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Toward Sustainable Urban Development: An Integrated Energy–Economic–Carbon Optimization Framework for Vertical Farming Buildings

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ABSTRACT

Vertical farming enables high-yield crop production with minimal land use in urban areas, supporting sustainable food systems, but its large energy demand presents a significant challenge. This study employs the vertical farming model developed by the German Aerospace Center to evaluate the impact of integrating passive building design, photovoltaic power systems, and energy storage systems on energy consumption, carbon emissions, and economic performance. By developing a parameter optimization model, the energy system of the vertical farming building can be systematically optimized. Using Shuangliu District in Chengdu, China as the case area, simulation results show that the annual energy consumption of the building is reduced by 84.7 million kWh, and carbon emissions decrease from 82.96 to 36.37 million kg CO_2 per year. The return on investment of the photovoltaic and energy storage systems in vertical farming reaches 11.07, indicating high economic viability alongside significant environmental benefits. These findings confirm the technical and economic feasibility of integrating renewable energy systems and energy storage into vertical farming, advancing its potential as a scalable model for low-carbon, resilient, and sustainable urban agriculture.

Keywords: Energy and economic analysis; Vertical farming buildings; Low carbon emission; Optimization framework; Sustainable urban development

NONMENCLATURE

Abbreviations	
ESS	Energy storage system
PVA	Present value
PVS	Photovoltaic power system
ROI	Return on investment
Symbols	
α	Installation angle correction factor
E	Energy consumption
K	Battery capacity
L	System efficiency factor
T	Transparency rate
η	Battery efficiency

1. INTRODUCTION

As urbanization accelerates, cities are facing challenges such as climate change, food insecurity, and rising urban energy demand. Vertical farming has emerged as a promising approach that utilizes urban land to efficiently produce fresh food for local populations [1]. Closely aligned with the United Nations Sustainable Development Goal 2 (Zero Hunger) [2], it offers a sustainable approach to urban food production and supports the vision of resilient future cities [3]. However, its high dependence on artificial lighting and controlled indoor environments leads to substantial energy consumption, raising concerns about its long-term sustainability [4].

Currently, considerable research has focused on developing energy-efficient vertical farming systems. Combining renewable energy systems, particularly photovoltaics [5], with vertical farming buildings has been proposed as a feasible solution to the high energy demand. The use of transparent photovoltaic panels on building façades has demonstrated superior energy-generation potential compared to rooftop photovoltaic systems alone [6]. Solar energy can also serve as a thermal resource; for instance, solar-driven combined cooling, heating, and power (CCHP) systems have achieved energy efficiencies of up to 14.62% when applied to vertical farms [7]. Moreover, incorporating large-scale vertical farming into urban energy systems, alongside wind power and demand response strategies, can reduce electricity costs and improve the utilization of local renewable energy [8]. Along with its high energy consumption, significant carbon footprint of vertical farming building cannot be ignored. Studies have shown that its baseline carbon footprint can be 5.7 to 16.7 times higher than that of open-field farming and conventional greenhouse horticulture [9]. Nonetheless, integrating

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vertical farming with advanced sustainable technologies can not only mitigate energy use and carbon emissions [10], but also contribute to lower indoor CO_2 concentrations through the natural photosynthetic activity of plants [11]. Overall, a holistic evaluation that collectively considers energy use, environmental impact, and economic viability is essential for advancing sustainable vertical farming practices [12]. Such integrated research enables a deeper understanding of how vertical farming systems can contribute to meet broader sustainability goals in urban contexts [13, 14].

This study addresses the urgent challenge of high energy demand in vertical farming by proposing an integrated approach that combines passive building design, solar panels, and on-site energy storage, and offers a novel, system-level strategy for achieving low-carbon and economical urban agriculture. This paper is structured as follows. Section 2 outlines the methodology, detailing the calculation approaches for assessing energy consumption, economic performance, and carbon emissions when vertical farming buildings are optimized through passive design, photovoltaic energy system (PVS), and energy storage system (ESS). Section 3 introduces the implementation of these methods using the EDEN vertical farming building, simulated via the Grasshopper digital platform, and presents the results, followed by the conclusion in Section 4.

2. METHODOLOGY

2.1 Vertical Farming Model

This study uses the feasible vertical farming study proposed by the Evolution and Design of Environmentally-closed Nutrition-Sources (EDEN) Labor of German Aerospace Center [15] as the theoretical model. Figure 1 shows the outer and inner structure of this building. This model has systematically researched the crop yield, water and nutrient consumption, LED and total energy consumption, costs and profits, etc.

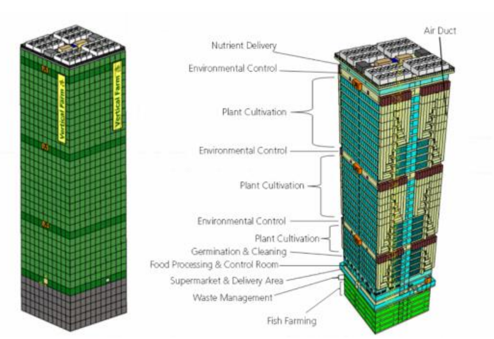

Fig. 1 Structure of Vertical Farming building

In the original EDEN vertical farming model, ten different crop types were considered, including cabbage. In our study, we simplify the system into a mono-crop vertical farming model focusing only on cabbage. Table 1 presents the adjusted parameters of the EDEN vertical farming building adapted for cabbage cultivation in Shuangliu, Chengdu.

Table 1. Vertical farming building parameters

Parameters	***Unit***	***Data***
Footprint	*m²*	*44*44*
Floor-to-floor height	*m*	*4.5*
Number of floors	*floors*	*25*
Total building area	*m²*	*48,400*
Total growth area for plants	*m²*	*92,718*
Daily lighting hours	*hours*	*12*
LED peak power	*Wh/m²*	*230*
Temperature for cabbage cultivation	*℃*	*10-22*
Humidity for cabbage cultivation	*%*	*65-80*
Average ventilation demand	*m³/m²·s*	*0.00518*
Total plant biomass yield	*ton/year*	*4,854*
Total energy consumption	*Gwh/year*	*150.84*

2.2 Optimization Framework

2.2.1 <u>Passive Building design concept</u>

This study integrates passive design strategies into the exterior facade of a vertical farming building to enhance energy efficiency and reduce dependence on artificial lighting. Transparent photovoltaic panels are incorporated into open windows on 80% of the south, east, and west sides, allowing for simultaneous natural lighting and electricity generation. Unlike conventional fully enclosed vertical farms, this design introduces controlled daylight on each floor. Based on sun path and irradiance analysis for Chengdu, the building's orientation and window placement are optimized to maximize daylight utilization. A real-time light intensity monitoring system activates supplemental LED lighting when illumination falls below 230 W/m². Additionally, waste heat from the LED panels is partly recovered to support the building's heating demand.

2.2.2 <u>Vertical Farming Optimization Methods</u>

This section introduces the methodology used to calculate the total energy demand, economic performance, represented by the return on investment (ROI) in this study, and carbon emissions of the vertical farming building.

(1) Total energy demand

In this study, two scenarios are proposed to enable comparative analysis between a baseline vertical farming system without passive building design, PVS or ESS (S1) and an optimized version integrated with passive building design, PVS and ESS (S2).

$$\boldsymbol{E_{S1} = E_{lighting} + E_{heating} + E_{cooling} + E_{ventilation} + E_{\text{humidity\_control}}} \quad (1)$$

$$\boldsymbol{E_{lighting} = P_{lighting} h_{lighting} A_{\text{building}}} \quad (2)$$

Where the $P_{lighting}$ is the peak power demand of LEDs; $h_{lighting}$ is the daily lighting hours; $A_{building}$ is the total building area. It is assumed that each square meter of the building is equipped with one LED panel.

$$\boldsymbol{E_{S2} = E_{\text{passive}} - E_{PVS-direct} - E_{battery-dis}} \quad (3)$$

$$\boldsymbol{E_{PVS} = E_{PVS,facade} + E_{PVS,rooftop}} \quad (4)$$

$$\boldsymbol{E_{PVS} = 365 \frac{A_{usable}}{1.1 A_{panel}} P_{panel} h_{sunlight} L(1-T)\alpha} \quad (5)$$

$$\boldsymbol{E_{battery-dis} = 250\mathrm{K}\eta_{battery} DoD} \quad (6)$$

$$\boldsymbol{E_{battery-ch} = \frac{E_{battery-dis}}{\eta_{battery} DoD}} \quad (7)$$

$$\boldsymbol{E_{PVS-direct} = E_{PVS} - E_{battery-ch}} \quad (8)$$

Here, the E_{passive} is the improved energy consumption after implementing passive building design concept, which will be simulated in Grasshopper platform in the next section; E_{PVS} represents the total electricity generated by all photovoltaic panels, including façade and rooftop panels; $E_{PVS-\text{direct}}$ is the portion of electricity directly supplied by the PVS during the daytime; A_{usable} is the usable area for installing solar panels. The factor 1.1 accounts for the required spacing between solar panels, representing a 10% increase in effective area per panel. P_{panel} is the peak power of solar panels; $h_{sunlight}$ is the peak sunlight hours in Chengdu. $E_{\text{battery-dis}}$ represents the amount of energy discharged from the battery to support the system load. In this study, a lead-acid battery is used in ESS. The battery is assumed to operate under moderate use conditions, with 250 charge-discharge cycles per year. DoD is the battery discharge depth.

The following table 2 shows the parameters for solar panels and battery.

Table 2. Solar panel and battery parameters

Parameters	***Unit***	***Value***
Peak power of solar panel	*W*	*210*
Solar panel size	*mm*	*L1200*W1800*D34*
System efficiency factor	*%*	*85*
Transparent rate for façade PVS	*%*	*30*
Installation angle correction factor	*-*	*0.37 for façade PVS; 0.95 for rooftop PVS*
Peak sunlight hours in Chengdu	*hours*	*5*
Battery efficiency	*%*	*85*
Battery capacity (Battery capacity meets 12h emergency lighting)	*Mwh*	*256*
Battery discharge depth	*-*	*0.8*

(2) Economic analysis (ROI)

In this section, we assess the economic viability of implementing PVS and ESS within an existing vertical farming facility. The analysis specifically focuses on the return on investment (ROI), based on net present value, to evaluate the financial impact of integrating these optimization strategies. As the building is assumed to be already constructed, the initial capital costs of the vertical farming structure itself are excluded, allowing the analysis to isolate the economic contribution of the PVS and ESS systems.

$$\boldsymbol{ROI = \frac{PVA_{\text{income}} - PVA_{cost}}{PVA_{cost}}} \quad (9)$$

$$\boldsymbol{PVA_{cost} = C_{\text{init}} + \sum_{t=1}^{n} \left(\frac{C_{O\&M,t} + C_{replace,t}}{(1+i)^t}\right) - \frac{S_{residual}}{(1+i)^n}} \quad (10)$$

$$\boldsymbol{PVA_{income} = \sum_{t=1}^{n} \frac{R_{energy-saved,t} + R_{subsidy,t}}{(1+i)^t}} \quad (11)$$

$$\boldsymbol{C_{\text{init}} = C_{PVS} + C_{battery} + C_{inverter}} \quad (12)$$

In the above equations, C_{init} is the initial cost of installing PVS and ESS. $C_{O\&M,t}$ is the operation and management costs per year (assumed 0.5% of the total initial costs), $C_{replace,t}$ is the replacement cost of battery and inverter (e.g. replacement every 10 years).

$S_{residual}$ is the final residual value (assumed 20% of the PVS costs). $R_{energy-saved,t}$ is the electricity cost saved by PVS and ESS per year; $R_{subsidy,t}$ is the subsidy per year (assumed 0.05 €/kWh × annual photovoltaic power generation). n presents the total system lifespan, which is assumed to be 25 years in this study; The parameter i denotes the annual discount rate, set at 10%. The variable t refers to each year within the evaluation horizon. The unit cost of solar panel installation is €0.37/W; The average electricity cost in Chengdu is 0.08€/kWh. Notice that the $C_{replace,t}$ equals to 0 when $t \neq 10, 20$.

(3) Carbon emissions

Vertical farming systems require high energy for lighting, HVAC, and environmental control, leading to significant carbon emissions, particularly when powered by fossil-fuel-based grids. Integrating on-site PVS and ESS provides a viable solution to reduce the reliance on grid electricity and thereby lower the overall carbon footprint. The following equations illustrate the carbon emission calculations under two scenarios.

$$\boldsymbol{Emission_{S1} = E_{S1} EF} \tag{13}$$

$$\boldsymbol{Emission_{S2} = (E_{\mathbf{passive}} - E_{PVS-\mathbf{direct}} - E_{baettery-dis})EF} \tag{14}$$

Here, EF is the emission factor of the electricity grid in Chengdu, which is assumed to be 0.55 kg CO_2 per kWh.

3. RESULTS

3.1 Simulation of Passive Building Design Performance

Grasshopper, a visual programming and parametric design tool integrated with Rhinoceros 3D, is utilized in this study as the primary simulation platform for evaluating the performance of the passive-design vertical farming building. In this research, it facilitates the import of meteorological data and solar radiation data specific to Chengdu, simulation of heating, cooling, lighting, ventilation and humidity control demands (denoted as E_{passive}) and the development of an optimized vertical farming model. Simulation results show that the annual energy consumption of the vertical farming building after optimization through passive building design is 110.33 GWh, representing a reduction of 40.51 GWh or approximately 26.87% compared to the original consumption of 150.84 GWh.

3.2 Comparison of Energy Consumption and Carbon Emission Results

Table 3 presents a comparison of energy consumption and carbon emissions under two scenarios. The total energy consumption comprises both lighting and environmental control, with the latter including cooling, heating, humidity control, and ventilation within the vertical farming system.

Table 3. Comparison of Energy Consumption and Carbon Emissions Between Scenarios

Factors (Gwh/year)	***S1***	***S2***
Lighting	*48.76*	*4.56*
Cooling	*102.08*	*38.54*
Heating		*15.25*
Humidity control		*5.92*
Ventilation		*1.86*
Energy consumption total	*150.84*	*66.14*
Carbon Emissions (kilotons/year)	*82.96*	*36.37*

As shown in Table 3, the integration of passive design, PVS and ESS significantly reduces the net annual electricity demand of the building from 150.84 GWh to 66.14 GWh, representing a 56.15% decrease. Lighting demand is reduced by over 90% through daylighting and renewable energy strategies, including contributions from both PVS and ESS discharge. Here, energy savings refer to reductions in electricity drawn from the external grid, reflecting net import reductions rather than total load. These results show the effectiveness of integrating architectural design with renewable energy systems to enhance the energy performance of vertical farming buildings. In terms of carbon emissions, the baseline scenario results in approximately 82.89 million kg of CO_2 annually. With the optimized scenario, emissions are reduced to 36.37 million kg, with a decrease of 46.52 million kg or 56.2%. This significant reduction highlights the climate mitigation potential of combining renewable energy and storage in high-density urban farming systems.

Figure 2 shows the overall energy consumption, a detailed breakdown of energy use by category under the optimized scenario, and the stepwise carbon emission reductions enabled by passive design, photovoltaics, and storage. It can be observed that cooling constitutes the largest share of energy demand in vertical farming, due to the need to maintain optimal temperatures for plant growth and to offset the substantial waste heat generated by LED lighting. This underscores the importance of waste heat recovery as a critical component in the energy system of vertical farming.

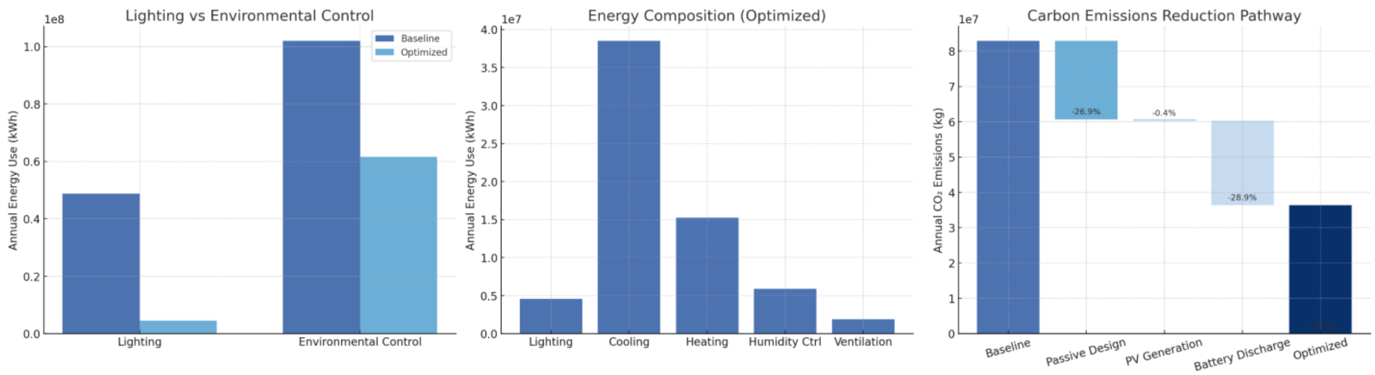

Fig. 2 Energy Use Breakdown and Carbon Emission Reduction Pathway in Vertical Farming System

3.3 Economic performance results

Table 4 below summarizes the key cost and income parameters used in the financial evaluation of the installed PVS and ESS and the results.

Table 4. Cost, income, and return analysis for the optimized PVS and ESS

Category	***Item***	***Value (in Euros)***
Costs	*Total initial costs*	*2,160,360*
	Operation and management costs per year	*10,801.80*
	Replacement cost of battery and inverter	*1,632,000*
	Final residual value	*105,672*
Income	*Electricity costs saved by PVS and ESS per year*	*3,535,522.16*
	Subsidy per year	*33,701.35*
Return	***ROI***	*11.07*

The results presented in Table 4 indicate that the ROI for the newly installed PVS and ESS in the vertical farming building reaches 11.07, reflecting strong economic performance under the optimized scenario. The income from electricity savings and subsidies is enough to cover the system costs and still deliver a solid return. This demonstrates that integrating PVS and ESS not only reduces long-term operational costs but also yields a competitive return on investment, reinforcing the financial feasibility of low-carbon energy strategies in vertical farming applications.

Sensitivity analysis, as shown in figure 3, illustrates that electricity price emerged as the most influential factor. Solar panels and battery costs also show moderate sensitivity, indicating that cost reductions in these components can enhance project profitability. In contrast, the O&M rate and government subsidy have relatively limited influence on the overall ROI.

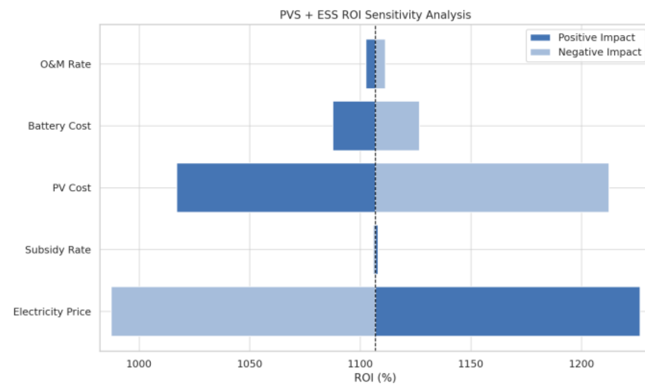

Fig. 3 Sensitivity analysis of ROI

3.4 Discussion

In our study, the battery is fully charged from the external power grid, potentially sourced from Sichuan's abundant hydropower. This not only facilitates low-carbon energy integration but also helps balance seasonal variability in hydroelectric output. Beyond reducing grid dependency, energy storage enhances operational resilience by maintaining crop lighting during outages, thereby ensuring yield stability. Additionally, it supports peak-valley load shifting to improve economic performance and grid efficiency, strengthening the overall sustainability of the system. The integration of further clean energy sources and advanced storage strategies will be a key focus of future research.

From a financial perspective, the integration of PVS and ESS demonstrates strong economic potential, as the high ROI reflects substantial long-term savings and favorable investment performance. It should be noted that this analysis focuses only on the added sustainability measures, assuming the vertical farming facility is already in place. A full assessment of the entire optimized vertical farming system would need to include the building's electricity demand as a cost and crop sales as part of the revenue. Our findings suggest that, due to its high energy consumption, vertical farming is not essentially cost-effective. However, with policy support such as a 50% subsidy on the initial PVS and ESS investment, the system could become financially viable.

4. CONCLUSIONS

This study proposes and validates an integrated optimization framework for vertical farming buildings that addresses energy and economic performance, and environmental impact through the combined application of passive building strategies, photovoltaic systems, and energy storage. The simulation-based comparison between baseline and optimized scenarios reveals that vertical farming, when supported by system-level energy strategies, can function not only as a sustainable food production unit to ensure local food security, but also as a low-carbon, energy-efficient urban infrastructure. The ability of the PVS and ESS system to generate substantial returns when integrated into vertical farming highlights its potential as a financially viable enhancement to urban agricultural infrastructure. These findings demonstrate that energy-integrated vertical farming can contribute meaningfully to the goals of sustainable urban development by aligning high-density food production with environmental responsibility, economic resilience, and spatial efficiency.

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