Solar Energy 155 (2017) 951–962

Contents lists available at ScienceDirect

Solar Energy

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

The contribution of water surface Fresnel reflection to BIPV yield

Franziska Dammeier [a,*], Gabriel Happle [b,c], Jürg Rohrer [a]

[a] Zurich University of Applied Sciences, Institute for Natural Resource Science, CH-8820 Wadenswil, Switzerland
[b] Future Cities Laboratory, Singapore-ETH Centre, CREATE Tower, Singapore
[c] Architecture and Building Systems, Institute of Technology in Architecture, ETH Zurich, CH-8093 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 5 April 2017
Received in revised form 10 July 2017
Accepted 11 July 2017

Keywords:
Fresnel
BIPV
Solar
Yield

ABSTRACT

Fresnel reflection on a water surface is highly variable throughout the year and can have a significant influence on building-integrated vertical PV panels, yet is generally disregarded in yield calculations. We analyze beam irradiances of two horizontal pyranometers situated next to a lake, one facing upwards and one facing downwards, to estimate the contribution of Fresnel reflection to the beam irradiance on a vertical surface. We show that in general the observed beam irradiance on the downward facing instrument matches the calculated Fresnel reflection. In contrast to other studies investigating water albedo, we also found that the reflection percentage decreases consistently with higher wind speeds and lower solar zenith angle. Fresnel reflection has the highest contribution for vertical surfaces in winter, with varying contributions between <1% and >30% of monthly global irradiance over the course of one year for different latitudes, and should thus be included in yield estimates for building integrated PV installations situated next to bodies of water.

1. Introduction

Sun glare on a body of water due to Fresnel lens reflection can represent a significant percentage of solar irradiance. With the increasing prevalence of building integrated photovoltaics (BIPV) the installed vertical solar panels can capture some of that Fresnel irradiance and convert it to electrical yield. Generally, water albedo is not particularly high and if a fixed value is needed, this value is usually assumed to be between 0.05 and 0.1 (e.g. Cogley, 1979; Payne, 1972). However, water albedo varies significantly with solar zenith angle (SZA), and for SZA > 75° reaches values of 0.2–0.5 under cloudless skies (e.g. Nunez et al., 1972; Payne, 1972). This effect is thus strongest in the respective winter months on both hemispheres. While these albedo values are used for global irradiance calculations, the Fresnel reflection contributes to the beam irradiance a panel receives.

The dependence of ocean albedo on SZA and wind speeds have first been studied many decades ago (e.g. Burt, 1954; Cox and Munk, 1956). Ocean albedo increases with increasing SZA for clear skies and stays relatively constant at low values for overcast skies (Burt, 1954; Payne, 1972). With higher aerosol optical depth this effect is reduced for high SZA (Jin et al., 2004). As different wind speeds result in different surface waves, ocean albedo at high SZA was found to decrease with wind speed (Burt, 1954; Jin et al., 2004). The water content, e.g. high turbidity or high chlorophyll concentration, can change the backscattering for different wavelengths and can thus increase albedo in particular at high SZA (Jin et al., 2004), resulting in higher measured values than what is expected from calculations. While albedo in general refers to the reflected global irradiance including backscattering from below the water surface, the Fresnel albedo is due to reflected beam irradiance on the surface. Fresnel albedo increases with increasing incidence angle onto the surface of interest, thus contributing especially during the morning and evening hours. However, the vast majority of studies on lake albedo generally attempt to characterize total albedo (e.g. Cox and Munk, 1956; Jin et al., 2004; Katsaros et al., 1985; Nunez et al., 1972; Payne, 1972) and do not focus on Fresnel reflection.

While a standard solar power plant or rooftop PV panels will receive no or extremely small reflected beam irradiance, vertical panels would see a significant portion of Fresnel irradiance. The rise of BIPV means a growing number of vertical PV installations with a large variance in azimuth. The quantification of BIPV yield is complex and an ongoing research topic (e.g. Kuo et al., 2016; Martínez-Rubio et al., 2016; Tripathy et al., 2017). However, even though many buildings are situated along shores, the possible influence of nearby bodies of water has so far not been included in BIPV (or other) yield calculations. We close this gap by

* Corresponding author at: Postfach, Campus Grüental, 8820 Wädenswil, Switzerland.
E-mail address: franziska.dammeier@zhaw.ch (F. Dammeier).

http://dx.doi.org/10.1016/j.solener.2017.07.041
0038-092X/

quantifying the contribution of Fresnel reflection to PV yield, and propose that for BIPV situated along shores Fresnel reflection should be integrated into yield calculations.

In our study we quantify the contribution of Fresnel reflection from the lake surface to the overall beam irradiance received by south facing, vertical PV panels. We analyze pyranometer data from a PV test system situated on the northern shore of a mid-sized lake in Switzerland. The data recorded on two horizontal pyranometers (facing upwards and downwards) are projected onto the vertical panel face and compared to the vertical pyranometer data. We then compare recorded and computed Fresnel irradiances and quantify the effect of wind speeds. Finally, we calculate the total contribution of reflected beam irradiance to PV energy yield over one year and, based on our measurements, estimate total percentages for different panel tilts and orientations.

2. Data

A PV test system consisting of solar panels and irradiance sensors was installed in an abandoned quarry to evaluate PV yield. The site is located on the northern shore of Lake Walenstadt in Switzerland (Fig. 1a) approximately 22 m above the lake surface and at a distance of 31 m from the shore (Fig. 1b), resulting in an average angle of 36° downslope. In total, 43 PV modules with 10 different module types and 11 pyranometers with 3 different types were installed at varying orientations and tilts. Only data from the western part of the test system was used in this study (Fig. 1c).

To analyze the contribution of lake surface Fresnel reflection onto the panel surfaces, two SPN1 pyranometers (Delta-T Devices, 2016) were installed near the PV panels (Fig. 2). Both pyranometers were installed horizontally with "SPN1 UP" facing upwards (tilt 0°) and "SPN1 DOWN" facing downwards (tilt 180°), so the former will not receive reflected beam irradiance from the ground or lake surface, while the latter will not receive direct beam irradiance from the sun. SPN1 UP was installed above the panel wall (Fig. 2, number 1) and SPN1 DOWN was installed on a mast protruding about 2 m from the slope towards the lake (Fig. 2, number 3). In addition, we use a CMP21 pyranometer (Kipp and Zonen, 2016) installed in the panel wall (Fig. 2, number 2) with an orientation of 0° (due south) and tilt of 90° (vertical).

The SPN1 pyranometers record both diffuse and global irradiance by using seven thermopile sensors and a fixed shading pattern, recording irradiance with a resolution of 0.6 W/m^2. The shading pattern is fixed, but designed in such a way that, at any given time and location, at least one thermopile sensor will always be completely unshaded, and at least one sensor is completely shaded. In addition, the shading pattern covers exactly 50% of the 180° field of view. This means that the shaded sensor will see approximately 50% of the diffuse irradiance, and the non-shaded sensor will see 50% of the diffuse irradiance plus the beam irradiance. The firmware then calculates beam irradiance as the maximum sensor value minus the minimum sensor value, and diffuse irradiance as twice the minimum sensor value (Delta-T Devices, 2016). The effective aperture for the thermopile sensor facing the sun is generally ±5°, but can have a maximum value up to ±25° depending on sun position (Badosa et al., 2014). The used pyranometers were factory-new and had been calibrated by the manufacturer against a CMP21 with shadow disk and tracker.

SPN1 pyranometers have a field of view of 180° and are heated to ensure stable recording conditions. They have a flat spectral range between 400 and 2700 nm, thus neglecting a part of the blue light spectrum. The overall uncertainty is given as ±8% for individual readings by the manufacturer. According to Badosa et al. (2014) the error for diffuse measurements is in the 10–17% range. The zero offset is <3 W/m^2 and data below this value have been removed from analysis.

The CMP21 pyranometer has a flat spectral range between 285 and 2800 nm and also possesses a field of view of 180°. The unit is heated and ventilated for stable recording conditions. The uncertainty is ±1.4% for individual measurements according to its calibration certificate. The zero offset is <2 W/m^2, and values below that have been removed from analysis.

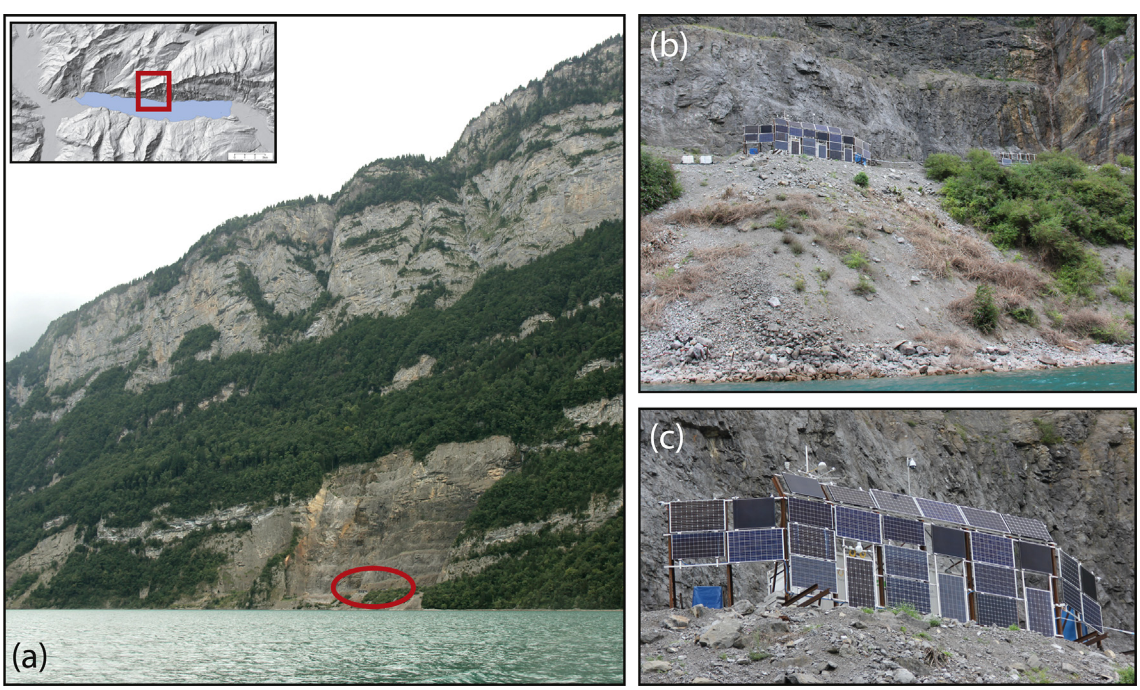

Fig. 1. Overview of the PV test system. (a) Red circle shows the location of the system on the lake shore (inset shows overview for reference). (b) Test system is situated at the top of a slope and is divided into a western and eastern part, with the eastern part further removed from the shoreline. (c) Close-up of the western part of the test system with the middle panels facing due south. The panels and sensors used in this study are located in this part. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)