The Effect of Surface Cover Vegetation on the Microclimate and Power Output of a Solar Photovoltaic Farm in the Desert

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Abstract

Part of a commercial solar photovoltaic farm in the hot dry Negev Desert of Israel was modified by planting low-rise surface cover crops in the spaces between the rows and beneath the solar panels. In two test plots of about 0.22 hectares each, modifications to the microclimate resulted in lower air temperature, higher humidity and reduced radiant loads on the lower face of the panels compared to a control plot that was not modified. PV panel temperature in the planted test plots was up to 4.5ºC lower, resulting in an increase of electricity output of 1.2% over the summer. Water consumption for irrigation was 24-30% lower in the partly shaded zones during the initial planting and growth phase (depending on the type of crop), but differences in the height of summer, once the crops had matured, was only 7-11% lower. The crop yields beneath a partly shaded area beneath the panels were about 60% of the yield in fully exposed areas of the site, but the Land Equivalent Ratio of the test plots was 1.67. An analytical model, adapted from the Faiman equation, can describe PV panel temperatures in the presence of crops accurately, providing a basis for estimating the electricity output based on their rated temperature coefficient.

Keywords: PV panel temperature, desert, pilot study, field experiment, Land Equivalent Ratio

1. Introduction

Agrivoltaic systems promise greater benefits from a limited site area (Dupraz et al, 2011), reflected in a Land Equivalent Ratio > 1, through dual use of the same plot for electricity generation and crop cultivation. Simulations show that there are trade-offs between higher density of solar panels and greater crop production in mono-facial panels (Dinesh and Pearce, 2016), as well as in bi-facial ones (Sun et al, 2018). Solar farms are known to generate a localized daytime heat island (Broadbent et al, 2019), which should lead to a reduction in the power output of the panels. Meanwhile, studies of rooftop PV have explored synergies between solar panels and a green roof, indicating that the presence of plants may lead to an increase in electricity output of approximately 1% relative to a non-planted roof (Ogaili and Sailor, 2016).

The objectives of the present study were to deploy a pilot study in an operational commercial solar farm to establish the magnitude of the electricity output premium; to monitor the microclimatic effects of vegetation in a full-scale solar farm; to assess the effects of panel shading on crops in a hot dry climate; and to describe the practical difficulties of retrofitting an existing solar farm through the addition of agriculture.

2. Methods

Two test plots of about 45x50 meters each in a commercial solar PV farm with mono-facial panels were modified by the addition of crops planted both beneath the panels and in the spaces between rows (Fig. 1, left). The electricity production from the test plots was compared to the output of an otherwise identical control plot that did not receive any treatment. The solar farm is located in Israel's Negev Desert, 31.01N 34.76E. The climate is characterized by sunny, dry summers with a mean daily maximum temperature (July) of about 34ºC and mild winters with mean daily max (January) of about 19ºC. Annual global horizontal solar radiation averages 2,365 kWh m^{-2}. Annual rainfall averages 105mm, with no rain occurring between May-September.

doi:10.18086/swc.2021.07.01 Available at http://proceedings.ises.org

The crops planted in both test plots were low-rise plants selected for their quick growth, low height and ability to create a complete cover of the surface: Dichondra repens and Viola hederacea in one plot and Pelargonium graveolens in the other. Planting was initiated in spring (April 2020) and full vegetated cover was achieved by June (Fig. 1, right). Measurements were then carried out continuously throughout the summer and autumn of 2020 and the winter of 2021.

An extensive monitoring infrastructure was installed to measure micro-meteorological variables including air temperature, humidity, wind speed and direction, and solar radiation for the site as a whole (Tab. 1). At each of the three plots, electric power, voltage and current were recorded, and measurements were made of temperature, humidity, and net all-wave radiation. The temperature of the solar panels was measured at 3 heights above the ground in each plot. Data were recorded on a Campbell CR1000 at 10-minute intervals.

Fig. 1: Left – aerial view of solar farm showing location of test plots. Right – Pelargonium in one of the test plots.

Tab. 1: Measurement instruments and locations

instrument	parameter	location
T-type thermocouples	panel temperature	panels
Campbell hygrovue5	air temperature, relative humidity	under the panels
Apogee net radiometer	net all-wave radiation	under the panels
CR Magnetics CR5210	electric current	panels
Phoenix Contact SCK-M-I-8S-20A	electric voltage	panels
GMX500	air temperature, relative humidity, wind speed and direction	edge of solar farm
Kipp & Zonen CMP3	global solar radiation	edge of solar farm

3. Results

3.1 Microclimate modification

Compared to the control plot, air temperature in both test plots was lower than air temperature in the control plot (Fig. 2, left). The difference was minimal at night and reached a maximum of about 1.4K in the early afternoon. Although we did not perform a complete energy balance for the three test plots, the temperature reduction is attributed to evapotranspiration from the crops: The decrease in air temperature in the test plots is mirrored by an increase in the moisture content of the air, as indicated by the relative humidity (Fig. 2, right). This difference was greatest in the morning hours and declined gradually in the afternoon.

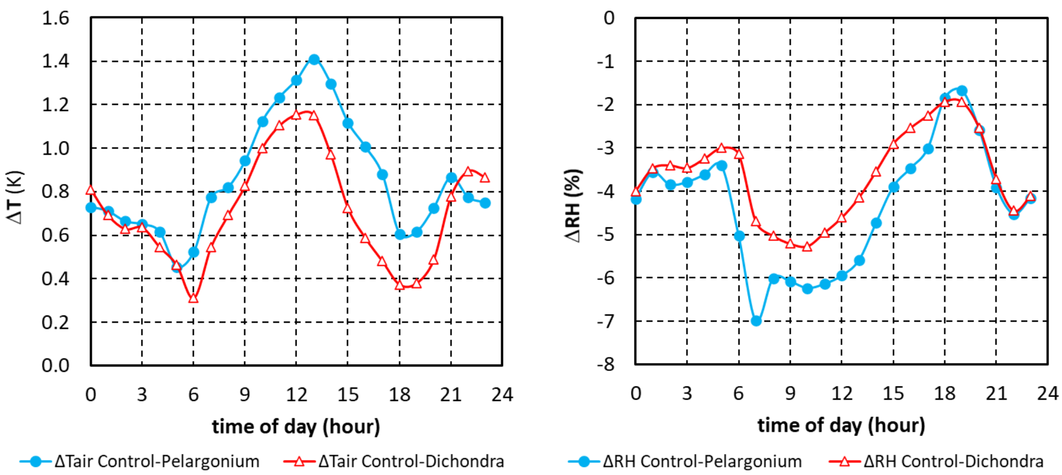

Fig. 2: Left – Average diurnal profile of the difference in air temperature between the control plot and test plots. Right - Average diurnal profile of the difference in relative humidity between the control plot and test plots, for the month of August 2020.

3.2 Panel temperature

PV panel temperature in the test plots was significantly lower than in the control plot during daytime, but nearly the same at night. The difference was substantially greater in the top row of panels than in the lower rows (Fig. 3): the lower face of these panels was exposed to less reflected solar radiation due from the plants (albedo 0.20-0.22) than from exposed desert soil (albedo 0.35) and to less IR radiation from the cooler vegetation. Panels in the lower part of each row were in deep shade and had a similar radiant balance in all test plots.

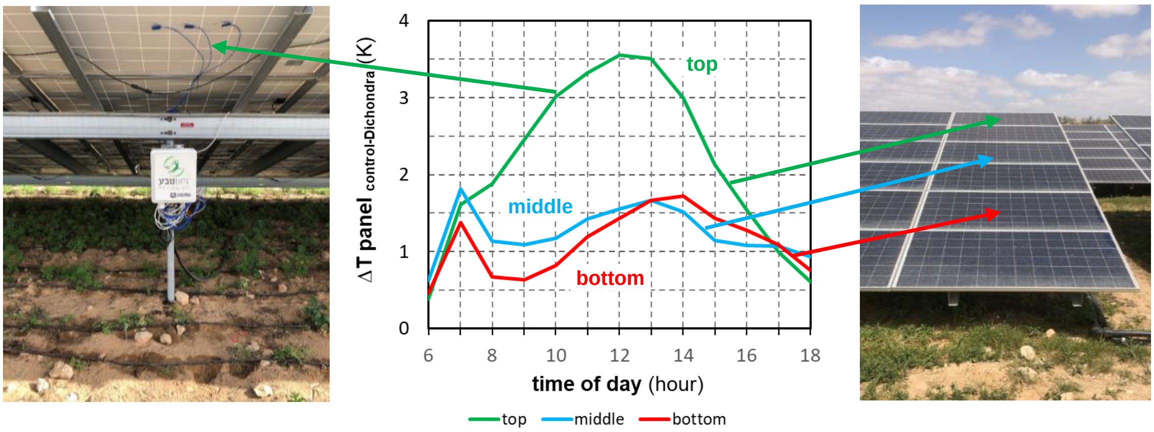

Fig. 3: The diurnal pattern of the difference in panel temperature between control plot and Dichondra test plot at 3 different heights above the ground, for the month of August 2020.

3.2 Power output

The electricity output of panels in the test plots was compared to the output of a similar string of panels in the control plot at three heights above the surface. To reduce potential error from differences among individual panels, output was measured for strings of 10 panels. The increase averaged 0.7% in the lowest row of panels (about 1 meter above the surface) and 1.2% at the upper row (about 2.5 meters above it). The measured improvement is consistent with output corrected for panel temperature using the manufacturer's temperature coefficient (-0.41% / K).

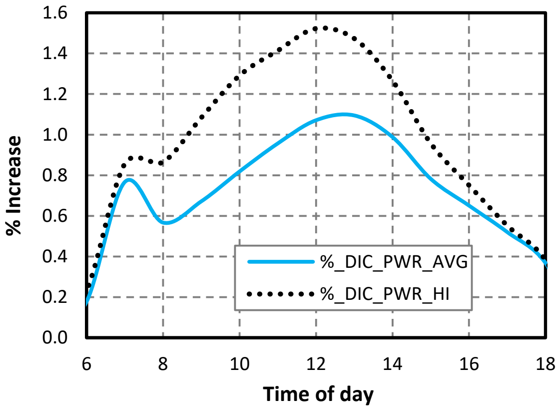

Fig. 4: The diurnal pattern of differences in power output between the Dichondra test plot and the control (average for July 2020). Note the difference between values for the upper row of panels only (HI) and the average for the entire plot (AVG).

3.4 Irrigation requirements

To support crop growth in this climate, irrigation is required. Water supply was metered separately for each zone in the test plots to assess the effect of shading on evapotranspiration (Fig. 5). During the initial establishment phase (in spring), Dichondra plants in the sun required an average of 94.2 m^3 per day per hectare, and plants in the shade beneath the panels required 71.3 m^3 per day per hectare, a reduction of 24%, while Pelargonium plants required 54 m^3 per day per hectare in the sun and 37.8 m^3 per day per hectare beneath the panels, a reduction of 30%. The corresponding figures for the summer period (June 26 – September 29), once the plants had matured, were 46.2 and 41.0 m^3 per day per hectare (Dichondra) and 37.3 vs. 34.8 m^3 per day per hectare (Pelargonium), so that differences dropped to only 11.3% and 6.7%, respectively.

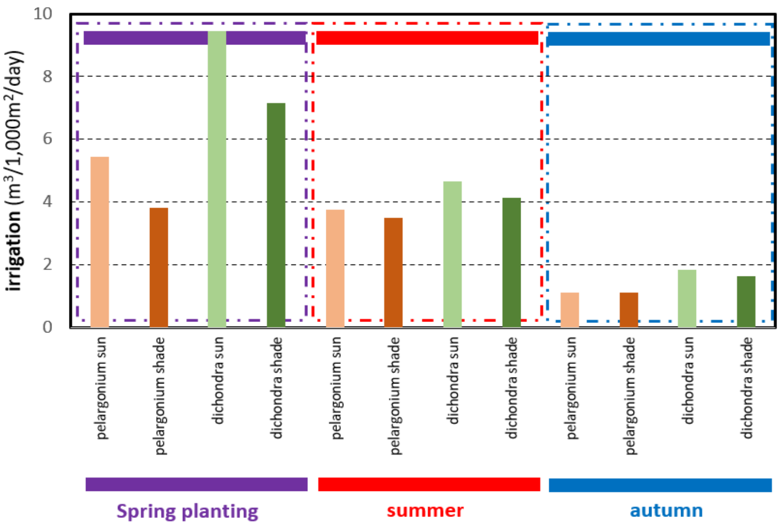

Fig. 5: Irrigation supplied to the test plots, accounting for season and exposure to sun.

3.4 Effect on crop growth

Plant growth was assessed by two metrics: plant morphology and crop biomass. The Pelargonium plants growing in partial shade beneath the PV panels reached an average height of 64 cm, compared to only 42 cm in the space between rows of panels, and had substantially larger leaves which were a deeper green in color (Fig. 6). However, the biomass harvested at the end of August from the sunny area was equivalent to 51 tons per hectare, compared to 38 tons in the semi-shaded area below the upper rows of the PV array and only 23 tons beneath the lowest rows, where plants were in deep shade.

Fig. 6: Pelargonium leaves from plants growing in partial shade (left) and full sunlight (right).

4. Analysis and discussion

A key to increasing electricity output of PV panels is lowering their temperature. A widely used correlation for estimating panel temperature T_m in different environmental conditions (Faiman, 2008), which was derived from empirical data at a desert test site in Israel, is given in Eq. 1,

$$T_m = T_a + \frac{E}{U_0 + U_1 \times W} \qquad \text{(eq.1)}$$

where T_a is air temperature [ºC], E is incident solar radiation [W m^{-2}], W is wind speed (m s^{-1}] and U_0 and U_1 are empirical constants equal to 6.85 and 25, respectively.

The Faiman correlation is very simple, and despite limited inputs it is quite robust. However, it does not support description of the effect of differences in ground cover that affect the absorption of radiation and wind speed adjacent to the panel. To address this limitation while retaining the simplicity of the original formulation, a small modification is proposed, based on empirical data from the present study:

$$T_m = T_a + \frac{\alpha E}{U_0 + U_1 \times W} \qquad \text{(eq.2)}$$

where α is panel absorptivity and the constants U_0 and U_1 are equal to 6.85 and 18, respectively. α is 0.91 for a panel above a planted surface, and 0.95 for a panel above a light-coloured desert soil, to account for greater reflection due to the higher surface albedo and the increase in the incident flux on the lower face. Correlations between measured and modelled panel temperature for the daylight hours (6:00-18:00) on a representative summer day showed excellent agreement for both types of surface cover (y=0.9929x, R^2=0.9976, RMSE=2.35K for the control plot; y=1.0036x, R^2=0.9977, RMSE=2.22K for the Pelargonium plot).

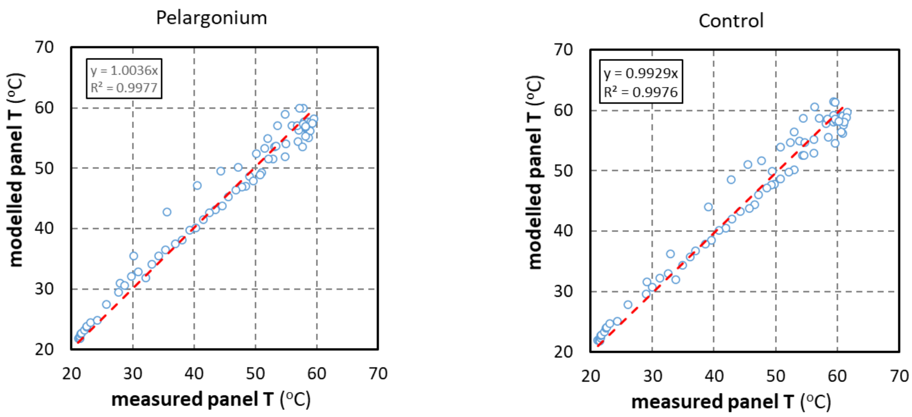

Fig. 7: Correlation between measured panel temperature in the Pelargonium test plot and temperature modelled using the revised Faiman model (left) and the control plot (right). Data for June 27, 2020.

Although not recorded quantitatively, visual inspection also showed that vegetation reduced exposure to airborne dust. This effect will be monitored accurately in future experiments.

5. Conclusions

The pilot study demonstrated that existing solar farms may be modified to allow dual use of the land to grow crops. In an installation with mono-facial panels designed *a priori* to optimize solar PV output, the presence of vegetation resulted in a modest increase of electricity output. The overall LER for the test plots was 1.67, but the economics of dual-use farms depends on the value of the crops grown and the cost of production, especially irrigation. Research is required to establish the most suitable crops for such installations and to optimize irrigation.

6. Acknowledgments

The experiment was made possible thanks to funding by the Israel Electric Corporation and the cooperation of EDF-Renewables.

7. References

Broadbent, A., Krayenhoff, E.S., Georgescu, M. 2019. The observed effects of utility-scale photovoltaics on near-surface air temperature and energy balance. J. Appl. Met. Clim. 58, 989-1006.

Dinesh, H., Pearce J. 2016. The potential of agrivoltaic systems. Renew. Sust. Energ. Rev. 54, 299-308.

Dupraz, C., Marrou H., Talbot, G., Dufour, L., Nogier, A., Ferard, Y. 2011. Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. Renew. Energ. 36, 2725-2732.

Faiman D. 2008. Assessing the outdoor operating temperature of photovoltaic modules. Prog. Photovoltaics, 16, 307–315.

Ogaili, H., Sailor D. 2016. Measuring the effect of vegetated roofs on the performance of photovoltaic panels in a combined system. J. Sol. Energy Eng. 138(6), 061009 (8p).

Sun, X., Khan, M., Deline, C., Alam, M. 2018. Optimization and performance of bifacial solar modules: A global perspective. Appl. Energ. 212, 1601-1610.