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Original article – Thematic Issue

Dynamic energy analysis of building-integrated rooftop greenhouse for urban agriculture

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Summary

Building-integrated rooftop greenhouses address global agricultural challenges of climate change, energy crisis, and food security. Urban agriculture systems with rooftop greenhouses offer sustainable food production solutions in urbanized cities. These systems demonstrate technical advantages through waste energy utilization, economic benefits from reduced distribution costs, and social benefits as community spaces. The greenhouse-building integration enables efficient energy exchange, resulting in a reduction of building energy loads by up to 19% annually and a decrease in greenhouse energy consumption by 12%. This system also minimizes carbon emissions through shortened distribution processes and improved energy management. Energy exchange between buildings and greenhouses optimizes crop growth conditions while utilizing building waste heat and carbon dioxide. This integration could enhance urban food security while potentially improving building energy efficiency and environmental sustainability in urban environments.

Keywords
climate change, energy efficiency, food security, greenhouse integration, urban agriculture

Significance of this study

What is already known on this subject?

- Previous studies have shown fragmented research on energy load reduction effects through passive heat exchange between rooftop greenhouses and buildings.

What are the new findings?

- This study presents a comprehensive analysis of carbon, energy, and water circulation through integrated systems between buildings and rooftop greenhouses. The integration resulted in a 19% reduction in building energy consumption and a 9% decrease in greenhouse energy use during the winter season.

What is the expected impact on horticulture?

- The findings support sixth-industry development in urban areas. Rooftop greenhouse facilities provide urban farmer training, education, tourism and services. These integrated systems establish new standards for urban agriculture growth.

Global crisis related to agriculture

Recently, there are globally important issues related to human survival and agriculture. The representative issues include global warming, energy crisis, food security, and so on.

Weather change

Climate change poses a crisis to sustainable food security. The continuous increase in average temperature, in which the variation of annual temperature extremes increases, leads to long-term climate effects. According to the 2022 IPCC Intergovernmental panel on climate change report, since the industrial revolution in 1900s, the global temperature rise has been made by humans. It also shows that the relationship between cumulative CO_2 emission and global warming for the five example scenarios by 2050 is a very linear relationship. Climate change is already affecting all inhabited areas around the world, and it has reported that human-made impacts are contributing to many observed extreme weather and climate change. It also causes changes in the growing season and types of crops. As we are entering an era in which it is difficult to secure the sustainability of open-field cultivation due to exposure to climate change, artificial climate control is necessary to ensure a sustainable food production source.

Energy

While today's energy crisis shares some parallels with the oil shocks of the 1970s, there are important differences. Today's crisis involves all fossil fuels, while the 1970s price shocks were largely limited to oil at a time when the global economy was much more dependent on oil, and less dependent on gas. The entire word economy is much more interlinked than it was 50 years ago, magnifying the impact. That's why we can refer to this as the first truly global energy crisis (IEA, 2022). Higher energy prices have contributed to painfully high inflation, pushed families into poverty, forced some factories to curtail output or even shut down, and slowed economic growth to the point that some countries are heading towards severe recession. In order to produce stable, high-quality agricultural products throughout the year, protected cultivation area is increasing more and more. Until now, only heating has been considered in protected cultivation, but due to recent global warming, cooling has also been considered seriously. Moreover, as facility agriculture becomes more advanced, energy costs inevitably increase.

Food security

According to the World Food Policy Report, future population growth is expected to increase food demand by 70% by 2050 compared to 2010 (FAO, 2013). However, the growth

rate of food production is expected to fall short of this, due to climate change, the area of arable land has decreased and the actual number of agricultural populations has decreased. It is likely to face a food crisis in which safe and nutritious food supplies are always available and accessible, such as agflation, where grain prices soared due to weather changes in 2008 (IMF, 2008). Therefore, a response strategy is needed. Korea has a grain self-sufficiency rate of 20% and a food self-sufficiency rate of less than 50% (KREI, 2008), which is the lowest in the food security index among OECD countries. In addition, due to the new infectious disease (COVID-19), the issue of ensuring food security is emerging worldwide, and the need for related food policy and technology development is increasing.

Development of artificially controlled production systems

Unlike open-field cultivation, which is directly affected by the external environment, protected cultivation uses facilities such as greenhouses to protect crops from the external environment or to improve quantity and quality through active environmental control. In the early days, it prevented frost damage and promoted growth by maintaining a higher temperature than open ground through warming or heating during the low-temperature period. It has developed into an intensive production method that allows year-round cultivation even under the distinct climate of the four seasons in Korea. In order to create an environment suitable for crop growth inside the facility, it is necessary to input energy such as ventilation and heating/cooling.

Highly developed cities consume energy, food, and water, causing supply problems. Due to urbanization, more than 80% of Korea's population lives in cities (World Bank, 2022), and cities have evolved into huge places of energy, food, and water consumption. Increased consumption in cities will require distant sources of supply, which has been pointed out increasing carbon mileage for supply. Currently, the supply structure of production sites remote from the city cannot guarantee the maintenance of the city if the production and supply of each production source are interrupted due to an unpredictable event.

Considering the problems in cities and agriculture mentioned above, urban agriculture is rapidly growing in developed countries such as Europe and North America. By type, it can be divided into urban vegetable gardens, plant factories (vertical farms), and rooftop greenhouses. According to FAO, traditional agriculture already has more than 80% of suitable land in use, and the declining farming population and scarcity of farmland are creating agricultural problems such as food security in the country (FAO, 2022). Urban agriculture can be the basis for solving these problems, and cities' idle buildings can supplement insufficient farmland. Typical urban agriculture includes vertical farms (plant factory) and open-field farming and greenhouse farming on idle land while a typical idle site in the city is the roof of a building. While there are very distinguishable 4 seasons in Korea, the rooftop greenhouses are emerging as an alternative to reduce energy load and reduce carbon emissions of building as well as greenhouse.

Plant factory

A plant factory is a technology that cultivates crops by completely artificially controlling the air temperature, humidity, carbon dioxide concentration, etc. using artificial light in a facility that is blocked from the outside. It is not affected by the natural environment and can produce crops like industrial products. As a countermeasure for crop cultivation against climate change, cultivation yield per area can be increased through multi-stage high-density cultivation, and the labor efficiency of workers can be improved. In addition, the inflow of pests and pollutants through clean rooms can be controlled, planned production is possible through stable production, and continuous production can be performed regardless of the season. It is possible to build in deserts and polar regions because of geographical location conditions and climate influence. Plant factories with these advantages have been recognized for their growth potential by large IT companies such as Amazon, Softbank, and Google, and are actively investing in funds.

Rooftop greenhouse

Worldwide, consumption continues to increase, with more than 20% of energy consumption being used in buildings and 40% of greenhouse gas emissions being emitted from buildings (IEA, 2019). Various efforts such as Building Energy Management Systems (BEMS), Green Remodeling, and Zero Energy Building have been attempted to save energy in buildings, and one of the countermeasures is the rooftop greenhouse. Rooftop greenhouse is a technology that can passively reduce energy by building a greenhouse on top of a building and actively reduce energy by utilizing the waste energy of the building. The waste energy and carbon dioxide from the building are used to control the greenhouse environment, optimizing factors such as temperature and carbon dioxide levels for plant growth. Additionally, various environmental controls inside the greenhouse, including light management, water supply, and nutrient delivery, are implemented to optimize plant growth. Building-type urban agriculture requires the improvement of energy independence, and the advantage is that additional area is unnecessary because idle space is utilized. So, it is used and distributed for various purposes in developed agricultural countries.

Advantages and disadvantages of urban agriculture

Urban agriculture has advantages in various aspects through technological convergence.

Technical advantage

In order to create an environment suitable for growing crops, greenhouses require various energies such as heating, cooling, carbon dioxide, and lighting. Unlike buildings, greenhouses show very diverse heat demand patterns because they are greatly influenced by seasonal/weather/hourly outdoor conditions. Urban agriculture can use energy that is wasted or unused in buildings for rooftop greenhouses and can create synergistic effects by reducing the cooling and heating load of buildings through the optimal operation of rooftop greenhouses. In addition, if the energy supply facilities of the building and the greenhouse are integrated, compared to the energy pattern of the building, the energy demand of the greenhouse is higher at night (heating in winter and cooling at night in summer), so the efficiency of distributed power generation and BEMS can be greatly improved through operating time control and energy storage.

Economic and environmental advantages

Along with the growing population, the consumption of food, water, and energy in cities has increased rapidly due to urbanization. In addition, as the quality of life of individuals

improves, the demand for high-quality fresh crops increases, so it is necessary to secure the marketability of the city. Urban agriculture, which has changed the supply structure with production within the city, can reduce costs as well as energy consumed in the cold chain distribution process as the cultivation, transportation, and storage processes are shortened compared to conventional cultivation. This leads to a reduction in greenhouse gas emissions, which can reduce the food mileage for consumers to use crops. In addition, the reduced time between production and consumption reduces waste, and as the crop matures and grows to its fullest, the maximum nutrient content is available.

Social advantage

Urban agriculture is used as a psychological healing space in densely populated areas due to urbanization, and also serves as a platform for community building such as social and hobby activities. In addition to job creation, educational programs are provided so that visitors can tour and experience agriculture in the city center. The 6th industry is based on all tangible and intangible resources that exist in rural areas, by linking agriculture, food, special product manufacturing/processing (secondary industry), distribution/sales, culture, experience, tourism, service (tertiary industry), etc. It refers to activities that create added value. Most consumers live in cities, and through urban agriculture, the 6th industry can be further vitalized, and more economic benefits can be obtained for consumers and farmers.

Related studies of A3EL

Although there are many advantages mentioned above, much effort is still needed to increase economic feasibility. Compared to general greenhouses in rural areas, profitability is inevitably low due to limitations that cannot be scaled up. To overcome this, 1) linkage with the 6th industry; 2) selection of vegetables and hedges suitable for urban agriculture and development of appropriate growth technology; 3) development of energy load and carbon emission reduction technology through linkage of air conditioning system between greenhouse and building, etc. of studies are needed. Moreover, unlike general rooftop greenhouses, plant factories require very high energy operating costs because they completely depend on phosphorescent light. In order to meet the economic feasibility, efficient interior space design is very important, and high value-added plants such as special crops and medicinal crops should be grown instead of general vegetables. Protected cultivation grows rapidly as it is modernized and enlarged, and the production scale per area greatly increases, accounting for about 60% of the total agricultural production (MAFRA, 2020). In particular, it is essential to input energy to create an appropriate environment for stable mass production throughout the year, but the energy load per unit area is high due to the relatively low insulation. Efforts are being made worldwide to realize the greenhouse gas reduction target (37% reduction target in all economic sectors compared to BAU by 2030, among which 18.2% reduction target in the building sector) after the Paris Agreement (UNFCCC, 2015). Greenhouse gases emitted from buildings account for about 39% of global greenhouse gas (GHG) emissions (IEA, 2019). In developed countries, including the United States, about 40% of GHG emissions are generated from buildings, and in Korea, GHG emissions from buildings account for 20% of the projected GHG emissions (850 million tons) (UNFCCC, 2020).

As an example of urban agriculture, I would like to briefly introduce the research related to urban agriculture conducted by the Aero-Environmental and Energy Engineering Laboratory (A3EL). This study aims to develop and demonstrate an urban building-rooftop greenhouse model that can reduce the energy consumption of buildings and spread urban agriculture by using rooftop greenhouses that are structurally combined with buildings and operate integrated energy. The model refers to a future eco-friendly energy-independent building model applied with AI-integrated Energy Management System (EMS)-based control platform technology by maximizing energy utilization of distributed resources by integrating energy between buildings and rooftop greenhouses.

Currently, the research rooftop greenhouse demonstration site is secured, and experiments are being conducted, and the business/commercial rooftop greenhouse is in the construction stage. In order to find ways to actively utilize waste resources such as CO_2 and unused energy such as ventilation heat generated from buildings for building integrated rooftop greenhouses, the organic analysis of the thermal behavior occurring between the rooftop greenhouse and the building structure and the dynamic energy load of the rooftop greenhouse and the building is calculated. As a result, we want to find the minimum energy operation scenario for each season and time. In addition, an experiment was conducted to analyze the sensible and latent heat energy of crops that affect the indoor air environment of the greenhouse, and heat exchange with surrounding air was considered through a regression model. As shown in the figure below, the thermal gain was evaluated by passively reducing the load even with the structure where the greenhouse was located on the roof of the building. In addition, the energy load reduction of each greenhouse and building was quantitatively analyzed by actively exchanging energy as needed. The building's surplus heat and carbon from occupant breathing can be supplied to the greenhouse and used for crop photosynthesis. In addition, the greenhouse can provide fresh air and moisture to the building to increase thermal comfort.

Sensible and latent heat of various crops

Crops are essential in dynamic energy calculations, affecting greenhouse loads by up to 40% (Boulard and Baille, 1987; Eumorfopoulou and Aravantinos, 1998). The field experiment was conducted in a greenhouse to design an energy model for each crop type (fruit, leafy vegetable). In order to consider the amount of heat transfer between the crop and the surrounding air, the leaf surface temperature and the amount of evapotranspiration were measured. These variables are highly related to sensible heat and latent heat, respectively. The heat exchange amount between the crop and the surrounding air was designed differently according to the growth of the crop by dividing the steps through the measured leaf area index. As a result, a multiple regression model was designed to estimate leaf surface temperature and evapotranspiration using the measured air environment values inside and outside the greenhouse (Yeo et al., 2022; Cho et al., 2022).

Energy model validation and load analyze of greenhouse and building

Building Energy Simulation (BES) models were developed and validated for rooftop greenhouses and buildings in the Korea Institute of Machinery and Materials (36°23'N, 127°21'E). The temperature of the rooftop greenhouse was heated at 24–26°C during the day and 14–16°C at night, and

the office building was heated at 20–23°C during the day using a heat pump and boiler. In each rooftop greenhouse and building, the internal temperature and gas consumption of the measured and calculated values were compared by unit time step. To validate the accuracy of the integrated energy model for the rooftop greenhouse and the building, statistical factors including Normalized Mean Bias Error (NMBE), Coefficient of Variation of the Root Mean Square Error (Cv(RMSE)), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) were calculated and compared with international standards. The results of the integrated energy model of the rooftop greenhouse and the building seem to be trusted.

Energy exchange between greenhouse and building

In order to compare energy savings when rooftop greenhouses are built in domestic and commercial buildings, the standard building shape, envelope, and HVAC in Korea were investigated based on the building register database. A rooftop greenhouse-building energy model was developed, and uncertain factors were introduced in the validated model. The results of the integrated rooftop greenhouse-building model and the greenhouse and building-alone model were compared. Depending on the greenhouse scenario, as shown below, it was found that the building-rooftop greenhouse integrated model can save about 19% of energy compared to a single building and about 12% compared to a single greenhouse throughout the year. In addition, if the surplus heat remaining after the occupant leaves the office building is sent to the greenhouse (1ACH of greenhouse ventilation), the energy load of the greenhouse can be reduced by 9% during the winter day. As a result, we derive energy consumption reduction scenarios by season and hour (Cho, 2020).

Conclusions

The integration of rooftop greenhouses with buildings offers a promising approach to reducing energy consumption and promoting sustainable urban agriculture. Combining rooftop greenhouses with building structures allows for the utilization of waste heat and carbon dioxide from buildings to enhance plant growth and improve energy efficiency. This integration contributes to mitigating the impacts of climate change, enhancing urban food security, and reducing greenhouse gas emissions.

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Supplemental Information

Supplemental Information – Table S1. Uncertainty index results for energy consumption and indoor temperature.

	Energy consumption				Indoor temperature					
	ASHRAE	IPMVP	Result (RTG)	Result (Bldg)	CIBSE	VDI	Results (RTG) V1	Results (RTG) V2	Results (RTG) V3	Result (Bldg)
NMBE (%)	≤ ±10	≤ ±5	2.02	1.94						
Cv(RMSE) (%)	≤ 30	≤ 20	34.27	28.31						
MAE (°C)					≤ 2.0	-	1.55	1.62	1.07	0.67
RMSE (°C)					-	≤ 1.5	2.01	2.09	1.36	0.99
R^2 (%)	0.75	0.75					0.9394	0.9382	0.9723	0.9772

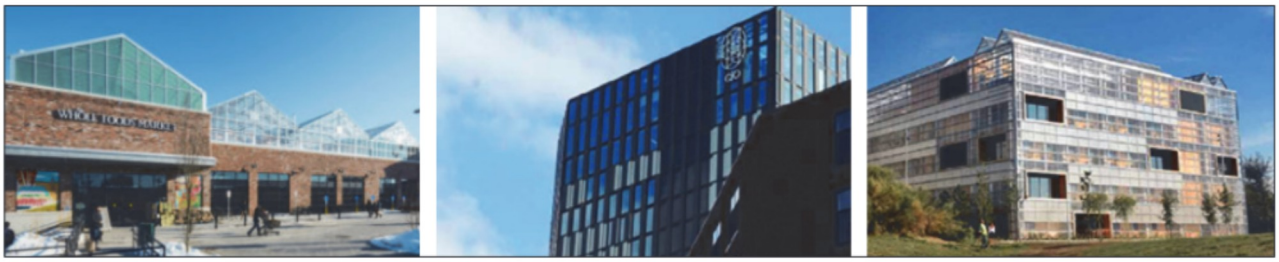


Supplemental Information – Figure S1. Example of plant factory invested in urban space.

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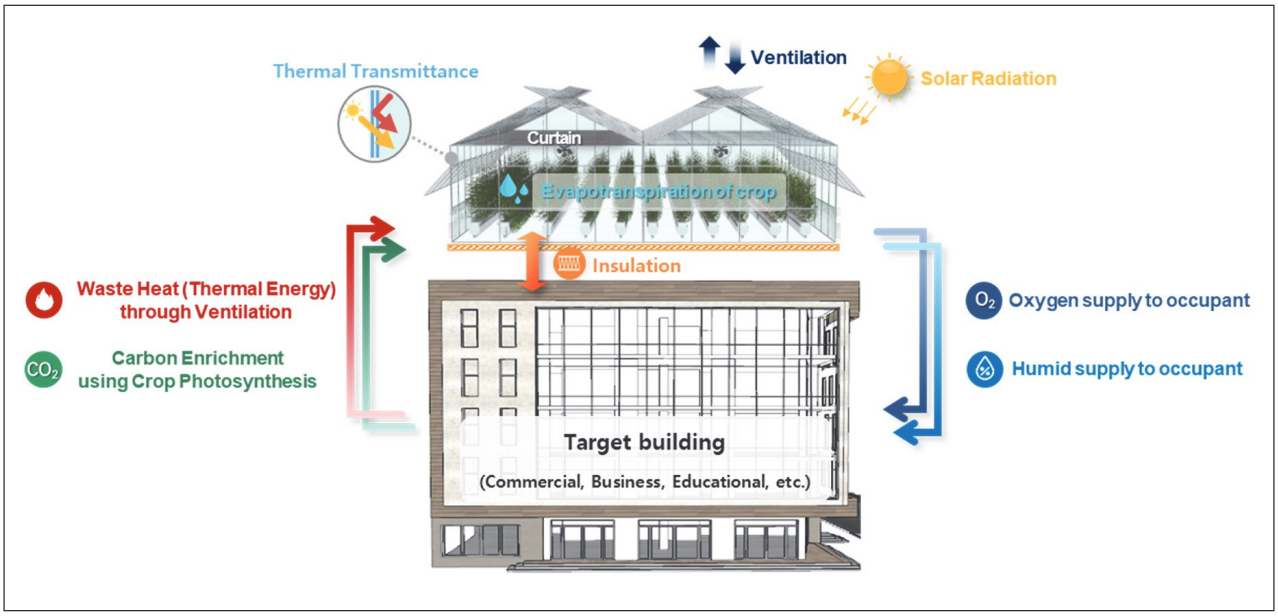


Supplemental Information – Figure S2. Example of building rooftop greenhouses for various purposes.

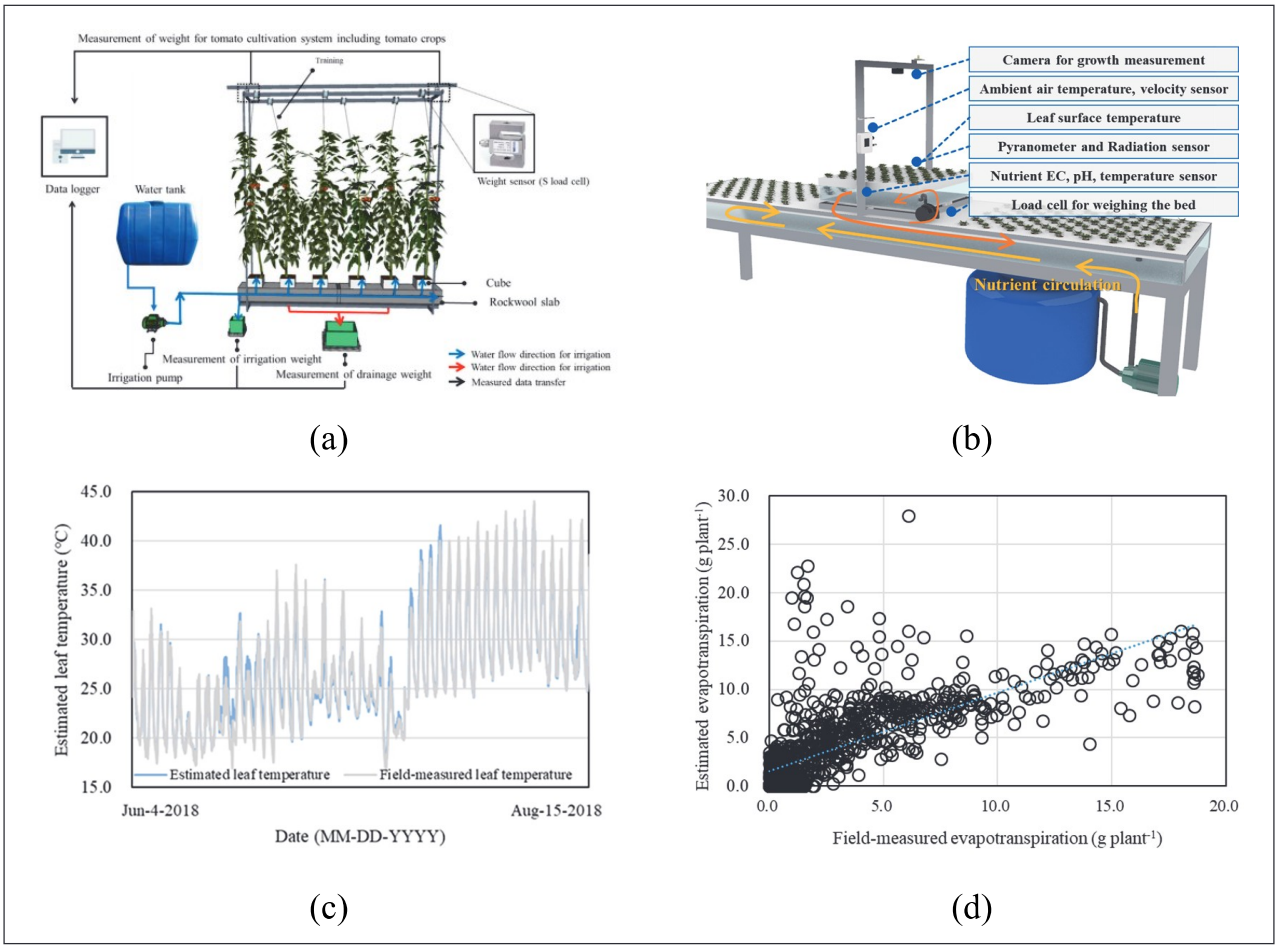
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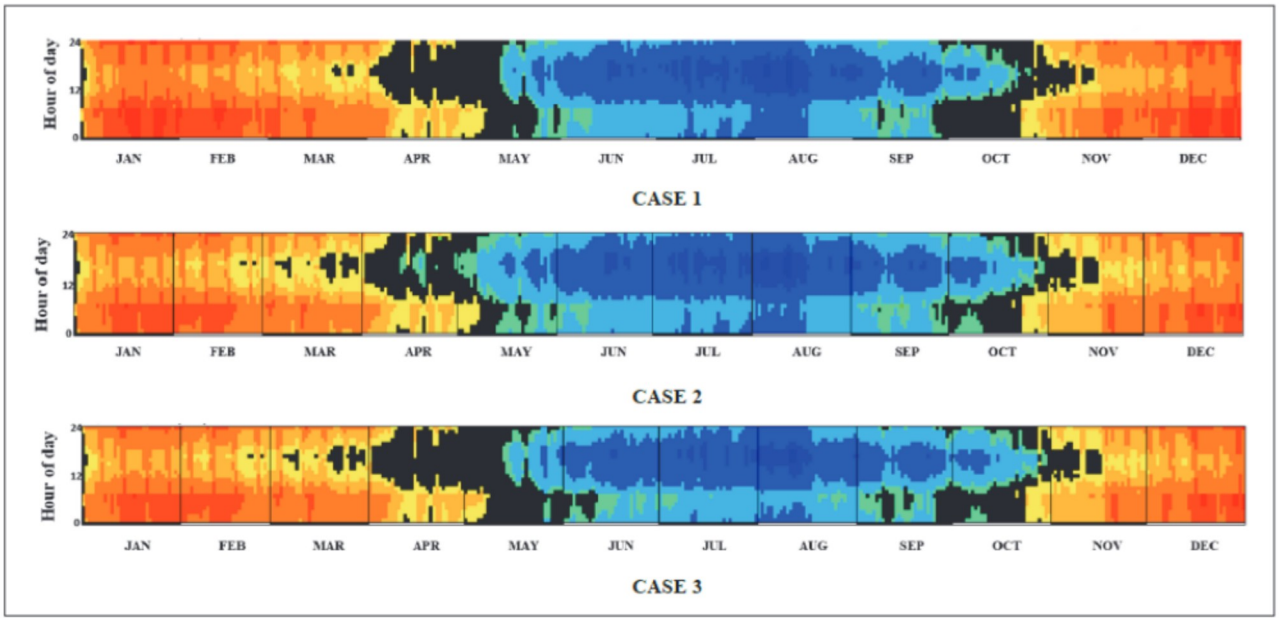
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Supplemental Information – Figure S3. Energy exchange of rooftop greenhouse and building.



Supplemental Information – Figure S4. (a, b): Schematic diagram of measuring evapotranspiration of tomato and bok choy; (c, d): Regression model for estimation of evapotranspiration and leaf temperature by growth stage.



Supplemental Information – Figure S5. Annual hourly energy consumption time maps; (a): building alone; (b): building under rooftop greenhouse with cooling; (c): building under rooftop greenhouse without cooling.