Applied Energy 212 (2018) 1126–1137

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Association of direct normal irradiance with El Niño Southern Oscillation and its consequence on concentrated solar power production in the US Southwest

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HIGHLIGHTS

- Influences of ENSO on DNI and CSP plants productions in four US southwest states are investigated.
- Responses of DNI to ENSO events are both location and seasonal dependents.
- Each ENSO event has unique influence on variability, characteristics and magnitude of DNI.
- Occurrence of ENSO events results in changing the anticipated outputs of CSP plants.

ARTICLE INFO

Keywords:
El Niño
La Niña
Direct normal irradiation (DNI)
Concentrated solar power (CSP)
Variability
Distribution

ABSTRACT

The US Southwest is among the most suitable regions for the employment of concentrated solar power (CSP). The high fluctuations of direct normal irradiance (DNI) lead to significant variabilities in CSP plants power output. El Niño Southern Oscillation (ENSO) has been proven as a large-scale climate phenomenon that influences the climatic behaviors and meteorological variables in the US southwest. In this study, the impacts of ENSO on DNI and CSP plants electricity production are investigated in four US southwest States of Arizona, California, Nevada and New Mexico, using 50 years (1961–2010) collected DNI data. The results demonstrate that responses of DNI to ENSO are both location and seasonal dependent due to the specific climate and DNI features of each site. Furthermore, the conducted analysis shows that each ENSO type and intensity has distinct impacts on DNI. The changes in the variability, distribution and magnitude of DNI during ENSO events can be due to changes in the atmospheric contents, cloud amounts and precipitation level caused by ENSO events. These changes lead to magnitude and continuity variations of CSP plants power output. Such variations necessitate optimizing the thermal energy storage utilization schedule and back-up energy source requirements for CSP power plants.

1. Introduction

The US Southwest is among the best regions in the world in terms of solar energy potential. In the Mojave Desert, the solar radiation level is up to two times more than other regions of the US. This enormous solar energy potential facilitates developing solar power plants as a clean alternative to conventional power plants such as natural gas and coal [1].

Solar electricity can be generated using photovoltaics (PV) and concentrated solar power (CSP) technologies [2,3]. CSP technologies utilize mirrors to concentrate solar energy in the form of direct normal irradiance (DNI) and convert it to heat in order to create steam and drive a turbine for generating electricity [4–6]. A high level of DNI is the most important parameter to power CSPs for electricity generation, and so the most appropriate sites for CSP development are in regions with clear sky conditions and high DNI such as those in the US Southwest [7].

DNI is highly variable; different atmospheric phenomena such as clouds covering the sun temporarily impact the level of DNI. High fluctuations of DNI result in variable power output of CSP plants. The intermittency in DNI brings uncertainty in the electricity production of CSP plants and risk of unpredicted imbalance in supply and demand. This potentially causes the network voltage and frequency to exceed the safe operation limits, and thus decreases the reliability of the network and increases the maintenance costs [8,9]. Since CSP plants require DNI to heat water and generate steam for producing electricity, anything that reduces the level of DNI in the sky can influence the steam conditions that can then damage equipment and lead

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https://doi.org/10.1016/j.apenergy.2017.12.102
Received 4 October 2017; Received in revised form 28 December 2017; Accepted 29 December 2017

to unsafe conditions. Industry-wide models suggest that a 5% negative anomaly in DNI during summer for a CSP plant can lead to approximately 1–1.5% decline in annual revenue for a CSP developer or operator [10]. Frequent and substantial departures from long-term average DNI highlight the necessity of analyzing the influence of DNI variability on both over- and under-performance of CSP plants.

Understanding the DNI variations throughout the year is valuable for CSP developers and decision makers. This can also be utilized to optimize the thermal energy storage charging/discharging schedules which can lead to financial benefits [11,12]. Furthermore, understanding the DNI variations can be helpful for optimizing the CSP plants by decreasing the heat loss and increasing the solar-to-electricity conversion efficiency [8,13,14]. Equally important, it is vital to determine the factors that influence the fluctuations of DNI in different time scales. Factors such as clouds, jet contrails, aerosol and climate have a higher influence on the plant production than what owners may expect [15].

There are different climate phenomena such as El Niño-Southern Oscillation (ENSO) that cause variability and influence global seasonal climate. ENSO is currently regarded as a key element for predicting different parameters in the US Southwest such as precipitation, drought, air temperature, wind speed, etc. [16–22].

Predictions based on the ENSO events are linked to the strength of an event such that stronger events provide higher predictive signals [23]. ENSO is a large-scale climatic variable pattern that is characterized by a periodic shift in the ocean-atmosphere conditions, especially the sea surface temperature (SST) across the equatorial Pacific Ocean. ENSO is a natural but largely unpredictable condition that results from complex interaction of clouds and storms, regional winds, oceanic temperatures, and ocean currents along the equatorial Pacific. It ranges from a warm phase called El Niño to a cold phase called La Niña, which both heavily influence the climate patterns in the US Southwest [19]. The condition is called Neutral when there is no El Niño or La Niña. Generally, El Niño is described with an abnormal increase of SST in the central and/or eastern equatorial Pacific Ocean, while the atmospheric component (Southern Oscillation) relates to an increase in the sea atmospheric pressure in the western Pacific Ocean. La Niña is the opposite phenomenon characterized by an abnormal decrease in the SST [24].

Recent studies presented in the literature discussed high influence of ENSO on renewable energy resources, especially solar and wind. Yip et al. [25] discussed potential impacts of ENSO on wind energy resources in Arabian Peninsula. Fant et al. [26] pointed out wind speed is largely influenced by large-scale oscillations such as ENSO. Bianchi et al. [27] studied the impacts of different large-scale climate phenomena such as ENSO on wind resources in southern parts of the South America. They discussed that ENSO events can be predicted on seasonal timescales. The results of this study demonstrated that ENSO may be utilized as a predictor of wind energy production on monthly and seasonal scales in many southern regions of South America. Prasad et al. [28] discussed high dependency of solar and wind energy resources on ENSO in Australia. In some studies, it was shown that ENSO has a direct influence on solar radiation variations. Mohammadi and Goudarzi [29] explored the sensitivity of different climatic parameters such as total solar radiation, wind speed and participation to ENSO events in California. Their conducted analysis illustrated that occurrence of ENSO events causes distinct impacts on the magnitude and distribution of the studied climatic variables. They found that the impact of each ENSO event on these variables is geographically and seasonally dependent. Based on the conducted study, ENSO was suggested as a useful prognostic tool for solar and wind energy and hydropower planning in California. Davy and Troccoli [30] studied the influence of ENSO on total solar radiation in Australia during summer and winter seasons, using a 20-year dataset from 1989 to 2008. They found out that the impact of ENSO on total solar radiation is an increase in the average total solar radiation in El Niño years compared to La Niña years. The results showed while there is generally a small variation in solar radiation due to ENSO during summer, it can lead to more than 10% variations in some locations during winter. Whitlock et al. [31] investigated the anomaly in total solar radiation due to El Niño and La Niña. They used a 10-year solar radiation data from 1983 to 1993 to generate global maps of locations with significant solar radiation variations. It was shown that most of the regions had a ± 15% year-to-year solar radiation variability; some regions had a higher variability for only several months. Prasad et al. [32] used DNI data from January 1990 to June 2012 to investigate the impact of ENSO on temporal and spatial variability of DNI across Australia and its importance for future CSP plants developments. It was demonstrated that ENSO has a significant impact on DNI variability in the North and Northeast of Australia with a greater impact during winter compared to summer.

The literature lacks detailed studies on the influence of ENSO on the level of solar radiation and in particular the DNI. The importance of such analysis can be better understood when regions with substantial DNI potential are studied. One example is the US Southwest where there is a large number of CSP plants. Therefore, considering the growing development of CSP power plants and proved influence of ENSO on renewable energy sources, the main objective of this study is to identify the relationship of the ENSO phenomenon with DNI in four US Southwest states of Arizona (AZ), California (CA), Nevada (NV), and New Mexico (NM). The selected case studies cover different climate conditions and DNI characteristics. The influence of ENSO events on variability, characteristic, magnitude, and distribution of DNI in this area and potential consequences on CSP plants yields is explored. This study also investigates the influence of intensities of El Niño and La Niña events on DNI level. To fulfil these objectives, very strong and strong El Niño as well as strong and moderate La Niña events are studied. Hourly averaged DNI datasets for a long-term period of 50 years from January 1961 to December 2010 provided by National Renewable Energy Laboratory (NREL) have been utilized for this study.

The main originality of this work, that has not been carefully addressed in previous studies, is a detailed study on the impact of ENSO events with different intensities on DNI with a focus on possible consequences on CSP plants power output. This study brings new contributions and useful insights to the risks associated to the CSP power plants when ENSO events occur. It can be utilized to anticipate the over and underperformance of CSP plants during ENSO events and perform financial and technical risk assessment. The analysis conducted in this work is valuable for project developers, power system operators and central planners.

2. Case study, data and methods

The Southwest, with substantial solar energy potential throughout the year, is the most suitable region for CSP development in the US. This region includes approximately 139,500 km^2 of suitable lands for CSP development, out of which 121,700 km^2 is located in four States of Arizona (AZ), California (CA), Nevada (NV) and New Mexico (NM) [33]. The existing CSP power plants are mainly constructed in AZ, CA, and NV [34]. Despite the substantial potential capacity for electricity generation using CSPs in NM, there is not currently any CSP plant operating in this State.

The US Southwest is the hottest and driest region in the US with a wide range of climates and climatic behaviors. It includes a wide range of geographical features ranging from valleys that are below the sea level to mountains with some of the highest peaks in the contiguous US. Except the North Pacific coast, most regions feature an arid or semi-arid climate in which high share of annual precipitation often happens during a particular time of the year. The seasonal cycle of precipitation is quite variable and it is mainly centered in the winter season in most regions [35].

To fulfill the study objectives, ten sites from four States that cover different climate conditions and different DNI intensities and characteristics are selected: Phoenix (AZ), Prescott (AZ), Tucson (AZ), Bakersfield (CA), Daggett (CA), Ely (NV), Reno (NV), Tonopah (NV), Las Vegas (NV), and Albuquerque (NM). The selected locations, with