Solar Energy 144 (2017) 244–253

Contents lists available at ScienceDirect

Solar Energy

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

Study on the local climatic effects of large photovoltaic solar farms in desert areas

Liwei Yang [a], Xiaoqing Gao [a,*], Fang Lv [b], Xiaoying Hui [a], Liyun Ma [c], Xuhong Hou [a]

[a] *Key Laboratory of Land Surface Process and Climate Change in Cold and Arid Regions, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, Gansu 730000, China*
[b] *Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China*
[c] *Beijing JKD Renewable Energy Technology Development Center, Beijing 100083, China*

ARTICLE INFO

Article history:
Received 24 August 2016
Received in revised form 23 December 2016
Accepted 8 January 2017

Keywords:
Meteorological observation
Photovoltaic farm
Desert areas
Local climatic effect

ABSTRACT

Large-scale solar power plants are rapidly increasing in size and number across the world. However, the surface heat balance is altered when a photovoltaic (PV) power plant is operating. Modifications to the surface albedo through the deployment of photovoltaic arrays have the potential to change radiative forcing, surface temperatures and local weather patterns. In this work, the field observation data from a large solar farm and a region without PV array in Golmud are used to study the impact of large solar farms in desert areas on the local meteorology. The results show that the total daily values of upward shortwave radiation and net radiation in the two sites are significantly different. The mean daily albedo in the solar farm is 0.19, while it is 0.26 in the region without PV. The annual mean net radiation in the solar farm is evidently higher than that of the region without PV. The daily range of soil temperatures at a depth of 5–10 cm in the solar farm is lower than that in the region without a PV farm. The annual range of soil temperatures at a depth of 5–180 cm in the solar farm is higher than that in the region without PV. The soil temperatures at different depths in winter in the solar farm are clearly lower than those in the region without PV. The daily mean of soil temperatures at a depth of 5–80 cm from October 2012 to March 2013 is clearly lower than that in the region without a PV array. The 2-m daytime air temperature in the two sites is essentially the same during winter, while during the other seasons, the daytime air temperature in the PV farm is higher than that in the region without PV, with the maximum difference appearing during the summer. The nighttime air temperatures at a height of 2 m during the four seasons in the solar farm are higher than those in the region without PV. The monthly average 2-m air temperature in the solar farm is higher than that in the region without PV.

1. Introduction

Renewable energy is considered an important solution for mitigating global warming, energy crisis and environmental pollution. The predominant renewable energy sources include wind, solar, biomass, hydropower and geothermal. Photovoltaic solar power systems have drawn tremendous attention from government sectors, researchers and the industry over the past several decades (Gagnon et al., 2002; Liu et al., 2015).

Large-scale solar power plants are rapidly increasing in size and number in China, as well as in other parts of the world. Photovoltaic (PV) power plants in desert regions have a promising future in China, considering the intense radiation received in large areas in China. However, the surface heat balance is altered when a photovoltaic power plant is operating. Modifications to the surface albedo through the deployment of photovoltaic arrays have the potential to change radiative forcing, surface temperatures and local weather patterns. Nemet (2009) investigated the net radiative forcing from the widespread installation of photovoltaics on the earth's surface. However, Nemet did not consider local microclimates, nor have his analytical results been verified with any field data. Genchi et al. (2002) estimated the impact of large-scale installation of PV systems in Tokyo on the urban heat island effect. The simulation results showed that it would be negligible. Tian et al. (2007) analyzed the effect of the PV module on the microclimate of the urban canopy layer, with the simulation results showing that the urban canopy air temperature alters little and the increase in the PV conversion efficiency can reduce the urban canopy air temperature. Taha (2013) evaluated the potential atmospheric effects of PV deployment in urban areas and the

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* Corresponding author.
E-mail address: xqgao@lzb.ac.cn (X. Gao).

http://dx.doi.org/10.1016/j.solener.2017.01.015

simulation results showed a 1–2 °C decrease in peak urban temperatures at six locations across California. Turney and Fthenakis (2011) identified 32 categories of impacts from the installation and operation of large-scale solar power plants. They found the impacts were either beneficial or neutral, except the local climate effect, for which they concluded that research and observations were needed.

The potential effects of the deployment of PV panels on climate have been discussed in previous studies. However, most of these studies focus on urban areas and use simulation methods. In this work, the impact of solar farms on the local meteorology in desert areas is assessed with observational data. It is believed that the results from this research can provide basic data support for the simulation of the local climate effect of a photovoltaic power station. Moreover, it may be useful for guiding the development and appropriate utilization of solar energy.

2. Materials and methods

2.1. Study area and field experiment description

The observation data is taken from Golmud (36°21′55″N; 95°06′48″E; a.s. 2868 m), Qinghai Province. After Tibet, the solar radiation in Golmud is the highest in China. Located at the south edge of the Qaidam Basin, the solar farm covers an area of 2.37 square kilometers, measuring 2296 m from east to west and 1271 m from north to south. The type of landform is Gobi Desert, with a continental plateau climate. The dominant wind direction in Golmud is the westerly wind.

Photovoltaic arrays are fixed. The azimuth of a PV array is south, with a tilt angle of 36°, a height of 2.5 m, and a spacing between each PV row in the solar farm of 6 m. The solar conversion efficiency of the solar panels is 15%. There are two observation points in this test; one is in the photovoltaic power station (site A), located at 36°20.128′ N, 95°13.372′ E at an altitude of 2927 m. The underlying surface is the Gobi. Detailed measurements taken at a height of 10 m were wind speed, wind direction, air temperature, humidity and solar radiation, while measurements taken at a height of 2 m were wind speed, wind direction, air temperature and humidity. The measurement taken at a height of 1.5 m was solar radiation. Soil temperatures at 5, 10, 20, 40, 80, and 180 cm were recorded in the solar farm. The other measurement point was outside the photovoltaic power station (site B), to be used as a reference point indicating ambient conditions. It was to the southwest of site A, located at 36°19.975′ N and 95°12.985′ E, at an altitude of 2933 m, with the underlying surface being Gobi with sparse vegetation. Detailed measurements taken at a height of 3 m were wind speed and wind direction, while measurements taken at a height of 2 m were air temperature and humidity. The measurement taken at a height of 1.5 m was solar radiation. Soil temperatures at 5, 10, 20, 40, 80, and 180 cm were recorded in the region without a PV array. The two observation sites were 645 m apart. The characteristics of the sensors can be found in Table 1. Fig. 1 shows an illustration of the solar farm and the locations where the field measurements were taken.

2.2. Data and methods

The present work is based on data acquired at a 10-min step since October 2012. All the data have been passed through data quality control. All of the observation times are recorded in Beijing time. NR is deduced from the energy budget equation:

$$NR = (DSR - USR) + (DLR - ULR) \tag{1}$$

$$A = USR/DSR \tag{2}$$

where NR, DSR, USR, DLR and ULR are net radiation, downward and upward shortwave radiation and downward and upward long wave radiation (W/m^2), respectively. A is albedo (Tyagi et al., 2012). The energy balance equation is:

$$NR = H + LE + G + S_e \tag{3}$$

where H is the sensible heat flux, LE is the latent heat flux, G is the soil heat flux, S_e is the solar panel electricity (Fig. 2). Due to the minimal precipitation in the Gobi area, the latent heat exchange is negligible. The land surface temperature (ST) is related to the surface long wave radiation by the Stefan-Boltzmann law (Wang and Liang, 2009):

$$ULR = \varepsilon_s \cdot \sigma \cdot ST^4 + (1 - \varepsilon_s) \cdot DLR \tag{4}$$

where ε_s is the broadband emissivity over the entire infrared region and σ is the Stefan-Boltzmann's constant (5.67×10^{-8} W m^{-2} K^{-4}). In the PV farm, 80% of the underlying surface is the ground, due to which, the emissivity ε_s is approximately 0.95. Therefore, ST can be estimated from Eq. (4). Soil thermal conductivity is calculated by the Harmonic method (Gao et al., 2009) as shown below.

The heat conduction equation (Horton et al., 1983) is:

$$\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} \tag{5}$$

where T is the soil temperature (°C), t is the time (s), z is the depth (m), k is the thermal diffusivity, $k = \lambda/C_p$, λ is the thermal conductivity (W m^{-1} °C^{-1}), and C_p is the volumetric heat capacity. The C_p and λ are assumed to be independent of depth and time.

For Eq. (5), it can be solved without initial conditions in semi-infinite space, and its upper boundary condition is assumed as Fourier series:

$$T(0,t) = \overline{T}(0) + \sum_{i=1}^{n} A_i \sin(i\omega t + \Phi_i) \tag{6}$$

The solution to Eq. (5) using superposition is:

$$T(z,t) = \overline{T}(z) + \sum_{i=1}^{n} A_i \exp(-B_i z) \times \sin(i\omega t + \Phi_i - B_i z) \tag{7}$$

where $\overline{T}$ is the mean soil surface temperature, A is the amplitude of the diurnal soil surface temperature wave, Φ is the phase, n is the number of harmonics, $B_i = \sqrt{i\omega/(2k)}$ is the damping depth of the diurnal temperature wave. If the soil temperature at a depth of z_1 is the upper boundary, the formula for calculating the temperature of soil at any depth by the method of harmonic is:

$$T(z,t) = \overline{T}(z) + \sum_{i=1}^{n} A_i \exp(-B_i z - z_1) \times \sin(i\omega t + \phi_i - B_i z - z_1)) \tag{8}$$

In the concrete calculation, the observed data of the two layers of soil temperature can be used to calculate the optimal estimation of the parameters (A_i, Φ_i) in Eq. (6), as well as the parameter (B) in Eq. (8) by using the least square method, thus obtaining the estimated value of soil thermal diffusivity (Horton et al., 1983). Taking the 5-cm soil temperature as the upper boundary (Eq. (6)), the least square method is used to fit different harmonic order numbers, with the second-order harmonic model having a high precision (correlation coefficient r = 0.998). Considering the simplification and precision of the model, the second-order harmonic model (n = 2) is used as the model of the harmonic method, $C_p = 1.47 \times 10^6$ J m^{-3} K^{-1}, in this paper. Therefore, soil thermal conductivity can be estimated using Eq. (8).