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Urban microclimate modeling for side-facade farming and agrivoltaic deployment in town estates

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ABSTRACT

Singapore, a highly urbanized island city with limited land and agricultural space, faces significant challenges due to climate change and the urban heat island effect (UHIE). This study investigates the feasibility and potential benefits of integrating vertical farming (VF) on building facades and agrivoltaic (AV) systems on the rooftops of public housing (HDB) estates as sustainable solutions. To evaluate local microclimatic conditions, solar irradiance mapping was conducted using ClimateStudio across three HDB estates, representing both old and new buildings, to identify suitable facade surfaces for VF systems. The irradiance data were further analyzed using an energy balance equation to assess surface temperatures, while additional parameters such as Daily Light Integral (DLI) and Photosynthetically Active Radiation (PAR) were incorporated to determine facade suitability for crop cultivation. The simulation results indicate that VF systems on HDB facades provide a substantial cooling effect by reducing heat transfer into buildings through the replacement of conventional materials with vegetation. This effect contributes to lower internal temperatures and enhances urban thermal comfort. Suitable crops were identified based on facade conditions: (i) green pepper, suitable for high-light environments; (ii) cabbage, ideal for mid-rise facades; and (iii) lettuce, which thrives in shaded areas.

Additionally, the study examined the design and feasibility of modular AV systems on HDB rooftops using Grasshopper and PVSyst simulation software. Various AV configurations were evaluated to optimize agricultural productivity and solar energy generation. Findings suggest that incorporating crops within AV systems not only supports food production but also enhances photovoltaic efficiency by mitigating panel temperatures. The combined implementation of VF and AV systems presents a promising strategy for reducing carbon emissions associated with vegetable transportation, contributing to urban sustainability goals. This research demonstrates the feasibility and benefits of deploying VF and AV systems on HDB buildings, supporting Singapore's objectives for food security, renewable energy, and climate resilience.

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1. Introduction

Global warming, primarily driven by greenhouse gas emissions, poses significant threats to coastal regions, including Singapore and other coastal nations, through rising sea levels. Additionally, the Urban Heat Island (UHI) effect has contributed to increased temperatures in residential estates compared to natural catchment areas within Singapore.

Urban infrastructure, characterized by impervious surfaces, inhibits natural water flow and evaporation processes. Consequently, surfaces such as concrete, metallic, or glass facades lack mechanisms for effective cooling. The physical properties of building materials, including their texture and color, influence their ability to reflect or absorb solar radiation.

Dull-colored and rough-textured materials, such as cement and asphalt, tend to absorb the full solar spectrum, converting it into heat. Current mitigation initiatives include the implementation of green roofs [1] and the application of cool paint, which has been demonstrated to alleviate heat absorption [2]. By implementing these initiatives, urban planners and policymakers can effectively address the challenges posed by global warming and the UHI effect, thereby enhancing the livability and sustainability of coastal cities like Singapore.

Green roofs encompass any type of roof design incorporating green technology. These technologies include vegetated roofs [3], cool roofs, and roofs equipped with solar panels for energy capture [4]. The green roof strategy represents a sustainable design approach addressing multiple urban environmental challenges. It effectively reduces stormwater runoff, provides additional greenery, improves urban air quality, and contributes to carbon dioxide sequestration. Furthermore, green roofs alleviate the burden on water treatment facilities, enhance the quality of water runoff, and reduce energy consumption for cooling due to their innovative structural designs tailored to the surrounding environment and climatic conditions [5].

Interest has also grown in exploring green walls, which can be applied to both interior and exterior surfaces of buildings. Green walls offer several benefits related to

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temperature regulation. The plants on green walls provide direct shading, thereby lowering surface temperatures by reducing the amount of solar radiation absorbed by building surfaces. Through photosynthesis and evapotranspiration, plants on green walls reduce the amount of heat transferred to the building structure.

Additionally, green walls act as thermal buffers, absorbing and dissipating heat during the day and releasing it at night to moderate temperature fluctuations [6].

Evapotranspiration, the process by which water is transferred from the land to the atmosphere via evaporation from the soil and other surfaces and transpiration from plants, plays a crucial role in cooling. During evaporation, heat energy is absorbed by water molecules, converting them to an energized gaseous state, which removes heat from the surrounding air. This process helps cool both the air and building surfaces, creating a cooler microclimate that contributes to mitigating the overall urban heat island effect.

Food security remains a critical concern for urban dwellers in Singapore. Since gaining independence, Singapore has had to relinquish farmland to accommodate industrialization and commercialization. With limited land available, competition between housing and farming projects is inevitable.

The COVID-19 pandemic served as a wake-up call for Singapore, highlighting the vulnerabilities in global supply chains and underscoring the importance of self-sufficiency in food production. As approximately 90% of Singapore's food supplies are imported, the country remains susceptible to supply disruptions caused by natural disasters and global crises. Achieving food self-sufficiency is essential for both social stability and economic growth [7].

Long-distance food imports significantly contribute to greenhouse gas emissions, prompting Singapore to aim for a reduction in its carbon footprint related to food transportation by increasing local food production. Annually, global food miles account for 3 billion tons of carbon dioxide (CO_2) equivalent emissions. Urban countries, which represent only 12.5% of the world's population, are responsible for 52% of international food miles and 46% of the associated emissions [8].

A study published in 2021 indicates that fruits and vegetables account for over one-third of annual transport emissions, despite constituting one-fifth of global food miles. This disparity arises because fruits and vegetables require intensive refrigeration throughout their transportation and have substantial weight compared to other food types. Transitioning to a purely domestic food supply could reduce food-miles emissions to 0.27 billion tons of CO_2 equivalent [9]. The absence of vegetation in urban areas contributes significantly to the establishment of the Urban Heat Island (UHI) effect, markedly increasing thermal stress for residents. Mitigation strategies are, therefore, essential to reduce urban heat, particularly in the context of urbanization, anthropogenic warming, and the increasing frequency and intensity of heatwaves. In this study, we propose the application of urban microclimate modeling for the residential areas of Ang Mio Kio, focusing on the integration of vertical farming (VF) on building facades and agrivoltaic (AV) systems on the roofs of public housing (HDB) estates.

The feasibility of incorporating vertical farming on rooftops as well as on the side facades of buildings is evaluated based on its yield potential. Furthermore, the impact of implementing agrivoltaic farm systems on cooling and the reduction of the UHI effect is analyzed and assessed in this work.

2. Materials and methods

2.1. Construction of 3D model with solar irradiance analysis

This study involved the creation of 3D models for two housing estates in Ang Mo Kio, Singapore, using ClimateStudio, a plugin for Rhino 7, and SketchUp. The housing estates examined are Cheng San Crest and Ang Mo Kio Town Estate Avenue 1 & 6. Solar irradiance mapping was conducted on all Housing and Development Board (HDB) surfaces from 7 AM to 7 PM across these estates. Each HDB block was assigned a space identification number for reference, as depicted in Figure 1(a).

The primary objective of the solar irradiance mapping was to quantify the solar irradiance on each facade of the HDB blocks and to assess whether the cultivation of vegetables would reduce solar heat accumulation by lowering overall solar irradiance on the building facades. Three types of vegetation: lettuce, pepper, and cabbage were selected for simulation in ClimateStudio.

, a control simulation was performed with no vegetation to establish the baseline solar irradiance exposure of each HDB surface throughout the year. The control scenario utilized white-painted concrete slabs as the material in ClimateStudio, mimicking the concrete facades of the simulated buildings. Subsequently, the three types of crops were modeled as vertical facades on the buildings labeled as Id1, Id2, and Id13.

For Ang Mo Kio (AMK) Town Estate Avenue 1 & 6, the design and modeling were conducted using SketchUp. Figure 2(a) illustrates the 2D plane view from Google Maps, while Figure 2(b) presents the SketchUp model of AMK Avenue 1 & 6, along with the equinox sun path at 4 PM on 21 March 2024.

Utilizing ClimateStudio within Rhinoceros 7, the Radiation Mapping feature was employed to analyze the average hourly irradiance values throughout the year. The resulting radiation mapping indicated that the optimal period for harnessing solar energy spans from 10 AM to 4 PM, during which there is minimal to no partial shading.

Figure 1. (a) Solar irradiance mapping – left (b) aerial view of Cheng San Crest with space ID of each HDB block – right.

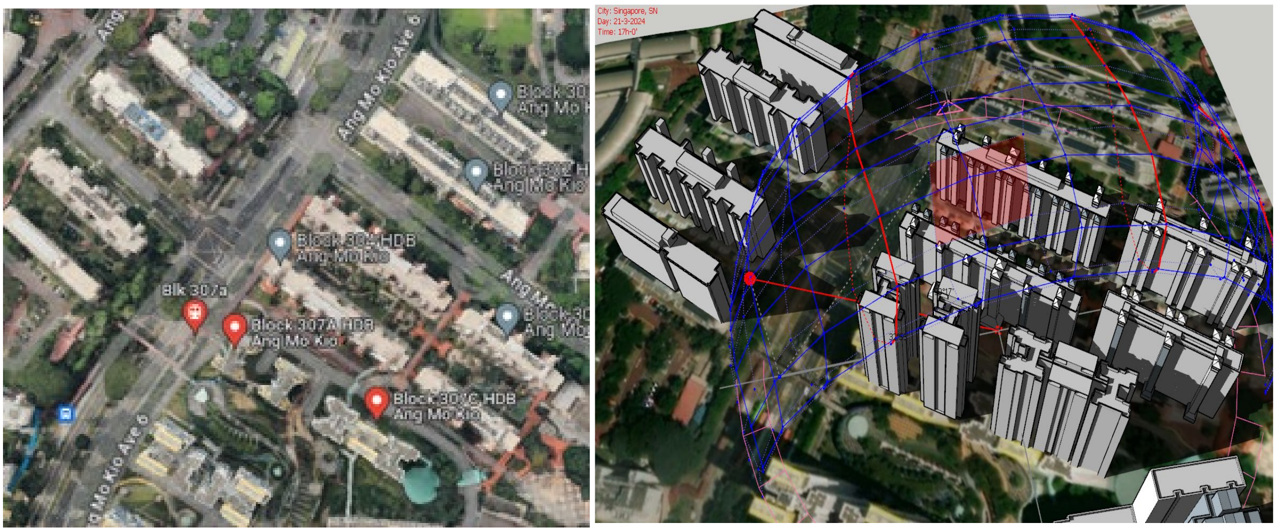

Figure 2. (a) Aerial view of - left (b) 3D model of the buildings with equinox sun path at Ang Mo Kio Town estate avenue 1 & 6 - right.

2.2. Agrivolatic design for rooftop thermal simulation

To evaluate the effectiveness of green roofs and optimize the design in terms of the distance between photovoltaic (PV) panels and planter units, an initial model was created using a concrete slab with an area equivalent to the agrivoltaic model. The second design incorporated a concrete slab with crops grown on top, in contrast to the initial design.

The objective of this study is to conduct simulations to identify potential temperature differences on the rooftop surface, comparing concrete with and without crops. For the simulation, the 440 WP N-type Monocrystalline solar panels from Jinko Solar, with an efficiency of 22.02%, were selected.

The solar panels were fixed at a 10° tilt, and the distance between the planter beds and the solar panels was varied to determine the impact on temperature reduction. This reduction is attributed to the transpiration effect of crops, as well as the cooling benefits provided to the rooftop concrete beneath the planter units.

The Grasshopper software, which requires solid models for accurate simulations, encountered some incompatibility when importing the 3D model from SketchUp into Rhino 7, as only meshes were imported. Consequently, there was a need to redesign a simplified model with identical dimensions directly in Rhino Grasshopper for the simulations. Due to the absence of specific crop materials, such as lettuce, within Grasshopper, an alternative material labeled "Grassy Lawn" was utilized.

2.3. Carbon accounting

Carbon accounting is conducted to find the difference in the amount of carbon emission emitted when vegetables are transported into Singapore from external sources such as Cameron Highland to supermarkets in four different locations in Singapore and when vegetables are transported from the vertical farm in Cheng San Crest to the same four supermarket locations.

As there are too many unknown factors when it comes to quantifying the building of the farm and the actual process of farming, only the fuel cost will be accounted for in both scenarios. The first scenario will account for the carbon emissions emitted when transporting vegetables from Green View Garden Hydroponics Vegetable Farm at Cameron Highland to supermarkets at AMK Hub and Tiong Bahru Plaza while the second scenario will account for the carbon emissions emitted when transporting vegetables from the vertical farm at Blk 501 at Cheng San Crest to the same supermarkets. There are three methods to conduct carbon accounting, the spend based, activity based or Hybrid based. All 3 methods will be used in both scenarios. The Volvo FH16 Heavy-duty diesel truck with a fuel efficiency with an average of 3 km per liter will be used to transport vegetables for both scenarios to ensure that there are no discrepancies in the fuel efficiency.

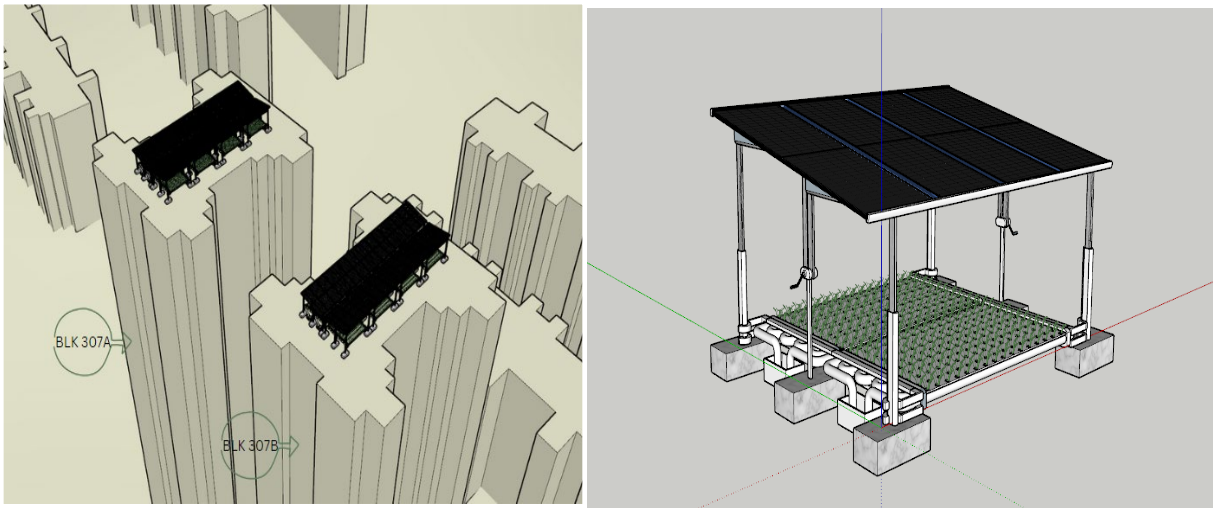

Figure 3. (a) Agrivoltaics structure proposed design in Town Estate model for Block 307A and 307B – left, (b) agrivolatic model with 8 solar panels mounted on a height above the planter bed at 30cm from the concrete slab of the rooftop – right.

3. Results and discussion

Cheng San Crescent, a public housing estate in Singapore, predominantly consists of 2- to 3-room flats and is home to a higher proportion of elderly residents, many of whom are retirees or from lower-income households. In this context, a proposal has been put forth to establish vertical farming on the side facades of these housing blocks, with the dual objective of mitigating the Urban Heat Island (UHI) effect and engaging residents in sustainable activities.

This initiative is also seen as a means to generate potential income for the residents, providing both social and economic benefits.

The results presented herein are based on modeling work that includes shadow analysis, the effects of solar irradiance change due to crop cultivation on the side facades of Cheng San Crescent, and the broader implications of such interventions on the local environment and community.

These modeling outcomes highlight the potential for reduced solar heat gain through the cultivation of vegetation on vertical facades, which can contribute to a reduction in the UHI effect and lower the building's overall energy demand.

The following results are of the modeling work including shadow analysis, the effect of change in solar irradiance due to crop cultivation at the side facade of the Cheng San Cresent, and how it can possibly contribute to a reduction in carbon footprint and lead to positive impact to the community. On the other hand, in the Ang Mo Kio Town Estate Avenue 1 and 6, comprising of pointed blocks like Block 306 and 307 A and B which houses typical 4- to 5-room HDB apartments.

The demographic of residents in this estate is primarily middle-income, with a significant proportion of working adults. In this context, it is deemed more appropriate to implement an agrivoltaic system, integrating solar panels with planter beds on the rooftops of these buildings.

The integration of solar panels and vertical farming on the rooftops serves a dual purpose: it helps mitigate heat absorption by the concrete surfaces during the day and provides a source of locally grown, low-cost leafy greens for residents. The high heat capacity of concrete poses challenges for cooling on higher floors, as it absorbs heat during the day and takes an extended period to dissipate it. The proposed agrivoltaic system offers a solution by cooling the rooftop concrete and enhancing energy efficiency.

Moreover, by reducing the cost of transportation and distribution of vegetables, the savings can be passed on to the consumers, benefiting residents economically. Given that the buildings in this estate are 30 stories tall, access to the rooftops for residents is not recommended for safety reasons. Therefore, it is advisable that the management and maintenance of both the edible crops and the solar photovoltaic systems be handled by professionals to ensure the sustainability and safety of the agrivoltaic farm.

3.1. Shadow analysis of the facade wall at Cheng San Cresent and the impact of solar irradiation.

The partial shading images presented in Figure 4, captured at various times of the day, offer insights into the impact of partial shading on crop growth throughout different periods of the year. The shading effect observed at 3:00 PM, in particular, illustrates the angle at which shadows are cast on the growth surface, influencing the available light for photosynthesis.

This reduction in the photoperiod, depending on the time of day and the seasonal variation in sunlight, can significantly affect the growth patterns and viability of different crop species. The Daylight Integral (DLI), a critical factor in determining the photosynthetic capacity and growth rate of plants, varies across different species of leafy greens. As each species has distinct DLI requirements, the availability of adequate light, especially during shaded periods, becomes a key consideration in selecting suitable crops for cultivation on vertical facades.

According to the simulation results, lettuce demonstrated superior growth performance when cultivated on such facades, compared to green pepper and cabbage. This can be attributed to lettuce's relatively lower DLI requirements, making it better suited for environments with intermittent shading.

Conversely, crops like green pepper and cabbage, which typically demand higher light levels for optimal growth, may face limitations under such shaded conditions.

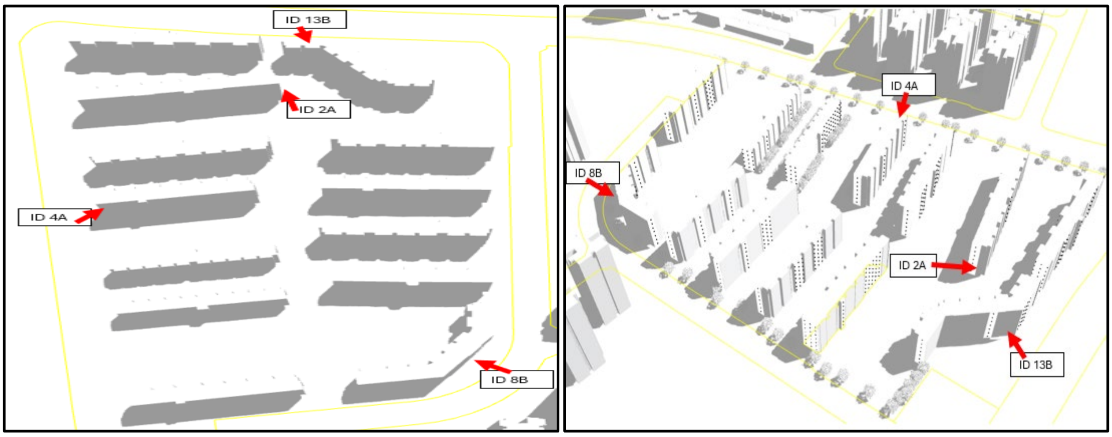

Figure 4. Shadow analysis of surfaces at Cheng San Crest with lettuce grown at its facade at (a) 12pm – left, and (b) 3pm during the summer solstice – right.

In the Cheng San Crest housing estate, the HDB blocks (ID3 to ID6 and ID9 to ID12) have elongated building structures, primarily aligned along a linear face. These blocks incorporate alternate outer facades, extending from both the front and rear to house essential vertical circulation elements, namely the lift lobby and stairways. These designated areas serve as optimal spaces for the cultivation of vegetation along the vertical facades, as illustrated in Fig. 5(a). The internal corridors within the residential blocks remain untouched to facilitate air circulation and regulate airflow throughout the building. The solar irradiance incident on the building facade along the corridors was averaged, and the results are presented in Fig. 5(b). The control simulation, which does not incorporate vegetation along the vertical facade, was compared to simulations in which crops, specifically lettuce, green peppers, and cabbages were modeled as being grown on the vertical facade of building blocks ID1 to ID13.

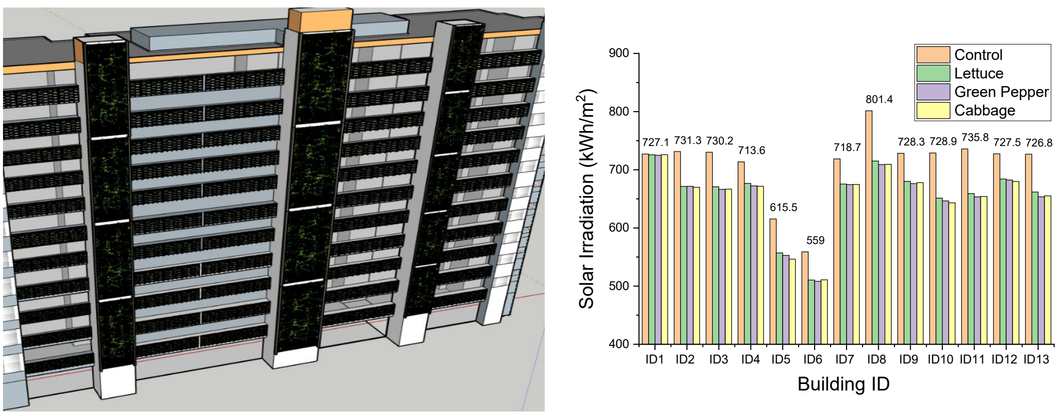

Figure 5. (a) Corridors with walkways for each residential units and green vertical façade – left, (b) average solar irradiance at the vertical façade of residential block ID1 to ID 13 – right.

The simulations demonstrate a reduction in solar irradiance by approximately 50 to 60 kWh/m^2 for buildings with vegetation on the vertical facade. This decrease in solar exposure can be attributed to the transpirational cooling effect of the crops, which helps to reduce the overall thermal load on the building compared to the control scenario without vegetation. Additionally, crops that are subject to shading at specific times of the day experience reduced solar irradiance, which is particularly beneficial given the abundant sunlight in Singapore. This shading effect plays a critical role in preventing physiological stress in crops, such as tip burn in lettuce, thereby contributing to improved crop health and sustainability in the urban environment.

3.2. Effects of growing vegetables on the temperature on side-facades of buildings

Correlation between solar irradiance and temperature can be found through the energy balance equation. This equation is commonly used to model the balance between the energy absorbed by a surface and the energy it loses through radiation and convection. In thermal equilibrium, the energy absorbed by the surface (Qin) is equal to the energy lost through radiation (Qrad) and convection (Qconv) [10].

$$Qin = Qrad + Qconv \quad (1)$$

According to the Stefan-Boltzmann law and Newton's law of cooling,

Radiative Heat Loss, Qrad = $\varepsilon \cdot \sigma \cdot A \cdot$ (T4-T4ambient)

Convective Heat Loss, Qconv = h · A · (T−Tambient)

Absorbed Solar Energy, Qin = $I \,.\, A \,.\, \alpha$

Therefore,

$$I \cdot A \cdot \alpha = \epsilon \cdot \sigma \cdot A \cdot (T^4 - T_{\text{ambient}}^4) + h \cdot A \cdot (T - T_{\text{ambient}}) \quad (2)$$

Where:

I = Incident solar irradiance (W/m^2)

A = Surface area (m^2)

α = Absorptivity of the surface

ϵ = Emissivity of the surface

σ = Stefan-Boltzmann constant (5.67 x 10^{-8} W/m^{2}K^4)

T = Surface temperature (K)

$T_{ambient}$ = Ambient temperature (K)

h = Convective heat transfer coefficient (W/m^{2}K)

Using the expression above, the temperature at the vertical facade can be approximated if the parameters of the cabbages, green pepper, lettuces, and the exterior painted concrete slabs are known. The surface temperature, T, can be determined by substituting the value of I from the solar irradiance mapping, h =2.5, ϵ = 0.8240 and α = 0.1760 from the parameters of the exterior white painted concrete slab provided in ClimateStudio. Since T is to the power of 4, the Newton-Raphson Method is needed to solve for temperature, T. A program was written using Python to solve for T and the result is tabulated in Table I.

Table 1: Surface temperature of the facades in some of the buildings, ID 8, ID 11 and ID 13 with growth of lettuce, green pepper, and cabbage.

Ambient Temp (K)	294.15	296.15	298.15	300.15	302.15	304.15	306.15	308.15	310.15	312.15	313.15
Ambient Temp (°C)	21	23	25	27	29	31	33	35	37	39	40
ID 80											
Control (°C)	22.71	24.69	26.67	28.64	30.62	32.6	34.58	36.56	38.54	40.52	41.51
Lettuce (°C)	22.28	24.26	26.25	28.23	30.21	32.2	34.18	36.17	38.15	40.14	41.13
Green Pepper (°C)	22.25	24.23	26.21	28.2	30.18	32.17	34.15	36.14	38.12	40.11	41.1
Cabbage (°C)	22.24	24.22	26.21	28.19	30.18	32.16	34.14	36.13	38.11	40.1	41.09
ID 11C											
Control (°C)	22.76	24.74	26.71	28.69	30.67	32.65	34.62	36.6	38.58	40.56	41.55
Lettuce (°C)	22.54	24.52	26.5	28.48	30.46	32.44	34.42	36.4	38.38	40.36	41.36
Green Pepper (°C)	22.52	24.5	26.48	28.46	30.44	32.43	34.41	36.39	38.37	40.35	41.34
Cabbage (°C)	22.52	24.5	26.48	26.48	28.46	30.44	32.42	34.4	36.38	40.35	41.34
ID 13A											
Control (°C)	22.89	24.86	26.84	28.81	30.79	32.77	34.74	36.72	38.7	40.67	41.66
Lettuce (°C)	22.52	24.5	26.48	28.46	30.45	32.43	34.41	36.39	38.37	40.35	41.34
Green Pepper (°C)	22.48	24.46	26.44	28.42	30.4	32.38	34.37	36.35	38.33	40.31	41.3
Cabbage (°C)	22.48	24.46	26.44	28.43	30.41	32.39	34.37	36.35	38.33	40.32	41.31

The temperature reduction on the vertical facades resulting from the cultivation of leafy greens is presented in Table I, compared to the control simulation. The simulated ambient temperature was varied between 21°C and 40°C, with increments of 2°C. The findings indicate that surfaces exposed to reduced solar irradiance consistently exhibit a corresponding decrease in surface temperature, establishing a clear correlation between solar irradiance and the thermal properties of materials. Specifically, a reduction in solar irradiance incident on a surface lead to a decrease in its surface temperature, and conversely, an increase in solar irradiance results in higher surface temperatures. These results exhibit the potential of vertical farming on the facades of HDB blocks to mitigate surface temperature, thus contributing to structural cooling effects. By reducing the solar heat gain on the building's exterior, the cultivation of vegetables on vertical facades can serve as a viable strategy for addressing the Urban Heat Island (UHI) effect.

This approach demonstrates the feasibility of incorporating vegetation into building design to lower ambient temperatures and enhance the thermal comfort of urban environments. Consequently, the adoption of such practices could play a significant role in reducing the overall heat load on residential buildings, making it a promising solution for improving the sustainability and livability of urban areas.

3.3. Comparative carbon emission for different accounting techniques for two growth sources

Based on an analysis of travel distances, the spend-based accounting method and hybrid-method accounting yield similar results when only fuel costs are considered, due to the absence of data regarding the indirect emissions associated with the purchased electricity used during the transportation process. Given this limitation, it is recommended that the hybrid method be employed for carbon accounting, as it provides a more comprehensive approach by incorporating elements from both activity-based and spend-based accounting.

The tabulated results presented in Table II clearly indicate that the carbon emissions associated with the transportation of vegetables from Green View Garden Hydroponic Vegetable Farm (Cameron Highlands) to AMK and Tiong Bahru Plaza (Scenarios 1A and 1B) are approximately ten times greater than the emissions resulting from the growth and harvesting of leafy greens at Cheng San Crest Blk 501 (Singapore) to the sale destination.

This disparity highlights the significant impact of transportation on the overall carbon footprint of the vegetable supply chain, suggesting that optimizing transportation logistics could play a key role in reducing emissions associated with food distribution.

Therefore, further research into transportation efficiency and the adoption of low-carbon transportation alternatives could complement efforts to reduce the overall environmental impact of urban food systems.

Table 2: Carbon accounting for the four scenarios using the activity-based, spend-based, and hybrid method accounting.

Scenario	Destination	Distance (Round-Trip)	Activity-Based Accounting	Spend-Based Accounting	Hybrid Method Accounting
1A	Green View Garden Hydroponic Vegetable Farm - AMK Hub	1208 km	1079.46 kg CO_2	1180.46 kg CO_2	1180.46kg CO_2
1B	Green View Garden Hydroponic Vegetable Farm - Tiong Bahru Plaza	1210 km	1080.92 kg CO_2	1181.92 kg CO_2	1181.92 kg CO_2
2A	Cheng San Crest Blk 501- AMK Hub	3.4 km	3.04 kg CO_2	104.036kg CO_2	104.036kg CO_2
2B	Cheng San Crest Blk 501- Tiong Bahru Plaza	30.0 km	26.8 kg CO_2	127.8 kg CO_2	127.8 kg CO_2

As an illustration, the hybrid method of accounting for Scenario 1A Green View Garden Hydroponic Vegetable Farm to AMK Hub is as shown for Scope 1 to Scope 3

- Scope 1 (Direct Emission): Emissions from burning diesel fuel in the heavy-duty diesel truck during the roundway trip.

Total Distance (Round trip): 1208 km

Total fuel consumption = (1208 km)/ (3km per liter) = 405.33 Liters

Total Carbon Emissions from fuel = 405.33 liters * 2.68 kg CO_2/liter = 1079.46 kg CO_2

- Scope 2 (Indirect Emissions): Not applicable as the indirect emissions from purchased electricity or other energy sources cannot be quantified
- Scope 3 (Other Indirect Emissions): Additional costs associated with the transportation process, such as maintenance and other indirect expenses are considered.

Total Indirect Emissions = Additional Costs * Emissio Factor = $100 SGD * 1.01 kg CO_2/SGD = 101 kg CO_2

Total Emissions (All Scope) = 1079.46 kg CO_2 + 101 kg CO_2 = 1180.46 kg CO_2

3.4. Outdoor thermal mapping with grasshopper for agrivolatic farm in block 307A and 307B of AMK Ave 6

As discussed in Section 3, the rooftop of Blk 307 A and 307 B on AMK Avenue 6 will be equipped with an agrivoltaic farm, distinguishing it from the green vertical facades proposed for Cheng San Crest. To assess the thermal performance of the rooftop under different conditions, an outdoor thermal analysis using Grasshopper was conducted.

This analysis simulated the thermal behavior of the rooftops based on weather data for March 21st, the spring equinox, from 12:00 PM to 3:00 PM. The results from the simulation revealed that the concrete rooftop without any additional installations exhibited surface temperatures ranging from 37.21°C to 39.89°C. When a grassy lawn material, representing crops, was introduced on the rooftop, the temperature decreased slightly, with the surface temperatures ranging from 37.08°C to 39.55°C.

More significantly, the integration of both photovoltaic (PV) panels and leafy green crops led to a further reduction in surface temperature, with temperatures ranging from 35.18°C to 35.45°C. This represents a cooling effect of approximately 4°C compared to the bare concrete rooftop. In contrast, the simulation of the rooftop with only PV panels, without crops, showed a surface temperature range of 36.48°C to 36.75°C. The presence of PV alone contributed to a reduction in temperature, it was not as significant as the combination of PV panels and crops.

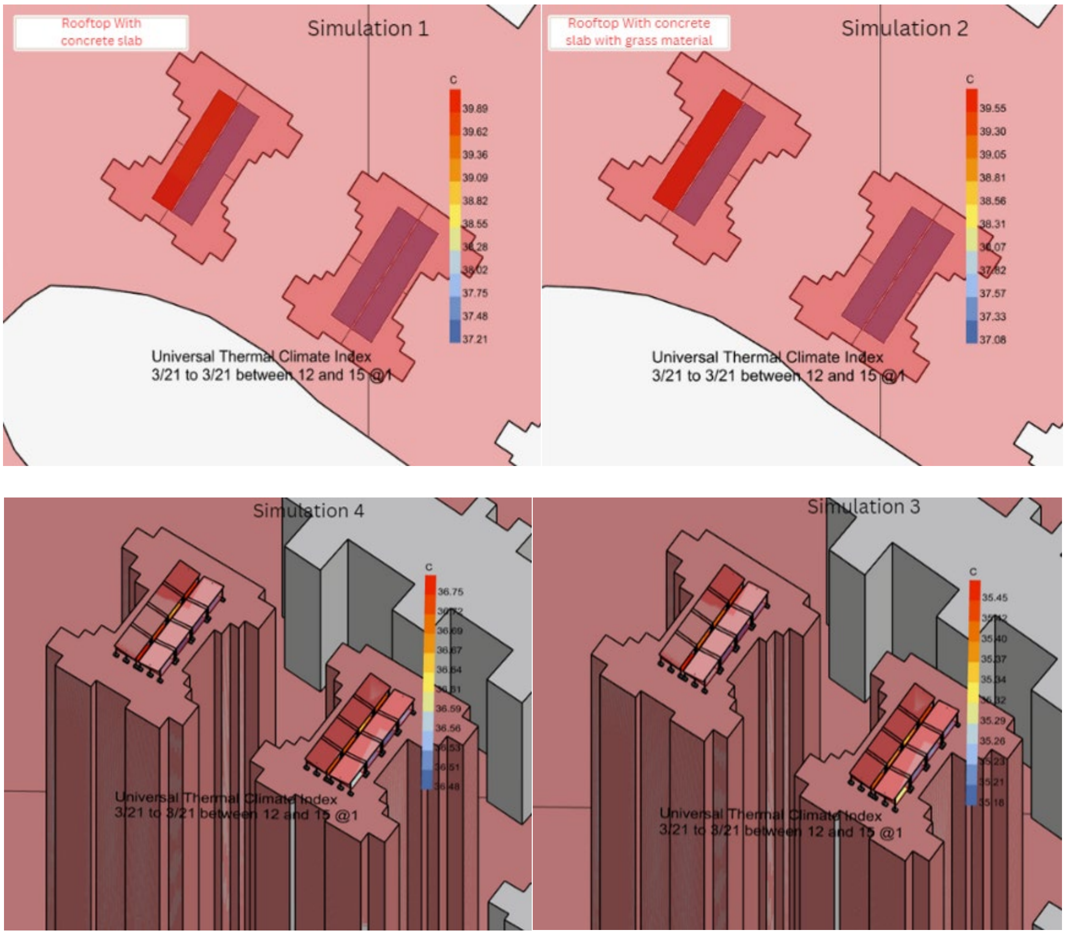

Figure 6. Simulation using Grasshopper to obtain the thermal mapping on concrete slab on rooftop (a) no PV and no leafy greens – upper left, (b) no PV but with leafy greens – upper right, (c) PV and leafy greens – below left, (d) PV with no leafy greens – below right.

To evaluate the impact of shading and cooling effects facilitated by the photovoltaic PV structure, which is positioned at a height of 2 meters above the flatbed or concrete slab, a simulation was conducted using Grasshopper. The objective of this simulation was to assess the temperature variations at different locations of the structure. By measuring the temperature across various points, the simulation provided insights into the cooling benefits and shading effects offered by the elevated PV installation. This analysis is crucial for understanding how the PV structure influences thermal dynamics on the underlying surfaces and contributes to temperature regulation, particularly in urban environments affected by the UHI effect.

Table 3: Range of temperature on the various structure of an agrivolatic farm.

Period of 12 pm to 3 pm - 21st March	Flatbed (°C)	Top of PV (°C)	Bottom of PV (°C)	Area (m^2), per building
Simulation 1 (No PV, Concrete)	37.21-39.89	-	-	150
Simulation 2 (No PV, leafy green)	37.08-39.55	-	-	150
Simulation 3 (PV, leafy green)	35.18-35.45	44.65-45.35	37.17-37.64	150
Simulation 4 (PV, Concrete)	36.48-36.75	44.66-45.42	37.62-38.11	150

The tabulated results indicate that the implementation of an agrivoltaic system significantly reduced the surface temperature of the flatbed. This reduction in surface temperature suggests that residents on the top levels of the residential estate would experience lower thermal loads, thereby reducing their reliance on cooling systems and, consequently, their energy consumption for air conditioning. The cooling effect provided by the agrivoltaic system not only offers direct economic benefits by lowering household cooling costs but also contributes to mitigating the Urban Heat Island (UHI) effect. By reducing the ambient temperature in the surrounding urban environment, this approach enhances thermal comfort and supports the sustainability of the residential estate. Thus, the agrivoltaic system represents an effective strategy for both environmental and economic improvements within urban settings.

3.5. Feasibility of commercial application

The costs associated with the installation, operation, and maintenance of agrivoltaic systems are critical for evaluating their financial viability. Using PVSyst software and assuming a project lifetime of 20 years, the total installation cost of the agrivoltaic system was estimated at SGD 49,388.54, with an annual operational cost of SGD 8,373.42.

The installation cost encompasses the construction of the PV system, including components such as the MPPT (Maximum Power Point Tracking) controller, inverters, grid connection, and the requisite lightning protection system for the rooftop installation.

The support structure for the agrivoltaic setup is constructed from Aluminum alloy (6005-T5) and stainless steel (SUS304), materials selected for their durability and suitability for Singapore's environmental conditions [11]. These materials, particularly when anodized, offer enhanced protection, providing resistance to corrosion, heat dissipation, and wear, which are crucial properties for the longevity of PV systems typically designed to last between 10 to 20 years [12].

The economic feasibility of the system is further illustrated in Figure 7, which details the installation costs, financing, and projected economic outcomes. One of the financial benefits of the agrivoltaic system is the ability to sell excess electricity generated back to the grid, which can offset ongoing maintenance and operational expenses.

Based on the projected financial analysis, the payback period for the system is estimated to be approximately 5.6 years, indicating a relatively short return on investment. This demonstrates the economic viability of agrivoltaic systems as a sustainable solution, offering both environmental and financial benefits over the long term.

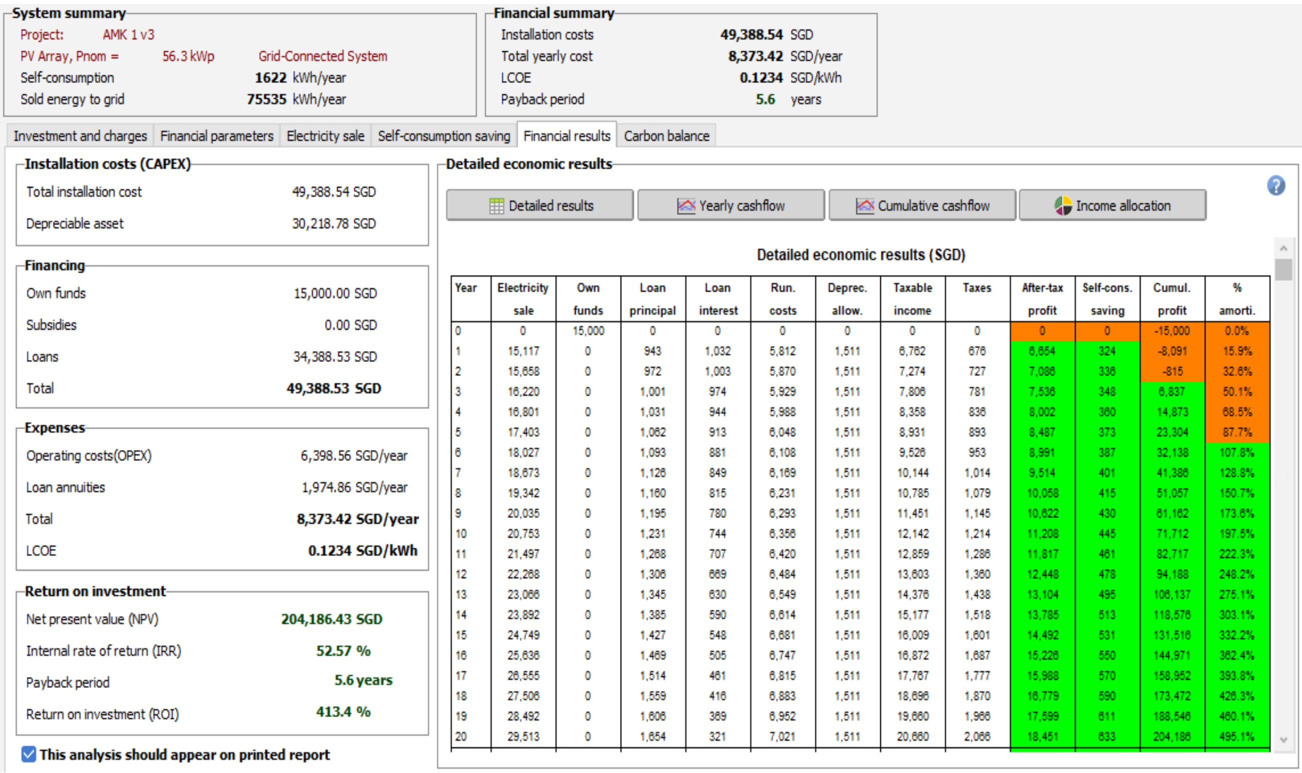

Figure 7. Financial overview of the project.

4. Conclusion

In conclusion, this study highlights the significant potential of integrating Vertical Farming (VF) and Agrivoltaic (AV) systems within urban environments, particularly in Housing and Development Board (HDB) estates in Singapore. The findings demonstrate that VF systems, when incorporated into the facades of HDB buildings, can effectively reduce heat transfer into the structures, thereby lowering internal temperatures and enhancing urban thermal comfort. Furthermore, the implementation of modular AV systems on rooftops not only facilitates local food production but also enhances the efficiency of photovoltaic (PV) panels by mitigating the temperatures of the panels, thereby optimizing energy generation.

The combined application of VF and AV systems presents a promising strategy for reducing the carbon footprint associated with vegetable transportation, aligning with broader urban sustainability goals.

This research emphasizes the feasibility and potential benefits of deploying these systems on HDB buildings, contributing to Singapore's objectives related to food security, renewable energy adoption, and climate resilience.

By addressing both environmental challenges, such as the Urban Heat Island effect, and food security concerns, the proposed solutions offer a comprehensive approach to urban sustainability. This study makes a compelling case for the integration of VF and AV systems in urban planning and development, advocating for their broader adoption as part of Singapore's long-term sustainability strategy.

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