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RESEARCH ARTICLE

REVISED Dynamic Energy Optimization and Lighting Flexibility Classification for Sustainable Vertical Farming: A Simulation-Based Multi-Scenario Analysis

[version 2; peer review: 1 approved, 2 approved with reservations]

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Abstract

Background

Vertical farming offers a promising solution to food production challenges in urban and climate-constrained regions, yet its high energy demand raises concerns about sustainability. Most existing studies assess energy demand and CO_2 emissions under static operational assumptions and lack a comprehensive framework linking seasonal renewable availability, crop cycle timing, and operational flexibility to system resilience and grid dependency.

Methods

This study evaluates the performance and carbon footprint of a fully enclosed pilot vertical farming unit in Northern Greece using TRNSYS 18 simulations and high-resolution environmental data. Forty-eight cultivation scenarios were generated by varying photoperiods, humidity levels, and HVAC setpoints to reflect seasonal Mediterranean conditions. Each scenario was analyzed for energy consumption, grid reliance, photovoltaic sufficiency, and life cycle CO_2 emissions. A dynamic crop cycle estimation model was applied to capture seasonal variability and align planting windows with solar energy availability. Performance benchmarking was implemented through a novel resilience-based multi-criteria framework combining energy-per-cycle metrics with two composite indices, the Grid Independence Index (GII) and the Seasonal Resilience Score (SRS), formulated in this study as a

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key methodological innovation. A Lighting Flexibility Classification System was further developed to determine the maximum safe reduction in artificial lighting without increasing total energy demand.

Results

The median carbon footprint across the 48 simulated scenarios was 3.67 kg CO_2 kg^{-1} of lettuce (Lactuca Sativa), with optimized configurations achieving substantially lower emissions compared to conventional greenhouse cultivation. Crop cycle duration varied between 34 and 52 days depending on photoperiod and temperature setpoints. Aligning cultivation cycles with high solar availability, combined with dynamic lighting adjustments, PV contribution to annual electricity coverage was significantly enhanced. In such configurations, lighting inputs were reduced by up to 10% without causing an increase in total system energy requirements.

Conclusions

The findings highlight the potential of simulation-based design for optimizing energy use and minimizing environmental impacts in control-environment agriculture. The proposed metrics and classification provide practical tools for improving the resilience and sustainability of vertical farming under Mediterranean conditions.

Plain Language Summary

This study looks at how vertical farming, growing crops in stacked indoor systems, can become more energy-efficient and environmentally friendly. Using a test facility in Northern Greece, simulation scenarios of 48 lettuce-plantings were produced with different lighting and climate settings. The electricity production was measured, along with calculations of the amount of energy coming from solar panels, and the amount of carbon dioxide (CO_2) released. This study also examined the best planting periods based on seasonal sunlight, tools to rate how independent the system was from the electricity grid and how flexible the lighting setup can be. Overall, the study shows that vertical farms can reduce their environmental impact with smart planning, especially when renewable energy is used.

Keywords

Vertical Farming, Lettuce Cultivation, Photovoltaic Integration, TRNSYS 18 Simulation, Energy Optimization, Carbon Footprint

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REVISED **Amendments from Version 1**

This revised version of the manuscript incorporates substantial improvements in response to reviewer feedback. The abstract and introduction have been strengthened to better highlight the research gap, novelty, and key quantitative findings. The literature review has been significantly expanded to include recent and relevant studies, and the overall structure of the manuscript has been reorganized to improve clarity and alignment with standard academic conventions.

The methodology section has been carefully revised to reduce redundancy, improve conciseness, and clearly define all analytical frameworks prior to their application. New clarifications have been added regarding system configuration, environmental control assumptions, and modeling approaches, including lighting, HVAC operation, and energy flows. All figures and tables have been enhanced for readability and repositioned appropriately, with descriptions now provided at their first point of citation.

In addition, new performance indicators and classification approaches have been more clearly introduced, and the results section has been streamlined to focus on interpretation rather than methodological description. Minor revisions have also been made throughout the manuscript to improve terminology consistency, grammar, and overall readability.

These changes collectively enhance the scientific rigor, transparency, and readability of the study while preserving its original scope and contributions.

Any further responses from the reviewers can be found at the end of the article

1. Introduction

The increasing demand for sustainable food production in densely populated urban areas has led to a growing interest in Vertical Farming (VF) systems. These closed-loop, climate-controlled environments enable year-round crop cultivation with minimal land use, reduced water consumption through hydroponic systems, and the elimination of pesticides and herbicides.[1,2] Vertical farms can yield significantly higher productivity per square meter compared to traditional open-field agriculture, making them a promising solution for future food security.[3] This productivity advantage, however, is accompanied by a well-documented trade-off in energy demand. Previous comparative studies have shown that while vertical farming systems achieve substantially higher yield per unit area than greenhouse (GH) cultivation, they also require significantly higher energy inputs, primarily due to artificial lighting and intensive climate control. Such findings underline the fundamental challenge of balancing yield intensification with energy efficiency in controlled-environment agriculture. Ch. Vatistas et al.[4] compared the lettuce cultivation between GHs and VFs and presents that VFs are more efficient than GHs in terms of yield per unit area, but require more energy to operate. Lighting alone, mostly provided by LED luminaires, accounts for 60–80% of total electricity consumption in typical VF setups.[5,6] Artificial lighting has therefore received significant attention in recent research, with studies analyzing photoperiod, Photosynthetic Photon Flux Density (PPFD), and lighting efficiency in relation to crop yield and economic performance. Such works demonstrate that lighting strategies can substantially influence productivity and operating costs. Nevertheless, lighting optimization is often evaluated independently of broader system interactions, such as HVAC demand, seasonal renewable availability, or grid dependency, limiting its applicability for holistic energy-resilient vertical farming design.[7] This heavy energy burden challenges the economic viability and environmental sustainability of VF, especially in regions with high electricity costs or low renewable energy penetration. To address these challenges, recent research efforts have focused on optimizing energy use through simulation-based design, renewable energy integration, and advanced control strategies. Energy modeling tools offer the ability to evaluate lighting regimes, thermal loads, and storage performance under different operating conditions.[8] Furthermore, integrating photovoltaic (PV) systems with battery storage and MPPT inverters has been proposed as a potential solution to enhance energy autonomy and reduce reliance on grid electricity.[9,10] Recent studies have explored near-zero and agrivoltaic configurations for controlled-environment cultivation, demonstrating the technical feasibility of coupling artificial lighting with on-site photovoltaic generation and storage systems. These works highlight the importance of system sizing and energy balance in reducing grid dependency and emissions, particularly in protected or enclosed growing systems. However, such approaches typically rely on fixed operational assumptions and do not explicitly address seasonal variability, crop cycle timing, or adaptive control strategies under fluctuating renewable availability.[11] To maximize the Vertical Farming benefits, the applicant must integrate energy-efficient systems and renewable energy sources to remain competitive against traditional agriculture powered by natural sunlight. J. Pimentel's study[8] explored different strategies for energy optimization to be integrated into urban infrastructure, utilizing a multipored model. The results showed that optimizing resource allocation and operation plans can lead to electricity cost savings of up to 40% daily and 31% annually. A case study in Malaysia assesses solar/hybrid/storage energy solutions, demonstrating that grid-connected solar PV systems can support up to 11.6% of VF energy demand while reducing dependency on utility grids and lowering CO_2 emissions. This study highlights the economic viability of renewable energy integration through Levelized Cost of Energy (LCOE) analysis. Technoeconomic assessments of indoor cultivation systems powered by renewable energy have further demonstrated the

potential for reducing operational emissions and costs under optimized configurations. While these studies provide valuable insights at the system or crop level, they generally focus on single-case analyses and do not offer transferable indicators to compare operational resilience, flexibility, or grid dependency across multiple scenarios and seasonal conditions.[12] Despite the growing body of literature on energy optimization, renewable integration, and lighting efficiency in controlled-environment agriculture, existing studies typically address these aspects in isolation. A comprehensive framework that jointly evaluates seasonal renewable availability, crop cycle timing, and operational flexibility, while providing quantitative indicators for grid dependency and operational resilience, remains lacking. This study addresses this gap by proposing a multi-scenario, simulation-based framework that integrates dynamic crop cycle scheduling, photovoltaic energy modeling, and novel performance metrics to support climate-resilient and low-carbon vertical farming operation. This study aims to assess the energy efficiency of a VF system under a Mediterranean climatic context through a scenario-based analysis. Using TRNSYS 18, 48 crop cycles are simulated to quantify lighting and HVAC energy demands. Scenarios include different photoperiod strategies and the integration of renewable energy systems. The objective is to identify optimal operational configurations that minimize energy use per unit of harvested biomass, contributing to the broader effort of improving VF sustainability. The key innovations of this work include the introduction of resilience indicators and a Lighting Flexibility Classification System for vertical farming operations.

2. Scope of the study

This study investigates the energy performance and carbon footprint of a fully controlled vertical hydroponic system designed for lettuce cultivation (Figure 1). Figure 1 shows the analyzed pilot vertical farming unit, comprising four cultivation shelves with LED lighting and integrated HVAC and nutrient delivery systems. Solar panels are mounted on top to enable partial energy autonomy. The internal layout includes environmental sensors, a nutrient reservoir (bottom left), and control electronics (left wall). The sketch was provided by the manufacturer. The analysis is based on dynamic simulations performed using TRNSYS 18, a transient system simulation tool, under a set of predefined technical configurations and operational conditions. The examined system operates in a Mediterranean area, specifically simulating climate data corresponding to Ptolemaida, Greece. Environmental control includes artificial LED lighting, HVACD systems (Heating, Ventilation, Air Conditioning, and Dehumidification), and automated irrigation via nutrient film technique (NFT) which is an active hydroponic system where plants are grown with their bare roots submerged in a shallow stream of nutrient-rich water that continuously circulates through watertight channels or gullies. This method uses a pump to deliver nutrients and water, while the shallow, oxygenated film ensures plants receive water, nutrients, and oxygen. NFT systems are water-efficient, require less space than other hydroponic methods, and are particularly suited for leafy greens and other fast-growing crops.[1] All simulations consider a fully enclosed environment, isolated from external natural light. In such fully enclosed vertical farming systems, thermal and moisture loads generated internally cannot be passively dissipated. Artificial lighting constitutes as a source of sensible heat, while crop evapotranspiration represents also a contributor to latent heat and humidity accumulation. Without active climate control, temperature and relative humidity would rapidly exceed optimal thresholds, leading to condensation, plant stress, and increased disease risk. Consequently, the operation of a heating, ventilation, air conditioning, and dehumidification (HVACD) system is a functional requirement rather than a design choice, ensuring stable microclimatic conditions suitable for lettuce cultivation The main focus of the analysis lies in the evaluation of Specific Energy Consumption (SEC), defined as electricity consumption per unit of harvested yield (kWh kg^{-1}), taking into account the impact of different operational scenarios, 48 in total, that vary in crop cycle duration, lighting profiles, and environmental parameters. Additionally, the study assesses the sufficiency of an integrated photovoltaic (PV) system with battery storage in covering the system's energy demands, both on an annual and seasonal basis. The analysis is based on the operational configuration of a pilot-scale vertical hydroponic unit, which provides the technical specifications and boundary conditions used in the simulation

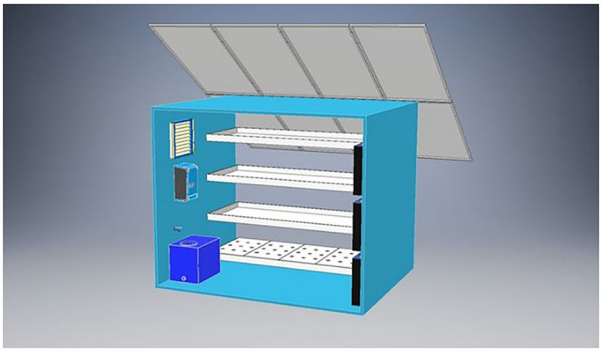

Figure 1. 3D visualization of the pilot vertical farming unit.

framework. These include the cultivation layout, system sizing, and representative energy consumption characteristics of the vertical farming installation. To place the performance of the examined system within a broader context, the results of the study are interpreted in relation to typical energy-use values reported in the literature for different agricultural production systems:

- **Open-field agriculture:** minimal energy use (≈0.35 kWh kg^{-1} lettuce), no artificial lighting, but high dependence on climatic conditions.[13]
- **Greenhouse cultivation:** moderate energy footprint (≈5.4 kWh kg^{-1}), with partial environmental control and occasional supplemental lighting.[1]
- **Conventional vertical farming (grid-powered):** high energy intensity (≈10–12.5 kWh kg^{-1}), dominated by artificial lighting and climate control requirements.[6,8]
- **Hybrid vertical farming systems with photovoltaic support:** potential for up to 50% energy self-sufficiency depending on location, crop scheduling, and storage capacity.[9–13]

This comparative perspective allows the investigated vertical farming system to be positioned within the broader landscape of controlled-environment agriculture and sustainable food production systems. The carbon footprint is calculated based on energy consumption and regional emission factors, allowing a comparative assessment with conventional farming systems. The potential benefits of dynamic lighting control strategies are also explored, as a means to reduce overall consumption without affecting yield.

3. Methodology

In order to assess the energy performance and sustainability potential of a vertical farming (VF) system, this study employs a scenario-based dynamic simulation framework that integrates environmental control parameters, crop cycle variation, and renewable energy contributions. The analysis focuses on a fully enclosed pilot-scale vertical farming unit, where environmental conditions are entirely controlled through artificial lighting and HVACD operation. The system operates with a self-consumption priority, where PV supply is directed first to loads, then to the to the battery, and finally to the grid. The methodological approach is designed to capture the complexity of VF operations by combining system-level energy modeling, crop growth cycle configurations, and photovoltaic energy supply analysis. The analysis unfolds across multiple stages. Initially, a comprehensive set of cultivation scenarios is defined, incorporating variations in cycle duration, lighting regimes, and harvest frequency. These scenarios are then used as input into a detailed simulation environment developed in TRNSYS 18. The model replicates the core subsystems of a VF unit. The system includes controlled-environment parameters, such as artificial lighting, HVACD (heating, ventilation, air conditioning, and dehumidification, in this case a heat-pump), circulation pumps and fans. The main technical components and auxiliary equipment, are summarized in Table 1. Simulations were run in TRNSYS 18 at 15 min timestep. For weather inputs Meteonorm data were used. Type 56 of TRNSYS components was used in order to simulate the ISOBOX (vertical farming unit) as a single zone building, where dehumidification modeled via latent load removal. First, the cultivation framework was defined based on lettuce (*Lactuca sativa*) as the model crop, selected due to its widespread use in controlled-environment agriculture and its well-documented sensitivity to environmental parameters such as photoperiod and temperature. Literature-derived cultivation conditions and pilot-scale operational data were used to establish representative environmental ranges and production parameters for the simulation scenarios. Next, the system setup and simulation architecture were defined in order to represent the structural and operational characteristics of the pilot vertical farming unit. This step includes the configuration of the energy system components, environmental control mechanisms, and renewable energy integration within the TRNSYS simulation environment.

Subsequently, a set of cultivation scenarios was defined to investigate how variations in environmental control parameters influence crop cycle duration and energy demand in vertical farming systems. The scenarios combine different temperature setpoints, humidity levels, and photoperiod durations representative of controlled-environment lettuce cultivation. Next, dynamic simulations were conducted to evaluate the temporal energy behavior of the vertical farming system under each defined cultivation scenario. The simulation process generated time-series outputs describing energy demand, photovoltaic production, and system operation throughout the annual cycle. A set of resilience indicators was developed to evaluate the degree of energy autonomy and seasonal robustness of the vertical farming system across the examined scenarios. These indicators enable the comparative assessment of photovoltaic contribution and grid dependency under varying operational conditions. Following this, multivariate statistical analysis was applied to classify the simulated scenarios according to their energy performance characteristics. Dimensionality reduction and clustering techniques were used to identify groups of scenarios with similar operational behavior. Finally, an adaptive lighting

Table 1. **VF Equipment Characteristics.**

Vertical Farming System Equipment													
Pumps		***Battery 2 V for our case 24 are used***		***Inverter***		***PV Characteristics***		***Heat Pump Technical Specifications***		***LED Lights***		***Fans***	
Types	**Values**	**Specification**	**Per Cell**	**Model**	**Voltronic Axpert VM III 5000–48**	**Model Name**	**LX-430M108H (N-Type Bifacial)**	**Nominal Cooling Capacity**	**3.4 kW (1.4–4.0 kW range)**	**Model**	**MARSHYDRO HYDRO**	**Model**	**PF28080R**
Flow Rate (m^3/h)	1	Nominal Voltage	2 V	Nominal Power	5000 VA/5000 W	Cell Type	Monocrystalline, Half-Cut, Bifacial	Nominal Heating Capacity	4.0 kW (1.4–5.2 kW range)	Power Consuption	300 W	Dimensions	280 × 280 × 80 mm
Head (m)	45	Capacity C120 (1,85 V/cell, 20 °C)	605 (Ah)	Output Voltage	230 VAC	Module Efficiency	22.02%	Cooling Power Input	~0.80 kW	PPFD at 30 cm	940 µmol/m^2/s	Voltage	230 V AC
Power (kW)	0.55	Capacity C120 (1,80 V/cell, 20 °C)	422 (Ah)	Output Frequency	50/60 Hz	Nominal Power (Pmax)	430 Wp	Heating Power Input	~0.99 kW	PPFD at 45 cm	780 µmol/m^2/s	Power Consumption	130 W
Current (A)	1.6	Recommended Float Voltage	2.23 V	Battery Voltage	48 VDC	Open Circuit Voltage (Voc)	38.93 V	Seasonal Efficiency (SEER/SCOP)	SEER ≈ 8.65 (Cooling), SCOP ≈ 5.10 (Heating)	Spectrum	Full Spectrum (IR + Red+Blue)	Current	0.35 A
Voltage (V)	230	Boost Charge Voltage	2.40 V	Max Charging Current	80 A	Short Circuit Current (Isc)	14.01 A	Nominal EER/COP	EER ≈ 4.23; COP ≈ 4.04	LED Type	Samsung + Epistar Diodes	Speed (RPM)	2,600 rpm
Rotational Speed (rpm)	2850	End-of-Discharge Voltage (C10 rate)	1.80 V	PV Input Voltage Range	60–145 VDC	Maximum Power Voltage (Vmp)	32.65 V	Operating Refrigerant	R-32 (environmentally efficient)	Cooling	Passive aluminum heat	Airflow	1,800–1,980 m^3/h (≈ 500–550 L/s)
Impeller Diameter (mm)	140	Internal Resistance	0.64 mΩ	Max PV Array Power	4000 W	Maximum Power Current (Imp)	13.17 A	Airflow (Cooling Mode)	~276–738 m^3/h (multiple fan speeds)	Dimming	0–100% knob dimming	Noise Level	68 dBA
Weight (kg)	8.5	Short Circuit Current (each)	3170 A	Max PV Input Current	66 A	NOCT (Nominal Operating Cell Temperature)	45 ± 2 °C	Indoor Unit Noise	Very low (bedroom/ office suitable)	Waterproof Rating	IP65	Bearing Type	Ball bearings
		Cycle Life 60% DOD (20 °C)	2000 cycles	Efficiency	93% (peak)	Temperature Coefficient (Pmax)	−0.29%/°C	Controls & Comfort Features	Inverter compressor, intelligent motion sensor, Wi-Fi control	Dimensions	600 × 300 × 70 mm		
		Self-Discharge Rate (20 °C)	~2.5% per month	Communication Interfaces	RS232, USB, Wi-Fi (optional), dry contact	Module Dimensions	1722 x 1134 x30 mm	Dimensions/ Weight (Indoor)	~778 × 299 × 272 mm; ~14.5 kg	Weight	5.2 kg		
		Recommended Temperature Range	10–30 °C					Certifications	EU Label A+++ for both heating & cooling				
		Pole Type	M10										

control strategy was introduced to evaluate the potential of demand-side flexibility in vertical farming operations. This approach examines how selective reductions in artificial lighting under low photovoltaic availability can influence system energy demand and crop cycle duration. This comparative framework allows the proposed model to be contextualized within the broader landscape of sustainable food production systems. This methodological structure ensures that the simulation captures both the technological intricacies and environmental implications of VF operation, providing a solid foundation for evaluating optimization pathways and energy-efficiency strategies. In the following section, the simulation framework is presented in more detail, including the system architecture, component modeling, and scenario parameterization.

3.1 Cultivation procedure

The selected crop for this analysis is lettuce (*Lactuca sativa*), a leafy green that has become a benchmark species in vertical farming studies due to its high responsiveness to microclimate conditions. It is a diploid species (2n = 18), photoperiod and temperature-sensitive, is widespread used in controlled-environment agriculture, and generally classified as a long-day plant. The experimental plant material, lettuce cultivar ROMANIA (Lactuca sativa), was obtained from Gemma Grow, a certified supplier of planting material within the Greek agricultural sector. The delivery was accompanied by a plant passport with the following specifications: A: Lactuca sativa, B: 02319004, C: 32658CINDEX, D: GR, Lot number: C.

Vertical farming system is realized in ISOBOX with galvanized metal construction of 4 cm sandwich panel insulation, Aluminium door with LED lights of 1 kW. The dimensions of the ISOBOX are 240 cm × 300 cm × 250 cm (L×W×H) (Figure 2) as shown in the sketch which will be introduced in TRNSYS 18 software. Figure 2 presents a simplified 3D illustration represents the pilot unit used in the vertical farming study. Dimensions are provided in meters. The orange structure represents the cultivation chamber, while the purple volumes indicate adjacent buildings or shading elements. This schematic was created using SketchUp. The cultivation area comprised four vertical hydroponic layers capable of housing up to 200 lettuce heads per cycle, producing approximately 40–45 kg of lettuce per cultivation cycle. The harvested mass per cultivation cycle was assumed constant across all scenarios, based on pilot-scale operation data and literature-reported fresh weight at physiological maturity for lettuce cultivation. To become more sustainable, VFs must reduce energy demand and develop energy-efficient systems. Table 2 presents a comparative overview of reported cultivation parameters for lettuce (Lactuca sativa) from the literature. These include photoperiod (in hours), humidity (%), temperature (°C), and total cultivation duration (in days), along with the cultivation system employed. This dataset serves as a benchmark for evaluating the environmental conditions used in this study's simulation scenarios. Where applicable, CO_2 photosynthetic photon flux density (PPFD) values are reported. Optimal growth has been observed under light intensities with photoperiods of 16 hours. As shown in Table 2, photoperiods between 12 and 20 h are commonly reported in vertical farming and indoor controlled-environment studies for lettuce cultivation. Based on the lighting conditions described in these studies, the applied 16 h photoperiod corresponds to photosynthetic photon flux density (PPFD) levels typically ranging between 200 and 350 $\mu mol \cdot m^{-2} \cdot s^{-1}$, resulting in daily light integral (DLI) values of approximately 11–20 $mol \cdot m^{-2} \cdot day^{-1}$. This range is widely reported as suitable for lettuce growth under controlled-environment agriculture, supporting efficient biomass accumulation without inducing photoinhibition. Photoperiods exceeding

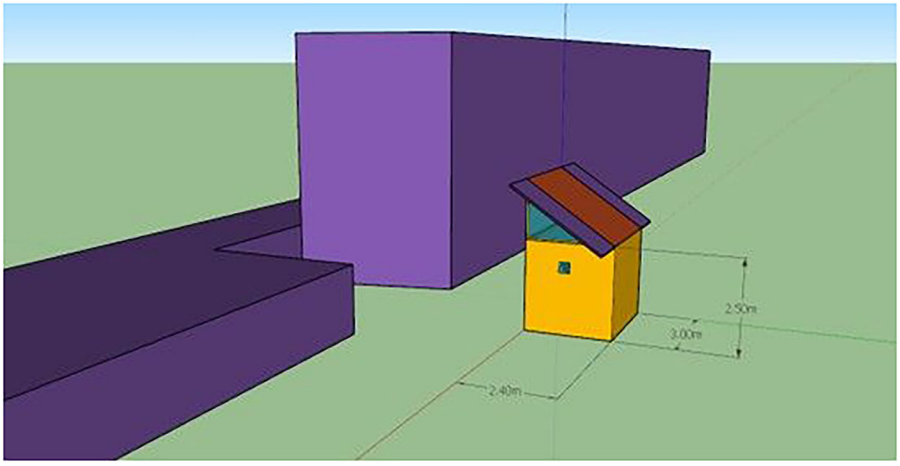

Figure 2. ISOBOX single-zone building exterior. Simplified 3D model of the pilot cultivation chamber (2.40 × 3.00 × 2.50 m) used in TRNSYS simulations, with adjacent blocks representing shading elements.

Table 2. Literature review on lettuce cultivation conditions.

Photoperiod	Humidity	Temperature	Duration	Cultivation type	CO_2	Ref.
16	60–80%	16–18 °C	transplanted 20 + 35 days	Vertical Farming (VF)		14
16–20	65%	22 °C	14 + 30	Indoor Controlled Environment Agriculture (CEA)		15
24		23,9	30 days	Hydroponic Yield		16
10	60–80	20,5–24	15 + 30	Tempered glass covered greenhouse (GH)		17
12–16	60–65%	21.7	29 + 48	Conventional soilbased cultivation (CN) system	11.97 m^{-2} s^{-1}	18
12–16	60–65%	22.3	22 + 40.5	Deep water culture (DWC) system	12.95 m^{-2} s^{-1}	
12–16	60–65%	23.3	22 + 47	Nutrient film technique (NFT) system	10.18 m^{-2} s^{-1}	
12		20–22	35			19
18		22–28		Directly from the Seeds in Three Separate NTF Hydroponic Systems		20
16–20	70–80	22–26/15–20	30 days			21
	65–75	24/18	19 days after transplantation			22
	60	11	34			23
	60	20	15			
	60	32	14			
	60–70	17–22	57 days			24

18 hours promote bolting, particularly under elevated temperatures. Optimal growth is achieved at 18–22 °C during the light period and 10–15 °C during the dark period. Exposure to temperatures above 28 °C, especially combined with long photoperiods, increases the likelihood of early flowering and bitterness due to increased sesquiterpene lactones. Lighting is user-defined electric load with scenario-specific photoperiod (10–16 h). Heat pump/HVAC: performance maps applied with heating/cooling setpoints 12–18 °C/20–28 °C. Deviations from these conditions can result in delayed growth, poor head formation, or early bolting.[13] No single temperature regime was defined as a fixed baseline for the 48 operational scenarios. Instead, temperature setpoints were selected to span a literature-informed control envelope for lettuce cultivation under vertical farming conditions. Heating setpoints ranged from 12 to 18 °C, while cooling thresholds ranged from 20 to 28 °C, covering both optimal and marginally suboptimal conditions reported in controlled-environment agriculture studies. This approach allowed the systematic evaluation of energy demand, grid dependency, and crop cycle behavior across realistic operational conditions, rather than benchmarking against a single assumed "optimal" temperature. The selected temperature ranges are consistent with reported optimal growth conditions for lettuce (18–24 °C during the light period) and documented tolerance limits below 14 °C and above 28 °C, beyond which growth delays or physiological stress may occur.

Each cultivation cycle begins with seed germination in nursery trays containing cocopeat or perlite for 10 days under constant 50–70% relative humidity. Dehumidification was modeled implicitly as part of the HVAC operation through latent load removal in the single-zone Type 56 model. A relative humidity control band was defined for the indoor air, and when the upper humidity threshold was exceeded, dehumidification was activated via the cooling system by removing latent heat from the air. No standalone dehumidifier component was modeled; instead, moisture control was achieved through the HVAC system's cooling and ventilation operation, consistent with typical enclosed vertical farming installations. The associated energy demand of dehumidification was therefore accounted for within the cooling load of the heat pump, as calculated by TRNSYS based on zone moisture balance and latent loads. Relative humidity control was implemented using a common upper-limit control strategy applied consistently across all scenarios. An indoor relative humidity control band of approximately 50–70% was defined, and dehumidification was activated when the upper threshold was exceeded. Scenario-specific humidity conditions were allowed to evolve within this control

framework, enabling the assessment of their impacts on energy demand and crop cycle duration. Following transplanting, crops were grown under controlled conditions in a vertical rack system with recirculating hydroponics. Two substrates were evaluated: (i) mineral wool (rockwool), and (ii) expanded clay pellets. The rockwool system exhibited superior water-holding capacity and capillarity, supporting maximum yields of 5.26 kg/m^2 per cycle, compared to 3.82 kg/m^2 in the clay pellet system. The nutrient solution was based on a modified Hoagland formulation with continuous pH and EC monitoring. The pH was maintained at 5.5–6.0, while electrical conductivity ranged from 1.8 to 2.2 mS/cm, adjusted according to growth stage. The solution was recirculated at a flow rate of 1.2 − 1.5 L/min, ensuring full saturation and oxygenation. Water temperature was kept at 18–20 °C to minimize thermal shock and root stress. No artificial CO_2 enrichment was applied. Instead, air exchange was passively regulated to maintain ambient CO_2 concentrations (~400–450 ppm). Relative humidity was controlled at 50–70%, with automated misting used during the seedling stage. The vertical racks consisted of 4 cultivation tiers spaced 50 cm apart, with LED luminaires delivering variable PPFD levels (200–350 µmol/m^2/s) depending on the lighting scenario. Harvest took place at physiological maturity, corresponding to an average fresh weight of approximately 120–150 g per head, based on pilot-scale operational data from the studied vertical farming unit and consistent with values commonly reported in the literature (Table 2) for lettuce cultivated under controlled-environment conditions, depending on lighting strategy and environmental control conditions.

3.2 System setup

Figure 3 illustrates the structure of the simulation model, including components for weather input, lighting, HVAC, photovoltaic power generation, battery storage, and crop energy demand. The model enables the calculation of total energy consumption and PV contribution under different cultivation scenarios. This flowchart was exported from TRNSYS 18 Studio. Within this environment, a full-year simulation was developed to capture quarter hourly fluctuations in energy demand and supply for the pilot VF system. Simulations replicate the structural and operational characteristics of the existing hydroponic vertical farm system operating under the COALITION project. The HVACD system was modeled, along with climate database taking from METEONORM for the case of Northern Greece.

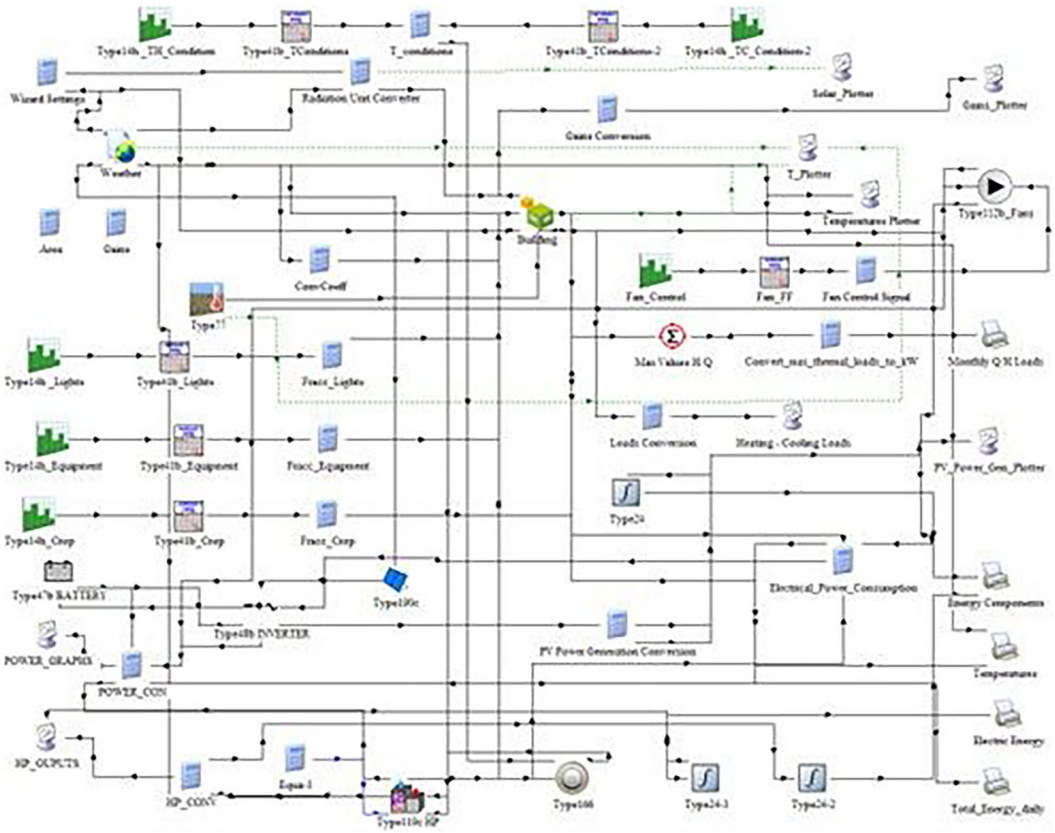

Figure 3. Configuration of the TRNSYS 18 model for the vertical farming unit. The schematic integrates weather inputs, lighting, HVAC, PV generation, battery storage.

All the energy components of the VF system, including lighting, heating, cooling, and dehumidification, were simulated in an integrated manner within TRNSYS 18 to assess seasonal performance. PV generation was also modeled matching the actual specifications of the installed VF system, which is integrated with inverter and batteries. The battery storage system was modeled as a 24 V battery bank, composed of series-connected 2 V cells. The 2 V value reported in Table 1 refers to the nominal voltage of individual battery cells, while the overall system operates at 24 V, consistent with typical small-scale PV installations. The energy systems were incorporated to simulate load shifting and storage of surplus PV energy production, while the MPPT inverter regulates energy from PV to storage, to consumption for the components that require energy and to the energy grid for surplus energy production. Thermal energy gains of the VF system derive from crop cultivation of lettuce in terms of latent heat throughout their evapotranspiration. Latent heat gains resulting from plant evapotranspiration were estimated by quantifying the mass of water transpired by lettuce plants and applying the latent heat of vaporization. Latent heat gains within the vertical farming unit were primarily attributed to plant transpiration during lettuce cultivation. Transpiration rates were quantified based on literature values reported for controlled-environment lettuce production, ranging between 0.2 and 0.5 L per plant per day, depending on lighting intensity, temperature, and relative humidity. The total latent heat load was calculated by converting the transpired water mass into latent heat using the latent heat of vaporization of water (h_fg ≈ 2450 kJ/kg at 20 °C). This load was implemented in TRNSYS Type 56 as an internal latent gain, allowing the HVACD system to dynamically respond through dehumidification. The NFT system was not treated as an independent humidity source, as moisture release originates from plant transpiration rather than the nutrient solution itself. The process accounts for the energy required to convert liquid water released by the plants into water vapor, which contributes to the internal latent load of the space. The total latent heat gain (Q_{latent}) was calculated using the equation:

$$Q_{latent} = m \cdot h_{fg} \tag{1}$$

where m is the mass flow rate of transpired water (kg/day or kg/h), and h_{fg} is the latent heat of vaporization of water which is approximately 2,450 kJ/kg, at 20 °C under standard atmospheric pressure. Transpiration rate was derived from literature values specific to indoor vertical farming conditions for lettuce, taking into account light intensity, temperature, and relative humidity. A value in the range of 0.2–0.5 l/day per plant was used to reflect typical water loss through transpiration under controlled environment agriculture (CEA).[25,26] Sensible heat gains concern the electrical equipment of the VF system including fans, pumps, and the lighting system. All electrical power consumed by the LED lighting system was assumed to be fully converted into internal sensible heat and explicitly included in the zone energy balance of the single-zone Type 56 model, directly affecting the heating and cooling loads calculated by the HVAC system. The model incorporates dynamic interactions between internal loads (e.g. lighting, plant evapotranspiration, electrical equipment, etc.), external climate conditions, and HVACD system. Indoor setpoints for each scenario (heating, cooling, humidity, lighting duration) were introduced as control parameters, dynamically adjusted to reflect realistic operating logic for lettuce cultivation. Humidification and dehumidification were accounted for by balancing vapor pressures based on the indoor air setpoints and crop transpiration rates.

3.3 Scenario definition and crop cycles

To explore the dynamic behavior of energy consumption in vertical farming, a number of cultivation scenarios were conducted, each representing a specific combination of environmental conditions relevant to lettuce growth in terms of temperature set-point and humidity levels. The indoor environmental conditions were tailored for safe lettuce growth. Lighting requirements were defined across various scenarios, reflecting the photoperiods. Thus, three key environmental parameters were systematically varied across scenarios (Table 3):

- Relative humidity, ranging from 50% to 70%,
- Photoperiod duration, from 10 to 16 hours per day, and
- Setpoint temperatures, with heating temperatures from 12 °C - 18 °C and cooling thresholds from 20 °C - 28 °C.

Each one of the scenarios represents a distinct cultivation schedule, with unique crop cycle durations and annual repetition frequencies. In order to find the required crop cycle for each scenario values were taken from literature overview as presented in Table 2 concerning the lettuce cultivation conditions as well as data taken from the operation of the installed VF system. Thus, a multiple linear regression model was developed to estimate crop cycle duration as a function of environmental control parameters. Using 48 scenario configurations, the model considered temperature differential (ΔT), photoperiod, and humidity as predictive variables.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_p x_p + \varepsilon \tag{2}$$

Table 3. Multiple Linear Regression Model.

ANOVA Table (Crop Cycle ~ ΔT + Photoperiod + Humidity)					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F-value**	**P-value**
ΔT	1	533.94	533.94	3879.33	<0.0001
Photoperiod	1	540	540	3923.33	<0.0001
Humidity	1	0	0	0	0.998
Residual	44	6.06	0.14		

Model Summary	
Statistic	**Value**
R-squared (R^2)	0.994
Adjusted R-squared	0.994
F-statistic	2601
Prob (F-statistic)	1.59E-49
Observations	48
Degrees of Freedom	44 (residual)

Coefficient Table					
Term	**Coefficient**	**Std. Error**	**t-value**	**P-value**	**Interpretation**
Intercept	57.02	0.512	111.3	<0.001	Base duration with zero inputs
ΔT	0.645	0.01	62.3	<0.001	Longer cycles with wider temperature gap
Photoperiod	–1.5	0.024	−62.6	<0.001	Shorter cycles with longer light periods
Humidity	~0.0001	0.007	≈ 0	0.998	No significant effect on crop cycle duration

Where:

- y: Dependent variable (response)
- β_0: Intercept (value of y when all $x_i = 0$)
- $\beta_1, \beta_2, \ldots \ldots, \beta_p$: Regression coefficients
- $x_1, x_2 \ldots, x_p$: Independent variables (predictors)
- ε: Error term (residual)

Thus, the final fitted model used in all scenario computations was:

$$\text{CropCycle}\,(\text{days}) = 57.02 + 0.645 \cdot \Delta\text{T} - 1.50 \cdot \text{Photoperiod} + 0.0001 \cdot \text{Humidity} \quad (3)$$

with $R^2 = 0.994$, Adj-$R^2 = 0.994$, and the humidity term non-significant ($p \approx 0.998$).

It should be noted that Equation (3) is valid only within the controlled lighting conditions examined in this study, corresponding to photosynthetic photon flux density (PPFD) levels in the range of 200–350 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Extrapolation beyond this PPFD range is outside the scope of the present analysis.

The following Figure (Figure 4) presents a 3D surface plot visualizing the Final Crop Cycle Estimation Model, which shows that crop cycles decrease significantly with increasing photoperiods, while they increase modestly with higher ΔT (temperature difference). This confirms the dominant role of light duration in accelerating growth, with ΔT offering a secondary, supportive influence.

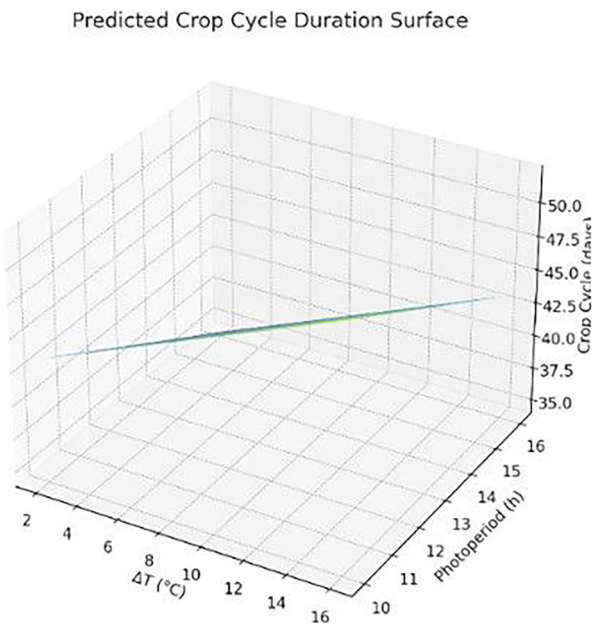

Figure 4. Predicted crop cycle duration as a function of photoperiod and temperature difference (ΔT). Longer light periods reduce cycle length, while wider ΔT slightly increases it.

The 3D surface represents the modeled crop cycle duration (in days) as a function of photoperiod (h/day) and temperature difference (ΔT in °C). Results were derived using a multiple linear regression model applied to simulation outputs. Graph produced using AI-assisted plotting tools.

Thus, the scenarios simulate a distinct cultivation strategy that leads to a different crop cycle duration, varying between 34 and 52 days as presented in Table 4. Shorter cycles (34–37 days) were observed in configurations combining high photoperiods (16 h), moderate humidity (50–60%), and elevated temperatures (18 °C heating, 20 °C cooling). Conversely, longer cycles (49–52 days) appeared in scenarios with lower light exposure (10 h), minimal heating (12 °C), and broader temperature differentials between day and night. This structured variation allows for assessing how tighter climate control and intensified lighting can accelerate plant development, thereby increasing the number of annual cycles, while also evaluating the trade-offs in energy demand and sustainability. TRNSYS 18 simulations produced energy demand profiles for lighting and HVACD, which were subsequently compared against simulated PV energy availability on a quarter hourly basis. The aim was to quantify PV sufficiency across all scenarios and to assess energy demands.

Table 4. Environmental parameter combinations across the 48 lettuce cultivation scenarios, with estimated crop cycle durations.

Scenario	Heating Temperature (°C)	Cooling Temperature (°C)	Humidity (%)	Photoperiod (hours)	Estimated Crop Cycle (days)
s1	12	28	50	10	52
s2	12	28	50	12	49
s3	12	28	50	14	46
s4	12	28	50	16	43
s5	12	28	60	10	52
s6	12	28	60	12	49
s7	12	28	60	14	46

Table 4. *Continued*

Scenario	Heating Temperature (°C)	Cooling Temperature (°C)	Humidity (%)	Photoperiod (hours)	Estimated Crop Cycle (days)
s8	12	28	60	16	43
s9	12	28	70	10	52
s10	12	28	70	12	49
s11	12	28	70	14	46
s12	12	28	70	16	43
s13	14	24	50	10	49
s14	14	24	50	12	46
s15	14	24	50	14	43
s16	14	24	50	16	40
s17	14	24	60	10	49
s18	14	24	60	12	46
s19	14	24	60	14	43
s20	14	24	60	16	40
s21	14	24	70	10	49
s22	14	24	70	12	46
s23	14	24	70	14	43
s24	14	24	70	16	40
s25	16	22	50	10	46
s26	16	22	50	12	43
s27	16	22	50	14	40
s28	16	22	50	16	37
s29	16	22	60	10	46
s30	16	22	60	12	43
s31	16	22	60	14	40
s32	16	22	60	16	37
s33	16	22	70	10	46
s34	16	22	70	12	43
s35	16	22	70	14	40
s36	16	22	70	16	37
s37	18	20	50	10	43
s38	18	20	50	12	40
s39	18	20	50	14	37
s40	18	20	50	16	34
s41	18	20	60	10	43
s42	18	20	60	12	40
s43	18	20	60	14	37
s44	18	20	60	16	34
s45	18	20	70	10	43
s46	18	20	70	12	40
s47	18	20	70	14	37
s48	18	20	70	16	34

3.4 Simulation process

Quarter-hourly dynamic simulations were performed in TRNSYS 18 over a full annual period (8,760 h) for each of the 48 scenarios. The model generated time-series outputs including: (i) indoor operative and ambient temperatures, (ii) total and beam solar radiation, (iii) HVAC heating and cooling loads, (iv) photovoltaic (PV) generation, (v) grid import/export flows, (vi) battery charge–discharge cycles, and (vii) auxiliary electrical consumption. These outputs formed the basis for the subsequent energy balance, resilience, and carbon footprint analyses, the results of which are presented and discussed in Section 4.

3.5 Resilience Indicators and Scenario Classification

To assess the adaptability of each vertical farming scenario under fluctuating solar and thermal conditions, two composite performance indicators were formulated based on the annual and monthly energy balance outputs derived from the TRNSYS simulations. These indices were specifically developed within the framework of the present study to quantify grid independence and seasonal robustness of photovoltaic (PV) integration. The first indicator, the Grid Independence Index (GII), captures the proportion of total annual energy demand that is covered by on-site PV generation and battery storage, thus reflecting the overall degree of energy autonomy. The second indicator, the Seasonal Resilience Score (SRS), was introduced to quantify intra-annual variability in PV contribution and expresses the system's ability to maintain PV sufficiency during its lowest-performing month relative to its average monthly PV coverage. These proposed indicators do not correspond to previously published formulations but are derived directly from fundamental energy balance relationships and were designed to enable comparative scenario-level resilience analysis within this work. Together, GII and SRS allow simultaneous evaluation of both structural energy autonomy and temporal robustness under seasonal solar variability.

$$\mathrm{GII} = \left(1 - \frac{\text{Annual Grid Energy Use}}{\text{Total Annual Energy Demand}}\right) \times 100 \tag{4}$$

$$\mathrm{SRS} = \frac{\text{PV Coverage in Lowest Month}}{\text{Average Monthly PV Coverage}} \tag{5}$$

$$\text{PV Coverage} = \frac{\text{PV Used}}{\text{Monthly Energy Demand}} \tag{6}$$

To further assess the robustness of each scenario under energy-constrained conditions, the resilience score of all scenarios was evaluated based on two dimensions: the worst-case PV deficit across a full crop cycle and the seasonal variability in PV availability. Four descriptive energy-performance typologies were set:

- **High Demand, Optimizable:** Heavy energy use but good potential for savings via cycle shifts or dynamic scheduling.
- **High Demand, Rigid:** High loads with limited flexibility, likely candidates for backup systems or setpoint reduction.
- **Moderate, Responsive:** Mid-range energy demand with high responsiveness, efficient and adaptable setups.
- **Stable, Low-Demand:** Low energy needs and minimal gains from optimization, ideal for low-intervention farming.

The calculated indices were subsequently used to generate comparative plots and scenario classifications, which are presented and discussed in the Results section.

3.6 Multivariate Scenario Classification

Principal Component Analysis (PCA) was applied to six standardized performance indicators derived from dynamic crop-cycle simulations (maximum HVAC demand, minimum PV availability, total cycle energy, optimized energy, energy savings, crop duration). K-means clustering ($k = 4$) was subsequently applied in the reduced PCA space to identify scenario groupings. The PCA-derived clusters align with the resilience typology defined in Section 3.5.

3.7 CO_2 Emissions Estimation

For each scenario (S1–S48), monthly simulation outputs were aggregated to derive annual system energy requirements. Electricity supply was modeled as a hybrid system combining on-site PV generation and grid electricity. Grid electricity

consumption was derived directly from the quarter-hourly TRNSYS energy-flow outputs and corresponds to the fraction of electrical demand not covered by on-site photovoltaic (PV) generation and locally stored energy. A self-consumption operating scheme was assumed, whereby PV electricity was first allocated to on-site loads, and any surplus was stored in the battery or curtailed; no feed-in to the grid was considered. Battery degradation effects were not included, as the analysis focuses on annual operational energy flows and associated CO_2 emissions. An emission factor of 0.256 kg CO_2/kWh was applied to grid-supplied electricity, based on the Greek National Inventory and the country-average electricity mix.[27] A life cycle assessment (LCA) of greenhouse gas emissions (GWP) was conducted per kilogram of harvested fresh lettuce (functional unit: 1 kg; average head weight 250 g). The system boundaries include operational electricity use (LED lighting, HVACD, water pumping/recirculation, valves, and monitoring/sensor systems) and cultivation-related inputs associated with a full crop cycle (e.g., substrates such as rockwool and clay pellets, growth media, and total water consumption). The life cycle inventory was established using real-time monitoring data from the pilot unit (e.g., water use, grid electricity), complemented with literature-based assumptions (e.g., germination duration). The resulting scenario-specific electricity uses and carbon footprint values are reported and discussed in Section 4.3 (Table 5).

3.8 Dynamic Lighting Control on Energy and Crop Cycle Duration

To enhance PV self-utilization and minimize grid dependency, a dynamic lighting strategy is implemented that selectively reduces artificial lighting during low-irradiance ("cloudy") days. Cloudy days were identified by applying a threshold-based condition on daily PV generation data. Specifically, days with production values below the 10th percentile of the annual PV generation profile or more than one standard deviation below the seasonal average were

Table 5. CO_2 Emissions for each scenario based on LCA.

CO_2 Emissions for Each Scenario based on LCA					
Scenarios	**Total Electricity (kWh)**	**Total CO_2 ($kgCO_2eq$/kg lettuce)**	**Scenarios**	**Total Electricity (kWh)**	**Total CO_2 ($kgCO_2eq$/kg lettuce)**
S1	2455.3	2.3	S25	3839.2	3.5
S2	3198.1	2.9	S26	4587.9	3.6
S3	3908.7	3.5	S27	5242.2	3.7
S4	4659.2	3.7	S28	5264.5	3.7
S5	2460.8	2.3	S29	3858.3	3.5
S6	3210.9	2.9	S30	4607.8	3.7
S7	3921.5	3.6	S31	5262.3	3.7
S8	4674.4	3.7	S32	5980.3	4.2
S9	2472.0	2.3	S33	3876.8	3.5
S10	3217.3	2.9	S34	4614.0	3.7
S11	3940.4	3.6	S35	5280.3	3.7
S12	4693.6	3.7	S36	6002.2	4.2
S13	3068.3	2.8	S37	4971.5	3.9
S14	3808.0	3.5	S38	5712.7	4.0
S15	4486.4	3.6	S39	6346.8	4.4
S16	5216.8	3.7	S40	7061.0	4.4
S17	3082.7	2.8	S41	4989.3	3.9
S18	3816.3	3.5	S42	5722.6	4.0
S19	4504.1	3.6	S43	6363.5	4.5
S20	5242.2	3.7	S44	7086.3	4.5
S21	3093.6	2.8	S45	5015.2	4.0
S22	3829.3	3.5	S46	5740.7	4.0
S23	4523.1	3.6	S47	6383.9	4.5
S24	5264.5	3.7	S48	7092.5	4.5

flagged as "cloudy". This method served as a proxy for reduced solar availability in the absence of direct irradiance data. On such days, lighting energy demand was proportionally reduced by 2.5%, 5%, 7.5% and 10%, resulting trade-offs in crop cycle duration were estimated using a regression model linking photoperiod to crop growth rate. The dynamic model ensures lighting reduction is only triggered when PV generation is insufficient, thereby reducing grid load without severely compromising crop timelines. Dynamic lighting reductions were assumed to influence the rate of crop development and cultivation time, while final harvest mass per cycle was preserved by extending the growing period until physiological maturity. This adaptive strategy offers a realistic and implementable approach to load shifting in vertical farming systems, especially where PV-battery systems are deployed. To support adaptive energy and schedule optimization in vertical farming systems, this work developed a predictive model for estimating crop cycle duration as a function of key environmental control parameters as discussed in Section 3.3. This model can be subsequently used to estimate the impact of dynamic lighting reductions on crop timing under various scenarios. Using the quarter-hour PV generation profile, days with significantly lower PV output compared to the seasonal average were tagged as cloudy or low-solar days. A rolling average threshold (bottom 10–15% of daily PV generation) was applied across the year to isolate these days. Once low-PV days were identified, reducing LED lighting load by 2.5%, 5%, 7.5% and 10%, was proposed, but only on those specific days. This was applied selectively, avoiding days with sufficient PV, to minimize system grid draw. Thus, for

Cloudy Day Detection Condition

P_i : Daily PV energy production on day i

μ_P : Rolling or seasonal average PV energy production

σ_P : Standard deviation of daily PV generation

T_P : PV production threshold for cloudy days $(\text{e.g., bottom } 10-15\%)$

A day is considered "cloudy" if:

$$P_i < \mu_P - a \cdot \sigma_P \text{ or } P_i < T_P \tag{7}$$

Where:

$a \in [1,1.5]$: sensitivity coefficient

T_P : empirically set percentile cutoff (e.g., 10th percentile of annual PV data).

Dynamic Lighting Reduction Application

L : Baseline lighting energy (kWh/day)

$\delta \in \{0.025, 0.05, 0.075, 0.1\}$: lighting reduction factor

$L' = L \cdot (1-\delta)$: adjusted lighting consumption on "cloudy" day

C : Baseline crop cycle duration (days)

$$C' = C + f(\delta) : \text{adjusted cycle duration via regression model} \tag{8}$$

The extended cycle duration C' is estimated using a linear model:

$$C' = a \cdot \delta + b \tag{9}$$

Derived from the photoperiod vs. crop duration model

By implementing the aforementioned formulas and by adjusting the new photoperiods as follows:

$$\text{Photoperiod}_\delta = \text{Photoperiod}_0 \cdot (1-\delta) \tag{10}$$

A new cycle length duration is recalculated based on the regression model with the new Photoperiod$_\delta$ and for all the scenarios the energy difference between the initial values for energy consumption and the values for energy consumption after the dynamic lighting control were calculated. The new cycle length durations for each scenario are presented in Table 6.

Table 6. Lighting Control Strategies Result.

Lighting Control Strategies Results				
Scenario	**Max Safe Lighting Reduction (%)**	**Rounded Crop Cycle (days)**	**Estimated Energy Use (kWh)**	**Energy Saved (kWh)**
S1	10	54	857.8	22.0
S10	10	51	902.5	25.1
S11	10	48	929.2	31.4
S12	7.5	45	954.3	10.1
S13	10	50	915.8	9.8
S14	10	47	948.1	14.4
S15	7.5	44	942.3	5.6
S16	10	42	951.5	3.5
S17	10	50	916.3	8.8
S18	10	47	947.9	13.4
S19	7.5	44	941.3	4.7
S2	10	51	902.0	26.1
S20	10	42	951.5	3.5
S21	10	50	916.3	8.8
S22	10	47	944.9	14.1
S23	7.5	44	941.2	4.4
S24	10	42	949.4	2.3
S25	10	47	995.7	6.3
S26	7.5	44	994.6	1.2
S27	10	42	1000.9	0.2
S28	2.5	37	966.4	11.0
S29	10	47	994.7	7.4
S3	10	48	929.1	32.4
S30	7.5	44	994.3	1.2
S31	7.5	41	990.9	9.7
S32	2.5	37	965.2	11.7
S33	10	47	994.0	5.2
S34	7.5	44	991.5	0.8
S35	7.5	41	988.3	9.3
S36	2.5	37	964.5	11.5
S37	0	0	0.0	0.0
S38	0	0	0.0	0.0
S39	5	38	1058.3	0.4
S4	7.5	45	953.2	11.6
S40	0	0	0.0	0.0
S41	0	0	0.0	0.0

Table 6. *Continued*

Lighting Control Strategies Results				
Scenario	**Max Safe Lighting Reduction (%)**	**Rounded Crop Cycle (days)**	**Estimated Energy Use (kWh)**	**Energy Saved (kWh)**
S42	0	0	0.0	0.0
S43	0	0	0.0	0.0
S44	0	0	0.0	0.0
S45	0	0	0.0	0.0
S46	0	0	0.0	0.0
S47	0	0	0.0	0.0
S48	0	0	0.0	0.0
S5	10	54	857.8	22.0
S6	10	51	902.5	25.1
S7	10	48	929.7	31.4
S8	7.5	45	953.6	10.8
S9	10	54	857.9	21.0

4. Results and discussion

4.1 Annual energy demand & grid dependency per scenario

4.1.1 Representative dynamic annual profiles. To illustrate the intra-annual dynamics of the simulated system, Figure 5 presents the annual time series for a representative intensive scenario (S40). Indoor operative temperature remained within the prescribed setpoint range (18–22 °C) despite significant outdoor fluctuations, confirming effective HVAC control (Figure 5a). Seasonal variability in solar radiation (Figure 5b) translated directly into PV production patterns (Figure 5d), with marked reductions during winter months. Heating loads peaked during winter, while cooling demand increased in summer (Figure 5c), reflecting the seasonal inversion of thermal requirements. These dynamics demonstrate the strong coupling between environmental control, renewable availability, and grid reliance, providing the foundation for the comparative scenario analyses that follow.

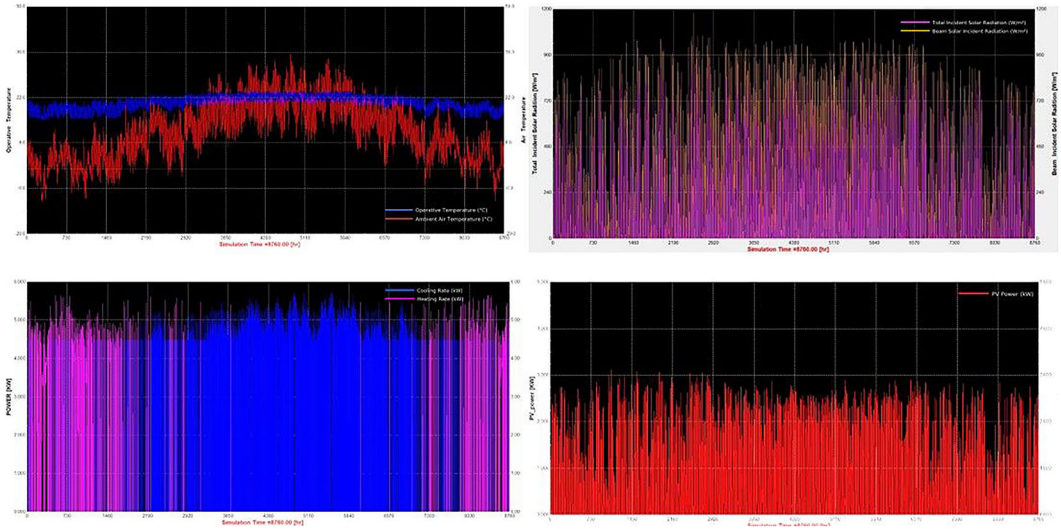

Figure 5. TRNSYS 18 Simulation Results for Specific Scenario. (a) Operative and ambient air temperature. (b) Total and beam incident solar radiation. (c) Heating and cooling loads. (d) Photovoltaic power output.

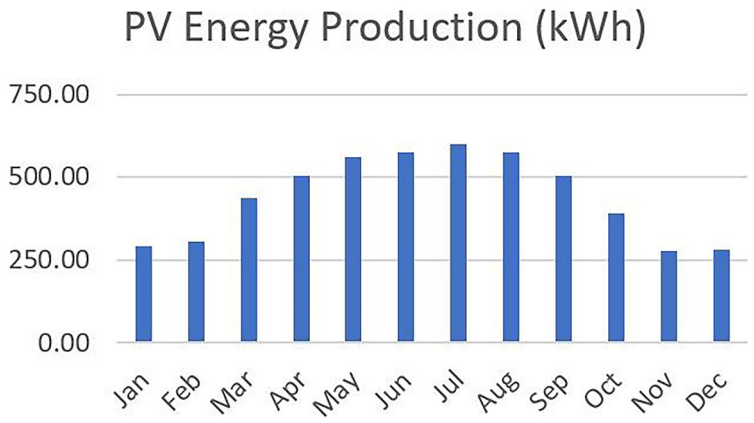

Figure 6. Monthly PV energy production profile for Northern Greece, with higher output in summer and lower in winter.

4.1.2. Annual PV energy production & energy analysis. The PV integrated into the VF unit was modeled under fixed operational parameters based on the optimal tilt angle and orientation, for the case of Northern Greece. The system's specifications remained the same across all 48 scenarios. Based on local solar irradiance data and TRNSYS 18 simulations, the annual electricity generation from the PV system was estimated at approximately 5,234 kWh, with monthly values ranging from 280 kWh in December to 600 kWh in July, following the typical seasonal pattern. This consistent energy profile served as the renewable input baseline across all scenarios. Any deviations in grid dependency, energy autonomy, or carbon footprint thus stem from the variation in environmental control settings (e.g., photoperiod, HVAC setpoints) rather than PV availability. Figure 6 illustrates the monthly distribution of PV energy production.

The total annual energy requirements of the VF system vary considerably across the different scenarios, ranging from approximately 6,100 kWh to over 10,500 kWh (Figure 7). Each stacked bar represents the total annual energy demand (gray), the portion covered by grid electricity (red), and any excess PV energy fed back into the grid (green), across 48 simulation scenarios. Diagram generated using Python-based visualization tools and refined using AI-assisted layout optimization. This variability reflects differences in environmental control strategies, such as photoperiod, HVAC setpoints and humidity levels which directly impact the system's lighting and climate energy loads. The amount of energy required from the grid also shows substantial fluctuation, spanning from almost 2,500 kWh in the most efficient scenarios (e.g., S1 and S5) to nearly 7,100 kWh in the most demanding cases. These figures underscore the importance of scenario configuration in determining energy autonomy. Scenarios with optimized settings, such as moderate temperature differentials and daylight-aligned photoperiods, demonstrate a significantly lower dependency on external energy sources. While the PV system contributes to reducing this grid reliance, the excess energy exported back to the grid remains relatively minimal in all cases, typically under 1% of total generation. For example, in scenarios like S1 and S5,

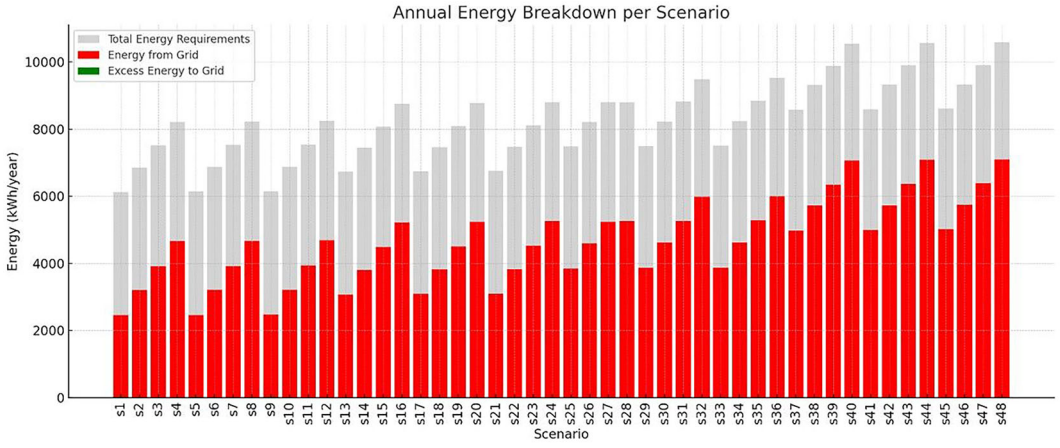

Figure 7. Breakdown of VF systems energy in annual basis.

although a small surplus of around 20 kWh is sent back to the grid, the majority of PV energy is consumed internally by the system (energy requirements and batteries). This indicates that the system operates close to a self-consumption model, with high internal utilization of PV electricity and limited overproduction. Overall, this energy breakdown confirms that while PV integration significantly offsets the total energy demand, grid dependency is still substantial in high-demand scenarios. The data also reinforces the value of seasonal crop scheduling, dynamic lighting control, and HVAC optimization to reduce total energy use and enhance self-sufficiency. In systems where excess PV is minimal, energy storage and load-shifting strategies become essential for further reducing grid reliance and improving energy resilience.

4.1.3 Analysis of monthly grid energy demand by scenario. While electricity generation from PV remains fixed across all scenarios, the monthly grid energy demand varies significantly depending on the crop cycle configuration. These differences stem from diverse environmental control strategies, including heating and cooling setpoints, lighting durations, and humidity levels, all of which affect the total energy load and its seasonal distribution. To capture this variability, Figure 8 presents a heatmap of monthly grid electricity use for each scenario. The x-axis spans the calendar months, while the y-axis lists the 48 crop cycle scenarios sorted approximately by increasing annual energy consumption. This visualization reveals several key insights. Scenarios with higher energy demand exhibit intense grid dependency during months with large temperature fluctuations such as August, December and January reflected as deeper red tones on the heatmap. In contrast, energy-efficient scenarios, such as those with moderate environmental setpoints and shorter crop durations (e.g., S1–S10), display lighter tones, indicating lower grid dependency across the year. A notable asymmetry emerges in summer, where PV production peaks but energy demand may still rise sharply due to active cooling demands. This seasonal interplay underscores the importance of crop scheduling and environmental strategy optimization, particularly in months with low solar availability. Scenarios that compress crop cycles into spring and autumn months tend to benefit more from direct PV utilization.

Heatmap showing the variation in monthly grid energy requirements (in kWh) across all 48 simulation scenarios (S1–S48). Darker shades indicate higher dependency on grid electricity. Visualization generated using Python (matplotlib/seaborn); layout enhanced using AI-assisted tools.

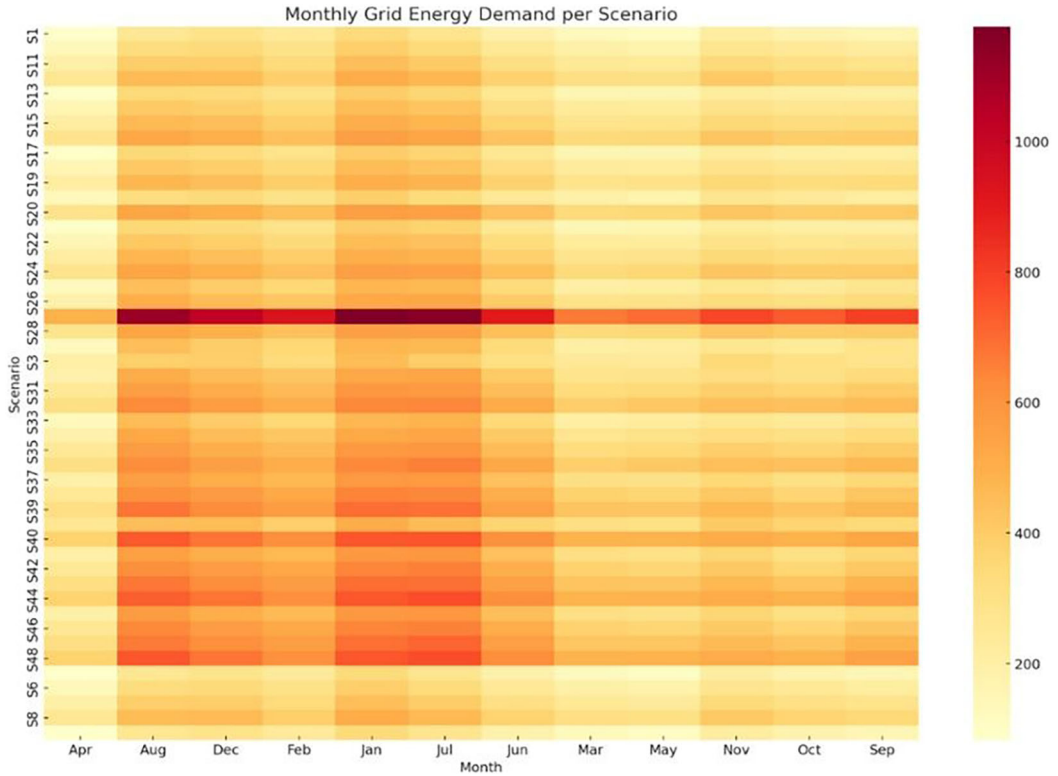

Figure 8. Monthly grid energy demand per scenario. Darker tones indicate higher dependency, with peaks in August, December, and January.

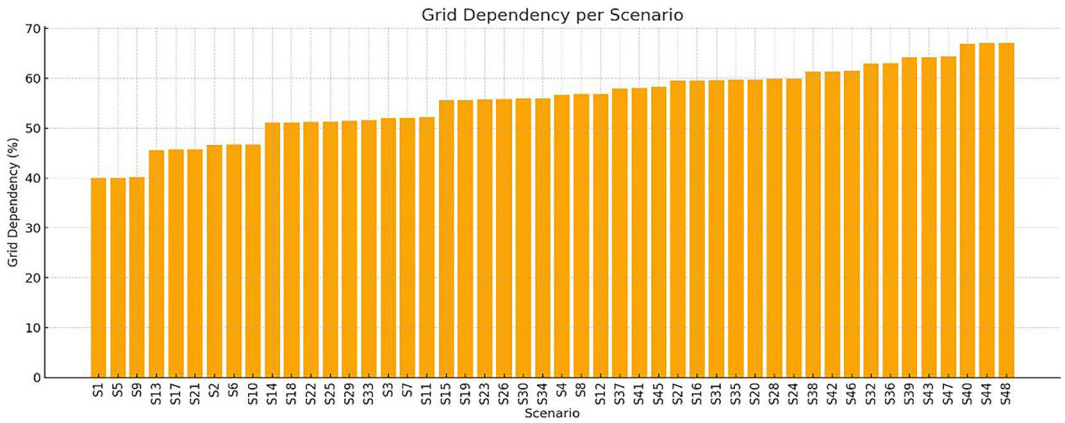

Figure 9. Grid dependency ratio for all 48 scenarios. Lower values (e.g., S1, S5, S9, S13) indicate higher PV contribution, while intensive scenarios (e.g., S44–S48) indicate higher grid reliance.

4.1.4 Grid dependency per scenario. To better quantify the extent to which each scenario depends on grid for electricity supply, the Grid Dependency Ratio was computed for all 48 crop cycles. This metric reflects the percentage of the total annual energy demand that is met by the national grid, after accounting for the fixed annual PV contribution. Nearly all scenarios exhibit very high PV utilization (>99.6%), meaning almost all solar energy is consumed by the system. Since PV production is fixed for all scenarios, efficiency hinges on reducing demand or improving storage/load matching. Thus, the total energy demand varied significantly as a result of changing photoperiods, HVAC setpoints, and humidity levels. This variation in demand causes the share of PV energy to fluctuate accordingly, impacting grid reliance. The bar chart in Figure 9 illustrates the Grid Dependency Ratio values per scenario. Bar chart illustrating the percentage of grid dependency for each of the 48 simulation scenarios (S1–S48), based on annual energy balance results. Higher values reflect increased reliance on external electricity sources and reduced energy autonomy. Plot generated using Python's matplotlib; layout support with AI-assisted enhancement. Scenarios such as S1, S5, S9, and S13 exhibit the lowest grid dependency (~40%), corresponding to milder temperature settings, shorter photoperiods, and moderate humidity levels. On the contrary, scenarios like S44, S47, and S48 demonstrate the highest dependency, exceeding 66%, primarily due to extended lighting durations and elevated heating setpoints. This visualization underscores the direct relationship between crop cycle intensity and grid reliance. Scenarios that aim for smaller crop cycles typically impose higher energy burdens, particularly in lighting and heat-pump use, thus diluting the relative impact of PV production. Conversely, scenarios with larger crop cycles align better with the PV output, requiring less energy from the grid.

4.2 Resilience analysis

The resilience map (Figure 10) illustrates the distribution of scenarios in terms of grid independence (GII) and seasonal robustness (SRS). Scenarios located in the upper-right quadrant exhibit both strong annual PV coverage and stable seasonal performance, representing the most resilient configurations. Among them, S22 and S11 achieved high values for both indices. Scenario S1 recorded the highest GII (68.3%), while maintaining moderate seasonal robustness (SRS = 0.643). In contrast, scenarios such as S40 and S43 fall into the low-GII/low-SRS region, indicating both high grid dependence and seasonal vulnerability.

Figure 11 presents the cycle-based resilience assessment using worst-case PV deficit as an additional stress indicator. Scenarios S22, S33, and S26 demonstrate strong performance under both annual and cycle-based criteria, whereas S9, S21, and S32 exhibit higher PV deficits and reduced resilience. Integrating cycle-level stress analysis refines scenario benchmarking by revealing vulnerabilities that are not evident from annual averages alone.

When resilience indicators were combined with energy cost and carbon emissions in a composite multi-objective assessment, scenarios such as S33 and S22 consistently ranked among the most balanced configurations, achieving favorable trade-offs between sustainability and robustness. In contrast, some scenarios with strong sustainability performance (e.g., low cost and emissions) fared poorly in resilience, revealing potential hidden vulnerabilities under real-world energy dynamics.

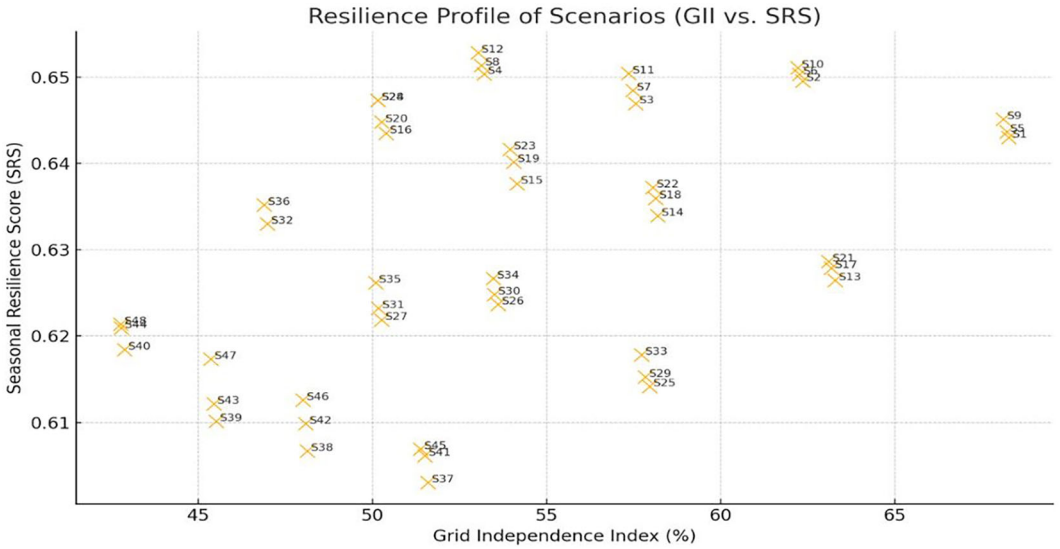

Figure 10. Resilience profile of scenarios based on GII and SRS. Upper-right cases are more resilient, while lower-left are grid-dependent.

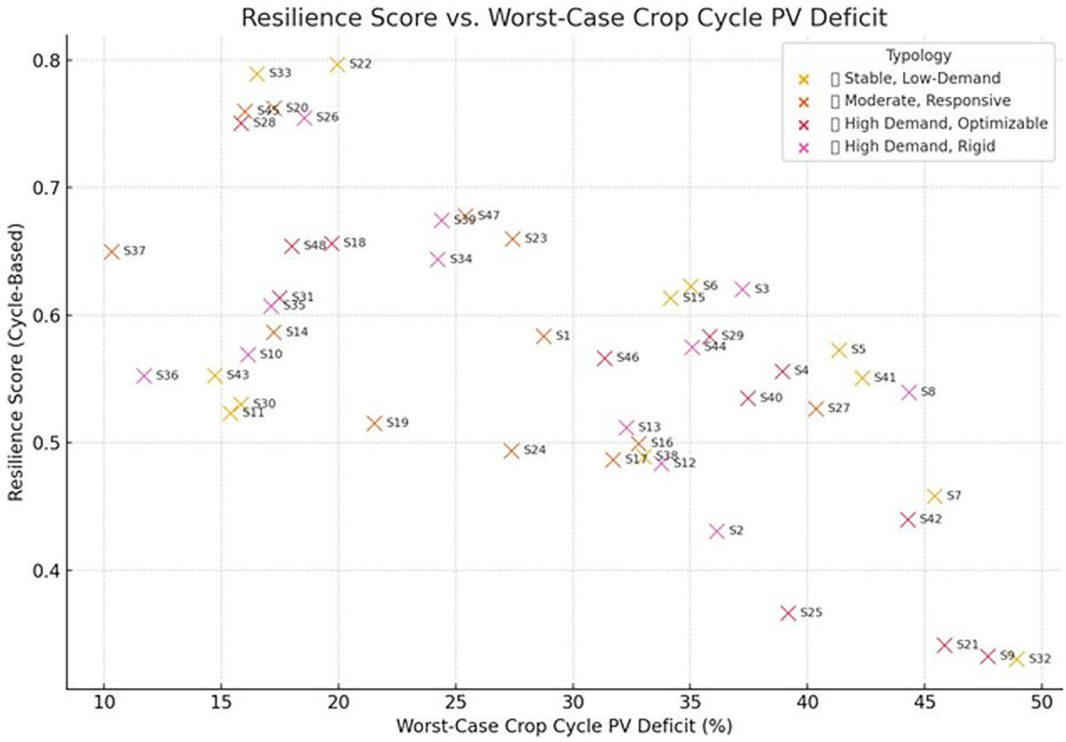

Figure 11. Resilience score versus worst-case PV deficit per crop cycle. Scenarios in the upper-right are more resilient, while those in the lower-left are vulnerable to energy shortages.

4.2.1 Optimal crop cycle and season placement. To better understand the interplay between energy efficiency and crop scheduling, a focused analysis was conducted on the minimum annual energy requirements associated with the most favorable crop cycle per scenario (Table 7). These values derive from dynamic simulations incorporating TRNSYS 18 data and seasonal variations.

Table 7. **Lowest Energy Demand Crop Cycles per Scenario.**

Scenario	First Day of Cycle	Last Day of Cycle
s1	291	342
s2	295	343
s3	297	342
s4	306	348
s5	291	342
s6	294	242
s7	294	339
s8	306	348
s9	292	343
s10	294	342
s11	294	339
s12	306	348
s13	72	120
s14	286	331
s15	289	331
s16	292	331
s17	72	120
s18	286	331
s19	289	331
s20	292	331
s21	72	120
s22	286	331
s23	289	331
s24	292	331
s25	286	331
s26	289	331
s27	291	330
s28	295	331
s29	286	331
s30	289	331
s31	291	330
s32	295	331
s33	286	331
s34	289	331
s35	292	331
s36	295	331
s37	288	330
s38	291	330
s39	294	330
s40	297	330
s41	288	330
s42	291	330

Table 7. *Continued*

Scenario	First Day of Cycle	Last Day of Cycle
s43	294	330
s44	297	330
s45	288	330
s46	291	300
s47	294	330
s48	297	330

A typical depiction of s17 concerning the lowest energy demand for a full crop cycle, as well as its start and end dates during the year is presented in Figure 12. The bar graph shows daily energy consumption (kWh) throughout the year, with the optimal crop cycle window indicated in green. This period was identified through simulation as the most energy-efficient and resilient interval for cultivation under Scenario 17 conditions. Diagram generated using AI-assisted plotting tools in Python for enhanced visual clarity. For this case the optimal crop cycle takes place in spring time.

A study was conducted on the optimal energy demand per scenario along with the corresponding first and last day of the crop cycle. The results are illustrated in Figure 13. The bar chart presents the total energy consumed (in kWh) during the most efficient cultivation cycle for each scenario (S1–S48). Scenarios are ranked from lowest to highest energy

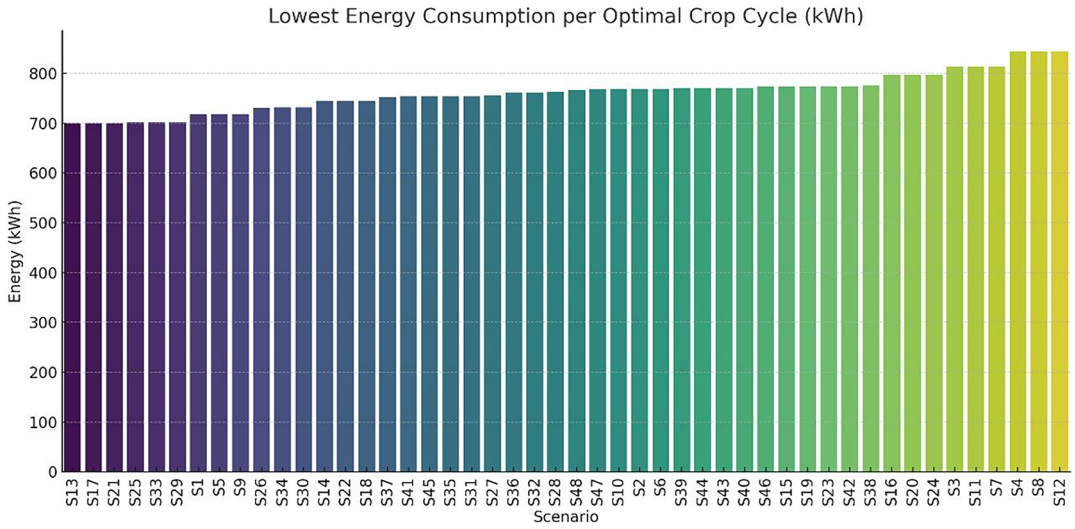

Figure 12. Optimal Crop Cycle Energy Profile example.

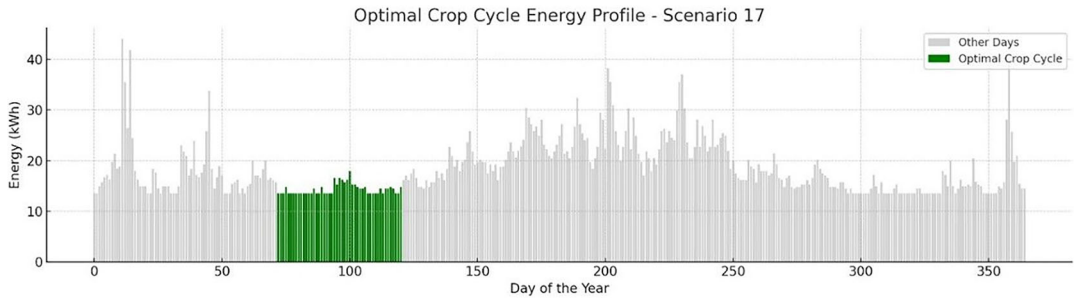

Figure 13. Optimal crop cycle energy demand across all scenarios.

requirement, illustrating the variation in energy efficiency depending on environmental and operational parameters. Chart created using Python with AI-assisted data visualization techniques.

Scenarios such as S1, S13, S17, and S21 exhibit the lowest energy consumption (approximately 700–720 kWh), while other scenarios (e.g., S4, S12, S8) surpass 840 kWh. These variations are primarily driven by setpoint configurations (e.g., heating/cooling set temperatures) and photoperiod duration.

To visualize how each crop cycle aligns with solar availability and ambient conditions, Figure 14 provides a dynamic Gantt chart of all scenarios, by providing information based on ascending energy requirements. Each row represents one of the 48 scenarios (S1–S48), while the green bars indicate the periods during which optimal crop cycles were scheduled. Red bars highlight energy-deficient periods that were excluded from scheduling due to low PV availability or high energy demand. This Gantt chart visualizes the adaptive temporal distribution of crop cycles throughout the year, according to energy sufficiency and environmental suitability. Chart produced using Python and AI-assisted scheduling analysis. Green bars indicate PV-favorable months (PV coverage >60%) which are ideal for starting crop cycles while red bars represent grid-stressed months (PV coverage <40%) where high-load operations are present. Blank months show a moderate energy balance where standard operations take place. Most high-performance scenarios (e.g., S1–S25) are clustered around the spring and autumn period, which offers favorable HVACD balance and improved PV yield. These scenarios avoid the extreme cooling load demands of summer and the high heating demands of winter. On the other hand, lower-ranked configurations like S4, S8, S12 are scheduled in late autumn or winter, where energy costs per cycle peak, and PV contribution is minimal. This temporal dimension of optimization demonstrates that seasonal timing is as



Figure 14. Dynamic scheduling Gantt chart of crop cycles across all scenarios.

critical as environmental control. Selecting appropriate crop windows allows the system to capitalize on periods of natural thermal neutrality and maximum PV availability, improving both energy independence and carbon footprint performance.

To improve the energy efficiency of the VF system, one of the most impactful considerations is the timing of crop cycles. Aligning planting and harvesting schedules with months that are favorable for PV generation, typically March through May and September through October, can significantly reduce reliance on grid electricity. During these periods, solar irradiance tends to be higher, leading to more effective utilization of PV energy. Conversely, planting during winter months, such as December and January, should be avoided due to reduced solar availability and increased dependence on the grid. In regions like Greece, strategic scheduling can reduce grid energy consumption by over 40 percent. Employing a calendar-based Gantt model to plan crop cycles around these optimal solar periods ensures that energy use is aligned with the natural availability of renewable resources. In addition to scheduling, the climate control parameters of the indoor environment play a critical role in managing energy demand. Efficient setpoints for heating, ventilation, and air conditioning (HVAC) systems are essential. Cooling temperatures should be maintained between near 28 °C to reduce the energy load on heat pumps for lettuce cultivation. Heating, on the other hand, should be limited to a range of 12 °C up to 16 °C to minimize energy consumption during colder months. Maintaining a relative humidity of 50% to 60% percent strikes a balance between optimizing plant transpiration and limiting energy-intensive dehumidification or humidification processes. It is also important to avoid extreme internal temperature gradients. Differences greater than 18 °C between daytime and nighttime settings can dramatically increase HVAC demand. A dynamic approach to climate control is recommended, where HVAC intensity is adjusted in accordance with seasonal energy availability. Lighting, as one of the most energy-intensive components in vertical farming, must also be managed with precision to improve overall energy efficiency. Ideally, lighting should be concentrated during the daytime to coincide with periods of high PV output, thereby making the best use of self-generated solar energy. Furthermore, lighting intensity should be modulated based on environmental conditions, such as cloud cover, and the availability of energy stored in on-site batteries. During times when HVAC demand is high, lighting loads should be reduced accordingly to avoid overlapping energy peaks, which can place excessive stress on the system and increase reliance on grid electricity. All these recommendations are presented in Figure 15. Five decision rules are applied to optimize the start date of cultivation cycles. Rule 1 allows crop start when PV forecast exceeds 60%. Rule 2 delays or clusters crops during low-insolation months (January or December). Rule 3 reschedules start dates that coincide with predicted PV dips. Rule 4 favors months with lighting durations >12 hours, while Rule 5 prioritizes forecast-based timing when grid electricity cost is high. These rules form the basis for dynamic Gantt scheduling in the simulation model.

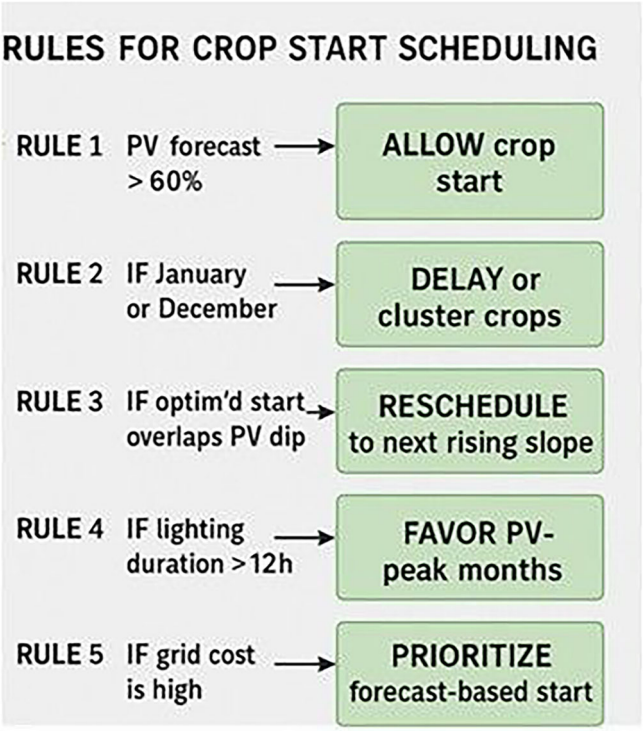

Figure 15. Rules for Crop Starting Scheduling.

To classify scenarios based on their energy behavior and adaptability, a Principal Component Analysis (PCA) was conducted on key performance indicators derived from dynamic crop-cycle simulations. The input variables included: (i) maximum HVAC energy during crop cycles, (ii) minimum PV availability within the worst energy period, (iii) total energy consumption over full cycles, (iv) optimized energy under ideal scheduling, (v) absolute energy savings from schedule optimization, and (vi) crop cycle duration. These features were chosen to jointly reflect both energy stress and operational flexibility of each vertical farming scenario.

The PCA reduced the six-dimensional dataset into two principal components, which together captured over 80% of the total variance. Principal Component 1 (PC1) was primarily associated with maximum cycle energy and energy savings (both negatively), while showing a slight positive correlation with crop cycle length and optimized energy use. This axis effectively separates scenarios based on energy intensity and flexibility. Scenarios with strongly negative PC1 scores exhibit high baseline energy demand but strong optimization potential, whereas those on the positive end are generally stable, lower-energy systems with flatter energy profiles and minimal gains from dynamic intervention. Principal Component 2 (PC2) captured the trade-off between cycle duration and optimized energy. It correlated positively with crop cycle length, and negatively with optimized cycle energy, distinguishing longer-duration, efficient scenarios from short-cycle, high-demand cases. Together, PC1 and PC2 define a spectrum from short, intensive, energy-heavy setups to long-duration, energy-optimized configurations. To further interpret the scenario landscape, k-means clustering (k = 4) was applied to the PCA-transformed data, resulting in four distinct clustering groups:

- Cluster 0: High Demand, Rigid - Scenarios with heavy HVAC and lighting loads but limited optimization response. Likely require infrastructural interventions or high-reliability backup systems
- Cluster 1: Moderate, Responsive - Highly responsive to schedule shifts. Suitable for adaptive lighting or seasonally adjusted planting windows
- Cluster 2: High Demand, Optimizable - Initially high-demand scenarios with excellent response to cycle alignment, ideal for predictive control
- Cluster 3: Stable, Low-Demand - Inherently low-energy systems that show little gain from optimization, potential candidates for passive operation or fixed setpoints

To further explore structural similarities among scenarios beyond individual resilience indicators, a Principal Component Analysis (PCA) was applied to key cycle-based performance metrics. The first two principal components explained more than 80% of the total variance (Figure 16), enabling a two-dimensional representation of scenario behavior. Principal Component 1 (PC1) primarily captured energy intensity and optimization potential, separating high-demand, high-savings configurations from inherently stable, low-energy systems. Principal Component 2 (PC2) reflected the trade-off between crop cycle duration and optimized energy demand, distinguishing longer-duration, energy-efficient setups from shorter, more energy-intensive configurations. Subsequent k-means clustering (k = 4) performed in the PCA-reduced space identified four distinct scenario groupings. One cluster comprised high-demand but highly optimizable configurations, characterized by strong responsiveness to scheduling adjustments. Another cluster represented rigid, high-load scenarios with limited optimization gains. A third group included moderate-demand, responsive systems balancing efficiency and flexibility, while the final cluster consisted of stable, low-demand scenarios exhibiting minimal deviation between baseline and optimized performance. The PCA-based classification complements the resilience framework presented in Section 4.2 by revealing structural energy-behavior patterns that are not fully captured by annual autonomy or seasonal robustness metrics alone. In particular, scenarios such as S22 and S33 consistently appeared within high-performance clusters, reinforcing their balanced trade-offs between energy efficiency, adaptability, and renewable integration.

4.3 CO_2 emissions comparison

4.3.1 Introduction-comparative carbon footprint of vertical, greenhouse, and open-field farming. Quantifying and comparing the carbon of farming systems is essential for evaluating their environmental sustainability, especially under the lens of climate change and decarbonization targets. In the context of vertical farming (VF), which relies heavily on artificial energy inputs, understanding the specific emissions per kilogram of output is a critical step toward evaluating its viability against more traditional systems such as greenhouses and open-field agriculture. Among the available metrics, CO_2 emissions per kilogram of produced lettuce in comparative studies is the most widely adopted indicator. This normalized unit allows for a consistent comparison across systems that differ significantly in scale, energy inputs, and yield densities. It also enables benchmarking of technological improvements, such as the integration of renewable energy systems or optimized climate control strategies. In this section, a comparison of the carbon emissions associated with VF, greenhouse, and open-field production systems takes place based on both published literature and simulation outputs.

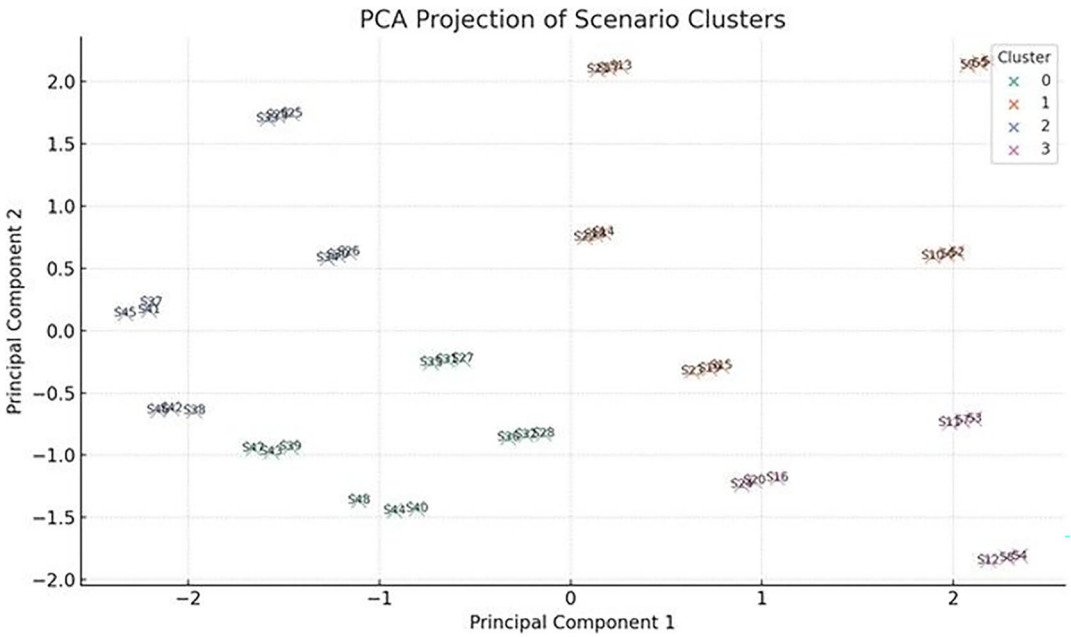

Figure 16. **PCA of examined scenarios.**

4.3.2 Comparison rationale. A comparative literature review of the carbon footprint associated with lettuce production across different agricultural systems reveals significant variation, primarily driven by energy inputs, yield density, and regional grid emission factors. Table 8 summarizes indicative values (in kg CO_{2eq}/kg lettuce) from key studies.

Several key factors influence the variability of carbon emissions in vertical farming systems, with the most significant being the carbon intensity of the electricity grid. Vertical farms that operate in regions where the electrical grid relies heavily on fossil fuels, such as coal or natural gas, tend to exhibit substantially higher CO_2 emissions. The energy source behind a vertical farm's electricity supply is therefore a primary determinant of its environmental impact. Lighting, also,

Table 8. **Overview on carbon footprint emissions for lettuce production.**

Source	Production System/Location	CO_2 Emissions ($kgCO_2$/kg lettuce)	Scenario Description
3	Vertical Farming (NL)	15.2	VF unit powered by Dutch electricity mix (high fossil share), full artificial lighting.
	Greenhouse (NL)	2.4	High-yield semi-closed greenhouse with combined heat and power (CHP) and some supplemental lighting.
	Open Field (NL)	0.35	Conventional outdoor farming with minimal mechanization, no artificial lighting.
28	Vertical Farming (EU)	11.6–14.7	Range for fully enclosed systems with LED lighting and mechanical HVAC.
9	Vertical Farming (MY)	6.1–9.4	Hybrid PV-grid system in tropical climate with reduced HVAC demand.
6	Vertical Farming	6.9–12.0	Results vary by lighting intensity and climate (warmer climates yield lower HVAC loads).
8	Vertical Farming	≈9.8	Multiparametric optimization across different energy sources and lighting profiles.
5	VF (Global Range)	8.0–18.0	Aggregated data from multiple studies covering global setups, including worst-case fossil grid mixes.
4	Greenhouse (EU)	2.5–3.2	Range from low-tech to advanced greenhouses with CO_2 fertilization and heat recovery.

represents another major contributor to overall energy consumption in vertical farming. Consequently, the lighting strategy adopted has a direct effect on emissions. Approaches that reduce the Daily Light Integral (DLI), such as spectrum-tuned LEDs or photoperiod adjustments, as well as the implementation of dynamic lighting systems that respond to real-time energy availability or crop needs, can substantially decrease total emissions. Heating, ventilation, air conditioning, and dehumidification (HVACD) systems also play an increasingly important role in emission profiles, particularly in tropical climates or facilities with suboptimal insulation. In such contexts, the energy demands of HVACD systems can rival or exceed those of lighting. Optimizing these systems through the use of energy-efficient heat pumps, and smart thermal setpoint scheduling is essential for minimizing emissions without compromising crop quality or yield. Finally, the method of normalizing emissions data has a significant impact on the interpretation of sustainability metrics. While some studies express emissions per square meter of cultivated area, this approach can obscure meaningful comparisons across systems with varying productivity. In this analysis, all emission values are normalized per kilogram of fresh produce, providing a more accurate and consistent basis for assessing the environmental performance of different vertical farming configurations. This yield-based normalization ensures that emissions are contextualized relative to actual product output, supporting more reliable benchmarking and decision-making.

4.3.3 Modeled carbon footprint of vertical farming scenarios. The scenario-specific total electricity consumption and corresponding life-cycle CO_2 emissions per kilogram of harvested lettuce are summarized in Table 5. Emissions were calculated based on scenario-specific grid electricity consumption and operational inputs, as defined in the LCA framework described in Section 3.4. Across the 48 operational scenarios, the carbon footprint ranged from 2.29 to 4.47 $kgCO_2eq/kg$ lettuce, with an average value of 3.61 $kgCO_2eq/kg$ and a median of approximately 3.67 $kgCO_2eq/kg$. Notably, 34 out of 48 scenarios exhibited emissions below the overall mean value. The observed variability reflects differences in lighting duration, HVAC loads, and PV contribution across seasonal configurations. Figure 17 illustrates the distribution of modeled emissions using a boxplot representation. Chart produced using Python and AI-assisted scheduling analysis. The interquartile range captures the concentration of most scenarios within a moderate emission band, while lower-end outliers correspond to reduced photoperiods and improved PV sufficiency. Conversely, high-emission scenarios are associated with extended lighting schedules and increased grid dependency. Although photovoltaic generation offsets a substantial share of electricity demand, residual reliance on the Greek electricity grid, characterized by moderate carbon intensity, remains the dominant contributor to overall emissions. Substrate-related impacts (rockwool and clay pellets) were included in the life-cycle assessment but contributed only marginally compared to operational electricity use. These findings indicate that emission reduction potential lies primarily in operational optimization strategies (e.g., dynamic lighting adjustment and shorter crop cycles) rather than material substitution alone.

4.4 Comparative evaluation with existing literature

The comparative analysis of CO_2 emissions between the simulations of the examined VF system scenarios and established literature benchmarks reveals valuable insights into the environmental efficiency of the system. Previous studies have reported wide ranges of CO_2 emissions per kilogram of fresh lettuce, depending on the cultivation system employed. Open-field agriculture typically exhibits the lowest footprint, as it relies entirely on ambient conditions and

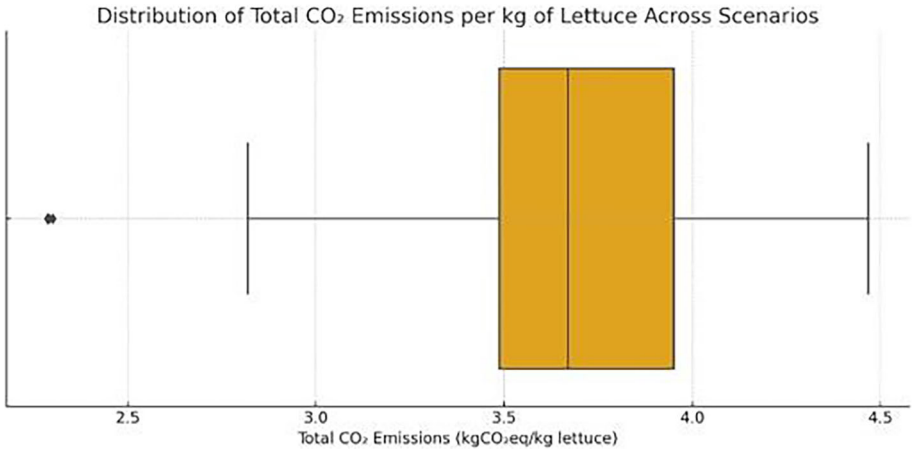

Figure 17. Distribution of CO_2 emissions across all scenarios. Most values cluster between 3.2–3.8 $kgCO_2eq/kg$ lettuce, with outliers below 3 and above 4.

excludes artificial climate control or lighting inputs.[3,8] As expected, open-field farming has significantly lowest CO_2 emissions, however this method limits lettuce production for a specific period in a year. Greenhouse production, offering higher yields and controlled environments, demonstrates average emissions mainly driven by supplemental lighting and heating demands. Vertical farming systems, on the other hand, present the highest carbon intensities, depending on the system configuration, location and energy mix.[5,6] These numbers stem from the near-complete reliance on artificial lighting as well as HVACD operations. Simulation results examined in this study showed that the best-performing scenarios reach values as low as 2.3 to 2.6 kg CO_2/kg, clearly outperforming average vertical farm benchmarks, and approaching or even surpassing greenhouse performance in terms of carbon efficiency. The median value across all 48 scenarios remains below the upper greenhouse threshold and well within the reported vertical farming range. Additionally, the carbon intensity of the local electricity grid emerges as a critical variable, aligning with findings from earlier work.[9,28] For instance, a low-emission grid or partial integration of photovoltaics and battery storage, as concluded in the examined scenarios, may yield even lower CO_2 emissions. Ultimately, while vertical farming still struggles to compete with open-field agriculture in carbon terms, our findings show that its footprint can be brought to a competitive level with greenhouses, especially when environmental control is optimized and renewable energy integration is enhanced. Figure 18 illustrates the comparative CO_2 emissions per kilogram of fresh lettuce produced under four distinct systems: open-field cultivation, greenhouse production, vertical farming based on literature data, and all 48 scenarios simulated in this study. Each green cross represents a scenario from this study, spanning a range of energy strategies and crop cycle timings. The blue dashed line indicates the reported emissions from open-field cultivation in the Netherlands, the red dashed-dotted line represents emissions from greenhouse cultivation, while the magenta solid line and red dotted line represent the average and maximum values reported for vertical farms, respectively. Several scenarios in this study achieve substantially lower emissions than most vertical farming benchmarks, highlighting the importance of optimized scheduling and PV integration. Chart produced using Python and AI-assisted scheduling analysis. The results demonstrate that the majority of scenarios are clustered around 3.2–3.8 kg CO_2/kg. These values are substantially lower than the average CO_2 emissions reported in the literature for vertical farming, which typically range from 6.2 kg CO_2/kg (average) up to 12 kg CO_2/kg (maximum). Notably, the lowest-emission scenarios in this study (e.g., S1, S5, S9) approach the levels observed in greenhouse systems (5.4–5.5 kg CO_2/kg) and, in rare cases, achieve emissions less than half of those reported in prior VF studies. Thus, greenhouse systems offer a middle ground, balancing environmental control with moderate energy use. In comparison, open-field systems maintain the lowest emissions footprint (~0.35 kg CO_2/kg), owing to minimal energy input but suffer from climate dependency and limited spatial efficiency.

4.5 Impacts of dynamic lighting control on energy and crop cycle duration

To evaluate the potential for energy optimization through adaptive lighting strategies, each of the 48 scenarios were analyzed to determine the maximum safe lighting reduction -defined as the highest percentage reduction in lighting duration that did not increase total energy consumption due to elongation of the crop cycles' duration. Based on this

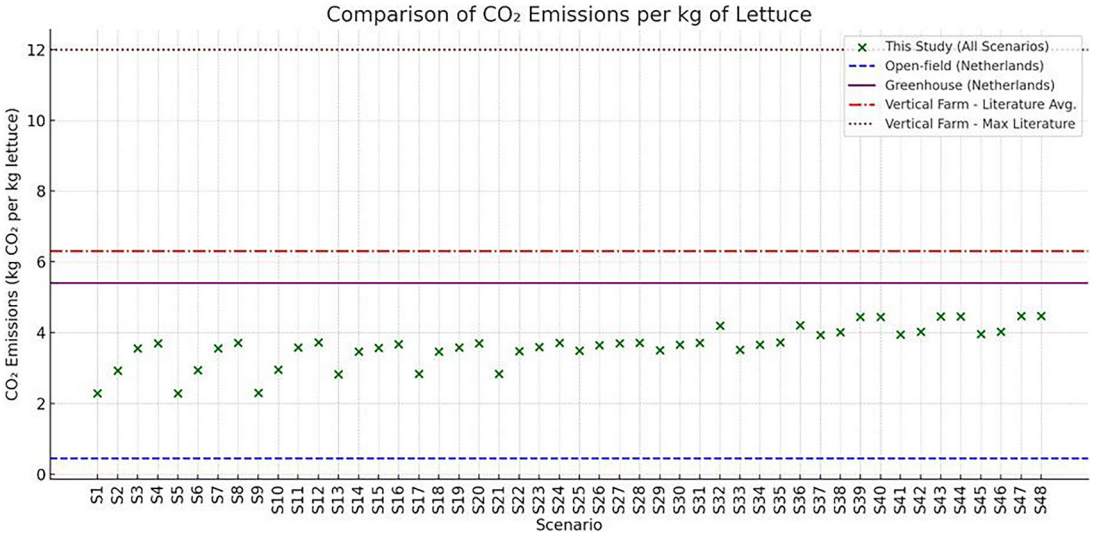

Figure 18. Comparison of CO_2 per farming option.

Table 9. Lighting Flexibility Clusters by Max Safe Reduction.

Max Safe Lighting Reduction Cluster	Flexibility Class	Description
10%	Highly Flexible	Lighting can be reduced to 90% with no penalty. These scenarios are excellent candidates for dynamic lighting controls, especially in response to PV availability or peak load management.
7.5%	Upper Moderately Flexible	Scenarios that tolerate up to 7.5% reduction. These allow meaningful energy flexibility but may require adaptive scheduling to maintain efficiency.
5%	Low Moderately Flexible	Only small reductions are beneficial. Use with caution — partial flexibility possible without increasing HVAC energy.
2.5%	Low Flexible	Very limited flexibility. Best suited for mild demand response or fixed reductions on high-PV days only.
0%	Rigid	No lighting reductions lead to savings. Avoid dynamic lighting — maintain fixed photoperiods to avoid energy penalties due to prolonged HVAC operation.

threshold, scenarios were classified into five distinct flexibility clusters: Highly Flexible, Upper Moderately Flexible, Low Moderately Flexible, Low Flexible, and Rigid (Table 9).

A visual cluster-based bubble chart was constructed, grouping scenarios according to these classifications and clearly highlighting their adaptability to lighting interventions (Figure 19). Scenarios are categorized into five lighting flexibility clusters: Highly Flexible, Upper Moderately Flexible, Low Moderately Flexible, Low Flexible, and Rigid. This classification reflects the degree to which dynamic lighting strategies can be applied within each scenario to shift energy loads, minimize peak demands, or align with PV availability. Highly flexible scenarios (in blue) demonstrate the greatest potential for energy management optimization through lighting schedules. Chart produced using Python and AI-assisted scheduling analysis. Scenarios in the Highly Flexible group (e.g., S1, S2, S13) demonstrated the ability to tolerate up to 10% reduction in lighting without energy penalty, making them ideal candidates for dynamic lighting control strategies that respond to PV availability or energy pricing signals. In contrast, Rigid scenarios (e.g., S37 to S48) showed no flexibility, as even minor reductions led to increased total energy due to extended crop durations and elevated HVAC demands.

This clustering approach not only provides insight into the operational flexibility of each scenario but also guides the design of responsive control policies. For example, Low Flexible or Moderately Flexible scenarios may benefit from more conservative or seasonal lighting adjustments, while Highly Flexible configurations can adopt real-time adaptive schedules. This classification is especially valuable when coupled with sustainability metrics, allowing for multi-criteria decision-making based on energy efficiency, CO_2 emissions, and operational resilience. Conversely, high-demand scenarios, especially those with long photoperiods or extreme HVAC loads, exhibited less flexibility. In these cases, the

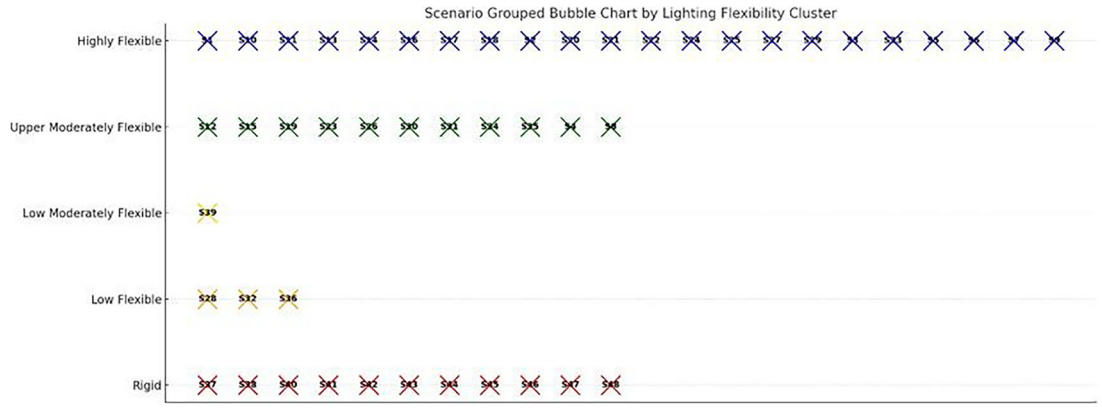

Figure 19. Scenarios grouped by lighting flexibility clusters. Highly flexible cases (blue) tolerate reduced lighting without energy penalty, while rigid cases (red) show no flexibility.

energy savings from reduced lighting were counterbalanced by increased cycle durations, resulting in little or no net benefit. An aggregate analysis across all 48 scenarios showed that lighting reductions of up to 10% consistently delivered measurable gains in energy savings, cost reduction, and carbon mitigation. However, in many scenarios beyond a threshold (e.g., 5%), the marginal benefits decrease, and the intervention became energetically inefficient due to extended growth durations. These findings confirm the feasibility of integrating dynamic lighting control in vertical farming, especially when guided by real-time PV generation forecasts or demand-response signals.

5. Conclusions

This study systematically evaluated the energy performance, environmental impact, and operational flexibility of a vertical hydroponic farming system under Northern Greece climatic conditions through a comprehensive simulation framework. Using TRNSYS 18-based modeling, 48 cultivation scenarios for lettuce production were analyzed, incorporating variations in photoperiod, humidity, HVACD setpoints, and renewable energy integration. A multi-criteria decision framework was introduced encompassing energy per cycle, emissions, and resilience. The results demonstrate that electricity demand in vertical farming is highly sensitive to crop cycle configuration, with artificial lighting and HVACD loads being the dominant contributors. By aligning crop cycles with PV availability, optimized schedules showed measurable reductions in grid reliance and excess generation. These insights were further extended into a proposed dynamic planting calendar and adaptive setpoint strategies for lighting and HVAC systems. Scenarios with longer photoperiods and extreme temperature differentials exhibited higher energy intensity and grid dependency. However, aligning crop schedules with seasons of milder weather conditions, particularly autumn and spring, allowed for improved PV utilization and lower energy demand from grid. The study also revealed marginal variability in carbon emissions across scenarios, ranging from 2.29 to 4.47 kg CO_2/kg lettuce. Notably, the best-performing configurations achieved emission levels outperforming even greenhouse systems and significantly better than previously reported VF benchmarks. These gains were achieved through strategic timing for optimal energy crop cycles, environmental control and integration with a PV-battery system. A combined assessment using indicators such as Grid Dependency Ratio (GDR), Grid Independence Index (GII), and Seasonal Resilience Score (SRS) enabled a multi-dimensional classification of scenario performance. Scenarios with low grid reliance and stable PV alignment were identified as optimal candidates for future deployment in energy-constrained or off-grid contexts. A key innovation of this work is the Lighting Flexibility Classification System, where each scenario was assessed for its capacity to safely reduce photoperiod without increasing total energy demand. Scenarios were grouped into five clusters, Highly Flexible, Upper Moderately Flexible, Low Moderately Flexible, Low Flexible, and Rigid, based on the maximum safe lighting reduction achievable. These classifications offer a practical guideline for implementing dynamic lighting interventions. For instance, scenarios like S1, S2, and S13 were found to tolerate up to 10% lighting reduction with net energy savings, making them ideal candidates for real-time lighting control. On the other hand, Rigid scenarios, primarily those with extreme temperature or humidity requirements (e.g., S37–S48), showed no capacity for lighting reduction without incurring increased HVAC energy costs. Overall, the integration of lighting flexibility, crop cycle adaptation, and renewable alignment advances our ability to design sustainable and intelligent vertical farming operations. The decision tools developed herein, including radar plots, quadrant maps, and bubble cluster charts, can guide farm designers, policy makers, and engineers in selecting optimal environmental strategies. Future work will extend this model to include real-time predictive control using live PV forecasts and feedback from plant physiology to further optimize energy use and crop yield outcomes. In conclusion, the findings confirm that vertical farming, while energy-intensive, can be significantly optimized through seasonal crop scheduling, moderate environmental control, and targeted lighting strategies. Under the right configuration, vertical farms can approach or even outperform greenhouse systems in both energy and carbon metrics, especially when partially powered by renewable sources. Future work should explore the integration of real-time environmental sensing, AI-driven lighting algorithms, and scalable PV-storage systems to further improve system autonomy, productivity, and sustainability. The multiple regression model shows that, when humidity levels remain within the acceptable range for proper plant growth, the scenarios indicate that variations in indoor humidity have a negligible impact on energy consumption.

Ethics and consent

Ethics approval and consent are not required.

Data availability statement

Underlying data

Zenodo: Dynamic Energy Optimization and Lighting Flexibility Classification for Sustainable Vertical Farming: A Simulation-Based Multi-Scenario Analysis https://doi.org/10.5281/zenodo.16926135.[26]

This project contains the following underlying data:

- TRNSYS 18 input files (tpf/log/txt/pti/lst/idf/dck/bld/plt) input configuration files used for running the 48 cultivation scenarios.
- Environmental Datasheets (tm2) raw environmental data used as model inputs
- Simulation Results (txt) raw and processed outputs from TRNSYS 18 simulations across all scenarios.
- Figure values (csv) data underlying figures and plots presented in the article

Extended data

Zenodo: Dynamic Energy Optimization and Lighting Flexibility Classification for Sustainable Vertical Farming: A Simulation-Based Multi-Scenario Analysis https://doi.org/10.5281/zenodo.16926135[26]

- Equipment Manuals (pdf) Manuals for the existing equipment in the existing isobox
- Python Scripts for scenario analysis (txt) Scripts used to process simulation results
- Scenarios and supplementary tables and data (xlsx/csv) All data for the 48 scenarios analysis
- Figures and Scenarios optimal crop profiles (jpg/png) All resulting figures from the analysis
- Tables (docx) All tables used in the final paper

Reporting guidelines

The authors confirm that no applicable reporting guidelines (e.g. CONSORT, STROBE, PRISMA) exist for the simulation-based methodological study presented herein as verified through the EQUATOR and FAIRSharing databases.

License

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Restrictions

Due to software licensing restrictions and proprietary dependencies of TRNSYS 18, the complete project files (including component libraries and simulation workspace) cannot be shared publicly. Sharing these files would require distribution of third-party licensed material that is not permitted under open access. These files are part of the licensed TRNSYS software package, which is distributed by the Transsolar Software Engineering: trnsys.de. Corresponding personnel: Alina Wagner email: hotline@Transsolar.com. Access to these resources require a valid TRNSYS licence.

Acknowledgements

Selected data visualizations presented in this article were created using AI-based tools (OpenAI ChatGPT4), with integrated charting functionality. These tools were employed solely for processing and visualizing datasets provided by the authors and do not influence the scientific interpretation or conclusions.

“We confirm that AI tools were used exclusively for generating selected figures in the manuscript, based on the authors’ own dataset. Specifically, OpenAI’s ChatGPT was used to assist in converting tabular or numerical data into visual descriptions, and Python (via code generated with ChatGPT’s assistance) was used to render the final charts and diagrams. These tools were not involved in writing, analysis, or simulation processes, nor in the preparation of the manuscript’s textual content. All underlying data used in the visualizations have been generated by our simulation models (TRNSYS) and are fully available for verification. The AI tools were applied solely as graphic utilities and did not influence the scientific interpretation or presentation of the results.”

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Publisher Full Text

Open Peer Review

Current Peer Review Status: ? ✓ ?

Version 2

Reviewer Report 25 May 2026

https://doi.org/10.21956/openreseurope.25420.r73915

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?

Yuyao Kong
University of Florida, Florida, USA

Introduction:

1. “previous comparative studies have shown that…” please add citations.
2. MPPT, this is the first time it shows up in the main text, please provide the full name of this term.
3. The term “near-zero” is ambiguous and should be explicitly defined. In the same sentence, the statement refers to “recent studies” but does not provide sufficient citations.
4. “However, such approaches typically rely on ..” please provide more detail on the methodologies used in prior studies to evaluate these parameters.
5. The phrase “multipored model” is unclear.
6. “J. Pimentel’s study explored different strategies…” it might be helpful if provide more details.
7. “A case study in Malaysia assesses ..” please provide reference
8. “Despite the growing body of…” please provide references
9. “Using TRNSYS 18…” what is it? Please provide full name and include the full software reference for TRNSYS 18, including the developer/vendor information, version number, and appropriate citation to improve reproducibility and methodological transparency.
10. “The objective is to identify … that minimize energy use per unit of harvested biomass” this is the place where the authors should define “Specific Energy Consumption (SEC)”, instead of defining it in the second section (the scope of the study).

Scope of the study: What is the purpose of this section? It looks not necessary and some of the content can be briefly integrated into methods section. Also, please avoid using the bold formatting in the main text, except for titles and headings, as they are more like a ChatGPT format.

Methods:

1. There are many repeated words, should be rewritten to improve conciseness.
2. The content presented in the “Scope of Study” section and the paragraphs preceding

Section 3.1 appears repetitive. Consider consolidating these parts into a single, more concise section to improve readability and avoid unnecessary duplication. Please maintain a clear and logical flow and focus on the most relevant methodological details.

3. There are too many details about lettuce, there is no need to introduce lettuce in detail. Scientific name, cultivar, vendor information is sufficient.
4. Were lettuce grown under all 48 scenarios? How many plants in each unit? How long was the planting cycle?
5. "The harvested mass per cultivation cycle was assumed constant across all scenarios, based on …" I don't understand it, how can different scenarios with different environmental conditions result in the same yield?
6. I don't understand why the authors provide a detailed list of literature reviews in this section, it can be summarized into one sentence with references cited.
7. I feel that Figure 1 and 2 can be combined into a single figure with subpanels (e.g., Figure 1A and Figure 1B). The production system can be introduced at one place. Right now they are in wo different sections and make it difficult to follow.
8. I couldn't read Figure 3 although I have downloaded it. Please improve the figure resolution.
9. Section 3.2 about the equation: " All electrical power consumed by the LED lighting system was assumed to be fully converted into internal sensible heat…" How about radiative and convective heat fractions?
10. The statement under the equation is too long and "Transpiration rate was derived from …" is repetitive words, it has been described above. The remaining parts of the paragraph should be in the main text.

Section 3.2:

1. "The indoor environmental conditions were tailored for safe lettuce growth." What does "safe lettuce growth" mean here? Do you mean normal growth?
2. I don't understand why Table 3 is shown here. It looks like results? Instead, Table 4 needs to be moved here.
3. Figure 4 should be in results section.

Section 3.5: please avoid using the bold formatting in the main text.

Section 3.7: "For each scenario… focuses on annual operational energy flows and associated CO_2 emissions" this can be deleted or shortened as it is repetitive information.

Section 3.8:

1. "To support adaptive energy and schedule optimization … on crop timing under various scenarios". This should be in discussion section.
2. This is repetitive words (it's similar information in the beginning of the paragraph).
3. "Thus, for…" is there missing content?
4. Equation 7 should be moved above annotations.
5. Table 6: the scenarios were not listed in order in the table.

Section 4:

1. I could not see a, b, c, d in Figure 5 but the authors used Figure 5a, 5b, 5c, 5d in the text.
2. Also the resolution of image is too low and I could not read axes titles.

General comments for the whole manuscript: The text has a lot of repetitive content and has to be reorganized to flow logically.

Is the work clearly and accurately presented and does it cite the current literature?

Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Controlled Environment Agriculture

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 23 May 2026

https://doi.org/10.21956/openreseurope.25420.r73708

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?

Adnan Arshad
Lanzhou University, Lanzhou, China

The author has made a comprehensive revision and addressed most of the comments; I suggest that the author revise figure 3—configuration of the TRNSYS 18 model for the vertical farming unit. -How is battery operation scheduled – rule-based (e.g., charge from PV excess, discharge when PV < load) or optimized? This affects how much grid electricity is displaced. -What is the temporal resolution of the emission factor? Monthly or hourly variation in grid carbon intensity could significantly affect results if the system uses grid electricity at different times of day. -Why 48 scenarios (S1–S48)?

Here are a few follow-up comments/suggestions:
- For spring-start cycles like S17 (day 72–120), is the energy saving primarily due to avoided

cooling, avoided heating, or better PV matching? What is the dominant HVACD component?
- PV coverage threshold: Figure 14; Are these fixed annual averages, or month-by-month dynamic thresholds from TRNSYS 18 simulations?
- Would the same day-of-year ranking hold for a different climate or is this result location-specific?
- what operational lifetime (years) would VF's higher embodied carbon be amortized relative to greenhouse/open-field? Does your comparison assume local open-field only during optimal outdoor seasons, or an annualized average including imports?

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 21 May 2026

https://doi.org/10.21956/openreseurope.25420.r73709

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Nima Asgari
Western University, London, Ontario, Canada

The authors have put effort on addressing my comments.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Solar PV, HVAC, Indoor Agrivoltaics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 30 December 2025

https://doi.org/10.21956/openreseurope.22555.r65518

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?

Nima Asgari
Western University, London, Ontario, Canada

While the research titled "**Dynamic Energy Optimization and Lighting Flexibility Classification for Sustainable Vertical Farming: A Simulation-Based Multi-Scenario Analysis**" provides valuable insights, significant level of revision is still necessary to ensure alignment with indexing standards. Otherwise, the article is not suitable for indexing.

1. Abstract: include the most significant achievements of the study both in qualitative and quantitative form. Numeric results are rarely included in current version.
2. Introduction: The literature review is too weak and completely unacceptable. Add the reviewed findings of recent and relevant research. Look at our recent research and the reviewed studies in them:
   - Reference 1: https://www.mdpi.com/2071-1050/16/14/6120
   - Reference 2:https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5104787
   - Reference 3:https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5775183
1. Scope of the study: in the text: "...electricity consumption per unit of yield (expressed in kWh/kg)..."; The technical term for this variable is Specific Energy Consumption (SEC).
2. Scope of the study: Use the last paragraph of this section, "This schematic shows the pilot .... was provided by the manufacturer." as a description for the Figure 1, right after the place you cite this figure for first time. The same issue is for Figure 2 and the last paragraph of section 3.1. All other figures have the same problem. Their description has been fell apart from their first citing location in the text.
3. Methodology: "... where PV supply is directed first to loads, **then** to the battery, and finally to the grid".
4. Methodology: The introductory descriptions before section 3.1 are repetitive, redundant and sometimes ambiguous. You need to make them short, sharp and to the point, and instead, bring more details in the following sections.
5. Methodology: why have you done a lit review in Section 3.1? ("Ch. Vatistas et compared the lettuce cultivation between GHs and VFs and presents that VFs are more efficient than GHs in terms of yield per unit area, but require more energy to operate"). It is not standard. You must discuss about the previous studies either in the Introduction or the Discussion.
6. Methodology: In the second paragraph of section 3.1: You need to justify your claims about the 16-hour photoperiod by providing sufficient information about PPFD and more importantly DLI.
7. Methodology: Table 1, Battery voltage is 2? You have mentioned that your case was 24 volt. Please indicate the specifications for your case.
8. Methodology: "Harvest took place at physiological maturity (~120–150 g fresh weight per head), ...". What is your reference for this?
9. Methodology: "Vertical farming system is realized in ISOBOX with galvanized metal construction...". This is firs time that you have talked about an ENCLOSURE in your text. This is important information which justifies the necessity for your HVAC system. You need to provide all basic and important information about your system in section 2. Scope of the study. You should assume that the readers DO NOT KNOW ANYTHING about your research. Hence, you should try to visualize the construction and the concept of your study in all introductory sections such as Abstract, Last paragraph of Introduction, Scope of the study, and Methodology.
10. Section 3.1: "All these components of the VF system are presented on the (Table 1) in the

Manuscript Tables section". What do you mean by mentioning "**Manuscript Tables section** "?

11. Methodology: the resolution of Figure 3 & 4 is extremely low! You must replace them.
12. Methodology: there is a lot of repetitive content in the Methodology section. You need to shorten them and make them to the point and mentioned once at the right place.
13. Table 3: "No significant effect on crop duration" should be "No significant effect on crop **cycle** duration".
14. Crop Cycle function: Photoperiod alone is not the only affecting parameter of lighting system, PPFD, thereby DLI matters a lot. You MUST indicate that this equation (fitted curve) is only valid for the controlled PPFD range of XXX-YYY, whatever is in your study.
15. Figure 4: This plot is not scientifically acceptable. The angle of plot does not provide sufficient information about the surface behavior. Rotate the plot to present the surface in an appropriate angle.
16. Figure 5: Completely non-readable titles and tick mark labels. Must be replaced. Instead of addressing like top left corner, it is recommended to separate them into four a, b, c, and d and address them like Figure 5a, etc.
17. Figure 5: This figure is actually part of results and along with all discussions provided MUST be transferred to Section 4. Same issue with Table 5 and the corresponding discussions.
18. Section 3.4: Long form of LCA must be defined at first-time-use place.
19. Figure 6 needs to have axes titles.
20. Figure 8: low quality-no unit mentioned! Avoid using AI to refine the pictures. You do not have to do that. The exports from Microsoft Excel, Python or other softwares can be still of good quality.
21. Equations 4-6: Put references.
22. Resilience and equations 4-6 must have been introduced in the Methods section. You have not mentioned anything about this investigation approach neither in methods nor in the scope of the study.
23. The same problem with PCA and Figure 15. The authors have tried to include all analytic methods and increase the content without following the standard article preparation layouts. Adding new evaluation approaches in the middle of results section distracts readers from the outcomes. I recommend either removing PCA analysis or shortening the content of pages 15-24 into two-three pages to select the best scenario(s). You definitely need to define them in Methods and Scope.
24. Again the methods about dynamic lighting control in the middle of results!
25. Table 7: The first study does not have the source. This should not be in Results section if you don't plan to compare with the outcomes of your study.
26. Figure 18 is very useful.
27. General comment for the whole manuscript: remove titles from all your figures.
28. General comment for the whole manuscript: The text is too long with a lot of excessive and redundant content. You have described your methodology, results, and approach taken to produce the results multiple times with different sentences. This is not a standard method of writing.
29. General comment for the whole manuscript: Avoid using — in the text which is basically introduced by ChatGPT.
30. General comment for the whole manuscript: Although they are minor but are important. You must review the whole manuscript to address the grammatical issues with the text. For

example: "**on the (Table 1)**" must be "**in Table 1**", and so on.

31. I'm not sure if you intendedly have provided descriptive text of figures at the last paragraph of each section or it has happened during the submission process. It is highly recommended to solve this issue and bring all descriptions right after where you cite the figure for first time.

References

1. Asgari N, Jamil U, Pearce J: Net Zero Agrivoltaic Arrays for Agrotunnel Vertical Growing Systems: Energy Analysis and System Sizing. *Sustainability*. 2024; **16** (14). Publisher Full Text
2. Asgari N, Basdeo A, Givans J, Pearce J: Lighting and Revenue Analysis of Grow Lights in Agrivoltaic Agrotunnel for Lettuces and Swiss Chard. 2025. Publisher Full Text
3. Asgari N, Saadat S, Pearce J: Technoeconomic Analysis of Indoor Basil Cultivation in Agrivoltaic Agrotunnels with Optimized Near-Zero Energy Systems. 2025. Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?
No

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?
I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Solar PV, HVAC, Indoor Agrivoltaics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 10 Mar 2026

Chrysovalantis Ketikidis

1st Comment: Abstract: include the most significant achievements of the study both in qualitative and quantitative form. Numeric results are rarely included in current

version. Suggested Reply: The abstract has been revised to explicitly include key quantitative outcomes of the study, in line with indexing standards. Numerical results have been added to highlight the achieved carbon footprint (median 3.67 kg CO_2 kg^{-1} of lettuce), the range of crop cycle durations (34–52 days), the contribution of photovoltaic energy to annual electricity demand in optimized scenarios, and the maximum lighting reduction (up to 10%) achievable without increasing total energy consumption. These additions improve the clarity and visibility of the study's main achievements while preserving the concise structure of the abstract.

2nd Comment: Introduction: The literature review is too weak and completely unacceptable. Add the reviewed findings of recent and relevant research. Look at our recent research and the reviewed studies in them:

- Reference 1: https://www.mdpi.com/2071-1050/16/14/6120
- Reference 2:https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5104787
- Reference 3:https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5775183

Suggested Reply: The Introduction has been substantially revised to strengthen the literature review, incorporating recent and relevant studies on PV-integrated controlled-environment agriculture, lighting optimization, and technoeconomic assessments, including the works suggested by the reviewer. The revised text now explicitly discusses the contributions and limitations of these studies and clearly positions the present work within the identified research gap, namely the lack of an integrated, scenario-based framework linking seasonal renewable availability, crop cycle timing, and operational flexibility with resilience and grid-dependency indicators.

3rd Comment: Scope of the study: in the text: "...electricity consumption per unit of yield (expressed in kWh/kg) ..."; The technical term for this variable is Specific Energy Consumption (SEC).
Suggested Reply: The manuscript has been revised to adopt the standard terminology Specific Energy Consumption (SEC) for electricity consumption per unit of harvested yield. SEC (kWh kg^{-1}) is now defined at its first occurrence in the Scope of the Study, and the term is used consistently throughout the manuscript.

4th Comment: Scope of the study: Use the last paragraph of this section, "This schematic shows the pilot .... was provided by the manufacturer." as a description for the Figure 1, right after the place you cite this figure for first time. The same issue is for Figure 2 and the last paragraph of section 3.1. All other figures have the same problem. Their description has been fell apart from their first citing location in the text. Suggested Reply: The manuscript has been revised to address this issue for all figures. Specifically, the descriptive text previously placed as standalone paragraphs at the end of sections has now been relocated to the body text, immediately following the first citation of each figure (Figures 1–19). This ensures that each figure is introduced and described at its first point of reference in accordance with standard publishing and indexing practices.

5th Comment: Methodology: "... where PV supply is directed first to loads, then to the

battery, and finally to the grid".
Suggested Reply: Then was added to the manuscript

6th Comment: The introductory descriptions before section 3.1 are repetitive, redundant and sometimes ambiguous. You need to make them short, sharp and to the point, and instead, bring more details in the following sections.
Suggested Reply: The introductory part of the Methodology section has been substantially revised to improve clarity and conciseness. The text was shortened and restructured to provide a clear overview of the methodological workflow without repeating detailed information. Descriptive and technical details previously included in the introductory paragraphs were relocated to the corresponding subsections (Sections 3.1-3.8), where they are discussed in a more structured manner. The revised introduction now briefly outlines the sequence of methodological steps, including cultivation procedure definition, system setup, scenario development, dynamic simulation, resilience indicator formulation, multivariate scenario classification, carbon footprint estimation, and adaptive lighting control, allowing the reader to better follow the analytical framework of the study.

7th Comment: Methodology: why have you done a lit review in Section 3.1? ("Ch. Vatistas et compared the lettuce cultivation between GHs and VFs and presents that VFs are more efficient than GHs in terms of yield per unit area, but require more energy to operate"). It is not standard. You must discuss about the previous studies either in the Introduction or the Discussion.
Suggested Reply: The cited comparative statement was removed from the Methodology section and incorporated into the Introduction, in line with standard academic structure, where previous studies and contextual background are discussed.

8th Comment: Methodology: In the second paragraph of section 3.1: You need to justify your claims about the 16-hour photoperiod by providing sufficient information about PPFD and more importantly DLI.
Suggested Reply: The justification of the 16-hour photoperiod was strengthened by explicitly linking photoperiod, PPFD, and daily light integral (DLI), using the literature data already summarized in Table 2. The revised text clarifies that the applied lighting conditions correspond to DLI ranges commonly reported for lettuce cultivation in vertical farming and indoor controlled-environment systems.

9th Comment: Methodology: Table 1, Battery voltage is 2? You have mentioned that your case was 24 volts. Please indicate the specifications for your case.
Suggested Reply: The battery system operates at a nominal voltage of 24 V. The value of 2 V reported in Table 1 corresponds to the nominal voltage of individual battery cells. This clarification has been added to the System setup section to explicitly describe the series-connected 2 V cell configuration forming the 24 V battery bank.

10th Comment: Methodology: "Harvest took place at physiological maturity (~120–150 g fresh weight per head), …". What is your reference for this?
Suggested Reply: The reported harvest weight of ~120–150 g per head corresponds to physiological maturity observed in the pilot vertical farming unit used in this study and is consistent with values commonly reported in the literature for lettuce cultivated under

controlled-environment and vertical farming conditions. This clarification and supporting reference have been added to the revised manuscript.

11th Comment: Methodology: "Vertical farming system is realized in ISOBOX with galvanized metal construction…". This is first time that you have talked about an ENCLOSURE in your text. This is important information which justifies the necessity for your HVAC system. You need to provide all basic and important information about your system in section 2. Scope of the study. You should assume that the readers DO NOT KNOW ANYTHING about your research. Hence, you should try to visualize the construction and the concept of your study in all introductory sections such as Abstract, Last paragraph of Introduction, Scope of the study, and Methodology.
Suggested Reply: Scope of the study was enhanced to explicitly explain why the fully enclosed nature of the vertical farming unit necessitates continuous HVACD operation. The revised text clarifies that internal sensible and latent heat loads from lighting and crop transpiration cannot be passively dissipated, making active climate control a functional requirement rather than a design choice. Brief contextual references to the enclosed system have also been added to the Abstract and Introduction.

12th Comment: Section 3.1: "All these components of the VF system are presented on the (Table 1) in the Manuscript Tables section". What do you mean by mentioning "Manuscript Tables section"?
Suggested Reply: The reference to a "Manuscript Tables section" was introduced during the submission process, where all tables were required to be extracted from the main text and compiled after the References section. To avoid any confusion for the reader, this wording has been removed, and the text now refers directly to Table 1, which presents the technical components of the vertical farming system.

13th Comment: Methodology: the resolution of Figure 3 & 4 is extremely low! You must replace them.
Suggested Reply: The resolution of Figures 3 and 4 has been improved in the revised manuscript. Both figures have been replaced with high-resolution versions to ensure better readability of the graphical elements and labels.

14th Comment: Methodology: there is a lot of repetitive content in the Methodology section. You need to shorten them and make them to the point and mentioned once at the right place.
Suggested Reply: The Methodology section has been carefully revised to reduce repetitive content and improve clarity and conciseness

15th Comment: Table 3: "No significant effect on crop duration" should be "No significant effect on crop cycle duration".
Suggested Reply: The word cycle was added in Table 3

16th Comment: Crop Cycle function: Photoperiod alone is not the only affecting parameter of lighting system, PPFD, thereby DLI matters a lot. You MUST indicate that this equation (fitted curve) is only valid for the controlled PPFD range of XXX-YYY, whatever is in your study.

Suggested Reply: The validity range of the crop cycle regression model has now been explicitly clarified in the manuscript. Equation (3) is stated to apply only within the controlled PPFD (200–350 μmol·m^{-2}·s^{-1}) range investigated in this study, avoiding extrapolation beyond the examined lighting conditions.

17th Comment: Figure 4: This plot is not scientifically acceptable. The angle of plot does not provide sufficient information about the surface behavior. Rotate the plot to present the surface in an appropriate angle.
Suggested Reply: The figure has been revised with an adjusted elevation and azimuth to better illustrate the linear gradient of crop cycle duration as a function of photoperiod and Δ T. Additionally, contour projections have been added to improve interpretability. The revised figure now clearly demonstrates the dominant influence of photoperiod and the secondary effect of temperature differential.

18th Comment: Figure 5: Completely non-readable titles and tick mark labels. Must be replaced. Instead of addressing like top left corner, it is recommended to separate them into four a, b, c, and d and address them like Figure 5a, etc.
Suggested Reply: Figure 5 has been reformatted to improve readability, with enlarged axis labels and tick marks. The panels have been separated and clearly labeled as Figure 5a–d, and the manuscript text has been updated accordingly.

19th Comment: Figure 5: This figure is actually part of results and along with all discussions provided MUST be transferred to Section 4. Same issue with Table 5 and the corresponding discussions.
Suggested Reply: Figure 5 and its associated interpretative discussion have been removed from the Methodology section and transferred to Section 4 (Results), where the dynamic annual system behavior is now presented under Section 4.1. The related descriptive content has been substantially condensed to focus strictly on result interpretation rather than methodological explanation. Similarly, Table 5 and its corresponding discussion of scenario-specific CO_2 emissions have been relocated from Section 3.4 to Section 4.3. The Methodology section (3.4) now includes only the LCA framework, system boundaries, emission factors, and calculation approach, while all quantitative outcomes and their interpretation are presented exclusively in the Results section.

20th Comment: Section 3.4: Long form of LCA must be defined at first-time-use place.
Suggested Reply: he full term “Life Cycle Assessment (LCA)” has now been defined at its first occurrence in Section 3.4. The term “Global Warming Potential (GWP)” has also been clarified accordingly.

21th Comment: Figure 6 needs to have axes titles.
Suggested Reply: Axis titles have been added to Figure 6, including “Month” on the x-axis and “PV Energy Production (kWh)” on the y-axis, improving clarity and readability.

22th Comment: Figure 8: low quality-no unit mentioned! Avoid using AI to refine the pictures. You do not have to do that. The exports from Microsoft Excel, Python or other softwares can be still of good quality.
Suggested Reply: The unit (kWh) has now been explicitly added to the color scale of Figure

8.

23th Comment: Equations 4-6: Put references
Suggested Reply: Equations (4) to (6) represent performance indicators formulated within the scope of the present study. These indices are derived directly from annual and monthly energy balance relationships obtained from the TRNSYS simulation outputs and were developed to quantify grid independence and seasonal PV resilience across scenarios. They do not correspond to previously published closed-form equations but are ratio-based indicators grounded in standard energy balance principles commonly applied in distributed energy system analysis. To clarify this, additional explanatory text has been added in Section 4.2 explicitly stating that these metrics are study-specific derived indicators.

24th Comment: Resilience and equations 4-6 must have been introduced in the Methods section. You have not mentioned anything about this investigation approach neither in methods nor in the scope of the study.
Suggested Reply: In the revised manuscript, the resilience assessment framework has been clearly introduced in the Methodology section. The Grid Independence Index (GII) and Seasonal Resilience Score (SRS) are now formally defined prior to their application in the Results section, and Equations (4) - (6) have been relocated accordingly. Additionally, the cycle-based resilience evaluation and the classification of scenarios into descriptive energy-performance typologies are now described in the Methods section to ensure a clear separation between methodological formulation and result interpretation. The Results section (Section 4.2) now focuses exclusively on the interpretation of the resilience maps and scenario performance, without introducing new analytical formulations.

25th Comment: The same problem with PCA and Figure 15. The authors have tried to include all analytic methods and increase the content without following the standard article preparation layouts. Adding new evaluation approaches in the middle of results section distracts readers from the outcomes. I recommend either removing PCA analysis or shortening the content of pages 15-24 into two-three pages to select the best scenario(s). You definitely need to define them in Methods and Scope.
Suggested Reply: In the revised manuscript, the PCA-based analysis has been substantially streamlined and structurally reorganized to improve clarity and alignment with standard article preparation layouts. First, the methodological description of the PCA and k-means clustering procedure has been moved to the Methodology section, where the input variables, dimensionality reduction approach, and clustering framework are now clearly defined prior to their application. This ensures that the analytical approach is introduced within the scope of the study before being interpreted in the Results section. Second, the PCA-related content in the Results section has been significantly condensed. Redundant explanations of principal component behavior and cluster characteristics have been removed, and the discussion has been limited to the interpretation of the projection and its implications for scenario classification. The revised section now focuses on how PCA complements the resilience framework rather than introducing an independent analytical layer.

26th Comment: Again, the methods about dynamic lighting control in the middle of results!

Suggested Reply: In the revised manuscript, the methodological framework of the dynamic lighting control strategy has been fully transferred to the Methodology section (new Section 3.8: *Dynamic Lighting Control on Energy and Crop Cycle Duration*). All threshold definitions for low-PV ("cloudy") day detection, regression relationships linking photoperiod reduction to crop cycle extension, and the corresponding mathematical formulations (Equations 7–10) are now clearly introduced prior to their application. The Results section (Section 4.5) has been revised accordingly and now focuses exclusively on the interpretation of scenario-level flexibility outcomes and cluster-based performance comparisons, without introducing new analytical formulations.

27th Comment: Table 7: The first study does not have the source. This should not be in Results section if you don't plan to compare with the outcomes of your study.
Suggested Reply: The first study presented in Table 7 is properly referenced, as indicated in the "Source" column ([3]). The three production systems (vertical farming, greenhouse, and open-field) correspond to the same referenced study and are therefore grouped under the same citation. No unreferenced data are included in the table.

28th Comment: Figure 18 is very useful
Suggested Reply: We sincerely thank the reviewer for this positive feedback. Figure 18 was intentionally designed to provide a clear comparative visualization of the modeled carbon footprint results against literature benchmarks, thereby facilitating direct interpretation of the environmental performance of the examined scenarios. We are pleased that the reviewer found it useful in supporting the overall analysis and conclusions of the study.

29th Comment: General comment for the whole manuscript: remove titles from all your figures.
Suggested Reply: All in-figure titles have been removed from the manuscript.

30th Comment: General comment for the whole manuscript: The text is too long with a lot of excessive and redundant content. You have described your methodology, results, and approach taken to produce the results multiple times with different sentences. This is not a standard method of writing.
Suggested Reply: The entire manuscript has been carefully revised to improve conciseness and eliminate redundant descriptions.

31st Comment: General comment for the whole manuscript: Avoid using — in the text which is basically introduced by ChatGPT.
Suggested Reply: All — where replaced.

32nd Comment: General comment for the whole manuscript: Although they are minor but are important. You must review the whole manuscript to address the grammatical issues with the text. For example: "on the (Table 1)" must be "in Table 1", and so on.
Suggested Reply: The entire manuscript has been carefully reviewed to correct grammatical and stylistic inconsistencies

33rd Comment: I'm not sure if you intendedly have provided descriptive text of figures at the last paragraph of each section or it has happened during the submission

process. It is highly recommended to solve this issue and bring all descriptions right after where you cite the figure for first time.
Suggested Reply: The manuscript has been carefully revised so that all figure descriptions now appear immediately after their first citation in the text. Redundant or misplaced descriptive paragraphs at the end of sections have been removed or relocated accordingly.

Competing Interests: No competing interests were disclosed.

Reviewer Report 27 November 2025

https://doi.org/10.21956/openreseurope.22555.r62490

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?

Adnan Arshad
Lanzhou University, Lanzhou, China

1. The current title is descriptive but could be more dynamic and precise to immediately capture the reader's interest and better reflect the paper's novel contributions. "Dynamic Energy Optimization in Vertical Farming: A Multi-Scenario Simulation Framework for Climate-Resilient and Low-Carbon Food Production".
2. The abstract effectively summarizes the work but can be strengthened by more explicitly stating the research gap and the novelty of the proposed metrics.
3. Explicitly stating the lack of a "comprehensive framework" in the background justifies the study's necessity.
4. Adding words like "novel" and "as a key innovation" helps flag the paper's original contributions (the new metrics and classification) to time-pressed readers and reviewers.
5. Minor tweaks like changing "life cycle and CO2 emissions" to "life cycle CO2 emissions" and adding "system" after "classification" improve readability and precision.
6. Clarify how the dynamic crop cycle model specifically translates environmental conditions (e.g., light integral from the varied photoperiods, temperature from HVAC setpoints) into a quantitative yield prediction (in kg) for each of the 48 scenarios?
7. Clarify which of these temperature regimes was used as the baseline or setpoint for your 48 operational scenarios? Furthermore, what was the scientific rationale—based on the cited literature or other sources—for selecting one range over the other in defining your model's "optimal" conditions?
8. Revise figures, fig 2, dimensions are not visible
9. You mention that the HVACD system was modeled within TRNSYS 18. Could you please detail the specific control logic implemented for the dehumidification (D) component?
10. What was the specific relative humidity setpoint or control band used to activate dehumidification?

11. How was the latent heat load from the plants and the NFT system quantified and input into the

simulation?
-How was the significant internal heat gain from the LED lighting explicitly integrated into the calculation of the HVAC heating and cooling loads within the TRNSYS model?
-
You state that surplus PV energy was "curtailed or stored locally." For scenarios with battery storage, how was the *grid electricity consumption* specifically calculated? Was it the energy drawn directly from the grid after the PV and battery system failed to meet the load, or was a specific charging/discharging efficiency and degradation factor for the battery accounted for when determining the net grid energy import over the annual cycle? This directly affects the accuracy of the core emissions calculation.
-Revise figures and improve quality.
-Fig. 9 add trend line
-The threshold for identifying "cloudy days" is defined using two different criteria: 1) days below the 10th percentile of annual PV generation, and 2) days more than one standard deviation below the seasonal average.

Could you clarify which of these two criteria was ultimately used to trigger the dynamic lighting reductions? The choice between an annual percentile and a seasonally-adjusted standard deviation would identify significantly different sets of days, potentially leading to different outcomes in both energy savings and the impact on crop cycle duration.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Climate-smart agriculture, digital agronomy

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 10 Mar 2026

Chrysovalantis Ketikidis

1st Comment: The current title is descriptive but could be more dynamic and precise to immediately capture the reader's interest and better reflect the paper's novel contributions. "Dynamic Energy Optimization in Vertical Farming: A Multi-Scenario Simulation Framework for Climate-Resilient and Low-Carbon Food Production
Suggested Reply: The title was revised to be more dynamic and to better highlight the paper's novel contributions. In particular, the revised title explicitly references the proposed Lighting Flexibility Classification and the TRNSYS-based simulation framework, which constitute key methodological innovations of the study.

2nd Comment: The abstract effectively summarizes the work but can be strengthened by more explicitly stating the research gap and the novelty of the proposed metrics.
Suggested Reply: The abstract has been revised to explicitly articulate the research gap addressed by this study, namely the lack of a comprehensive framework linking seasonal renewable availability, crop cycle scheduling, and operational flexibility in vertical farming. In addition, the novelty of the proposed performance metrics and the Lighting Flexibility Classification system is now clearly highlighted to guide readers toward the paper's original contributions.

3rd Comment: Explicitly stating the lack of a "comprehensive framework" in the background justifies the study's necessity.
Suggested Reply: The Background of the abstract was revised to explicitly state the lack of a comprehensive framework in existing studies, thereby strengthening the justification and necessity of the present work.

4th Comment: Adding words like "novel" and "as a key innovation" helps flag the paper's original contributions (the new metrics and classification) to time-pressed readers and reviewers.
Suggested Reply: Explicit terminology was added to the abstract to clearly flag the paper's original contributions, including the proposed performance metrics and the Lighting Flexibility Classification system.

5th Comment: Minor tweaks like changing "life cycle and CO2 emissions" to "life cycle CO2 emissions" and adding "system" after "classification" improve readability and precision**.**
Suggested Reply: Changes were made in the paper.

6th Comment: Clarify how the dynamic crop cycle model specifically translates environmental conditions (e.g., light integral from the varied photoperiods, temperature from HVAC setpoints) into a quantitative yield prediction (in kg) for each of the 48 scenarios?
Suggested Reply: The dynamic crop cycle model was designed to estimate cultivation cycle duration as a function of environmental control parameters (photoperiod and temperature setpoints), rather than to explicitly simulate biomass accumulation. Harvested yield per cultivation cycle (kg) was assumed constant across all scenarios, based on pilot-scale operation data and literature-reported fresh weight at physiological maturity for lettuce grown under controlled PPFD conditions. Environmental parameters therefore influence

quantitative yield indicators indirectly, by modifying crop cycle duration and seasonal timing, which in turn affect total energy consumption and life-cycle CO_2 emissions per kilogram of harvested lettuce. This clarification has been added to the Methodology section.

7th Comment: Clarify which of these temperature regimes was used as the baseline or setpoint for your 48 operational scenarios? Furthermore, what was the scientific rationale—based on the cited literature or other sources—for selecting one range over the other in defining your model's "optimal" conditions?
Suggested Reply: We did not adopt a single temperature regime as a baseline. Instead, the 48 scenarios span a literature-based operational envelope for lettuce cultivation in vertical farming. Heating (12–18 °C) and cooling (20–28 °C) setpoints were selected based on reported optimal and tolerance ranges in controlled-environment agriculture studies. This design choice enables the assessment of energy and resilience trade-offs across realistic operational conditions, rather than benchmarking against a single assumed optimal case.

8th Comment: Revise figures, fig 2, dimensions are not visible
Suggested Reply: Figure 2 was revised so dimensions are visible.

9th Comment: You mention that the HVACD system was modeled within TRNSYS 18. Could you please detail the specific control logic implemented for the dehumidification (D) component?
Suggested Reply: Dehumidification was modeled implicitly as part of the HVAC operation in the single-zone TRNSYS Type 56 model. A relative humidity control band was defined, and when the upper humidity threshold was exceeded, moisture removal was achieved through latent heat removal via the cooling system. No standalone dehumidifier was explicitly modeled; instead, dehumidification energy demand was included in the HVAC cooling load, as calculated by TRNSYS based on zone moisture balance. This clarification has been added to the Methodology section.

10th Comment: What was the specific relative humidity setpoint or control band used to activate dehumidification?
Suggested Reply: Relative humidity was controlled using an upper-limit control strategy. An indoor relative humidity control band of approximately 65–75% was applied, and dehumidification was activated when the upper threshold was exceeded. Moisture removal was achieved via latent heat removal through the HVAC cooling operation, and the associated energy demand was included in the cooling load. This information has been clarified in the Methodology section.

11a th Comment: How was the latent heat load from the plants and the NFT system quantified and input into the simulation?
Suggested Reply: Latent heat loads were quantified based on plant transpiration rather than the NFT system itself. Transpiration rates were taken from literature for indoor lettuce cultivation (0.2–0.5 L $plant^{-1}$ day^{-1}), and the corresponding latent heat was calculated using the latent heat of vaporization of water. This latent load was implemented as an internal latent gain within TRNSYS Type 56, enabling the dehumidification component of the HVACD

system to respond dynamically. The NFT system was not modeled as a separate latent source, since moisture release originates from plant transpiration.

11bth Comment: How was the significant internal heat gain from the LED lighting explicitly integrated into the calculation of the HVAC heating and cooling loads within the TRNSYS model?
Suggested Reply: The electrical power consumption of the LED lighting system was fully treated as internal sensible heat gain within the single-zone Type 56 model. This heat gain was explicitly included in the zone energy balance and directly influenced both heating and cooling loads calculated by the HVAC system. Lighting power profiles varied by scenario according to the defined photoperiods, ensuring that the thermal impact of lighting was dynamically captured throughout the simulations.

12th Comment: You state that surplus PV energy was "curtailed or stored locally." For scenarios with battery storage, how was the *grid electricity consumption* specifically calculated? Was it the energy drawn directly from the grid after the PV and battery system failed to meet the load, or was a specific charging/discharging efficiency and degradation factor for the battery accounted for when determining the net grid energy import over the annual cycle? This directly affects the accuracy of the core emissions calculation.
Suggested Reply: Grid electricity consumption was obtained directly from the quarter-hourly energy flow outputs of the TRNSYS model and represents the portion of electrical demand not covered by on-site PV generation and locally stored energy. Under the adopted self-consumption scheme, PV energy was prioritized to supply on-site loads, while surplus energy was stored or curtailed, with no feed-in to the grid assumed. Annual grid electricity consumption was then used for the CO_2 emissions calculation. Battery degradation was not included, as the study focuses on operational performance over an annual time horizon. The manuscript has been clarified accordingly.

13th Comment: Revise figures and improve quality.
Suggested Reply: All figures have been revised and exported to meet the minimum required quality standards. Specifically, all images are provided at a resolution of at least 300 dpi, with improved clarity of labels, axes, and legends to ensure readability in both digital and print formats. No changes were made to the underlying data or results.

14th Comment: Fig. 9 add trend line
Suggested Reply: Figure 9 has been updated to include a linear trend line. The added dashed line highlights the overall increase in grid dependency across scenarios, improving visual interpretation without altering the underlying data.

15th Comment: The threshold for identifying "cloudy days" is defined using two different criteria: 1) days below the 10th percentile of annual PV generation, and 2) days more than one standard deviation below the seasonal average. Could you clarify which of these two criteria was ultimately used to trigger the dynamic lighting reductions? The choice between an annual percentile and a seasonally-adjusted standard deviation would identify significantly different sets of days, potentially leading to different outcomes in both energy savings and the impact on crop cycle

duration.
Suggested Reply: The final implementation of the dynamic lighting control strategy, a single primary operational criterion was used to trigger lighting reductions. Specifically, cloudy days were identified as days with daily PV generation below the 10th percentile of the annual PV production profile. This percentile-based threshold was selected to ensure a consistent and conservative identification of low-solar-availability days across the entire year. Deviations greater than one standard deviation below the seasonal average were monitored as a supplementary indicator of low-solar conditions during preliminary analysis, but they did not independently trigger lighting reductions in the final simulations. The manuscript has been revised to clarify this distinction and improve methodological transparency.

Competing Interests: No competing interests were disclosed.