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Quantifying the Distribution of Evapotranspiration at PV and APV Sites Using Soil Moisture

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Abstract. Solar panels affect the distribution of water and energy reaching the ground causing changes in soil moisture, evapotranspiration and percolation. In the context of Agri-Photovoltaics those changes influence plant growth and yield as well as irrigation demands while large Photovoltaic installations could potentially lead to changes in the water balance of the catchment. In either case, evapotranspiration plays an important role as the installation of panels of any design leads to shading thereby reducing the water loss to the soil through evapotranspiration. As it is difficult to measure evapotranspiration, the authors proceeded using soil moisture observations to quantify evapotranspiration pattern in dry periods. They found on average a 44 % higher evapotranspiration rate over 12 dry periods of varying conditions under the panels compared to a reference area at the research site Pillnitz. However, similar observations at the second site, Weesow show also a reversed behaviour due to reduced soil water availability as a result of the higher evapotranspiration at the reference area.

Keywords: Evapotranspiration, Soil Moisture, Photovoltaics

Introduction

Limited natural resources on one hand and climate change on the other hand have driven the development of renewable energy concepts. Solar radiation is a source of energy abundantly available and consequently photovoltaic systems have been at the heart of the development amounting to a worldwide installed capacity of 942 GW in 2021 [1]. The installation of ever larger Photovoltaic sites (PV) and the related problem of loss of arable land has led to the subsequent emergence of the concept of Agri-Photovoltaics (APV), where farming is done under and between the panels. Since the emergence of the idea in the 1980ies [2], numerous small APV sites have been installed worldwide [3]. They are often subject to accompanying research regarding their impact of coverage and shading on plant growth and yield, irrigation including the technical design [3], [4], [5], [6] while there is still little research on the impact of large PV sites on the environment. In either case, coverage and shading by solar panels affect amount and distribution of energy and water reaching the ground. While water is re-distributed with less water reaching under the panel rows and concentrated runoff from the panel surfaces at their edge, solar energy is reduced thereby directly affecting evapotranspiration (ET). Feistel et al. [7], [8] have demonstrated changes in soil moisture (SM) pattern and evapotranspiration at a number of PV and APV sites.

Evapotranspiration is difficult to measure and methods have their individual limitations. Potential evapotranspiration (ETP) is often used compensating for the lack of data providing actual values of ET. Deriving ETP from energy budget has the distinct disadvantage of providing an estimate for conditions that assume the availability of sufficient water to satisfy the atmospheric demand. This is critical, as ET is a function of soil moisture in periods of reduced soil water content. Investigating changes in amount and spatial pattern of ET caused by solar panels requires measurements suitable to address high spatial variation and adaptability to measuring under the panels. It renders methods based on remote sensing with achievable resolutions of up to 15 m [9] but also eddy-correlation techniques with their requirements on the upwind distance to the nearest surface change (fetch) unsuitable. Precision lysimeters measuring ET based on the mass balance have been used for decades. Their accuracy depends on the area, soil mass and the type of scale [10]. Large lysimeters providing highly accurate data have predominantly been used for long-term studies. They are expensive and the installation of a sufficient number to allow for statistically sound data collection might not be feasible. Smaller size lysimeters have their own challenges with respect to the selection of depth and area suitable to represent natural crop development [10].

Changes in soil moisture during dry periods are the result of the loss of water through ET assuming that water neither percolates into deeper layers nor moves laterally. There is a large variety of soil moisture measurements well established although here as well respective error sources and limitations must be considered [11]. Using soil moisture to determine ET is therefore a promising approach in particular where high spatial distribution such as changes in pattern caused by solar panels is required. Shah et al. [12] followed earlier studies applying the approach to determine ET at a site of shallow groundwater covered by forest and grass land, respectively. Frequency domain reflectometry (FDR) was deployed for continuously recording soil moisture to a depth of 150 cm. Lateral subsurface flow was taken into account by analyzing soil moisture at night when ET was zero. Monthly daily averages of ET were compared to results from pan evapotranspiration and were found to be in good agreement. The authors conclude that estimating ET from soil moisture profiles improves the quantification of the combined process of evaporation from the upper layers and root water uptake reaching deeper into soil. Hess at al. [13] in their work on rain gardens compared changes in soil moisture during dry periods to changes in lysimeter weight readings. FDR was deployed to record soil moisture profiles. They found ET from soil moisture data at three different depths to be strongly correlated to the lysimeter readings. Comparing results from different depths (10, 35 and 65 cm) they concluded that "the bottom soil moisture sensor provided the best estimate of evapotranspiration". Wang et al. [14] have also deployed FDR SM measurements to estimate ET from grass land during two short summer periods. The results were compared against potential evapotranspiration and ET from a lysimeter. The authors concluded that "it is feasible to use soil moisture fluctuation signals to reflect evapotranspiration".

1 Materials and methods

1.1 Estimation of evapotranspiration from soil moisture in dry periods

Excluding any vertical drainage, lateral flow or capillary rise, the variation in soil moisture of a vertical column of soil during a dry period is equal to the loss of water through ET:

$$\frac{\partial cSM}{\partial t} = ET \tag{1}$$

where cSM is the total soil moisture of the soil column in mm as determined in Equation 2 below, t is the time and ET is the evapotranspiration in mm/t.

$$cSM = \int_{SS}^{D} SM \cdot dz \tag{2}$$

where SM is the soil moisture in %, SS is the soil surface, D is the depth of the soil column considered in mm and z is the depth below soil surface in mm.

1.2 Locations and measurements

Data collected at four sites in Germany are presented or referred to in this paper. The sites comprise the research APV-site of the University of Applied Sciences Dresden (HTWD) at Pillnitz, a PV plant in Boxberg and the lysimeter station Brandis, all of them were subject to preliminary investigations to shape targeted future research. Measurements of SM at six depths between 10 and 100 cm were taken along transects perpendicular to the panel rows focusing on the area under the panels, between the panels and at the dripping edge. For reference, the same data was collected at a site without impact of solar panels.

Based on the findings of the preliminary investigations indicating a reduction in evapotranspiration, current research at one of the largest PV-sites in Germany focuses on the impact of coverage and shading on soil moisture and evapotranspiration. The solar park of EnBW AG in Weesow, northeast of Berlin (Figure 1) was built in 2020 and has been providing power since 2021. HTWD accompanies the operation with a long-term study. The site [15] and measurements are summarized in Table 1.

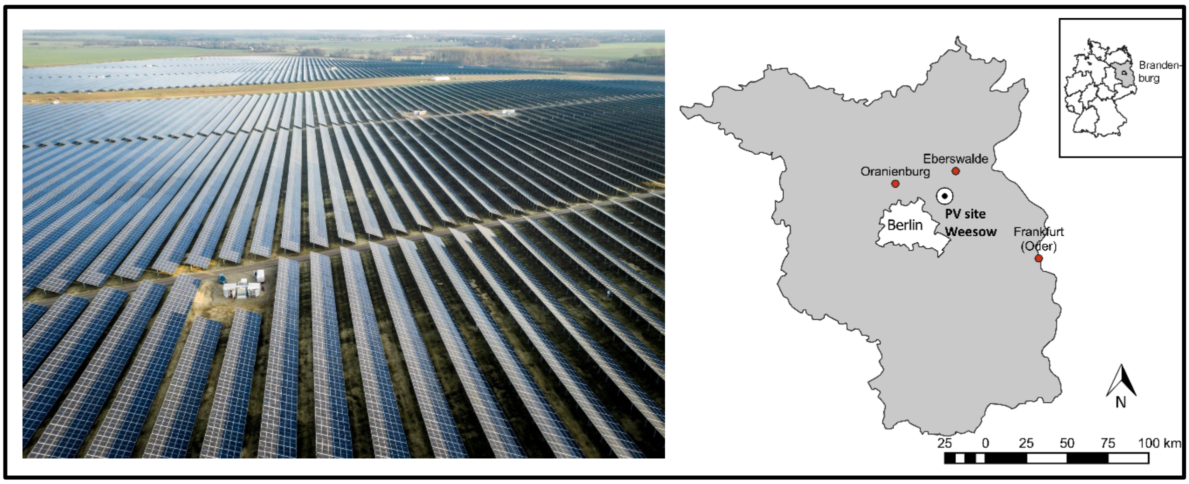

Figure 1. Location and aerial view of the PV site in Weesow.

Table 1. Information about the solar park and the measurements in Weesow.

Information	**Details**
Soil	Sand-boulder-clay mosaics on moraine depressions
Vegetation cover	Site specific herbs and grass
Land use	Sheep grazing
Average annual precipitation	575 mm
Area	164 ha
Number of modules above each other	6
Frame height upper/lower	0.80 m / 2.15 m
Type of soil moisture sensors	TDR probe PR2/6 of Delta-T Devices
Location and measurement points (MP) of the SM profiles	Reference area: MP 6-5, 6-6, 6-7 Under the panels: MP 1-1, 1-2, 1-3
Depths of SM profiles	10, 20, 30, 40, 60 und 100 cm
Type of rain gauge (RG)	Kalyx of EML Ltd.
Location RG	Reference area
Start data collection at reference area	9 May 2020
Start data collection under the panels	15 October 2021
Interval	10 min
Data storage	DeltaLINK-Cloud

1.3 Data processing

Original SM records and climatic data have been imported and will be stored and managed in a time series database (InfluxDB) and a connected visualization tool (Grafana). This application set is the base for data handling, standard dashboards and a data store for other analyzing tools like Python or R. For the detailed data analysis with data validation, selection of suitable dry periods and the calculation of average daily ET values Python scripts have been applied. After checking the time series, the records representing soil moisture at individual measuring points (MP) have been averaged and linearly interpolated to derive profiles of 10 cm intervals to a depth of 100 cm. The selection of dry periods was subject to the condition that no precipitation occurred for 8 days and that there were no effects from a previous precipitation event (no delayed increase in soil moisture in observation layers). Where available field capacity has been deployed to exclude percolation through gravity affecting the results. Changes in soil moisture at 100 cm depth has been checked selecting periods where zero change in SM indicates that there is no upward movement by capillary rise from deeper layers. Daily average SM has been used to quantify the loss in SM and as such the evapotranspiration. Analyzing daily pattern at different depths provides information on the water movement in the soil. Changes during the night when the loss through ET is zero can indicate lateral flow particularly at sloping sites and shallow groundwater table as observed by Shah et al. [12] or movement by capillary rise such as identified by Wang et al. [14]. Comparison of different depths help indicate the layers where soil water is taken from for evapotranspiration. For the calculation of ET, average daily soil moisture has been used ignoring any diurnal variations.

1.4 Potential evapotranspiration as reference

Potential evapotranspiration (ETP) was calculated for the reference area at the Agri-PV site Pillnitz following the FAO-56 Method [16] and was used for checking and interpretation.

2 Results and discussion

2.1 Preliminary data at the APV pilot site Pillnitz - comparison of reference area and area under the panels

Figure 2 shows a comparison of average daily ET under the panels and at the reference area for 12 dry periods between 3/2019 and 6/2021. ETP at the reference area is also shown to characterize the individual meteorological conditions. On average over 12 dry periods ET at the reference area was 1.6 ±0.7 mm/d compared to 0.7 ±0.4 mm/d under the panels.

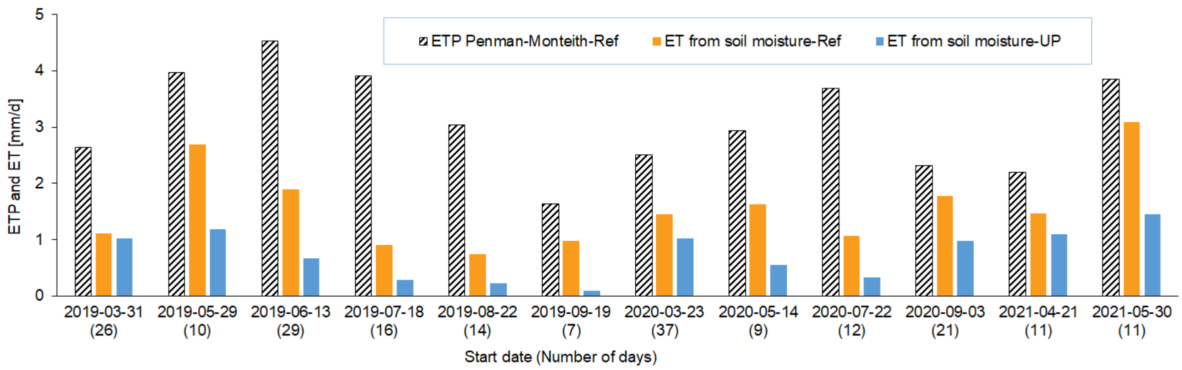

Figure 2. Average daily evapotranspiration at the reference area (Ref) and under the panels (UP) at Pillnitz for twelve dry periods and average daily potential evapotranspiration at the reference area.

2.2 PV site Weesow - comparison of reference area and area under the panels

Three dry periods in 2022 have been analyzed comparing the area under the panels with the reference area. The three periods are distinctly different starting with wet conditions in early spring and gradually moving through dry conditions to a period in summer where soil moisture in the upper layer was depleted. Total and average daily ET have been calculated from the decline of soil moisture at the reference area and under the panels.

Figure 3 shows a comparison of SM at 10, 40 and 100 cm during period 1 (16 March – 2 April 2022). It demonstrates that early in spring the soil was relatively wet. In the upper layers, the soil was generally wetter at the reference area as a result of direct exposure to rainfall compared to the area under the panels which shield off some of the precipitation. At 10 cm, SM declines at a faster rate at the reference area confirming higher ET rates. Figure 4 showing the loss from individual soil layers demonstrates that at the reference area the loss is limited to the upper 50 cm of the soil while under the panels water is taken from deeper layers, too.

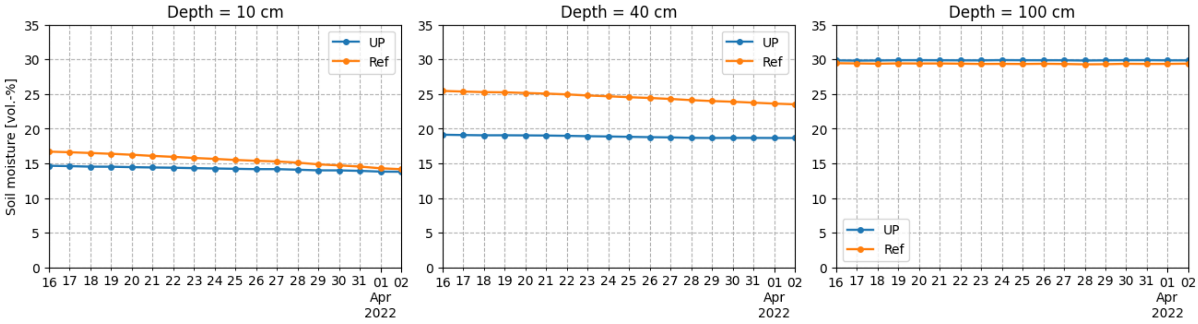

Figure 3. Daily soil moisture at 10, 40 and 100 cm at the reference area (Ref) and under the panels (UP) at Weesow during period 1.

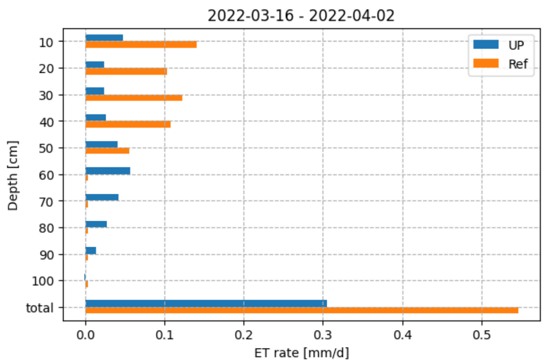

Figure 4. Average daily evapotranspiration from each soil layer and in total at the reference area (Ref) and under the panels (UP) at Weesow for period 1.

Figure 5 displays the comparison of soil moisture at 10, 40 and 100 cm during period 2 (25 April – 4 May 2022) later in spring. At 10 cm, SM at the reference area was equal to the moisture under the panels at the start of the period as result of higher ET rates. As SM decline rates continue to be higher at the reference area, the soil moisture remains lower than under the panels throughout the period. At 40 cm depth, SM is still higher at the reference area although declining faster than under the panels.

There were no changes in SM at 1m depth justifying the assumption to limit the layers included in the calculations to this depth. The respective loss from individual soil layers in Figure 6 follows the same pattern as during period 1.

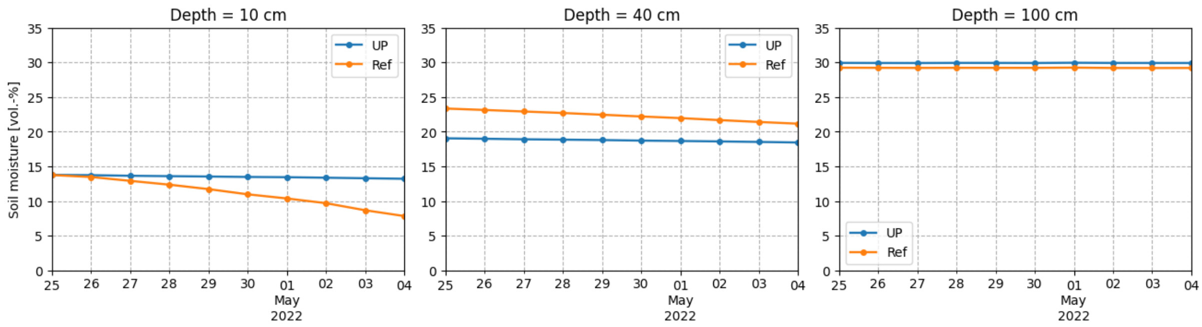

Figure 5. Daily soil moisture at 10, 40 and 100 cm at the reference area (Ref) and under the panels (UP) at Weesow during period 2.

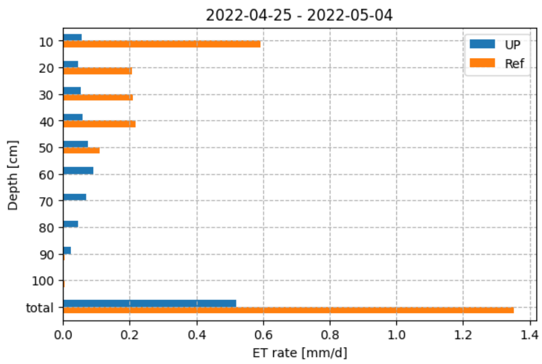

Figure 6. Average daily evapotranspiration from each soil layer and in total at the reference area (Ref) and under the panels (UP) at Weesow for period 2.

Soil moisture at 10, 40 and 100 cm for period 3 (6 August – 14 August 2022) later in summer is shown in Figure 7. SM is now lower at the reference area at all depths. It can also be seen that water was lost from 100 cm at the reference area indicating a shift to deeper layers as the upper layers are depleted of water. Limited water availability is reflected in the evaporation rates shown in Figure 8 resulting in a reversal of the pattern with higher ET under the panels where water availability is still higher compared to the reference area. Figure 8 also shows in more detail the shift of the water uptake to deeper layers.

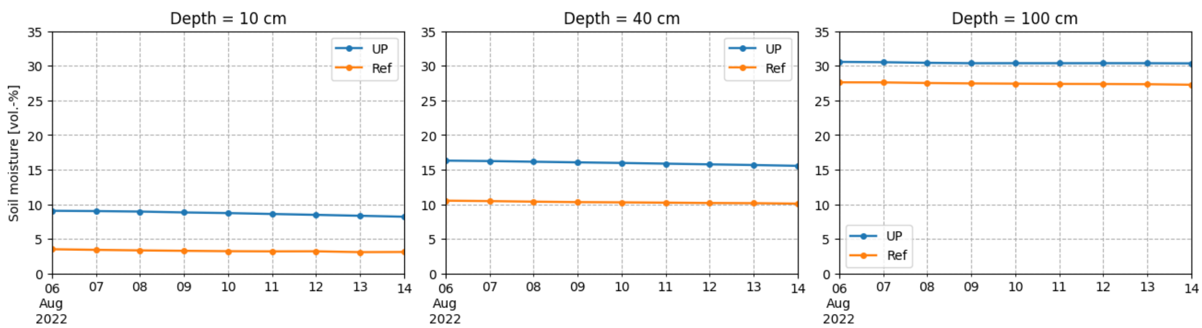

Figure 7. Daily soil moisture at 10, 40 and 100 cm at the reference area (Ref) and under the panels (UP) at Weesow during period 3.

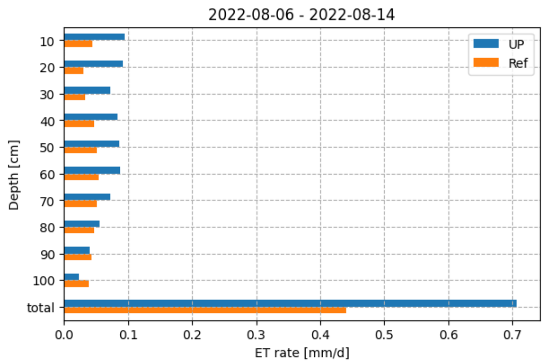

Figure 8. Average daily evapotranspiration from each soil layer and in total at the reference area (Ref) and under the panels (UP) at Weesow for period 3.

3 Conclusions and Recommendations

Comparing data and results to those described by Shah et al. [12] and Wang et al. [14] the authors conclude that SM profiles can be used to quantify the loss through ET in dry periods. While Shah et al. [12] analysed soil moisture to a depth of 150 cm, at the Agri-PV site Pillnitz and the PV-site Weesow soil moisture profiles to a depth of 100 cm have been suitable to account of the loss in soil moisture through evapotranspiration. Daily ET during dry periods can be quantified from soil moisture profiles taken into account the depth of the root zone and ensuring no loss through percolation or gain from capillary rise. During periods where the soil is replenished by precipitation and percolation takes place from the surface into the deeper layers the methodology is not suitable. Here lysimeters could be employed to quantify all components of the soil water balance with ET as the residual. The results confirm that shading caused by solar panels results in a reduction in evapotranspiration leading to a longer preservation of water during dry periods under the panels.

Data availability statement

The data where this study based on are available via our database server upon request.

Author contributions

Ulrike Feistel: conceptualization, funding acquisition, methodology, supervision, writing – original draft; Susanna Kettner: funding acquisition, project administration, writing – review and editing; Jakob Ebermann: investigation; Fabian Müller: data curation, formal analysis, methodology, software, visualization, writing – review & editing; Emese Krajcsi: data curation.

Competing interests

The authors declare no competing interests.

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