RESEARCH ARTICLE | DECEMBER 06 2022

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AIP Conf. Proc. 2635, 070001 (2022)
https://doi.org/10.1063/5.0105646

Improvement of Electrical Efficiency in a PV Solar Farm Utilizing Agriculture

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Abstract. The effect of vegetation on solar PV panel efficiency was tested in a commercial solar farm in the Negev Desert of Israel. Panel temperature of mono-facial modules in two test sites of 0.22 hectares each with different plant treatments was up to 3.5°C lower at midday compared to the panel temperature in an adjacent reference plot with bare loess soil. The temperature difference was not uniform, being greatest for the upper panels in a ground-mounted array (average reduction 2.2°C), and lowest for panels closest to the ground (1.0°C reduction). The temperature reduction is attributed primarily to smaller fluxes of solar radiation reflected from the plants, which have a lower albedo than the bare soil, and to less infrared radiation emitted from the plants, which are cooler. A small reduction in air temperature due to evapotranspiration also contributed to this outcome. Electricity production measured in the test plots was approximately 1% higher over the summer test period. The Land Equivalent Ratio (LER) of the test plots was 1.67, reflecting the combined contribution of the increased electricity production, the value of the crops, and the reduction in site maintenance costs.

INTRODUCTION

Agrivoltaic systems promise greater benefits from a limited site area [3], reflected in a Land Equivalent Ratio > 1, through dual use of the same plot for electricity production and agriculture. Simulations show that there are trade-offs between higher density of solar panels and greater crop production in mono-facial panels [2] as well as in bi-facial ones [8]. Solar farms are known to generate a localized daytime heat island [1], 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 [7].

The objectives of the present study were to deploy a pilot study in an operational commercial solar PV farm to establish the magnitude of the electricity output premium from the presence of vegetation; 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.

The study was conducted as a response to a Call for Proposals by the Israel Electric Corporation which sought to conduct research to develop Israel's sustainable energy infrastructure. As a small, rapidly developing country, it is considered imperative to maximize land-use and to develop the country's local energy sources. Current energy production goals are set to produce 30% of Israel's energy demand from renewable sources by 2030, most of which

AgriVoltaics2021 Conference
AIP Conf. Proc. 2635, 070001-1–070001-7; https://doi.org/10.1063/5.0105646
Published by AIP Publishing. 978-0-7354-4276-4/$30.00

will be solar (Decision 465 of the Parliament). This is a significant increase from the current 3.7% electricity produced from renewable sources in 2019 [6].

METHODOLOGY

The experiment was conducted in an existing solar PV facility in the Negev Desert (31.01N, 34.76E). At the site, rows of mono-facial PV panels are ground-mounted on south-facing frames supporting 6 panels each at a fixed tilt angle of approximately 30 degrees.

The site has a desert climate that is characterized by hot, sunny summers with a mean daily maximum temperature (July) of about 34ºC and mild winters with mean daily maximum (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.

Three test plots (45x50 meters each) were chosen within the PV facility (FIGURE 1): one control plot with standard PV facility maintenance (minimizing plant growth by mechanical means and chemical spaying), and two test plots with vegetation planted under the panels and between rows: Lemon geranium (*Pelargonium graveolens*) in one plot, to represent a commercial crop, and Australian Viola (*Dichondra repens* and *Viola hederacea*) in the other, planted as a groundcover that required less intensive care.

Vegetation was planted in April (after the seasonal rains but before the most extreme heat of the season). Site preparation included plowing, fertilization, and installation of drip irrigation – all standard for crops in this region. 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. Full ground cover was achieved within two months (FIGURE 2).

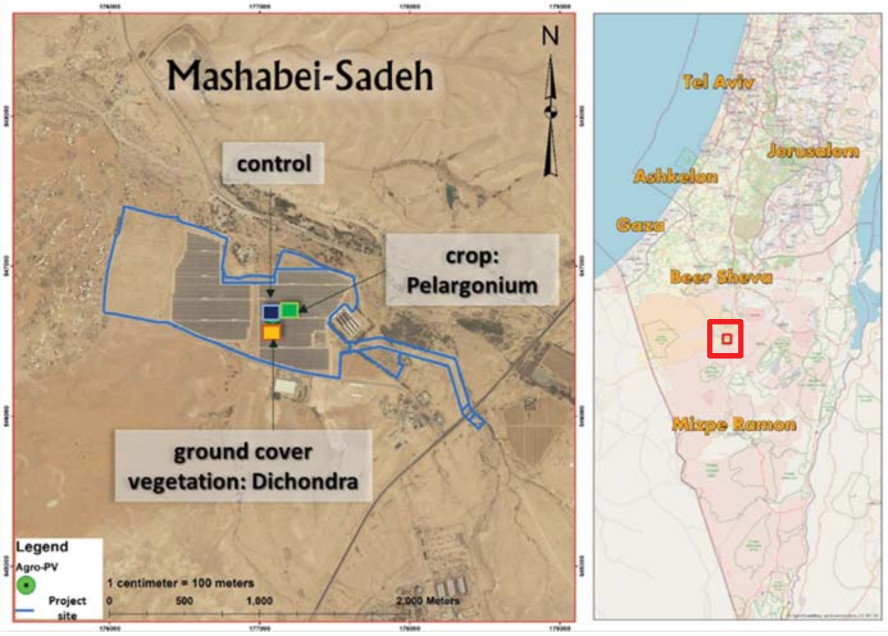


FIGURE 1. Three experimental plots, each 0.22 hectare in area: one control plot, one agricultural plot (Pelargonium), and one non-intensive groundcover (Dichondra).

FIGURE 2. Contrast between the untreated soil surface (foreground) and the planted test plot.

Measurements were carried out continuously throughout the summer and autumn of 2020 and the winter of 2021. The monitoring infrastructure was installed to measure micro-meteorological variables at three levels: for the entire research site (air temperature, humidity, wind speed and direction, and solar radiation), below the panels (air temperature, humidity and net all-wave radiation), and at the panels (temperature, at several locations in each array). At each of the three plots electric power, voltage and current were recorded for 10-panel strings near the centre of each plot, 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, measured at 1-second intervals and recorded on a Campbell CR1000 every minute, were later averaged for processing at 10-minute intervals. TABLE 1 below summarizes the instrumentation deployed during the study.

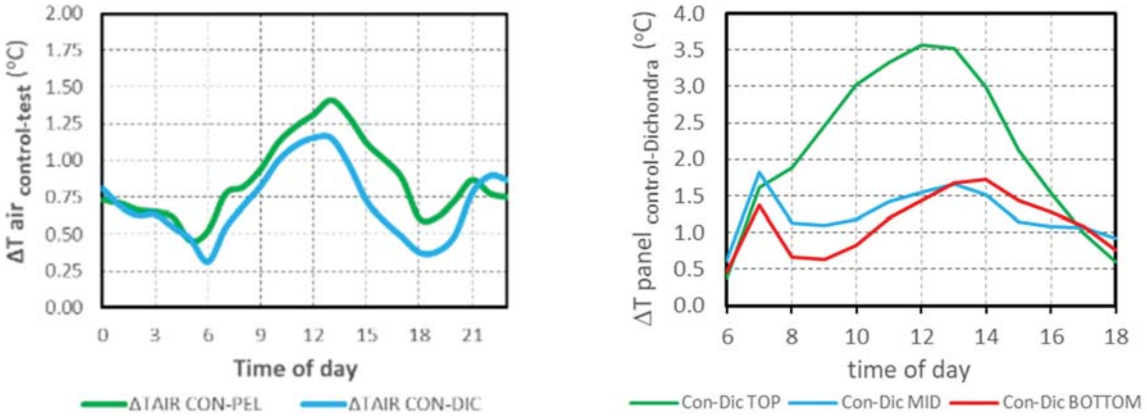
TABLE 1. Measurement instruments and locations

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	site
Kipp & Zonen CMP3	global solar radiation	site

RESULTS

Microclimate and Panel Temperature

Compared to the control plot, both air temperature (FIGURE 3a) and PV panel temperature (FIGURE 3b) in the test plots were significantly lower during daytime, but nearly the same at night. The difference was substantially greater in the top row of panels than in the lower rows: the lower face of these panels was exposed to less reflected solar radiation 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. The surface below the panels in the lower part of each row was in deep shade and had a similar radiant balance in all test plots, irrespective of the ground cover.



(a) (b)

FIGURE 3. (a) Difference in **air** temperature between control plot and test plot. (b) Difference in **panel** temperature between control plot and test plots. In both figures, larger values indicate panels in test plots were cooler. Data for August 2020.

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) (see FIGURE 4). The measured improvement is consistent with output corrected for panel temperature using the manufacturer's temperature coefficient (-0.41% / ºC).

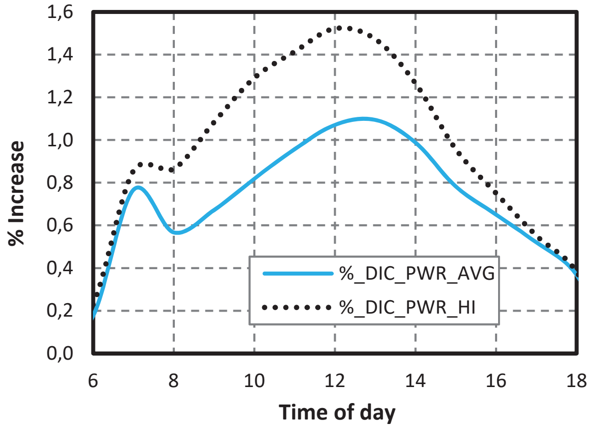


FIGURE 4. The diurnal pattern of differences in power output between the Dichondra test plot and the control (average for July 2020). Note the difference between values for the upper row of panels only (HI) and the average for the entire plot (AVG).

Shade Effect on Vegetation

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. During the initial establishment phase, plants beneath the panels required an average of 90 m^3 per day per hectare in the shade and 118 m^3 per day per hectare in the sun, a reduction of 24% (Dichondra), and of 47 m^3 per day per hectare in the shade and 68 m^3 per day per hectare in the sun, a reduction of 30% (Pelargonium). During the period June 26 – September 29, once the plants had matured, irrigation was reduced to 75 and 45 m^3 per day per hectare (Dichondra and Pelargonium, respectively), and differences in irrigation dropped to only 6.5% and 11.3%.

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 colour (FIGURE 5). 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.

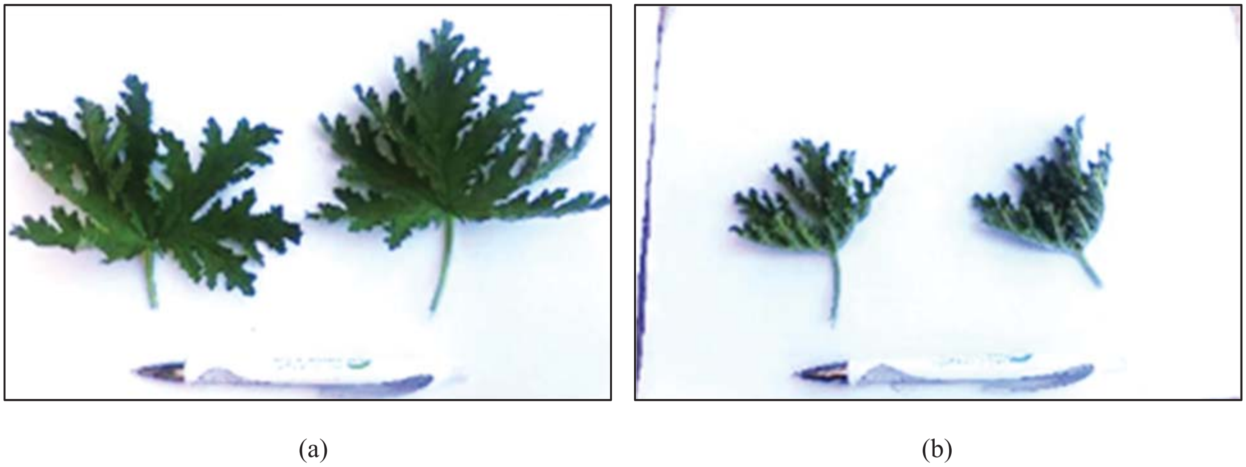


FIGURE 5. Pelargonium leaves from the shade plot (a) and from the sunny plot (b). While plants in the shade were taller and had larger leaves, total biomass was greater in the sun.

Faiman Model for PV Panel Temperature: Confirmation and Adjustment

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 [4], which was derived from empirical data at a desert test site in Israel, is given in Eq. 1,

$$T_m = T_a + \frac{E}{U_0 + U_1 \times W} \tag{1}$$

where T_a is air temperature [°C], 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:

$$T_m = T_a + \frac{aE}{U_0 + U_1 \times W} \tag{2}$$

where α is panel absorptivity and the revised constants U_0 and U_1 are equal to 6.85 and 18, respectively. The value of 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 a representative day showed excellent agreement for both types of surface cover ($y=0.9929x$, $R^2=0.9976$ for the control plot; $y=1.0036x$, $R^2=0.9977$ for the vegetated plot, FIGURE 6).

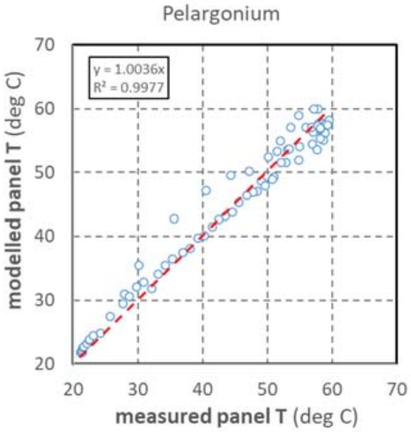


FIGURE 6. Correlation between measured panel temperature in the Pelargonium test plot and temperature modelled using the revised Faiman model. Data for August 3, 2020.

Land Equivalent Value (LER)

The land equivalent ratio (LER) was calculated to account for the added benefit of the crops in the test plot. Costs included agricultural equipment (irrigation, tools, machinery), water, fertilizer, seedlings, manpower. Benefits accrued from a modest increase in electricity production, the added value of the agricultural product, minimized need of pesticide and plant removal, and upgraded drainage infrastructure (by stabilizing the soils via plant roots). The primary benefit was attributed to the agricultural crop, which due to the lower output from the shaded areas was comparable to about 2/3 of agricultural produce of a fully exposed plot. The resulting LER of the test plots was 1.67.

DISCUSSION AND CONCLUSIONS

The introduction of plants below and between mono-facial PV panels in the two test plots yielded an average increase in electricity production of 1.2% over the summer, compared with an untreated control plot. This is consistent with the lower panel temperature measured in the test plots. The calculated LER for the test plots was 1.67.

Based on our findings, we recommend planting agricultural vegetation between the rows of panels as well as under the highest panels due to their ability to cool these panels as well as the relative ease of harvesting crops in these areas. Under the lowest panels, we recommend planting a non-intensive groundcover to stabilize soils and to reduce erosion, thus minimizing long-term damages to panel infrastructure during extreme rain-events, and to stifle undesirable weed growth.

Challenges were experienced in retrofitting an existing solar farm to include agricultural produce due to limitations in harvesting capacity based on the size of machinery required. Furthermore, the relatively low seating of the panels (0.7 m above the ground at the lowest point) limits the types of crops that may be grown in similar sites due to concerns of shading the panels.

Much of the improvement in power output in our study is attributed to the reduction in longwave radiation received at the back side of the panels, which led to lower temperature. Developments in bi-facial solar photovoltaics (e.g. Guerrero-Lemus, 2016) may offset this benefit. However, the interaction between solar electricity production and crop cultivation is complex, and is affected by the deployment of the panels. For example, a study of various heights of bi-facial modules in India indicated a higher crop yield for panels placed at a higher pitch, but a lower energy yield (Vijayan, et al. 2020). Still, the LER of such plots increased to 1.54 compared to an optimally tilted PV farm, suggesting significant potential for mixed-land use utilizing bi-facial panels.

In continuation of this study, future research will investigate variations of solar panels and their placement (single-axis tracking coupled with N-S arrangement of rows, mono-facial vs. bi-facial, and varying panel heights above the ground), examination of types of plants with different evapotranspiration regimes, and exploration of the ecological potential of preserving wildlife corridors in sensitive areas by planting local flora instead of agricultural crops.

ACKNOWLEDGMENTS

The research was funded by the Israel Electric Corporation. We are grateful to the site operators, EDF Renewables, for their support and collaboration in this project.

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