Simulating the Microclimate of a Pilot Greenhouse for the EU Project REGACE on Innovative Agri-Voltaic Technology

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Abstract

Agri-Photovoltaics (Agri-PV) integrated in greenhouses optimize land use by combining solar energy production with crop cultivation, promoting sustainable agriculture. The REGACE project, funded by Horizon Europe, aims to develop innovative technology for PV in greenhouses to ensure uninterrupted food production. This paper introduces the initial steps of REGACE's vision by creating a dynamic model using Dynamic Building Simulation (DBS) software to understand the relationship between plant growth, energy use, and microclimate conditions in a pilot greenhouse at the University of Thessaly, Greece. The study uses the Penman-Monteith evapotranspiration model to simulate the greenhouse's thermal dynamics, identifying discrepancies between model predictions and actual temperature and humidity levels. The paper discusses these issues, attributing them to model simplifications and the need for more precise data on shading curtains and cooling systems.

1. Introduction

In the face of escalating global challenges such as climate change, resource depletion, and increasing population demand, there is an urgent need to develop innovative and sustainable solutions in agriculture. One promising avenue is Agri-Photovoltaics (Agri-PV) which has emerged as a viable approach to optimize land use by combining solar energy harvesting with agricultural activities (Dinesh & Pearce, 2016; Schweiger & Pataczek, 2023). Greenhouses (GHs) provides a controlled environment for optimizing crop growth, extending growing seasons, and protecting plants from adverse weather conditions. The integration of photovoltaic (PV) technology within greenhouse structures represents a progressive step toward achieving sustainability and energy efficiency in agricultural practices. In this framework, the project REGACE (www.regaceproject.com), funded by Horizon Europe will develop and validate a disruptive innovative technology to generate renewable electricity in greenhouses in all seasons of the year to enable the constant production of food without energy limitations.

In the last 20 years, several studies have focused on different aspects of energy optimization in greenhouse production (Rodríguez et al., 2015). Either the focus has been on the introduction of new technologies, e.g., infrastructure (glass and screen types), light-emitting diodes, or other types of equipment. Various projects have focused on the development of various IT and decision support systems for improved climate control that balances optimal photosynthesis and plant growth (or transpiration) with energy consumption and cost (Zhang et al., 2020).

However, there is a lack of correlation between morphological plant development, optimization of energy consumption, and production. In greenhouses, energy optimization, product flow, and artificial climate are currently operated as three separate systems. In practice, these systems are undoubtedly interconnected in greenhouse production. The REGACE approach aims to create a Digital Twin (DT) ecosystem, REGACE DT that integrates crop production, PV production and microclimate model-

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ling with the final objective of integrating these aspects using Artificial Intelligence techniques.

The main goal of the work presented here is to build a dynamic model of the greenhouse using an advanced software for Dynamic Building Simulation (DBS) taking into account the plant interaction with the environment. DBS is a powerful means of estimating trends in indoor environmental variables and energy demand as climatic conditions change and as a function of the building envelope characteristics. The greenhouse, being an enclosed space, can be assimilated to a building and as such can be simulated in dynamic conditions using the tools that are commonly used for building simulation. The thermal field inside the greenhouse, however, is also affected by a number of physical processes such as plant growth and water use that must be properly considered within the dynamic model (Baglivo et al., 2020; Ouazzani Chahidi et al., 2021).

In the current discourse of greenhouse optimization, various researchers have dedicated efforts to study structural configurations, ventilation systems, and the implications of evapotranspiration on environmental parameters such as temperature and humidity. Stanciu et al. (2016) provide insight into the thermal dynamics within a polyethylene greenhouse, analysing the effects of different orientations and ventilation regimes in Bucharest's seasonal extremes, emphasizing the role of evapotranspiration. Similarly, Abdel-Ghany and Kozai (2006) evaluate a small glass greenhouse in Tokyo, focusing on temperature and humidity fluctuations during a short summer period, highlighting evapotranspiration's significant impact.

In contrast, Mobtaker et al. (2019) prioritize the study of thermal transmittance through different glass roof shapes and orientations in Tabriz, without considering evapotranspiration or ventilation systems. Singh et al. (2018) advance this approach by modeling a large greenhouse in Punjab with a double gothic arch structure, integrating natural ventilation and a thorough analysis of evapotranspiration's comprehensive impact using Matlab-Simulink.

Fitz-Rodríguez et al. (2010) have developed a variable model applicable to various U.S. locations, considering different heights and roof shapes of greenhouses, including the effects of material selection, evapotranspiration, and integrated heating/cooling systems.

Innovation in greenhouse energy sustainability is represented by Ouazzani Chahidi et al. (2021)), who simulate a glass-covered greenhouse integrated with photovoltaic panels and a geothermal pump in Albenga, focusing on internal temperature regulation, energy efficiency, and solar energy utilization.

Baglivo et al. (2020) employ TRNSYS software for a detailed simulation of a greenhouse in Crotone, taking into account plant evapotranspiration, natural ventilation, and temperature control systems, presenting data over varying time scales. This software's versatility is further echoed in the studies of Opeyemi Ogunlowo et al. (2023) and Brækken et al. (2023), who employ TRNSYS and IDA ICE for dynamic greenhouse modelling, examining the influence of structural designs, climatic conditions, and operational systems on yearly temperature, humidity, and energy patterns.

In our approach we wanted to improve the capability of the software IDA ICE to simulate the microclimate inside a greenhouse by implementing the evapotranspiration equations directly into the energy balance of the thermal zone of the tool. In this way we have created a new custom zone that could take into account the hygrothermal interaction of the plants with the greenhouse's microclimate. The findings of our work will be used to better understand the physics behind the greenhouse system and, together with data gathered in the pilot, will contribute to the development of a reliable DT of the system.

2. Simulation and Experiment

2.1 Pilot Greenhouse Description

The approach consists in the construction of a DBS model in the IDA ICE 4.8 (Sahlin et al., 2003) environment of one of the 5 pilot greenhouses of the REGACE project. The objective is to reproduce the indoor microclimate also considering the evapotranspiration process due to the presence of crops. Evapotranspiration is a combined mechanism that comprises the loss of water from the soil both by evaporation from the soil surface and by transpiration from the leaves of the plants through their stomas.

In order to take into account this mechanism in the greenhouse simulation, the regular thermal zone model implemented in the software has been modified integrating the heat and moisture balance equations with the evapotranspiration model of Penman-Monteith (Monteith, 1965).

Fig. 1 – Aerial and front view of the pilot greenhouses from Google Maps

The simulations were performed for a six-span N-S oriented gothic arch greenhouse, located at the University of Thessaly near Volos (Latitude 39.22', Longitude 22.44, Altitude 85 m), on the coastal area of Eastern Greece. According to the Köppen-Geiger classification, the prevailing climate in this region is categorized as Csa (Hot-summer Mediterranean climate).

The side walls of the greenhouse are covered by polycarbonate sheets (thickness of 1 cm) while the roof is covered by polyethylene films (thickness of 180 μm, light transmission of 93%). Polycarbonate sheets are also used to cover the internal side walls between the six spans forming in this way six independent compartments with dimensions of 9.6 m (width) and 25 m (length) each. The greenhouse has a gutter height of 5.0 m and ridge height of 7.35 m. Each greenhouse compartment is equipped with: (a) a continuous roof vent opened whenever the greenhouse air temperature exceeded 21 °C during the day or 18 °C during the night, or whenever the greenhouse air relative humidity exceeded 95% during the night or 87% during the day (max vent opening for dehumidification of 10%) (b) a pad (15 cm thick, 9.6 m width and 2.0 m height) and fan (capacity of 35 000 m^3 h^{-1}, 1.1 kW) system operating whenever the air temperature exceeded 25 °C, (c) a pipe rail heating system (12 pipes of 5.1 cm diameter) operating to maintain a greenhouse air temperature of 18 °C during the day and 14 °C during the night (max pipe temperature set at 60 °C), (d) a thermal/shading screen with light transmission of about 50% and energy saving of 60% used during the night reducing mainly thermal radiation heat transfer, whenever the outside air temperature was 2 °C lower than the heating temperature set point or during the day whenever the outside solar radiation exceeded 750 W m^{-2}. Each greenhouse compartment is equipped with six hydroponic gutters of 20 m each located 0.5 m above the ground at a distance of 1.6 m between each other, holding 19 perlite slabs of 35 L each (average substrate water content of 25-30%) the substrates used for rooting/cultivation of the crop. A drip irrigation system was used for the crop fertigation needs with 5 drippers per slab.

External environmental data were obtained through on-site measurements (referred to year 2020). These data include parameters such as temperature, humidity, radiation, wind speed and direction, and rainfall. Internal measurements of temperature and humidity within the six zones at ground level were also recorded. Table 1 shows type of main sensors, accuracy ad scan rate.

Table 1 – Characteristics of the sensors installed outside and inside the greenhouses in Volos

Variable	Type	Accuracy	Scan rate
Temperature	PT100	0.1 °C	15 min
Relative Humidity	Capacity	±3%	15 min
Solar irradiance	Thermopile	±10 W/m^2	15 min

A critical aspect of this study involved decomposing measured global solar irradiance into the direct and diffuse components as requested by the IDA ICE local climate file ingested by the model. We used the decomposition model by Erbs implemented in PVLib (Jensen et al. 2023) collaborative platform for PV simulation to calculate direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) based on global horizontal irradiance (GHI), zenith angle, and day of the year.

2.2 IDA-ICE Modelling of the Greenhouse

The GH geometry and materials together with the evaporative cooling system have been implemented in IDA ICE 4.8 (Fig. 2) and the regular thermal zone has been replaced with a new custom zone that considers the evapotranspiration mechanism. Table 1 shows the main thermal properties of the GH cover (polycarbonate for the side walls and polyethylene for the roof).

IDA ICE provides direct and indirect evaporative cooling system in its environment. Suitable modifications have been applied to the components to fit the specifications of the real fan-pad (only direct evaporative cooling).

This component was developed to closely mimic the system's functionality. Observations from the simulation revealed that the air exiting the pad was cooler compared to the incoming air, particularly during periods of high summer temperatures.

Table 2 – Thermal properties of the GH envelope

TYPE	g	Tsol	Tvis	Uw (W/m²K)
Polycarbonate Corrugated	0.773	0.631	0.636	2.527
Polyethylene	0.830	0.771	0.884	5.299

Additionally, the trends in absolute humidity showed an increase when there was a divergence in temperatures, indicating the effective operation of the fan and pad setup.

Furthermore, in the testing greenhouse, a Natural Ventilation and Temperature Control system was implemented. Natural ventilation was facilitated by opening windows located on the roof of each zone. As a first attempt the temperature setpoint for window opening has been set at 20 °C.

In the simulation of shading, an integrated window shading approach was adopted for all the roof windows. The control of the shading curtains was based on the measurements of global radiation components, specifically DNI and DHI.

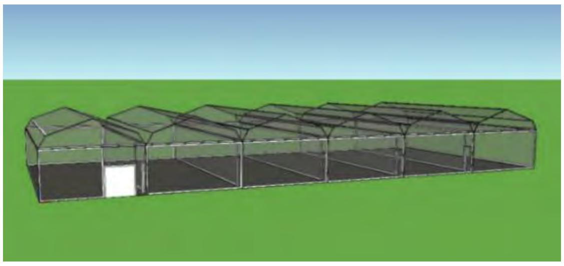

Fig. 2 – IDA ICE greenhouse representation

2.3 Evapotranspiration Due to Plants

In order to take into account the plants' evapotranspiration in the greenhouses we have developed a tool within IDA-ICE 4.8. To do that, we have designed a custom zone within the DBS software that considers the crop evapotranspiration process. This is modelled as proposed in Katsoulas and Stanghellini (2019). In particular, the Penman-Monteith equation is used to compute the evapotranspiration mass flow, $\dot{m}_{ET_0}$(in kg s^{-1}) (Monteith, 1965):

$$\dot{m}_{ET_0} = A_c \frac{\Delta R_n + \rho C_p D_i g_a}{\lambda\left[\Delta + \gamma\left(1 + \frac{g_a}{g_c}\right)\right]} \quad (1)$$

where R_n is the net radiation intercepted by the crop (Wm^{-2}), D_i is the vapor deficit of the air (kPa), g_a and g_c are the crop aerodynamic and stomatal conductances (ms^{-1}), Δ is the slope of the saturation vapor pressure-temperature relationship ($kPa\,K^{-1}$), γ is the psychrometric constant ($kPa\,K^{-1}$), A_c is the crop area (m^2), and ρ, C_p, λ are the air density (kgm^{-3}), specific heat capacity ($J\,kg^{-1}K^{-1}$) and latent heat of vaporization ($J\,Kg^{-1}$). In the zonal model, the aerodynamic and stomatal conductances (g_a, g_c) are assumed to be constant and must be provided by the user. On the other hand, Δ is computed as:

$$\Delta = \frac{4098 P_{v,sat}}{\left(T + 237.3\right)^2} \quad (2)$$

with T and $P_{v,sat}$ being the air temperature and the saturation vapor pressure (kPa).

Following Katsoulas and Stanghellini (2019), the intercepted net radiation is modelled as:

$$R_n = a\left(1 - e^{-k_s LAI}\right) R_s \tag{3}$$

where R_s is the solar radiation per unit area (Wm^{-2}), a is an empirical constant (indicating the fraction of net radiation absorbed by the crops), k_s is the extinction coefficient for shortwave radiation, and LAI is the leaf area index. In the zonal model, the coefficients a and k_s are set to 0.86 and 0.7. In addition, the solar radiation R_s is calculated as the shortwave radiation reaching the floor divided by its area (since the crops are assumed to be at the ground level). Moreover, the leaf area index is multiplied by a "schedule factor" in IDA ICE, since LAI is not constant throughout the year.

Finally, the latent power related to the evapotranspiration mass flow is calculated as in (Baglivo et al., 2020):

$$P_{ET} = \dot{m}_{ET_0}\left(\lambda + C_{p,v} T\right) \tag{4}$$

($C_{p,v}$ is the specific heat capacity of the vapor, $J\,kg^{-1}K^{-1}$).

In the zonal model, the evapotranspiration mass flow is added to the humidity balance equation:

$$\rho V \frac{dW}{dt} = F_{occ} + F_{eqp} + F_{lks} + F_{trm} + F_{lu} + \dot{m}_{ET_0} \tag{5}$$

where W is the vapor fraction, V is the zone volume, F_{occ} is the vapor flow due to occupants, F_{eqp} and F_{lu} are the vapor flows due to equipment and local units, F_{lks} and F_{trm} are the vapor flows through leaks and air terminals.

On the other hand, the latent evapotranspiration power is included as a sink term in the energy balance equation:

$$\begin{aligned} &\rho V\left(C_p + WC_{p,v}\right)\frac{dT}{dt} + \rho V \lambda \frac{dW}{dt} = \dot{Q}_{occ} + \\ &+\dot{Q}_{eqp} + \dot{Q}_{lu} + \dot{Q}_{cv,srf} + \dot{Q}_{cv,lt} + \dot{Q}_{dv} + \dot{Q}_{lks} + \\ &+\dot{Q}_{trm} + \dot{Q}_{Loss} - P_{ET} \end{aligned} \tag{6}$$

where $\dot{Q}_{occ}$, $\dot{Q}_{eqp}$ and $\dot{Q}_{lu}$ are the heat flows from occupants, equipment, and local units (both convective and latent contributions), $\dot{Q}_{cv,lt}$ and $\dot{Q}_{dv}$ are the convective heat flows due to lights and convective devices, $\dot{Q}_{lks}$ and $\dot{Q}_{trm}$ are the heat flows due to leaks and terminals, $\dot{Q}_{cv,srf}$ are the convective heat flows at the surfaces, and $\dot{Q}_{Loss}$ are the heat losses to the zone. In this study the simulation was carried out for the most critical summer season with a variable simulation time step with maximal time step of 1.5 hours and an output time step of 1 hour.

3. Results

The GH model has been built and the first tests on the model functionality have been carried out. A first preliminary validation with available micro-climate data is presented in this paper. We focused on the first greenhouse (GH1) cultivated with tomatoes.

3.1 Annual Trends of Temperature and Relative Humidity as Affected by Different Cooling Systems

This section presents the outcomes of year-long simulations conducted on the greenhouse model, focusing on GH1 zone while exploring different cooling system configurations. GH1 By sequentially implementing various cooling systems, the aim is to illustrate how temperature and relative humidity align with measured values as the complexity of the cooling systems increases. The simulation sequences are as follows:

- Initial simulation without any cooling system.
- Simulation with ventilation and window opening control set at 20 °C.
- Simulation adding shading to the ventilation setup.
- Simulation incorporating evaporative cooling alongside ventilation and shading.
- Simulation involving ventilation, shading, evaporative cooling, and integrating evapotranspiration theory with minimal crop size.
- Further simulation with ventilation, shading, evaporative cooling, and evapotranspiration theory applied with maximal crop size.

This systematic approach in introducing cooling systems in the simulations provides a deep insight into the impact of each addition on the internal greenhouse climate.

Starting from a scenario where no active or passive cooling was utilized, the initial simulations were based on the climatic data from the Volos climate file and the greenhouse's geometric model. The temperatures remained below 40 °C during the coldest months, but a notable increase was observed from late March to early October, attributed to the substantial incident radiation on the greenhouse covering, leading to an intensified greenhouse effect. Notably, temperatures exceeding 60 °C were frequent during the summer months, which severely impacts crop viability.

Although the introduction of a controlled shading system, which affects both direct and diffused radiation, results in a reduction in temperature, this change is not immediately evident from the temporal temperature trend. Furthermore, with the addition of evaporative cooling, an additional 2–5 °C reduction in temperature is achieved.

The evaporative cooling system operates continuously throughout the day. The relatively minor variations in temperature and relative humidity can be attributed to changes within the evaporative cooling system. These observations confirm the operation of the evaporative cooling system, although it should be noted that the use of default values and the incremental approach detailed in this study may limit the results to some extent.

Additionally, the subsequent implementation of evapotranspiration into the model introduces the physical presence of crops within the greenhouse system, thereby fundamentally altering the interactions among various internal thermal flows. In the absence of crops, the thermal power reaching the ground is partly exchanged through conduction to deeper layers and partly transmitted through convection towards the internal air and radiation, resulting in increased sensible heat and subsequent temperature rise. However, with the presence of crops, a portion of the available sensible heat is utilized as latent heat for water vapor formation, released into the internal air from the plants and soil. Consequently, the internal air temperature is expected to decrease while humidity rises, with variations largely dependent on the size of the plants. Initially, a model representing the plants during their early growth stage, where their impact on internal temperature and relative humidity variation is minimal, was implemented (LAI = 1).

As a final step, we added the evapotranspiration model into the simulation dynamics, focusing on how this influences internal air conditions such as temperature and relative humidity. Analysis of internal temperature trends during hot summer months (Fig. 3) revealed a decrease in temperature up to 20-35 °C accompanied by increasing humidity levels (exceeding 50%) as plants grow (LAI = 4).

These fluctuations align with the maximum and minimum evapotranspiration rates. Monthly average analyses revealed temperature decreases from non-cooled to maximum evapotranspiration cases in warmer months, while relative humidity showed an opposite trend, increasing with cooling system complexity during hot periods.

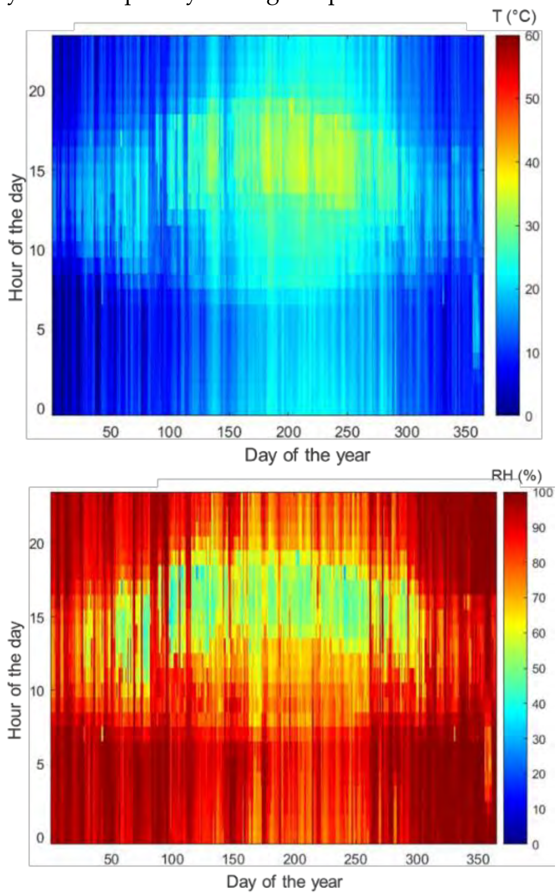

Fig. 3 – Carpet plot for yearly values of greenhouse internal temperature and relative humidity with ventilation, shading, evaporative cooling and maximum evapotranspiration (LAI = 4)

3.2 Daily Trends of Temperature and Relative Humidity Inside the Greenhouse

Results from the daily variability shows that the most substantial deviations in measured values typically occurred during the months of July and August, between 3:00 PM and 7:00 PM or 8:00 PM on the same day, with deviations averaging up to 6 °C for temperature and 20% for relative humidity. Fig. 4 shows the first ten days of June where, on the contrary, the agreement with the measured values is fairly good. In this case maximum evapotranspiration (LAI = 4) was considered. Despite the abovementioned variations, the introduction of cooling systems brought about significant daily enhancements in both thermal conditions and humidity levels compared to scenarios with no cooling in place. Among the systems analysed, natural ventilation, shading, and the natural variability in crop size through evapotranspiration emerged as key contributors to the improvement of the internal greenhouse climate.

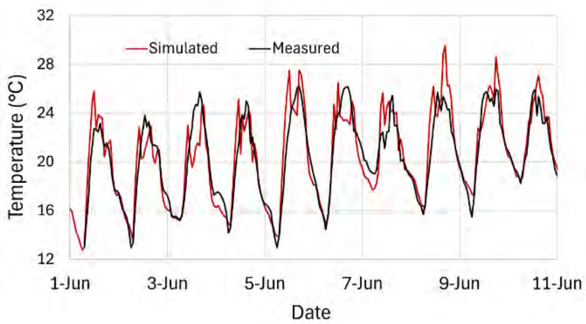

Fig. 4 – First 10 days of comparison in June between simulated internal temperature of the greenhouse with ventilation, shading, evaporative cooling and maximum evapotranspiration (LAI = 4) and the measured temperature

While natural ventilation exhibited high efficiency, it showed limitations in maintaining optimal relative humidity levels between 11:00 AM and 3:00 PM, prompting evaporative cooling and other complementary systems to become notably effective during this period, establishing an optimal synergy among multiple subsystems.

3.3 Comparison Between GH1 and the Area Without Crops

In the study, comparisons were made between greenhouse conditions featuring different cooling systems in the presence of crops (GH1) and an area without plants (Zone 1). The analysis aimed to emphasize the role of evapotranspiration in greenhouses and its impact on overall cooling effectiveness. Initially, a scenario was considered where all cooling systems were active but with minimal evapotranspiration (LAI = 1). It was observed that in winter, the temperature deviation between Zone 1 and GH1 was minor, but this difference became more pronounced in the warmer months due to increased radiation and enhanced evapotranspiration effects.

Subsequent simulations with maximum evapotranspiration (LAI = 4) revealed significant deviations in temperatures during the summer, with GH1 showing up to a 10 °C advantage due to the cooling effect of evapotranspiration.

Further comparisons of measured and simulated temperature and humidity trends for all greenhouse zones, particularly in July, highlighted the influence of shading effects on different zones relative to the sun's position.

4. Conclusion

In this study, we develop a dynamic greenhouse simulation model using the IDA ICE software, to simulate a greenhouse situated near Volos, Greece.

The findings from our simulations revealed differences between the model-predicted internal temperatures and humidity levels and those recorded in the actual greenhouse. These discrepancies became more pronounced as external temperatures increased. Despite these discrepancies, the installed cooling systems were effective in significantly mitigating these differences. For instance, in the absence of cooling measures, internal temperatures could reach up to 70 °C, which were reduced to approximately 30-35 °C with cooling interventions. Similarly, the minimum relative humidity levels were observed to increase from 10% to a range of 50-60% due to the cooling systems.

A notable challenge encountered in the model pertained to accurately simulating conditions between 3:00 and 7-8:00 pm during summer days. This issue was primarily attributed to the assumptions made regarding the physical properties and placement of shading curtains. These curtains are strategically placed between the greenhouse's upper and lower sections to optimize shading. However, for simplicity and due to the constraints of the simulation software, the model treated these shading elements as if they were fully integrated within the structure. Additionally, the lack of precise data on evaporative cooling led to the reliance on default software values, further contributing to the discrepancies observed. This study underscores the importance of accurate data and the need for refinement in simulation models to closely mimic real-world conditions.

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Acronyms

Agri-PV: Agri Photovoltaics
DBS: Dynamic Building Simulation
DHI: Diffuse Horizontal Irradiance
DNI: Direct Normal Irradiance
DT: Digital Twin
GH: Greenhouse
GHI: Global Horizontal Irradiance
LAI: Leaf Area Index
PV: Photovoltaic

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