

# Regional Atmosphere-Solar PV Interactions

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**Abstract** — The relative importance of atmospheric variables such as temperature, humidity, aerosols, clouds, soiling, and snowfall, are considered for arid versus temperate regions, with specific comparison of the U.S. Southwest and Saudi Arabia with the U.S. Southeast and Ontario, Canada. Meteorological data from representative sites in these regions were obtained from NOAA NCDC, NREL TMY3, NASA AERONET, PME JRCC, and KACST to identify key atmospheric variables for each region. Estimates of the change in average monthly PV performance due to atmospheric variables are 0 to <-6% for temperature, <-1% to >1% for humidity, <-0.1% to >0.1% for aerosols, 0 to <-30% for clouds, 0 to <-3% for soiling with cleaning, and 0 to <-5% for snowfall. The energy density of CdTe PV systems (Wh/m<sup>2</sup>) in a hot and humid climate such as Jeddah, Saudi Arabia is projected to exceed that of multi-c-Si by ~20% by 2017 due to improvements in module efficiency and differences in temperature coefficient and spectral response to humidity.

**Index Terms** — meteorology; photovoltaic systems, cadmium telluride, CdTe, PV, spectrum, soiling

## I. INTRODUCTION

The atmospheric sciences have been critical to identifying global environmental challenges such as climate change. They have also played an important role in deploying commercial solutions to these challenges such as wind energy. However, the atmospheric sciences have been less extensively utilized in deploying solar energy, despite the important role of atmospheric conditions with regard to solar energy performance [1].

While standard reference conditions used to characterize solar photovoltaic (PV) performance include ASTM G173 spectrum, air mass of 1.5, incident irradiance of 1000 W/m<sup>2</sup>, and operating temperature of 25°C, real-world conditions often differ from these reference conditions in important ways. Atmospheric variables have important effects on solar PV performance (Table 1), and these effects can vary regionally. For example, while temperature impacts and soiling may be important for arid regions, humidity and cloud cover may be more important in temperate regions.

In the U.S., deployment of large-scale PV systems has been concentrated in the Sunbelt region of the U.S. desert Southwest. Better understanding of the influence of regional atmospheric conditions is needed to guide PV deployment of large-scale PV systems in other climate regions. In this study, atmospheric variables that affect solar PV electricity generation are regionally reviewed.

TABLE I

ATMOSPHERIC VARIABLES AFFECTING PV PERFORMANCE

Temperature	Change in the instantaneous power generation of a module due to deviations in module temperature from 25°C. Module temperature is affected by ambient air temperature and irradiance.
Humidity	Change in the spectral content of solar radiation due to greater absorption or scattering of some wavelengths
Aerosols	A reduction in the power of the solar radiation due to absorption, scattering and reflection in the atmosphere
Clouds	
Soiling	A reduction in the effective solar radiation due to absorption, scattering and reflection at the module surface
Snow	

## II. METHODS

Atmospheric variables affecting PV performance are considered for arid versus temperate regions, with specific comparison of the U.S. Southwest and Saudi Arabia with the U.S. Southeast and Ontario, Canada. Meteorological data from representative sites in these regions were obtained from NOAA NCDC (Phoenix, AZ, Miami, FL, Detroit, MI; years 1981-2010) [2], NREL TMY3 database (Phoenix, AZ, Miami, FL, Detroit, MI; years 1991-2005) [3], NASA AERONET (Maricopa, AZ, years 2000-2010; Jeddah, S. Arabia, 2012-2014; Key Biscayne, FL, 1994-2011; Toronto, Canada, 1996-2013) [4], PME JRCC (Jeddah, S. Arabia; years 1985-2010) [5], and KACST (Jeddah, S. Arabia; years 1996-2000) [6].

Impacts of these atmospheric variables on PV module performance have been estimated based on analysis of module temperature coefficient, spectral shift factor due to humidity and aerosols as modeled with NREL SMARTS [7], comparison of clear sky (Haurwitz [8], Ineichen and Perez [9] models) and observed global horizontal irradiation with cloud cover, and on-site soiling and snowfall data. These impacts are quantified relative to annual energy generation for perspective cadmium telluride (CdTe) PV systems in each location.

## III. RESULTS

Comparison of atmospheric variables across regions indicates significantly different factors affecting PV performance across seasons (Figures 1-8).

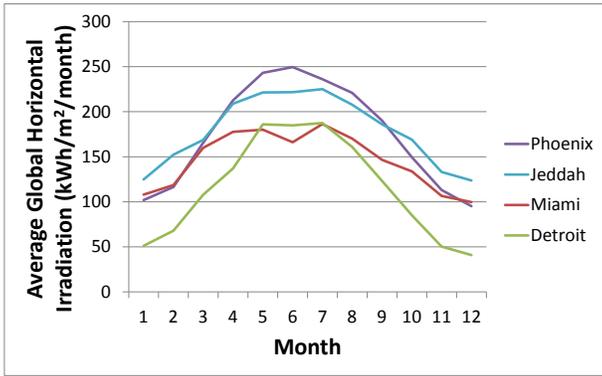


Fig. 1. Average global horizontal irradiation [3,6]

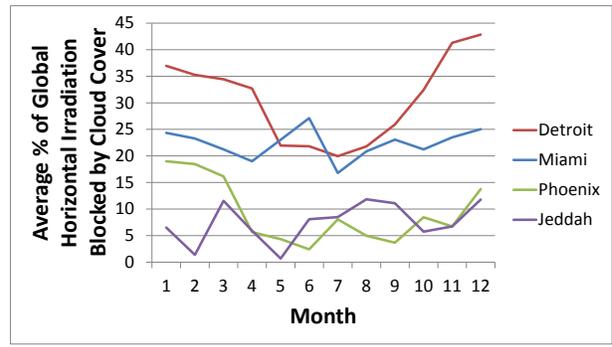


Fig. 5. Average cloud coverage [3,8,9]

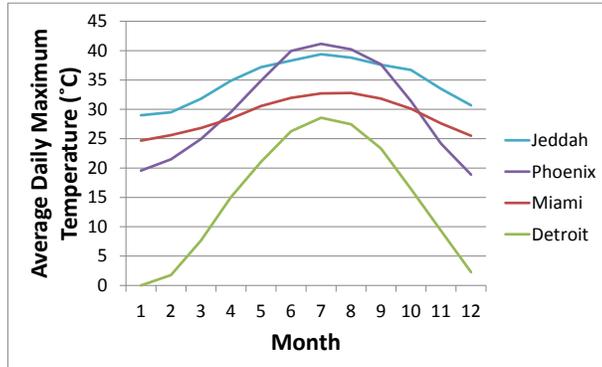


Fig. 2. Average daily maximum temperature [2,5]

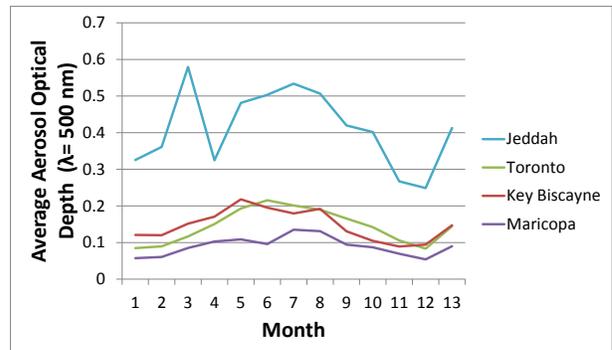


Fig. 6. Average aerosol optical depth [4]

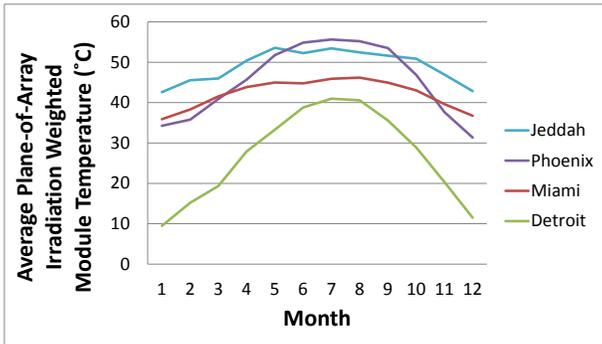


Fig. 3. Average module temperature

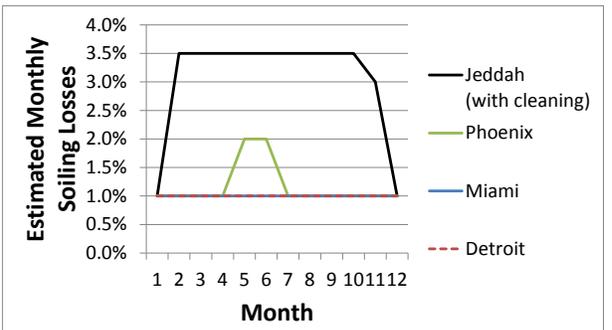


Fig. 7. Average soiling losses

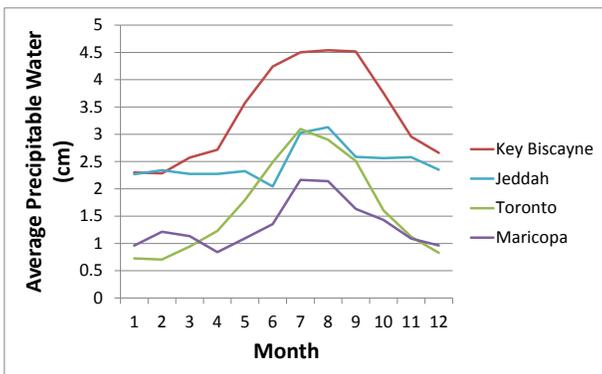


Fig. 4. Average precipitable water content [4]

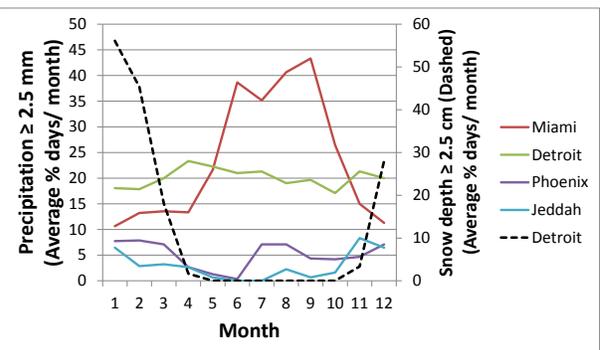


Fig. 8. Average precipitation rate and snow depth [2,5]

TABLE II

SCREENING ASSESSMENT OF ATMOSPHERIC VARIABLES AFFECTING PERFORMANCE OVER SEASONS<sup>a</sup> FOR CdTe PV SYSTEMS

	U.S. Southwest				U.S. Southeast				Ontario, Canada				Saudi Arabia				Performance Impacts (positive indicates gain from nameplate)		
	Sp	Su	F	W	Sp	Su	F	W	Sp	Su	F	W	Sp	Su	F	W	○	●	●
	0 to -2.9%			-3 to -5.9%			< -6%												
Temperature	●	●	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Humidity	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	< -1%	± 1%	> 1%
Aerosols	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	< -0.1%	± 0.1%	> 0.1%
Clouds	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	0 to -10%	-11 to -30%	< -30%
Soiling <sup>b</sup>	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	0 to -1%	< -1 to -3%	< -3%
Snow	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	0	0 to -5%	< -5%

<sup>a</sup>Sp=Spring; Su=Summer; F=Fall; W=Winter

<sup>b</sup>Soiling assessment includes cleaning

Key atmospheric variables in the U.S. desert Southwest are high temperature with potential for soiling accumulation during annual spring drought and high humidity during summer monsoon. Factors in the U.S. Southeast are high humidity and moderately high temperature and cloud cover during most of the year. Key variables in Ontario, Canada are high cloud coverage year round, high humidity and moderately high temperature in summer, and persistent snowfall in the winter. Key variables in Jeddah, Saudi Arabia are high temperature, humidity, and aerosol loading year round resulting in high potential for soiling impacts.

Estimates of the relative change in average monthly PV module performance relative to nameplate rating are 0 to <-6% for temperature, <-1% to >1% for humidity, <-0.1% to >0.1% for aerosols, 0 to <-30% for clouds, 0 to <-3% for soiling with cleaning, and 0 to <-5% for snow (Table II).

#### IV. DISCUSSION

The role of each atmospheric variable with respect to PV performance is discussed below.

##### A. Temperature

Strevel et al. evaluated the effect of module temperature on PV performance [10]. Module temperature is a function of the ambient temperature and the amount of irradiance incident on the module surface. In a typical region of high solar irradiance such as the U.S. Southwest, the majority of solar energy production occurs when the module operating temperature is much greater than 25°C, with the temperature coefficient expressing the instantaneous rate of change of power output as a function of module operating temperature. Crystalline silicon (c-Si) PV modules typically have a temperature coefficient of -0.45 to -0.5% per °C compared with -0.25% per °C for CdTe PV modules (Fig. 9), updated to -0.29% per °C effective 2014.

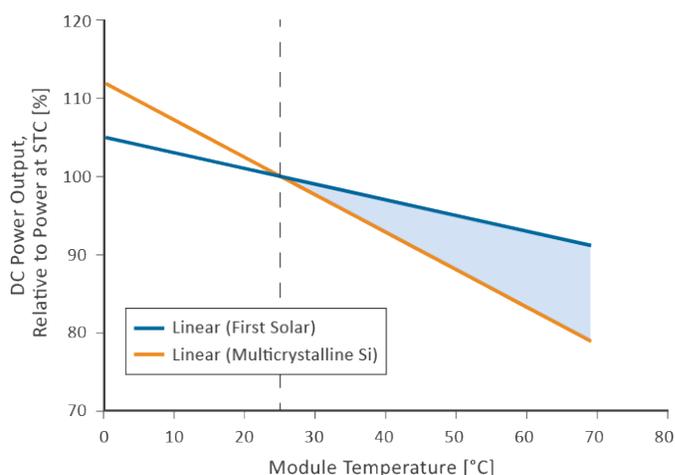


Fig. 9. CdTe and c-Si power output vs. temperature [10]

##### B. Humidity

Nelson et al. investigated the effects of atmospheric precipitable water content on CdTe PV performance using the spectral shift factor (M), a metric indicative of how much the performance of a PV system will vary from nameplate due to deviations from the ASTM G173 spectrum [11]. A strong dependence of M on precipitable water content arises from water vapor's absorptivity being highly wavelength dependent, with very low absorptivity in the wavelengths at which the CdTe quantum efficiency (QE) is high (Fig. 10). On average the magnitude of the annual shift in the spectrum is less than 1% except in the relatively high humidity environments, such as Miami, FL and Jeddah, Saudi Arabia, where CdTe PV power plants will perform better than predicted without a spectral correction (Fig. 11).

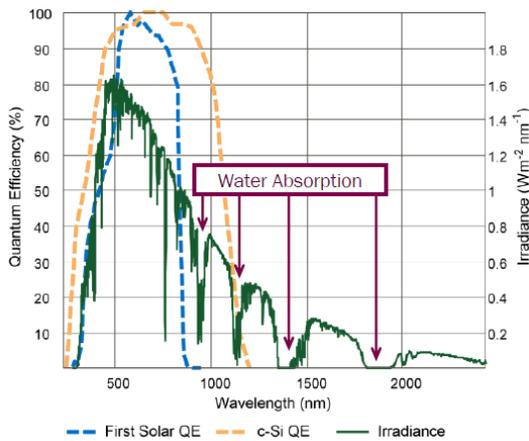


Fig. 10. Spectral irradiance and quantum efficiency [12]

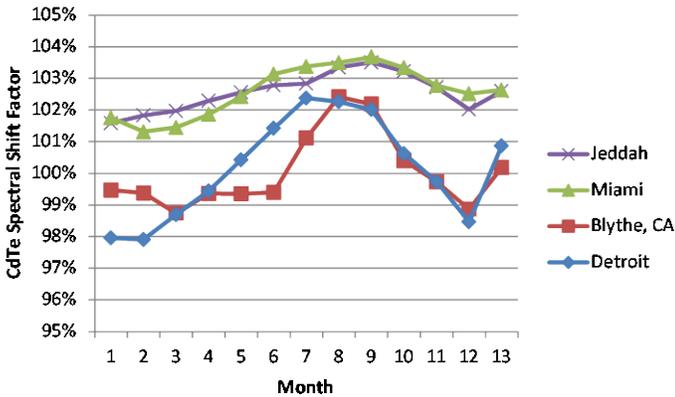


Fig. 11. CdTe spectral shift factor

### C. Aerosols

Aerosol loading in the atmosphere introduces a diffuse or indirect component into solar radiation by scattering light. In the U.S., aerosol concentrations generally follow an East-West spatial trend, with fine mass concentrations about a factor of four greater in the East than West, with sulfates and organics being the largest constituents [13]. Significant dust storms periodically affect the U.S. Southwest during the summer monsoon season and aerosol loading is high year-round in Saudi Arabia (Fig. 6). Maywerk and Ramanathan investigated the effects of continental aerosols on the global, direct, and diffuse portion of spectral irradiance [14]. Continental aerosols were found to shift the peak in the direct solar radiation from 470 nm for pristine conditions to 580 nm for the polluted region. In the case of CdTe PV, normalized quantum efficiency is higher at 580 nm (0.99) than at 470 nm (0.76) (Fig. 10).

### D. Clouds

Depending on the type of cloud cover, incident power can be strongly reduced. High, thin cirrus clouds act in a way similar to clear air because they are highly transparent to shortwave radiation. In contrast, low stratified clouds such as stratocumulus clouds are much thicker than high cirrus clouds,

and therefore do not allow as much solar energy to reach the Earth's surface. Deep convective clouds, such as cumulonimbus clouds, can be many kilometers thick and also strongly reduce shortwave radiation reaching the Earth's surface.

Numerical weather prediction models are used to forecast cloud cover and associated impacts on solar irradiation for several days in advance. Recent efforts have been undertaken to improve the accuracy and resolution of these forecasts using high resolution satellite data and the community mesoscale model WRF to develop short term nowcasts [15].

To help improve grid integration of variable power sources, some utility-scale PV power plants now have power plant controller architecture to regulate real and reactive power output from the PV plant, such that it behaves like a single large generator. For example, plant-level control functions at the 290 MWac Agua Caliente solar project, Yuma County, Arizona include dynamic voltage and/or power factor regulation, power output curtailment, ramp-rate and frequency controls, and start-up and shut-down control [16]. When the plant is curtailed to a specified limit and the plant has additional available generating capacity, the plant-level control functions can minimize the impact of cloud passage on a portion of the plant by increasing the output of other inverters that are not impacted. This will result in increased energy yield (Fig. 12).

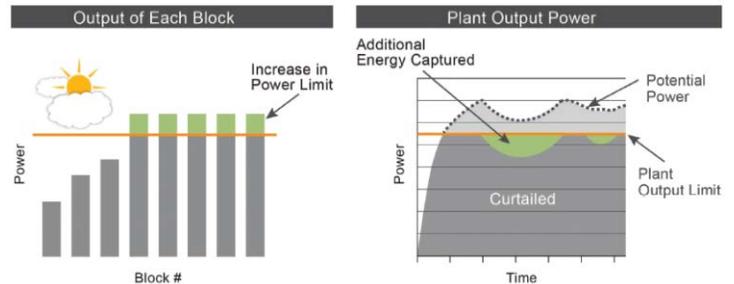


Fig. 12. Impact of Cloud Passage on a PV power plant with controller architecture [16]

### E. Soiling

Soiling from dust and dirt directly impacts the performance of PV modules. In most climates, cleaning is not necessary as soiling losses are minimal and dust is periodically removed by wind and rainfall. An exception is for humid, dust-prone climates, which can transform dry dust into clustered and sticky dust. For example, in the Middle East region, dry brush cleaning methods have been implemented [17], limiting soiling losses to less than a few percent per year without the use of water. In U.S. locations, cleaning is typically not necessary.

### F. Snow and other variables

Severe winds, hail, and heavy snowfall can potentially damage PV system components. As a result, PV modules are subjected to hail impact testing and static and dynamic load testing to simulate wind, snow and ice loads at varying

temperatures and load rates (e.g., IEC 61215, IEC 61646). In addition to modules, PV balance of systems (BOS) are also designed to meet specified wind and snow loads. For example, the BOS design for the 550 MWac First Solar Topaz project in San Luis Obispo County, CA accounts for wind and snow load of 137 km/hr and 24 kg/m<sup>2</sup>, respectively [18]. In the case of tracking systems, on-site weather stations allow for automated stowing in the case of strong winds.

Corrosion from ambient moisture ingress and sandblasting from wind-blown particulates can also potentially damage PV system components. IEC 61701 salt mist corrosion testing and IEC 60068-2-68 dust and sand environmental testing can characterize PV modules for such conditions. In addition, long-term parallel testing protocols such as the Thresher Test and Long Term Sequential Test have recently been developed to further extend test durations to better differentiate PV modules in long-term field performance [19].

### G. Energy Density

While PV technology roadmaps typically focus on module efficiency (W/m<sup>2</sup>) improvements, energy density (Wh/m<sup>2</sup>) roadmaps may be used to incorporate the effects of atmospheric variables on field performance. The energy density of CdTe PV systems in a hot and humid climate such as Jeddah, Saudi Arabia is projected to exceed that of multi-c-Si by ~20% by 2017, due to improvements in module efficiency and differences in temperature coefficient and spectral response to humidity (Fig. 13). The projection assumes an industry average module efficiency roadmap for multi-c-Si from GTM Research, Photon Consulting, and Bloomberg.

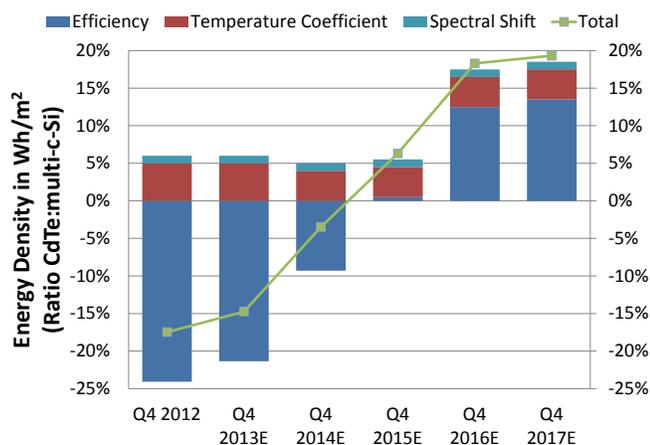


Fig. 13. Energy density roadmap for CdTe PV relative to multi-c-Si PV in a hot and humid climate such as Jeddah, Saudi Arabia [12]

## VI. CONCLUSION

The relative importance of atmospheric variables such as temperature, humidity, aerosols, clouds, soiling, and snowfall,

are considered for arid versus temperate regions. Major factors in the U.S. Southwest are high temperature with potential for soiling accumulation during annual spring drought and high humidity during summer monsoon. Factors in the U.S. Southeast are high humidity and moderately high temperature and cloud cover during most of the year. Key variables in Ontario, Canada are high cloud coverage year round, high humidity and moderately high temperature in summer, and persistent snow fall in the winter. Key variables in Jeddah, Saudi Arabia are high temperature, humidity, and aerosol loading year round resulting in high potential for soiling impacts. Estimates of the relative change in average monthly PV module performance relative to nameplate rating are 0 to <-6% for temperature, <-1% to >1% for humidity, <-0.1% to >0.1% for aerosols, 0 to <-30% for clouds, 0 to <-3% for soiling with cleaning, and 0 to <-5% for snow. While PV technology roadmaps typically focus on module efficiency (W/m<sup>2</sup>) improvements, energy density (Wh/m<sup>2</sup>) roadmaps may be used to incorporate the effects of atmospheric variables on field performance. The energy density of CdTe PV systems in a hot and humid climate such as Jeddah, Saudi Arabia is projected to exceed that of multi-c-Si by ~20% by 2017 due to improvements in module efficiency and differences in temperature coefficient and spectral response to humidity. Future research on this topic may include analysis of atmosphere-solar PV interactions in highly polluted atmospheres.

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TITLE OF PAPER/ARTICLE/REPORT: Regional Atmosphere-Solar PV Interactions

COMPLETE LIST OF AUTHORS: Sinha, Parikhit; Hayes, William; Ngan, Lauren

IEEE PUBLICATION TITLE (Journal, Magazine, Conference, Book): Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th

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