Regace: a multilateral strategy for integrating solar energy production and crop growth in greenhouse agrivoltaics

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1 INTRODUCTION

REGACE is a Horizon Europe project focused on the development of **agrivoltaics in greenhouse settings**.

It involves **six pilot greenhouses** located across Europe: **two in Germany** (Watzkendorf and Berlin), **one in Vienna**, Austria, **one in Pontinia**, Italy, **one in Volos**, Greece, and **one in Kfar Qara**, Israel.

This work uses the Pontinia greenhouse (*Figure 1*), located within the *Fattoria Solidale del Circeo* (FSC) as a reference.

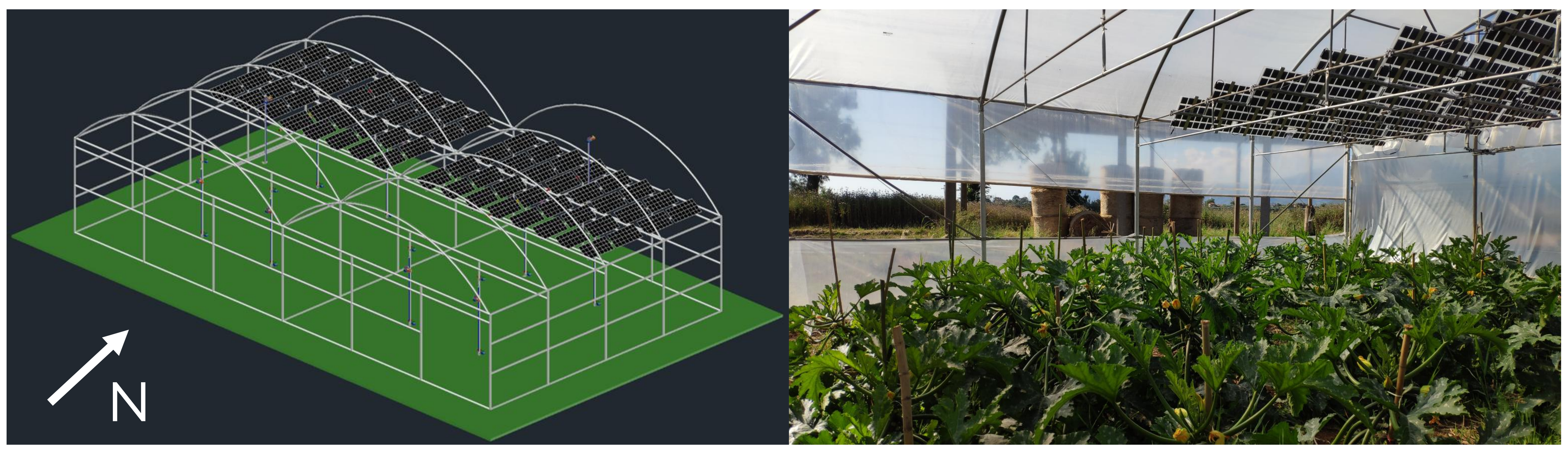

Figure 1 – CAD representation and view from inside of the FSC greenhouse.

Each greenhouse is equipped with custom-made bifacial photovoltaic (**BFPV**) panels with power ratings ranging from 55 to 125 W (75 W for FSC). The panels feature **spaced-out cells**, to allow sunlight to reach the crops below, and **single-axis tracking**. In FSC, the modules are installed in one of the two sections of the greenhouse, leaving the other as a reference open section. The greenhouse also includes **microclimate monitoring** and an **automated irrigation** system. Furthermore, **crop monitoring** methods are in place to assess the growth and quality of the plants and fruits.

2 MICROCLIMATE MONITORING

To enable comprehensive environmental monitoring, the greenhouse was equipped with sensors placed at three vertical levels (Figure 2):

- **Ground level**: Sensors for soil temperature and moisture, air temperature (T), relative humidity (RH), and CO_2 concentration.
- **Adjustable level** (0.1 to 2 meters): Sensors for T, RH, photosynthetically active radiation (PAR), and illuminance (LUX).
- **Top level** (3.2 meters): Sensors for T and RH.

Additional sensors monitor the performance of the BFPV system: **2 pyranometers** on the front side of the panels for **POA irradiance**, **2 pyranometers** on the rear side for **reflected irradiance**, **2 inclinometers** to measure **panel tilt angle, 4 temperature sensors** to monitor the rear **surface temperature of the modules, 4 LUX sensors** (2 below the panels and 2 outside), to compare **light levels**.

Two additional measurement points were set-up above the panels, one in the BFPV-covered section and one in the open section. These include T, RH, CO_2, LUX, and PYR.

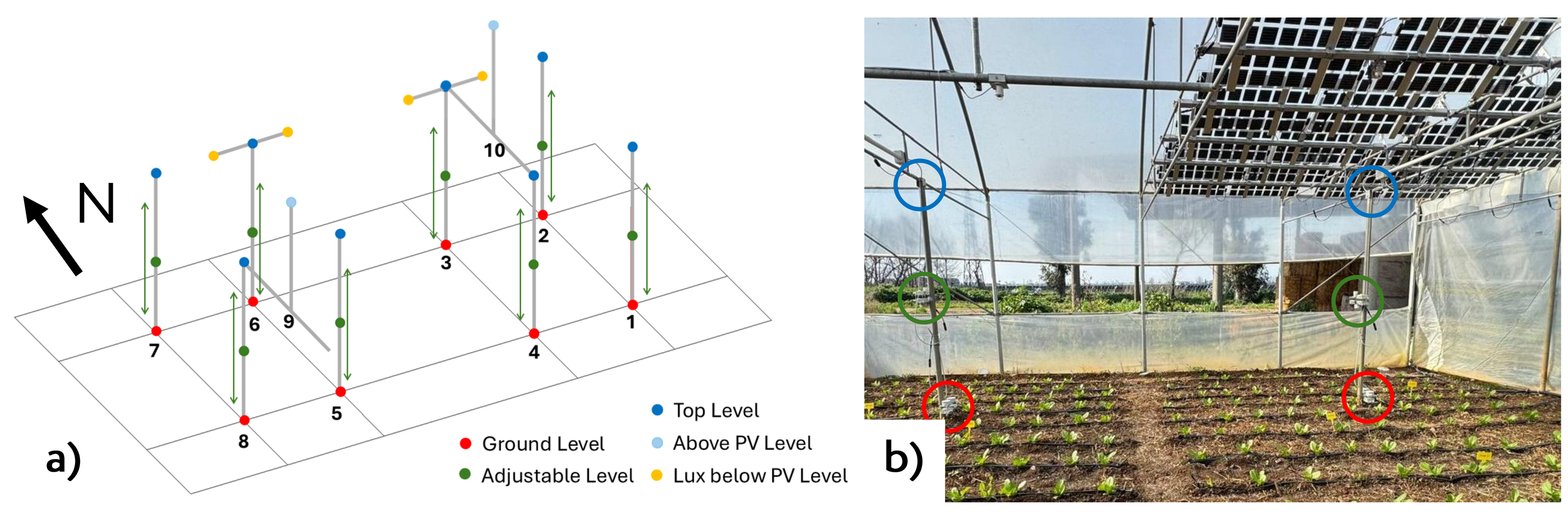

Figure 2 – Measurement points in the greenhouse (a), view of the installation (b).

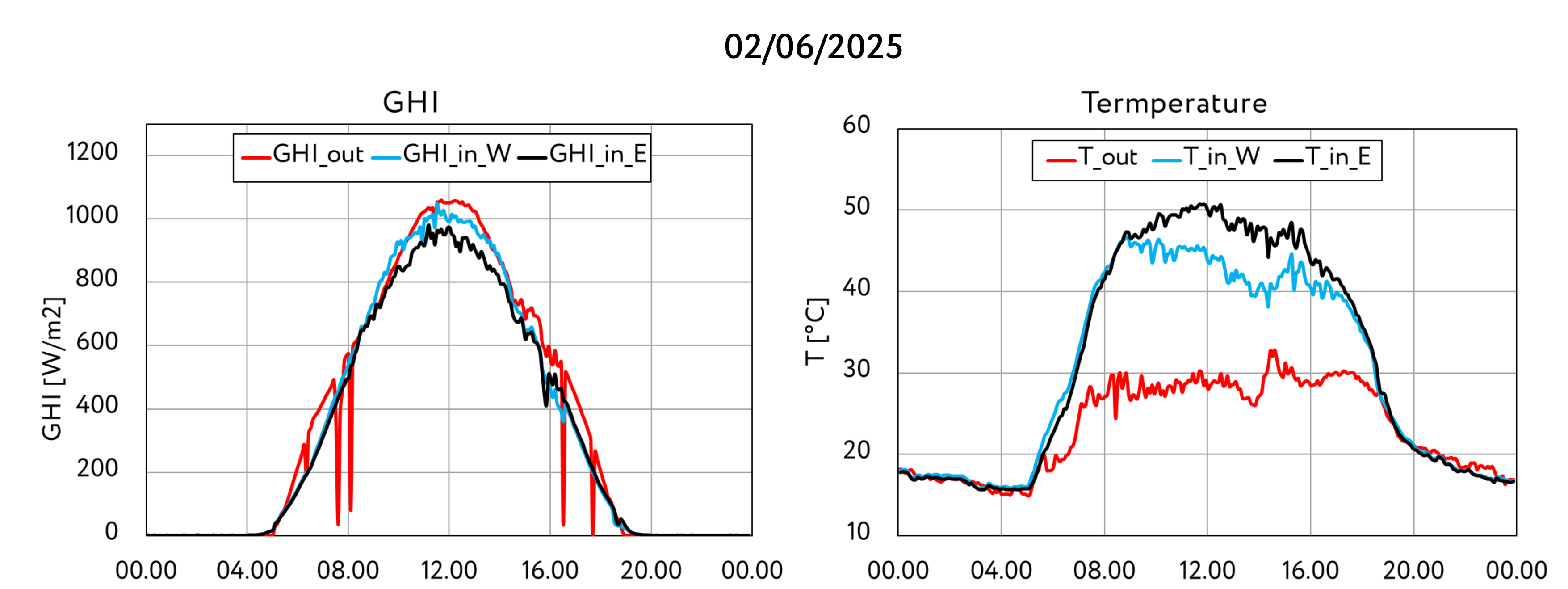

Figure 3 – Comparison between irradiance (left) and temperature (right) measured outside the greenhouse and inside above the PV.

GHI does not change significantly between outside the greenhouse and just underneath its cover. On the other hand, air temperature inside appears to raise more than outside throughout the day (*Figure 3*).

3 BIFACIAL PV PRODUCTION

64 modules rated at 75 W are installed inside the FSC greenhouse (*Figure 4*), **totaling 4.8 kWp**.

Samples of the modules underwent a **preliminary characterization** at EsterLab, at the University of Rome Tor Vergata, consisting in verification of the electrical parameters, the temperature coefficients and measurement of the rear-irradiance-driven power gain (BiFi). Furthermore, the samples are currently under **long-term performance and degradation testing** in both bifacial and monofacial configurations (*Figure 5*).

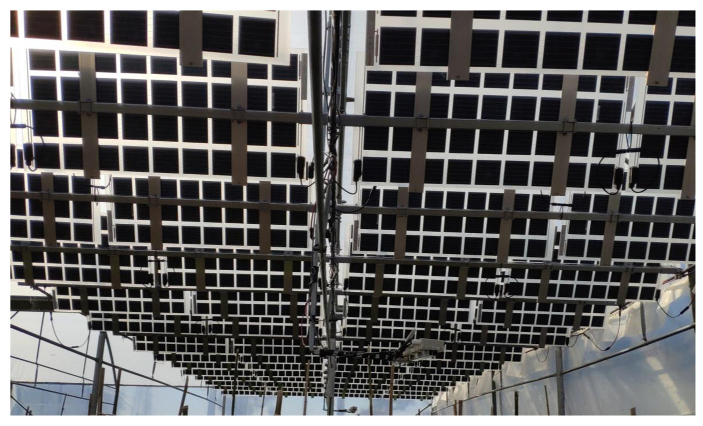

Figure 4 – BFPV array installed inside the FSC greenhouse.

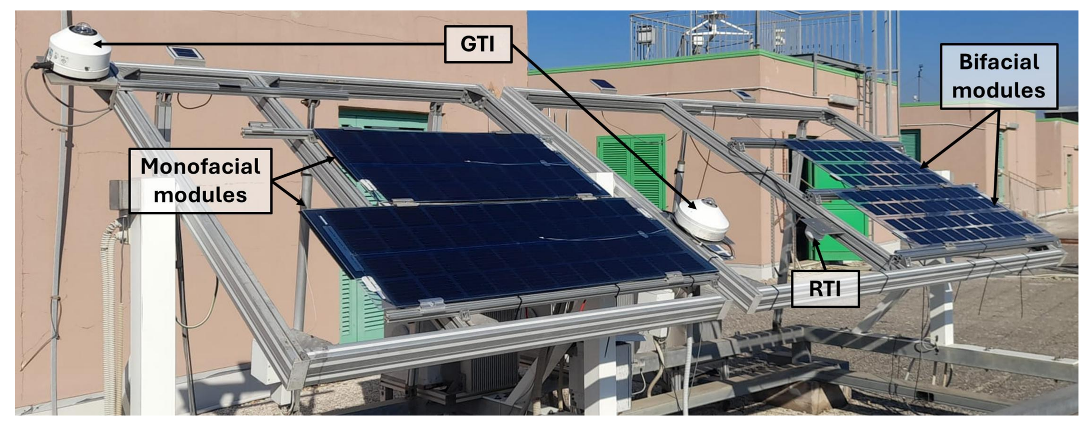

Figure 5 – Long-term performance and degradation testing currently in progress at EsterLab.

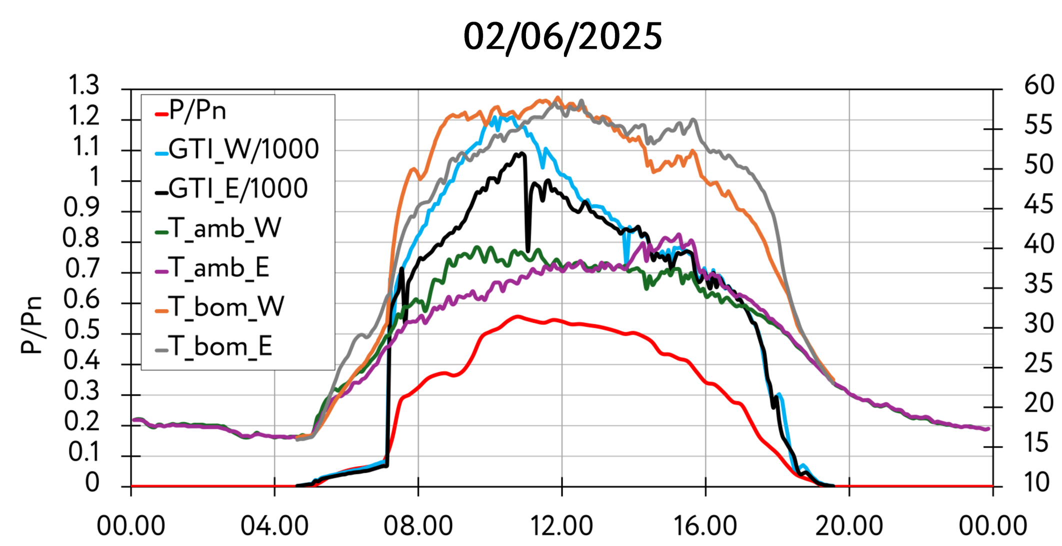

Figure 6 – PV performance and temperatures for a sunny day.

The plant has shown a PV power generation up to approximately **2.7 kW** on a fully sunny day. The difference with its peak power of 4.8 kW (**P/P_n = 0.56** at most) is likely due to the modules being installed **inside the greenhouse**, where irradiance and microclimatic conditions are far from ideal (*Figure 6*). Although the greenhouse cover is transparent, it causes sunlight diffusion due to both its **filtering** properties and **soiling**.

The **total PV production** from the start of 2025 to the end of August was **3.33 MWh**.

The amount of energy produced **monthly** is shown in *Figure 7* and ranges between **83.73 kWh in January** and **622.73 kWh in June**.

In terms of **daily** production, on a fully sunny day it can exceed 20 kWh. For reference, 02/06/2025 saw an energy production of **22.26 kWh**.

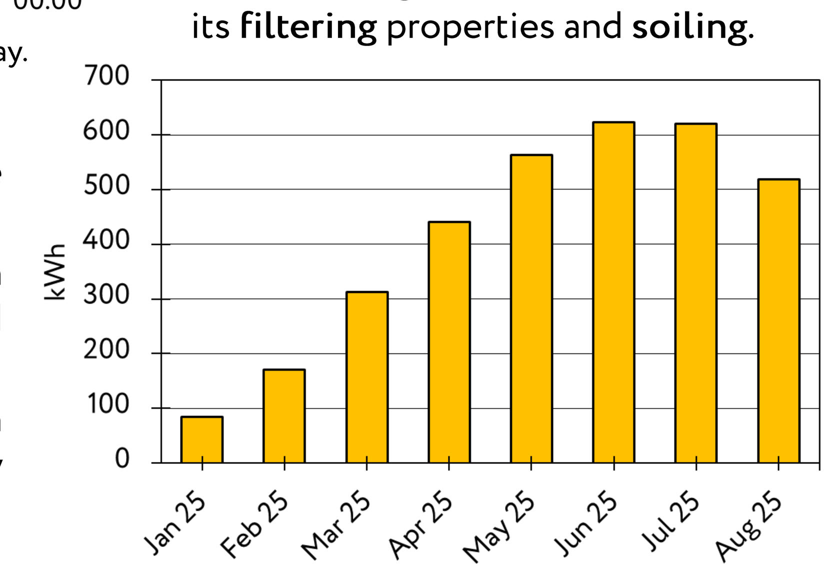

Figure 7 – Monthly energy production from PV.

4 CROP YIELD

Crop growth is evaluated by **comparing the yield** of plants grown under the BFPV system to those in the reference section, based on their **weight at harvest**.

The first planting took place on February 19th, 2025, and included **lettuce** and **zucchini**. The greenhouse was divided into four sections, as shown in *Figure 8*: two under the BFPV panels (PVW and PVE) and two in the reference area (REFW and REFE).

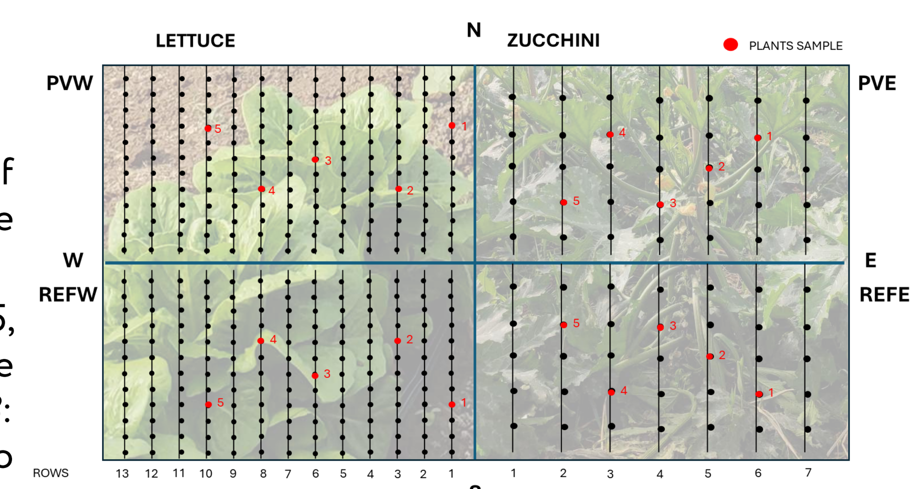

Figure 8 – Layout and sample plants for the first plantation.

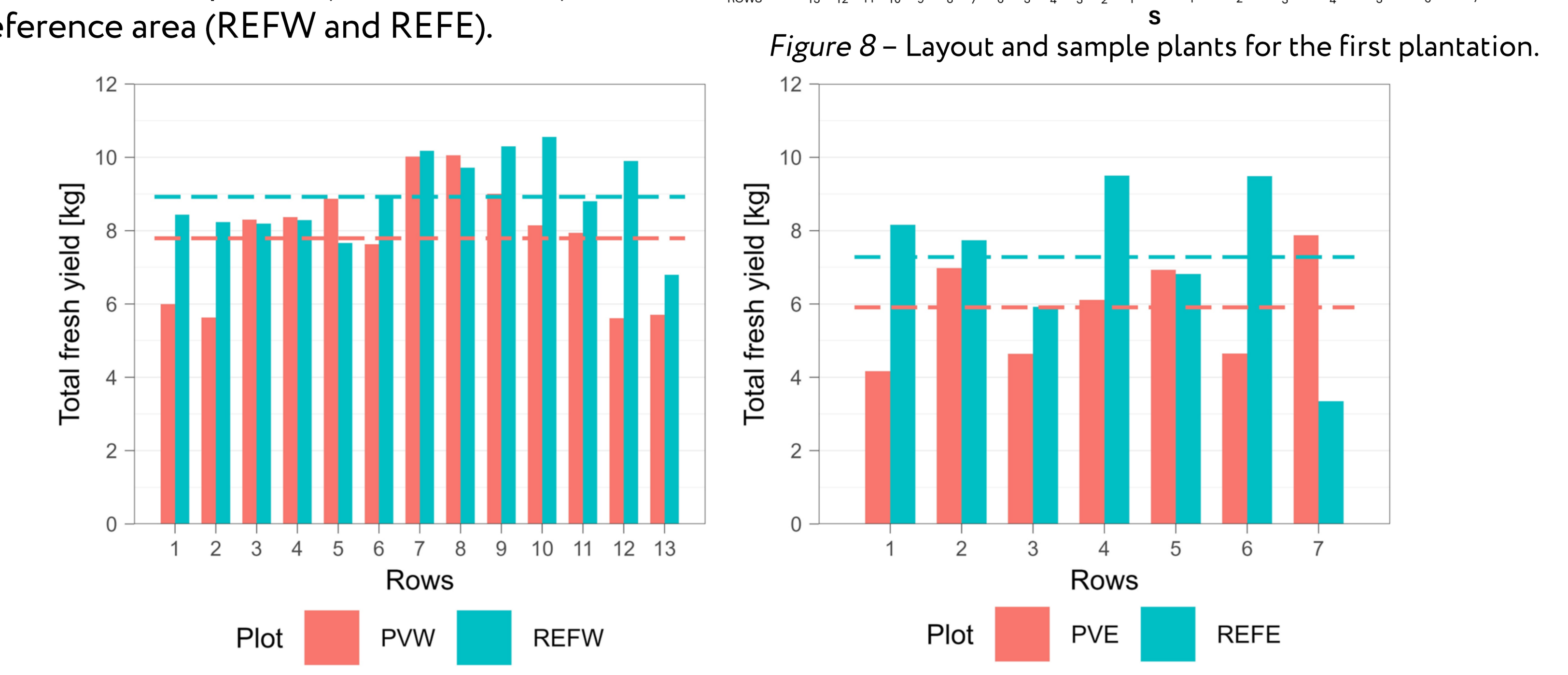

Figure 9 – Overview of the total fresh yield for lettuce (left) and zucchini (right).

Table 1 – Fresh yield of the first plantation

	Lettuce		Zucchini	
	Total yield	Avg per row	Total yield	Avg per row
PV	101.3 kg	7.8 kg	41.4 kg	5.9 kg
REF	116.0 kg	8.9 kg	51.0 kg	7.3 kg

Overall, the presence of PV modules appears to **reduce** crop yield (*Figure 9* & *Table 1*). However, the current tracking algorithm is designed to **optimize energy production**, not considering plant growth. Updating it to **account for plant needs** could improve crop yield.

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