nor winter times for PV Module A in Berkeley, but it usually yields the highest energy output over the whole year. Decrease (increase) in tilt angle is required to optimize energy yield for summer (winter). Moreover, the difference in energy yields for a given PV system at different latitudes, with optimized tilt angles, is much smaller in summer (1.4%) than that in winter (15%), when comparing northern U.S. cities with southern ones. This large energy yield difference in winter would increase the Levelized Cost of Electricity (LCOE) for northern cities.

Fig. 5 plots the 12 months' breakdown for the Berkeley data in Table 2 for a few optimized tilt angles, which result in the maximum energy yields during the summer, the winter, or the whole year. In a semiannually-fixed tilt configuration where the solar panels are tilted at two different angles in winter (blue) and in summer (red), the total annual energy yield would be more optimized than the 3 cases shown in Fig 5. It is worth noting that around April and September, the energy yield difference between the summer-optimized tilt angle and the winter-optimized tilt angle is relatively not significant. Therefore, there is a large time window for tilt angle changes in late March and September. Another observation is that increasing tilt angle in winter to larger than latitude angle is less effective in increasing energy yield, compared with decreasing tilt angle in summer. Considering shading and the economics of ground cover ratio [14, 15], the semiannually-fixed tilt configuration, in practice, may choose a tilt angle in winter, not optimized for energy yield per area of solar panels but for energy yield per area of constrained rooftop.

TABLE 2.
AVERAGE DAILY ENERGY YIELDS (KWH/M^2)

Tilt angle = Latitude +		**Austin, TX** (N 30.17^0)		**Berkeley, CA** (N 37.73^0)		**Minneapolis, MN** (N 44.96^0)	
		Summer	Winter	Summer	Winter	Summer	Winter
Year	0	1.500	1.370	1.505	1.287	1.499	1.174
	-4	1.541	1.335	1.534	1.256	1.527	1.143
	-8	1.559	1.300	1.563	1.208	1.549	1.110
	-12	1.577	1.253	1.580	1.180	1.565	1.072
Summer	-24	1.601	1.065	1.590	1.018	1.579	0.933
	-26	1.599	1.043	1.593	0.986	1.577	0.908
	-28	1.589	1.003	1.589	0.952	1.572	0.875
	-30	1.583	0.967	1.583	0.918	1.572	0.844
Winter	10	1.410	1.432	1.406	1.343	1.396	1.217
	12	1.380	1.446	1.377	1.355	1.382	1.232
	14	1.338	1.442	1.361	1.361	1.357	1.227
	16	1.331	1.453	1.334	1.355	1.325	1.235

The key advantage of the semiannually-fixed tilt configuration, compared with fixed-tilt at the Latitude Angle (LA) is a significant boost in energy yields in summer months (see Fig. 5), which is achieved by improving the angular distribution of solar irradiance (see Fig. 6). Comparing with a flat horizontal surface, the fixed-tilt configuration shifts the angular distribution of sunlight in June towards larger AOIs, while a smaller tilt angle in the semiannually-fixed tilt configuration shifts the distribution towards smaller AOIs and hence increases energy yields.

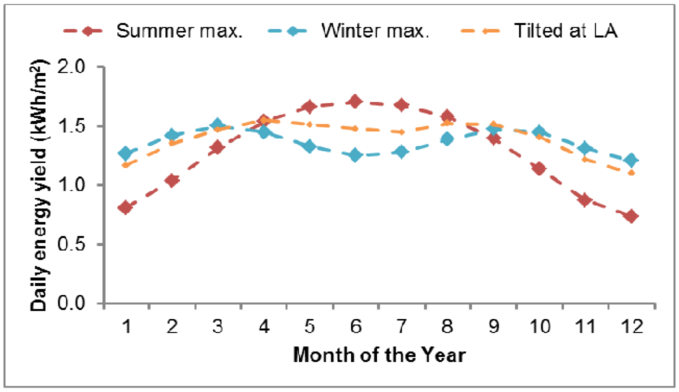

Fig. 5. Average daily energy yields (Jan. to Dec.) for selected tilt angles in Berkeley.

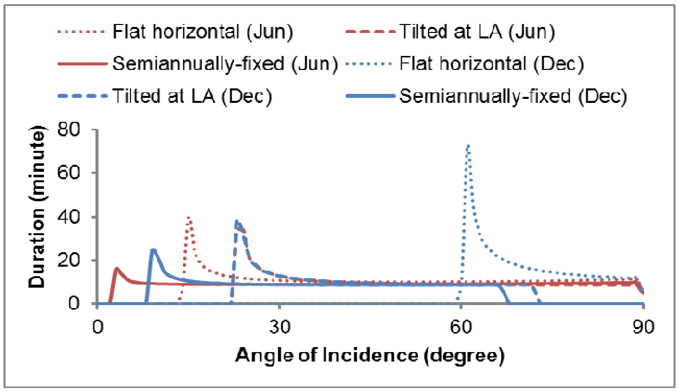

Fig. 6. Angular distributions of solar irradiance in Berkeley between summer and winter.

C. The economics of optimized tilt angles

The semiannually-fixed tilt configuration is more attractive compared with conventional rule-of-thumb rooftop PV system installations, in terms of both performance and economics. Table 3 highlights some key performance results for a given PV system in Berkeley, where the electricity rate is among the highest in the nation (see Fig. 7). In terms of energy yield, the Capacity Factor (CF) is improved by an average of 5.8% over the year. As the summer electricity rate for commercial usage is typically higher than winter rates, the 15.6% increase in July's CF alone would contribute a value of $19.55 at a discount rate of 5% and over a lifetime of 25 years. Therefore, the balance of system, which allows such a semiannually-fixed tilt configuration, is likely to increase the value of the PV system, if the incremental cost is well below about $74/m^2.

TABLE 3.
VALUE OF THE SEMIANNUALLY-FIXED TILT CONFIGURATION

	Present value of yield improvement	Ratio of Added value to Installed cost	Capacity factor	
			Fixed tilted at LA	Semi-annually fixed
Year	$74.25	8.16%	0.320	0.338
Summer	$45.96	5.05%	0.345	0.365
July	$19.55	2.15%	0.332	0.384

To focus on the effect of solar irradiance on the economics of solar electricity, the Levelized Cost of Electricity (LCOE) is solely based on a cost of $5/W, without accounting for geographically varying factors such as maintenance cost, tax benefits, and subsidies. As a result, the presented LCOE tends to be the lower-bound value. It is also worth noting that the capacity factor in this study is the upper-bound value, as the clear-sky model neglects the effect of clouds. Nevertheless, the energy yield ratio between semiannually-fixed tilt configuration and fixed-tilt configuration tends to be little affected, as both tilt configurations will be affected by cloud equally.

The market potential of PV technology is mainly determined by the competition between local electricity rate and solar electricity's LCOE. Fig. 7 also shows the average commercial electricity rate in the lower 48 states [16]; typically a low electricity price is strongly correlated with the use of coal in electricity generation. Among the 3 cities in this study, Berkeley has the largest market potential with the LCOE of solar below the electricity rate for commercial usage. Besides California, the northeastern states present another viable market for solar electricity. Although the southern states are blessed with good solar resources, government subsidy is necessary for PV technologies there, due to low electricity rates.

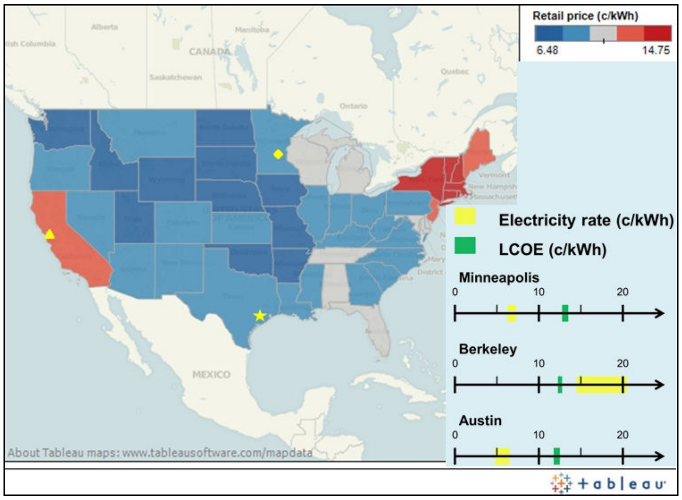

Fig. 7. Geographical differences in electricity rate and LCOE for the 3 cities.

D. Quantitative assessment of different solar cells

When different solar panels are applied the same set of analysis as outlined in the previous sections, a solar manufacturer can decide on the cost-effectiveness of certain technological improvement, and a solar developer can choose the PV system for a particular location with the highest rate of return. The difference in daily energy yields between the 2 sets of EQE data is less than 0.2%, similar to the conclusion from a previous study [1].

In section A, we saw the energy yields could differ by about 4%, after accounting for angular and spectral effects. The little difference in energy yield from the 2 sets of EQE data might be because that that they have very similar angular and spectral variations (see Fig. 8). The 2 PV modules' angular response in a given wavelength is the same, as they are derived from the same modeling. Neither does the spectral response have no clear preference for short-wavelength photons or long-wavelength ones. Therefore, it might still be interesting to test the angle-and-wavelength-resolved solar irradiance data on the measured angle-and-wavelength-resolved EQE data.

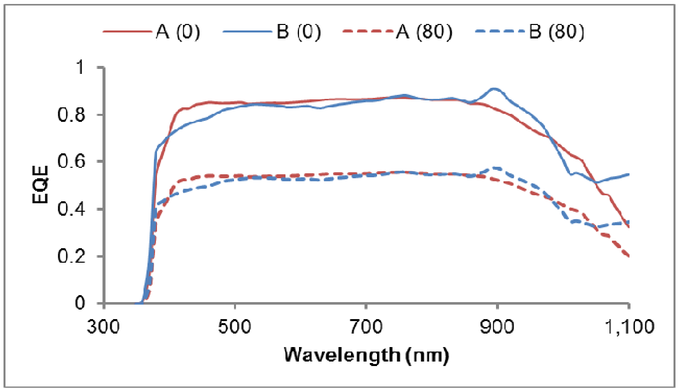

Fig. 8. Comparison of EQE profiles for PV module A and B.

IV. SUMMARY

In this paper, we presented a systematic approach for optimizing PV system performance on commercial rooftops, and quantifying the economic benefits of such improvement. The method also presented a readily way for evaluating the cost-effectiveness of different solar cells. The results also highlighted the geographical difference in energy yields and economics for a given PV system. Moreover, the balance of system, which enables the semiannually-fixed tilt configuration for solar panels, could create significant value for a given PV system and present a market potential. More analysis and irradiance data can be found online [17].

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