Energy Use of Building Integrated Agricultural (BIA) Space and its Impact on the Host Building

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CONSOMMATION ÉNERGÉTIQUE D’UN ESPACE D’AGRICULTURE INTÉGRÉE AU BÂTIMENT (AIB) ET SON IMPACT SUR LE BÂTIMENT HÔTE

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RÉSUMÉ

L'intérêt croissant pour l'agriculture urbaine (AU) découle de divers facteurs tels que la densification urbaine, la demande croissante en alimentation et l'impératif d'améliorer l'accessibilité alimentaire. L'agriculture en environnement contrôlé (AEC) peut être considérée comme l'un des options viables de l'AU, et gagne en popularité car elle permet la production alimentaire toute l'année dans les climats froids et les zones urbaines. Dans des régions comme le Québec, aux climats difficiles, la production agricole toute l'année est facilitée par des environnements contrôlés, allant des serres traditionnelles au sol aux espaces d’agriculture intégrée au bâtiment (AIB). L’AEC offre de nombreux avantages, notamment une productivité accrue des cultures, l'élimination de l'utilisation de pesticides chimiques et la possibilité de contrôler les conditions intérieures indépendamment du climat extérieur. Cependant, les impacts potentiels de ces méthodes de production restent mal compris en raison d'un manque de données et d'analyses approfondies.

L'utilisation de systèmes agricoles sophistiqués dans des espaces intégrés aux bâtiments, tels que des installations hydroponiques empilées verticalement sous un éclairage artificiel, permet un contrôle précis des conditions environnementales. Le contrôle précis des conditions environnementales intérieures, telles que la température de l'air, l'humidité, la concentration de dioxyde de carbone (CO_2) et les paramètres d'éclairage (y compris le type d'éclairage, l'intensité et la durée des périodes lumineuses/sombres), entraîne des rendements nettement plus élevés par rapport à l'agriculture conventionnelle. Néanmoins, ces avantages sont compensés par la consommation d'énergie substantielle associée aux pratiques de AEC, notamment l'utilisation de l'éclairage artificiel. L'objectif principal de cette thèse est de quantifier les effets de ces conditions intérieures qui sont essentielles pour atténuer l'empreinte environnementale et la consommation d'énergie associées à ce type de production alimentaire, en mettant l'accent sur la nécessité d'une évaluation approfondie

L'étude proposée évalue la performance énergétique globale (c'est-à-dire la consommation annuelle d'énergie et la demande électrique maximale) d'un espace d'Agriculture Intégrée au Bâtiment (AIB) à l'intérieur de son bâtiment hôte, un immeuble de bureaux de taille moyenne de 3 étages situé à Montréal, modélisé dans EnergyPlus, pour plusieurs scénarios opérationnels présentant différentes conditions environnementales intérieures. Les scénarios catégorisés se concentrent sur la densité de flux de photons photosynthétiques, le type d'éclairage, la température et les points de consigne d'humidité relative. En ce qui concerne l'évaluation de l'AIB uniquement dans les scénarios, la consommation d'énergie variait entre 2355 et 6920 MWh, représentant une variation de 65%. En analysant le bâtiment hôte avec BIA intégré, la variation de la consommation d'énergie était similaire, soit 66%, variant de 2994 à 9063 MWh. Les résultats obtenus peuvent guider la mise en œuvre des espaces AIB.

Mots-clés : agriculture en environnement contrôlé (AEC), efficacité énergétique, agriculture intégrée au bâtiment (AIB), consommation d'énergie d'éclairage, conditions d'environnement intérieur

ENERGY USE OF BUILDING INTEGRATED AGRICULTURAL (BIA) SPACE AND ITS IMPACT ON THE HOST BUILDING

Arefeh MORADI

ABSTRACT

The burgeoning interest in urban agriculture (UA) stems from urban densification, escalating food demand, and the imperative to enhance food accessibility. Controlled Environment Agriculture (CEA) can be considered a viable representative of UA, gaining popularity as it enables year-round food production in cold climates and urban areas. In regions like Quebec with challenging climates, agricultural year-round output is facilitated through controlled environments, ranging from traditional ground-based greenhouses to innovative building-integrated agricultural spaces (BIAs). CEA offers numerous advantages, including increased crop productivity, eliminating chemical pesticide uses, and controlling indoor conditions independently of outdoor climate. However, the potential impacts of these production methods still need to be better understood due to a lack of comprehensive data and analysis.

Utilizing sophisticated agriculture systems within building-integrated spaces, such as vertically stacked hydroponic setups under artificial lighting, enables precise control over environmental conditions. Accurate control of the indoor environment conditions, such as air temperature, humidity, carbon dioxide (CO_2) concentration, and lighting parameters (including the type of lighting, intensity and duration of photo/dark periods), results in significantly higher yields than conventional agriculture. Nevertheless, these advantages are offset by the substantial energy consumption associated with CEA practices, particularly artificial lighting. The main objective of this thesis is to quantify the effects of these indoor conditions, which are essential to mitigating the environmental footprint and energy consumption associated with performing this type of food production, emphasizing the need for thorough assessment and evaluation.

The proposed study assesses the overall energy performance (i.e., annual energy consumption and peak electricity demand) of a Building Integrated Agriculture (BIA) space within its host building, a medium-sized 3-storey office building located in Montreal, modelled in EnergyPlus, for several operating scenarios featuring different indoor environment conditions. The categorized scenarios focus on Photosynthetic Photon Flux Density (PPFD), lighting type, temperature and relative humidity setpoints. Regarding assessing the BIA solely in scenarios, energy consumption ranged between 2355 and 6920 MWh, representing a 65% variation. In analyzing the host building with integrated BIA, the variation in energy consumption was similar, 66%, ranging from 2994 to 9063 MWh. The obtained results can guide the implementation of BIA spaces.

Keywords: controlled environment agriculture (CEA), energy efficiency, building integrated agriculture (BIA), lighting energy consumption, indoor environment conditions

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LIST OF ABBREVIATIONS

ACH	Air Change per Hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIAs	Building-Integrated Agriculture space
BPS	Building Performance Simulation
CEA	Controlled Environment Agriculture
CO_2	Carbon Dioxide
CWEC	Canadian Weather for Energy Calculation
DLI	Daily Light Integral
DX	Direct expansion dehumidifier
GH	Greenhouse
HPS	High-Pressure Sodium (type of light)
HBM	Heat Balance Method
HVAC	Heating, Ventilation, and Air Conditioning
LAI	Leaf Area Index
LED	Light-Emitting Diode (type of light)
NECB	National Energy Code of Canada for Building
O_2	Oxygen
PAR	Photosynthetic Active Radiation
PPFD	Photosynthetic Photon Flux Density
RH	Relative Humidity
RTGH	Rooftop Greenhouse

UA	Urban Agriculture
VF	Vertical Farm
VPD	Vapor Pressure Deficit

INTRODUCTION

As the issue of food insecurity continues to expand on a global scale, with its detrimental consequences being increasingly evident due to the impacts of global warming, there has been an undeniable question regarding how to propose alternate solutions to conventional agriculture. In an attempt to address this pressing problem, the idea and practice of urban agriculture has experienced a significant surge in popularity, as it presents itself as a sustainable alternative to the traditional or soil-based agricultural methods that not only have numerous adverse effects on the environment but also face significant limitations in terms of production capacity. The emergence of urban agriculture with controlled environment agriculture (CEA) strategies as one of the potential solutions to these challenges is a reflection of the growing recognition of the need for innovative and sustainable approaches to food production to ensure long-term food security and mitigate the adverse effects of climate change (Despommier, 2013).

The conventional agricultural industry is recognized as a significant consumer of energy worldwide and must prioritize the development of strategies for achieving carbon neutrality (Muñoz-Liesa et al., 2020). Furthermore, the building sector accounts for 40% of global energy consumption and CO_2 emissions, significantly contributing to environmental concerns (Raji et al., 2015). Consequently, given the substantial quantities of waste materials and energy flows in urban environments, there exists a remarkable opportunity to explore the potential reuse of these resources in urban agriculture while also maximizing the utilization of underutilized urban spaces in residential and commercial buildings (Martin et al., 2022).

Regarding the types of urban agriculture, it can take the form of a warehouse, a repurposed shipping container, a greenhouse (either on the roof or on the ground), or a building-integrated agricultural (BIA) space. BIA spaces can be vertically stacked hydroponic farming systems known as vertical farms (VF), and there are two types of BIA: one that receives natural lighting and can supplement it with artificial lighting if needed, and one that relies solely on artificial lighting (Talbot & Monfet, 2024). Despite the ability of urban agriculture to use CEA techniques to facilitate vegetable cultivation in any geographical or atmospheric conditions, providing suitable environmental conditions and supplementary lighting necessitates substantial amounts of energy. The energy demand, especially electricity, is expected to increase and is frequently derived from non-renewable fossil fuels due to the sluggish transition to sustainable energy sources(Weidner et al., 2021). Consequently, pursuing enhanced resilience or self-sufficiency may result in a significant ecological impact on carbon emissions.

This study aims to evaluate and understand the impact of different indoor conditions on the energy consumption and demand of a BIA space and its host building while considering the crop growth interactions. The central concept underpinning this research project is to function with maximum energy efficiency by carefully considering all available avenues. These avenues encompass the electrification of various systems, identification of ideal indoor conditions, and assessing how each parameter influences the reduction of energy while simultaneously increasing production levels yield. When exploring the most optimal growing conditions, considering the impact of these combinations on energy consumption is often disregarded, as the primary focus tends to be maximizing yield and maintaining high quality (Martin et al., 2023). The indoor environmental conditions necessary for agricultural productivity, such as temperature, humidity, lighting intensity, and CO_2 concentration, are maintained through heating, ventilation and air conditioning (HVAC) and other systems.

Chapter 1 reviews the literature on urban agriculture, the most common types of BIA spaces, interactions between plants and their environment, the energy exchange between BIA spaces and host buildings, indoor environmental conditions to be maintained, HVAC systems, and existing prospects. Chapter 2 presents the research objective and proposed methodology. Chapter 3 introduces the results obtained. Chapter 4 discusses the relevance of the obtained results. The thesis brings to an end with a conclusion and various appendices.

CHAPTER 1

LITERATURE REVIEW

1.1 Controlled environment agriculture in an urban context

Agricultural practices are crucial: population expansion, rising evidence of food scarcity, and decreasing land availability are only a few issues stressing the need to upgrade existing agricultural processes (Waldron, 2018). In addition to the three reasons above, recently, the world witnessed some unexpected disasters which affected global food security. Belleri and Ratti (2023) state, "Feeding the growing urban masses will be an extraordinary challenge amidst the convulsions of climate change, and both the Covid-19 pandemic and Russia's invasion of Ukraine remind us that international supply chains are only as strong as their weakest links". Considering all potential threats, there is an undeniable need to reduce dependence on conventional agriculture to provide the necessary products.

Urban Agriculture (UA) can be a viable solution for alleviating global concerns. From the exact definition perspective, Urban agriculture (UA) is a popular urban design option to mitigate the environmental effects of urban food needs. Food production in and around cities uses pre-existing urban material energy fluxes as production variables (Goldstein et al., 2016). It is commonly described by its location within or adjacent to an urban area, as well as by its connections to the city, both physically and socially. However, some aspects of cities may cause this term to be used differently (Dorr et al., 2021).

Expanding urban agriculture through controlled environment agriculture systems encompasses different types of spaces and concepts. As illustrated in Figure 1.1, the perception of UA can be considered from several perspectives.

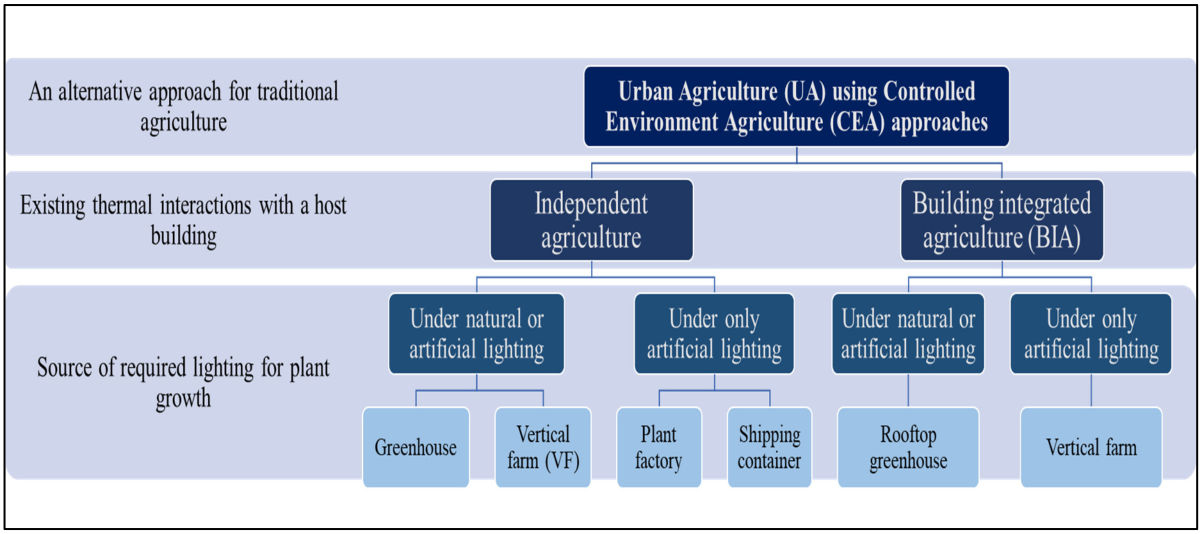


Figure 1.1 Urban agriculture related concepts
Adapted from Talbot (2019)

All forms of indoor farming are now referred to as controlled environment agriculture (CEA). CEA has rapidly evolved into a commercially viable approach for the large-scale production of a diverse range of crops in the last five years with the introduction of spectrum-specific, higher efficiency light-emitting diode (LED) grow lights, as well as computer-assisted control systems for monitoring and delivering precise amounts of nutrients, adjusting the pH, temperature, and oxygen content(O_2) of the nutrient solution, and assessing the growth and overall health of each crop (Despommier, 2013). As a result, technologies for controlled environment agriculture (CEA) are gaining popularity to produce more food with a smaller environmental footprint and fewer resources.

Various methods in CEA can alter plant environments. Ideally, crop growth occurs in regions with perfect conditions, free from extremes and not needing protective structures. This independence of conventional agriculture from controlling growth conditions and structures can be considered an advantage of this type of agriculture. However, most countries need controlled environments due to harsh conditions. While technology in the greenhouse industry is advanced in temperate climates, improving protected agriculture in extreme climates remains crucial. Tropical, arid, polar, and urban areas pose distinct challenges. High solar radiation in tropical and arid zones leads to temperature and humidity issues, making open structures susceptible to pests. Conversely, polar and urban environments lack solar exposure, demanding controlled air quality with enclosed structures. Sustainability and energy efficiency are common concerns across these settings. Protected agriculture methods offer solutions for high-quality crop production in extreme climates, driving the need for advancements and challenges review (McCartney & Lefsrud, 2018).

1.2 Building integrated agriculture

As shown in Figure 1.1, urban agriculture encompasses different farming approaches, including Building Integrated Agriculture, which is described in more detail as it is central to this project.

Building-integrated agriculture (BIA) in urban domains is proposed to be ecologically sustainable compared to traditional commercial farming methods (Ahamed et al., 2023). It achieves this by diminishing the distance food travels, reducing land and water consumption, and enhancing crop yields (Benis et al., 2017b). However, there are some significant trade-offs between BIA and conventional agriculture that should be considered, such as higher initial capital costs of BIA facility, energy-intensive activities of BIA, existing the possibility of thermal exchange of BIA with the host building and weather-dependent growth in conventional agriculture.

Agriculture is one of the significant energy-intensive sectors globally that urgently needs to develop plans for carbon neutrality. The sector's heavy reliance on non-renewable energy sources and the considerable greenhouse gas emissions associated with agricultural activities contribute to the negative impacts of climate change. The need for transformation in agriculture is evident, as current systems are overly dependent on non-renewable energy (Martin et al., 2023). A significant amount of energy consumption and CO_2 emissions arise from the building sector, accounting for 30-40% of global energy consumption across the world. The building sector also accounts for about one-third of greenhouse gas emissions (Opoku et al., 2022). Subsequently, because of vast amounts of residual material and energy streams by urban environments, there is a tremendous chance to investigate the reuse of these streams for urban agriculture, as well as the make use of underutilized urban spaces in residential and commercial structures (Martin et al., 2022).

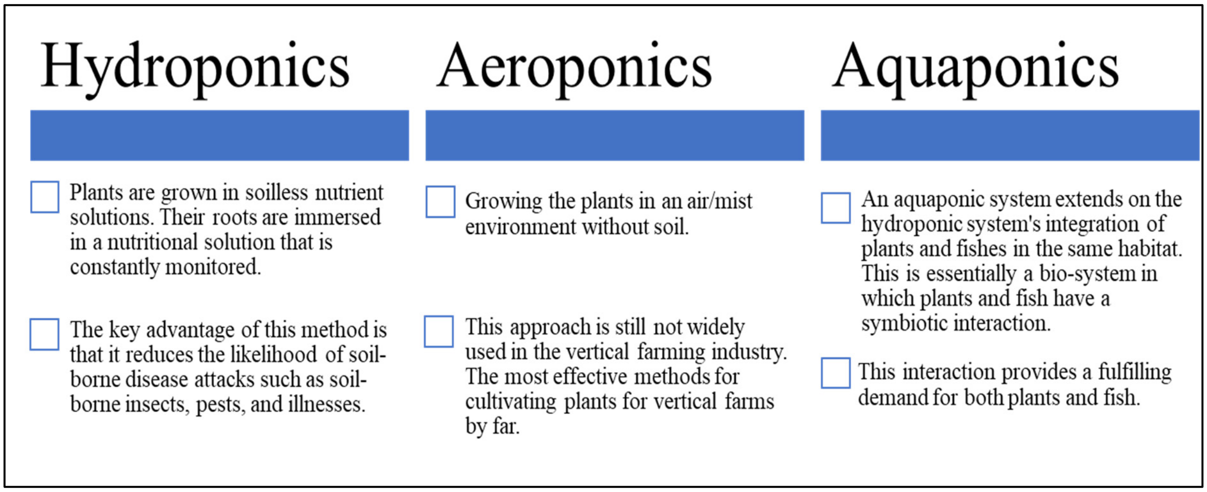
BIA can use cutting-edge methods to carry out agricultural production inside or outside (roof, balcony and yard) of a host building. A greenhouse (GH) situated on a building's rooftop or a vertical farm (VF) housed within a high-rise building floor are both forms of Building-Integrated Agriculture (BIA). Given their potential for multifaceted interactions with their respective host buildings, these structures- whether rooftop greenhouses or vertical farms- are categorized under the scope of BIA.

1.2.1 Vertical farming

Vertical farming (VF) involves stacking crops vertically rather than horizontally. It can thus generate more productivity out of a limited piece of land under fully controlled indoor conditions, such as temperature, humidity, lighting, and CO_2 concentration (Kozai et al., 2020).

Over recent years, the development of Indoor Vertical Farming has shown significant expansion. Forecasts indicate an anticipated compound annual growth rate (CAGR) of 25.9% from 2022 through 2029 for this innovative farming method (Ahamed et al., 2023). Despite that, overcoming high energy demand, substantial capital costs, and constraints in cultivating diverse crop varieties are pivotal barriers to attaining the ultimate sustainability goals. Also, the energy use of VF only with artificial lighting may generate significant greenhouse gases in some locations (Benis et al., 2017b). Consequently, these trade-offs should be carefully measured.

For the most VF facilities, no natural light is used, leading to high energy costs because the plant is grown entirely using artificial lighting (Chand et al., 2023). From the diversity of cultivated crop types, it should be mentioned that tiered cultivation has been limited to plants less than 30 cm in height, such as lettuce, herbs and seedlings (Talbot, 2019). Figure 1.2 shows the categorization of growing approaches in VF.



Hydroponics

- ☐ Plants are grown in soilless nutrient solutions. Their roots are immersed in a nutritional solution that is constantly monitored.
- ☐ The key advantage of this method is that it reduces the likelihood of soil-borne disease attacks such as soil-borne insects, pests, and illnesses.

Aeroponics

- ☐ Growing the plants in an air/mist environment without soil.
- ☐ This approach is still not widely used in the vertical farming industry. The most effective methods for cultivating plants for vertical farms by far.

Aquaponics

- ☐ An aquaponic system extends on the hydroponic system's integration of plants and fishes in the same habitat. This is essentially a bio-system in which plants and fish have a symbiotic interaction.
- ☐ This interaction provides a fulfilling demand for both plants and fish.

Figure 1.2 Different types of vertical farming
Adapted from Chand et al. (2023)

A well-engineered indoor growing facility can reduce or eliminate a wide variety of fertilizer-related diseases; by design, hydroponics and aeroponics use nutrient solutions that do not include any metabolic waste from human metabolism, avoiding the problem of harsh contamination of food sources entirely (Despommier, 2013).

Within the industry, there is a widespread belief that a VF cannot afford to compete with a GH because of the high energy costs associated with artificial lighting. Eaves and Eaves (2018) stated that Canada is uniquely positioned to be a leader in the VF market because VF are electricity-intensive, and Canada enjoys some of the lowest electricity prices in North America. Their study found that in a cold climate like Quebec, the cost of running a semi-closed hydroponic VF and a semi-closed hydroponic GH (which cools and dehumidifies using vents) facilities with similar indoor conditions for growing lettuce are very similar, while the net profit is higher for the VF (Eaves & Eaves, 2018). Also, it can be mentioned that one significant disadvantage of GH is that they are frequently located far from metropolitan centers, where real estate prices are lower. On the other hand, a VF with numerous layers of growing units minimize the facility's footprint, lowering the cost of being located closer to metropolitan centers and allowing the farmer to deliver fresher produce (Despommier, 2013).

The establishment of vertical farms in urban areas can be projected to create job opportunities. A diverse range of job descriptions forms the workforce within a typical large-scale indoor growing facility. These roles span various functions necessary for the operation and management of the vertical farm, including tasks related to cultivation, technology maintenance, logistics, and management (Despommier, 2013).

1.2.2 Greenhouses

As shown in Figure1.1, a greenhouse can be considered a subtype in both independent agriculture and BIA concerning its characteristics, location, and function, developing an urban context and synergy with the environment. Bastien’s (2015) thesis includes a complete literature review with a comprehensive focus on the development of greenhouses in urban contexts and the potential of their integration with buildings.

Because of the solar energy they collect, greenhouses allow plants to be grown outside of the farming season. This energy, which will enable plants to photosynthesize, also heats the growth space, extending the growing season. Traditional soil-based cultures or seedlings can be accommodated in the greenhouse. A hydroponic cultivation system can also handle more high-tech systems allowing for soil-less production (Talbot, 2019).

The ventilation system releases excess energy while heating or cooling adjusts deficiencies or surpluses. A greenhouse's transparent, conductive façade design balances solar energy with outside temperature influences. The correlation between expenses (heating and cooling) and benefits (solar radiation) in greenhouse production heavily depends on the site's latitude and external climate conditions (Graamans et al., 2018). Poorly managed interior environmental conditions are especially vulnerable to solar heat gains; therefore, these hourly variations lead to significant fluctuations in both temperature and humidity.

A rooftop greenhouse is the most common type of integrated agricultural area within buildings. These rooftop greenhouses increase solar exposure in metropolitan regions and capture and reuse heat escaping from the building's roof during the winter. This heat recovery method eliminates the need for heating in rooftop greenhouses in Mediterranean climes, but it may contribute to excessive heat on the building's highest floor (Gomes et al., 2016). Figure 1.3 shows an urban rooftop GH.

Figure 1.3 Urban rooftop greenhouse
Taken from Bastien (2015)

1.2.3 Comparative analysis

One of the most published subjects in this context in which researchers work is a comparison between a VF and GH in similar indoor conditions to evaluate profitability and their advantages and disadvantages within a range of essential criteria such as annual energy consumption (kWh), electricity demand (kW) and total dry matter of cultivated crop (kg). Eaves and Eaves (2018) conducted a simplified study based on the use of degree days in the Quebec province. They stated that a VF used more electricity for lighting facilities. Still, it is more expensive to maintain the regulation of internal conditions for a GH due to its poor insulation in a harsh climate. Also, Graamans et al. (2018) obtained similar results. They mentioned that in extremely dark/cold regions located in high latitudes, VF is more suitable than GH because heating requires more electricity than lighting.

On the other side, Harbick and Albright (2016) conducted their simulation in four different climate zones (1) Warm – Humid, (2) Cold – Dry, (3) Cold – Humid, (4) Hot – Dry, and they used an identical temperature setpoints and lighting intensity for both VF and GH. At the end of their research, they found that in all climate zones, greenhouses consume less energy and have a lower carbon footprint than plant factories, providing equal yields, mainly when the plant factories employ simple reheat HVAC systems. The only advantage of plant factories appears to be their small physical footprint.

Regarding high productivity and efficient resource utilization (water, CO_2, and land), a vertical farm facility creates a precisely controlled environment by employing a CO_2 enrichment system and other technologies, alongside a HVAC system, to regulate and stabilize diverse indoor environmental conditions. On the other hand, in a greenhouse, reliance on outside air to offset solar effects can cause significant disparities in the indoor conditions of a greenhouse. This dependency limits the CO_2 levels maintained inside, prohibiting higher levels than outside air. Sub-optimal CO_2 concentrations hinder plant growth, impeding their full potential. Moreover, outdoor air heightens the risk of pest infestation and disease transmission (Kozai et al., 2020).

1.3 Building performance simulation

The complexity of designing the built environment, involving diverse technical areas, multifaceted performance goals, and widespread uncertainty, poses significant challenges.

Building performance simulation (BPS) tools are designed to facilitate the interdisciplinary effort of developing buildings and affiliated systems. The technology heralds a future in which practitioners can routinely model the interacting heat, air, moisture, light, sound, electrical, pollutant, and control signal fluxes, fostering performance improvement by design (Clarke & Hensen, 2015).

Building energy modelling can be completed using different simulation software packages such as TRNSYS (Beckman et al., 1994) and EnergyPlus (Crawley et al., 2001). OpenStudio (Guglielmetti et al., 2011) is a graphic user interface for EnergyPlus that facilitates designing, generating input, and visualizing output. Until recently, these tools were primarily geared at buildings with human occupants and did not allow for the simulation of plants and their interactions with the environment. Most of the studies on the indoor agriculture domain have neglected the impact of thermal interactions of plants with their environment (Sethi et al., 2013). Since one of the purposes of BPS tools is to determine expected heat exchanges, it must be able to accurately model all of these thermal plants' reactions, specifically the most important ones. However, some researchers have attempted to adapt BPS tools to incorporate plant analysis developed in agriculture. Kokogiannakis & Cooper (2015) and Ward (2015) were among the first to establish a novel approach to integrating an indoor agricultural space into a building using ESP-r and TRNSYS, respectively.

Regarding the importance of quantifying the thermal interaction of plants with the surrounding environment, practical research has been done by Talbot & Monfet (2020) about estimating the impact of crops (lettuce) on measured loads of a BIA space. They used an existing steady-state lettuce thermal model balance developed by Graamans et al. (2017), which was integrated into a building model via BIA space in TRNSYS. To estimate the possible crop heat gain/loss effect, they did the first baseline simulation with design conditions without heat gain/loss induced by crops. Then, they added a lettuce model coded as a TRNSYS component to their baseline performance to evaluate the impact of having VF on the sensible heating and cooling demand of the host building.

From an environmental impact perspective, Benis et al. (2017a) created a simulation-based analysis approach to assess the environmental implications of BIA in urban areas. They compared them to conventional farming in rural locations in EnergyPlus. They modelled and compared four agriculture spaces for a city in Portugal: (1) a passive rooftop greenhouse, (2) a "high performance" rooftop greenhouse with a hydroponic system, (3) a BIA space with daylighting and electric lighting, (4) a BIA space with electric lighting only. This analysis included water consumption, tomato production, transportation energy use, greenhouse gas emissions, local economy and energy consumption distribution. However, the heat gains/losses of the plants and a calibration were not included. The conducted workflow aimed to give the practitioner actual evaluation for design decision-making while implementing BIA in a given neighborhood.

In the meantime, Benis et al. (2017b) have systematically applied a strategy across multiple cities globally, as outlined in their study, to better understand the potential of BIA in mitigating food-related carbon emissions across diverse regions. Their comprehensive assessment assumes a favorable outlook for the overall evaluation of a particular area. In such instances, architects and urban planners can utilize a process grounded in climate data, agricultural needs, and farm layout to assess the feasibility of BIA for a specific location. This workflow aims to aid users in developing a localized BIA system while optimizing crop production and energy usage. The inclusion of a model for plant growth and evapotranspiration was part of the analysis.

Concerning the comparison of different types of CEA, Harbick and Albright (2016) compared annual energy consumption between plant factories and greenhouses with similar dimensions and characteristics located in four distinct ASHRAE climates (2B, 3A, 6A, and 6B) in the U.S using EnergyPlus. They demonstrated that, given similar production, plant factories consume significantly more energy and have more significant carbon emissions than traditional greenhouses for various climates.

One of the studies that was carried out on designing an appropriate HVAC system and the impact of adding a crop thermal model was done by Lalonde et al. (2019). They utilized TRNSYS to replicate the simulation environment's current building structure and attributes. They employed best practices, including two suggested HVAC systems, and sized them accordingly for efficiency. In the design step, the proposed HVAC systems were created to simulate their operations within the building structure, and then to evaluate the impact of heat exchanges induced by plants, they added the crop model. They found the significance of considering the sensible heat exchange between plants (contributing to cooling) and the surroundings when sizing heating systems effectively. Additionally, the substantial latent heat exchange from the plants through evapotranspiration enabled the proper sizing of dehumidification systems, which is crucial in cold climates to prevent condensation within the building structure. Also, when heating equipment size is based on sensible heating load calculation that ignores crops, it may result in periods where the temperature set-point still needs to be fulfilled (Talbot & Monfet, 2020). This consideration is vital to prevent moisture-related issues in the building envelope.

Regarding the feasibility and validation of the energy model in urban design, Liebman-Pelaez et al. (2021) proposed establishing an EnergyPlus model of a hydroponic container farm in Boston, Massachusetts. Their methodology was to transform the verified energy model into a “generic container farm simulation template, template container farm (TCF)” that urban modelling tools can use in the future. Their study aimed to investigate the model's shortcomings in predicting hourly cooling loads and identify areas for improvement, such as accurately representing crop-surface energy exchanges. Investigating the thermal effects of plant evapotranspiration within a hydroponic container farm and compliance with ASHRAE Guideline 14–2014 were included.

BPS tools also help with strategic decision-making throughout the design, undertake scenario analysis utilizing new technology or design methods, and estimate the effects of changing an existing building. Furthermore, BPS can serve as a virtual test bed for evaluating the potential of hypothesized (but unrealized) materials, components, and systems designed to generate a competitive edge by boosting performance cost-effectively (Clarke & Hensen, 2015).Also, building performance simulation tools offer the most promising solution for modelling building integrated agricultural areas.

1.4 Interactions of plants with their environment

Cultivating crops within building-integrated agriculture plays a substantial role in shaping a building's heating and cooling demands. Studies have suggested incorporating crop models into building performance simulations to assess their influence on internal thermal dynamics (Graamans et al., 2017). This approach helps evaluate the effects of crop energy balance on overall thermal requirements, thereby affecting the design of HVAC systems and peak load estimations within integrated agricultural environments. In building-integrated agriculture spaces, estimating crop-related peak loads is crucial to size HVAC systems for indoor environmental control appropriately (Talbot & Monfet, 2020). Strategies involving heating and cooling exchange between architectural elements and farming spaces demonstrate the potential for efficiently managing thermal loads (D'Ostuni et al., 2022).

Studies have analyzed the impact of crops on heating and dehumidification loads in building-integrated agriculture spaces, emphasizing the importance of understanding thermal dynamics for effective system design (Lalonde et al., 2019). Building-integrated rooftop greenhouses have been shown to reduce cooling and heating loads by mitigating heat gains or losses through building surfaces (Yeo et al., 2022). Integrating greenhouse systems within a building structure not only influences the thermal behavior of the space but also provides opportunities to manage heating and cooling requirements effectively(Caplow & Nelkin, 2007). Regarding climate, crop models are essential for building integrated agriculture (BIA) space in cold climates. They play a crucial role in estimating internal humidity levels. This estimation is pivotal as condensation within external walls can compromise the building envelope's integrity, especially in winter. Accurately predicting humidity levels influenced by plants is vital to mitigate the risk of structural damage caused by condensation (Lalonde et al., 2019).

1.4.1 Plant activity

The most influential biological processes through which plants interact with their surrounding environment are photosynthesis, photorespiration, respiration, and transpiration. Mass and heat are exchanged between plants and their environment within these phenomena. Mass transfer includes CO_2, O_2, H_2O, and nutrients.

- Photosynthesis: During the photoperiod, plants absorb CO_2 and H_2O and they produce carbohydrate, O_2 and H_2O. Two by-products that improve air quality are transmitted to the environment through the stomata: oxygen and water vapor.
- Photorespiration: This process coincides with photosynthesis but oppositely, reducing its efficiency.
- Respiration: During the dark period, the plant absorbs oxygen, converts carbohydrates from photosynthesis into usable energy and releases CO_2 and water vapor.
- Transpiration: It occurs mainly through the stomata that open during photosynthesis but also during respiration. The difference in vapor pressure between the two causes water vapor diffusion from the plant to the surrounding air. At leaf temperature, vapor pressure equals vapor saturation, whereas vapor pressure in the air varies with moisture content (Kozai et al., 2015).

As mentioned, plants release O_2 and absorb CO_2 during photosynthesis, opposite to how humans breathe. Furthermore, the photosynthesis of plants occurs throughout the day while commercial buildings are in operation, which is why VF is beneficial for lowering indoor CO_2 concentrations in commercial buildings, leading to decreased HVAC energy use. VF may lessen commercial buildings required fresh air supply rate when paired with other air purification techniques, significantly saving the energy used for building ventilation. It may also enhance indoor air quality. The CO_2 concentration is typically used to calculate the necessary fresh air volume when planning ventilation systems(Shao et al., 2021).

1.4.2 Thermal behavior of plants

In addition to the impact of mass transfer through crop growth with its environment, heat is exchanged. Thermal synergy can be pivotal in the host building's energy consumption and peak demand. This exchange consists of different heat fluxes, as illustrated in Figure 1.4 and defined according to the heat balance Equation(1.1).

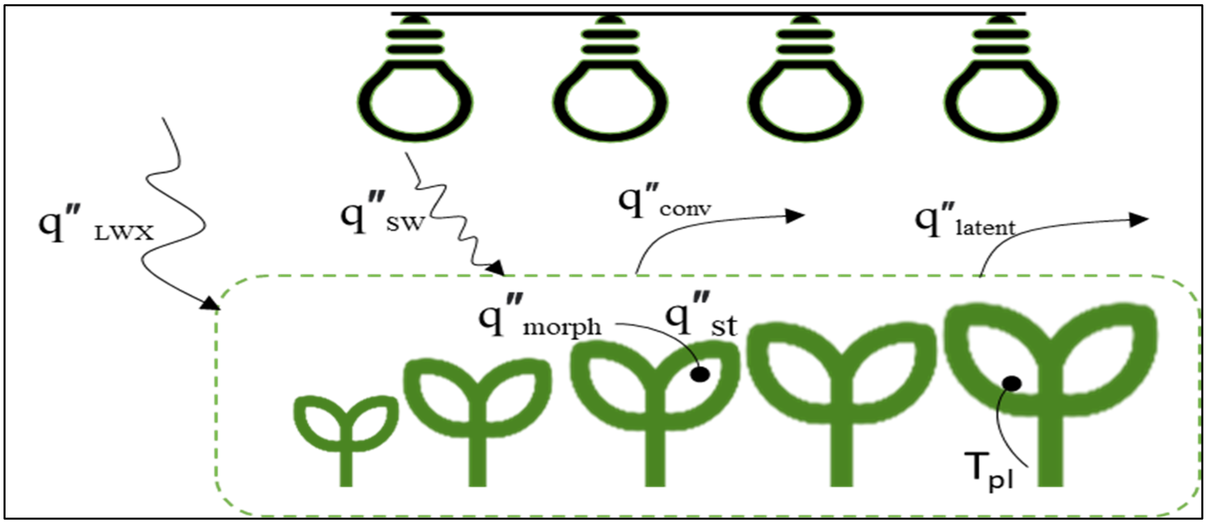


Figure 1.4 Energy balance between crop and environment
Adapted from Talbot and Monfet (2021)

$$q''_{sw} + q''_{LWX} - q''_{st} - q''_{morph} - q''_{conv} - q''_{latent} = 0 \tag{1.1}$$

where;

q''_{SW} is the short-wave radiation flux absorbed by the crops from lights;

q''_{LWX} is the net long-wave radiation flux exchange between surfaces;

q''_{st} and q''_{morph} are the fluxes stored within the leaves, stems and fruits or used for photosynthesis and plant development, respectively (negligible) (Talbot & Monfet, 2021);

q''_{conv} is the convective exchange flux with ambient air, which can cause the crop cooling effect;

q''_{latent} is the latent exchange flux with ambient air, mainly by leaf transpiration.

Since VFs are usually performed in airtight spaces, their energy demand is driven by two main internal sources: the gains from artificial lighting and the gains/losses induced by the crops (Talbot & Monfet, 2020). Lighting generates radiative (long-and short-wave) and convective heat gains. Simultaneously, transpiration from crops induces evaporative cooling. The need for dehumidification (latent cooling) and substantial sensible cooling arises due to internal sources affecting the controlled environment in vertical farming spaces (Graamans et al., 2018; Lalonde et al., 2019).

Calculating the crop's energy behavior in both stages is critical, including how it transpires, reflects light, and transfers heat and radiation. Cooling and vapor removal are two distinct processes, and the relationship between sensible and latent heat is an essential element in energy consumption. As a result, the energy balance must be based on an accurate calculation of the crop transpiration coefficient, which is the fraction of the radiation load dissipated as latent heat by the crop (Graamans et al., 2018). To guarantee efficient crop growth, specific indoor conditions must be maintained (section 1.6). This matter can be addressed by choosing an appropriate HVAC system (section 1.7).

1.5 Impact of BIA on building synergy performance modeling

BIA systems can be viewed as a promising approach to increasing the energy efficiency of buildings through the possibility of thermal interactions with them. Roof greening, vertical greening, terrace planting, and sky gardens (interior and outdoor) are the most typical sites in a building where plants can be accommodated, particularly in high-rise construction in an urban context (Raji et al., 2015). From improving thermal comfort, BIA spaces in rooftop greenhouses can enhance energy performance and air quality, especially for poorly insulated free-running buildings due to their inadequate indoor comfort related to temperature and high CO_2 concentration (Ledesma et al., 2022). Regarding indoor air quality (IAQ), there are three aspects of indoor plants' ability to improve interior comfort: temperature decrease, humidity, and purification. Additionally, from a psychological perspective, plants can help create a comfortable environment by lowering stress and promoting health and well-being (Raji et al., 2015).

Integrating vertical farming into commercial buildings may be a way to lower indoor air pollution and building ventilation energy (Shao et al., 2021). To take advantage of potential interactions between growing plants indoors and the host building, some detrimental conditions reduce the quality of interactions. Figure 1.5 shows the most common reasons for absorbing lower CO_2 content and higher photorespiration.

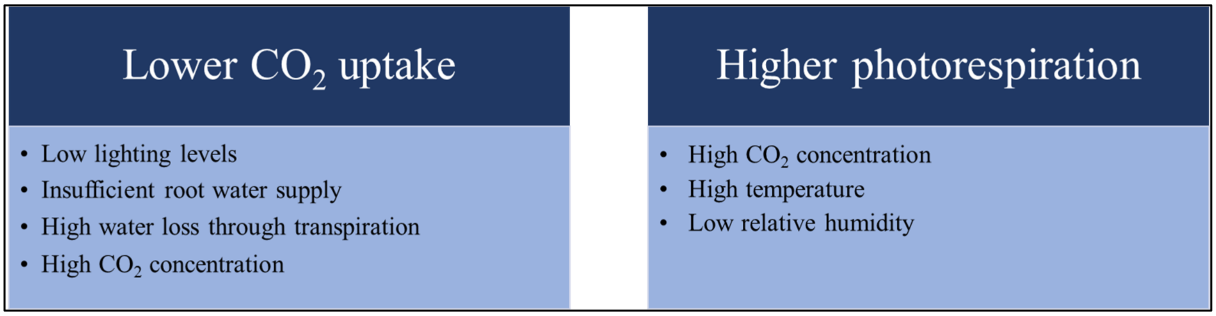


Figure 1.5 CO_2 reduction reasons
Adapted from Kozai et al. (2015)

Adding VFs into buildings is one of the latest approaches and acclimatized directions in ecological design, which can absorb CO_2 and release O_2 based on plants' biological processes such as photosynthesis. Office buildings are appropriate for integrating VF into their scheme because of their spatial form, working schedules, and other features (Shao et al., 2021).

However, it is questionable if the potential reliance on the synergistic impact of combining BIAs, especially greenhouses and forced waste airflows in buildings, could improve the energy efficiency of both systems; some research has been done about the promising impact of this symbiosis. Munoz-Liesa et al. (2022) assessed the energy recovery potential of exchanging airflows in a rooftop greenhouse integrated with an office building HVAC system in a Mediterranean environment (Barcelona region, Spain) in their study. Using monitored and calibrated energy model data revealed that the BIA could operate as a solar collector and sink for a building's low-grade waste heat while taking advantage of active ventilation strategies. Incorporating rooftop greenhouses into underutilized urban fabric spaces can help decarbonize buildings and urban agriculture while improving the combined systems' energy performance (Muñoz-Liesa et al., 2022).

An alternative practical work to evaluate gaining additional system energy efficiencies between a BIA and its host building has been done by Munoz-Liesa et al. (2020). Their simulation results indicated that their designed clear Polycarbonate rooftop greenhouse (U-value of 5.7 $W.m^{-2}. k^{-1}$) can passively retrieve a reasonable amount of annual heating energy from the building (especially during nighttime) if it is provided with the same heating measure by the HVAC system of the host building. Furthermore, their final results also quantified that adding BIA impacts additional insulation value, especially in winter, which results in an annual energy saving of approximately 4% of the yearly energy needs of baseline building. When considering the trade-offs between additional energy required to operate BIA into building space and facilitate thermal exchange between them, the annual net energy gains saving for the whole system are promising.

From the bidirectional exchange of thermal energy between VFs and buildings, this integration can reduce the total combined energy use of both entities. This means that the waste heat produced by the vertical farm can heat the building, reducing the need for additional energy sources. The ideas above were proposed by Blom et al. (2023). They indicated that the interactive exchange of energy between vertical farms and buildings could collectively decrease the total annual energy consumption of the climate systems by 12 to 51% in the Netherlands. The final noticeable results of their study provide a first step in quantifying the potential energy savings and resource synergies between vertical farms and buildings.

1.6 Indoor environmental conditions

As defined earlier, having a BIA space, specifically a VF within the building, is based on fully controlled environmental conditions, leading to higher crop productivity and independence of external conditions such as climate and seasonal limitations. This higher yield is feasible by maintaining specific indoor environmental conditions to improve plant growth (Talbot et al., 2022) :

- Lighting intensity (spectrum and duration)
- Temperature
- Humidity
- CO_2 concentration

VPD, also known as Vapor Pressure Deficit, refers to the disparity between the vapor pressure encompassing the leaf and surrounding air. Cultivators frequently utilize this metric to regulate indoor conditions, thus obviating the need to manipulate temperature and humidity levels separately (see equation (2.1)) (Talbot et al., 2022). VPD fluctuation can significantly affect the yield and quality of crops. In lettuce, drastic VPD fluctuation led to a gradual decrease in stomatal conductance and CO_2 assimilation rate, reducing photosynthetic performance and plant growth (Inoue et al., 2021). On the other hand, moderate VPD fluctuation maintained leaf expansion and CO_2 diffusion efficiency, leading to enhanced plant growth compared to drastic VPD fluctuation (Goncharov et al., 2023). For lettuce and other leafy greens, it is recommended to maintain the VPD between 0.65 kPa and 0.9 kPa (Ahamed et al., 2023; Kozai et al., 2015).

HVAC and other supplementary systems regulate these conditions, and maintaining an optimal range can be considered highly energy-intensive and expensive.

1.6.1 Indoor temperature

Plant photosynthesis does not behave strictly on temperature control, provided it is within a “reasonable range” (Körner et al., 2009). However, high-temperature stress can stimulate changes in, for example, water relations, photosynthetic activity, hormone production, and cell membrane thermostability (Waraich et al., 2012).

The optimal temperature range for lettuce in a plant factory typically falls between 18°C and 25°C during the day/photoperiod, which enhances CO_2 uptake and improves lettuce growth. During the night/dark period, it is generally recommended to maintain temperatures between 10°C and 18°C. These temperatures support optimal growth and development, promoting healthy lettuce cultivation (Carotti et al., 2021; Duggan-Jones & Nichols, 2015).

1.6.2 Humidity level

Because relative humidity within the agricultural space directly influences plant transpiration rates, it must be efficiently maintained (section 1.4.1). Humidity levels between 70 and 80% promote vegetative growth and reduce water stress by causing stomata closure (Ahmed et al., 2020). Plants will take more water via their roots to avoid drying when relative humidity is less than 70% due to the increased vapor pressure difference between the plant and the ambient air (Kozai et al., 2020). High relative humidity, however, might cause fungal and mold growth and/or jeopardize the envelope's integrity, depending on the materials employed (DCA, 2018).

Tip burn is a physiological disorder stemming from a calcium deficiency in young leaves, which is usually triggered by high levels of relative humidity, temperature, and lighting intensity or, in some situations, occurs within high pH and water stress, not by a lack of calcium content in the nutrient solution (Holmes et al., 2019). Lettuce tip burn, the most common disease in plant factories, causes yellowing of the higher tip edges and leaf curling, dramatically reducing crop quality and yield. According to research, the possibility of lettuce tip burns during the growth stage is caused by the suppression of transpiration in the high-humidity environment of plant factories, resulting in the difficulty of Ca^{2+} being delivered quickly from the culture solution to the leaves via the roots. (Haibo et al., 2023).

1.6.3 Lighting

Lighting for plants is different from humans' vision. Light energy for humans is measured in lumens with units of lux. On the other hand, light energy for plants, as they absorb only part of the light spectrum for photosynthesis, is measured as Photosynthetic Active Radiation (PAR), as shown in Figure 1.6. PAR defines the type of light on the lighting spectrum where plants respond best to photosynthesis and typically look at the wavelength range of 400nm to 700nm. In the PAR zone, agriculture lighting measures the light which falls on the crop, which is expressed as PPFD or Photosynthetic Photon Flux Density ($\mu mol \cdot s^{-1}.m^{-2}$), which radiation is emitted by artificial lighting for the duration of the photoperiod, depending on the lighting intensity. Any photons within this spectrum absorbed by the plant will contribute to photosynthesis (Kusuma et al., 2020; Nájera et al., 2023). Light intensity is also crucial, with recommended values ranging from 350 to 600 $\mu mol \cdot m^{-2} \cdot s^{-1}$ depending on the temperature. For low temperatures, light intensities of 350 to 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ are recommended, while for medium and high temperatures, intensities of 350 to 600 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 500 to 600 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively, are optimal (Ahmed et al., 2020).

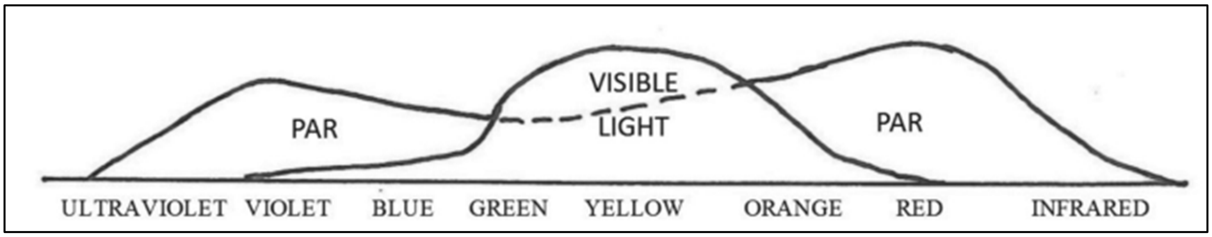


Figure 1.6 Relation between PAR and Human eyes
Taken form Jonlin & Lewellen (2017)

There are different types of lighting for indoor farming design. The two most commonly used are high-pressure sodium (HPS) and light-emitting diode (LED), which have different characteristics. Other lighting used by growers and researchers in the VF domain includes T5 fluorescent, metal halide, ceramic metal halide (CMH) and induction lighting, each of which has its supporters and detractors (Jonlin & Lewellen, 2017). As pointed out, the significant dependency on artificial lighting in VF causes considerable energy consumption and cost (Section 1.2.1). Table 1.1 lists the most critical advantages and disadvantages of LED vs. HPS.

Table 1.1 Advantages and Disadvantages of LED vs. HPS Lighting for VF
Adapted from Ahamed et al. (2023); Jonlin & Lewellen (2017)

	LED	HPS
Advantages	• LED lights consume significantly less energy (30 to 40%) than HPS lights, resulting in cost savings over time. • LEDs have a longer lifespan than HPS, reducing the frequency of replacements. • LEDs provide even coverage of light uniformity over the plant's canopy. • Growers can specify the light spectrum to optimize crop growth, improving yields and quality.	• HPS lights are relatively inexpensive to purchase initially. • HPS lights generate considerable heat, which can contribute to maintaining optimal temperatures in cooler climates. • For some crops, the spectrum that HPS lights emit is especially beneficial during the blooming and fruiting periods, increasing crop yields.
Disadvantages	• Some LED types have been noticed to create delays in plant growth.	• HPS lights are energy-extensive compared to other alternatives, potentially leading to higher electricity costs. • The excess heat emitted by HPS lights may require supplementary cooling demand.

1.6.4 CO_2 concentration

In an indoor agricultural space, it is recommended to keep the CO_2 concentration equal to or higher than the outdoor condition (around 400 ppm) by a CO_2 enrichment system to enhance the photosynthesis rate during the photoperiod (Kozai et al., 2020). CO_2 concentration in the 1000-1500 ppm range is optimal for high growth rate, productivity, and CO_2 utilization efficiency. However, it is worth mentioning that high CO_2 concentrations can also decrease CO_2 utilization efficiency. This means that even though the plants may be taking in more CO_2, they may not be using it as efficiently for growth and development, such as the effect of increasing the plant's stomatal resistance, which reduces water loss through transpiration (Ahmed et al., 2020).

1.7 HVAC system

The HVAC system plays a pivotal role in building integrated agriculture by creating and maintaining an optimal growing environment for plants; regarding designing, selecting components and following guidelines, similar criteria (ASHRAE, 2007a) must be respected as methods used for building science domain. One of the disparities of paramount importance is designing the HVAC system for a BIA, which should meet specific needs compatible with plant growth, particularly for maintaining temperature and humidity in a constant optimal range. An appropriate HVAC system can contribute to a sustainable vertical farming operation by reducing energy consumption, water consumption, and operational costs.

Load calculations consider both internal and external heat gains (occupants, lighting, equipment, etc.) to determine the highest reasonable loads to size HVAC equipment. External gains/losses include conduction through the building envelope, solar heat gains through fenestration, and infiltration heat gains/losses. The environmental design conditions impact these gains and losses (ASHRAE, 2007a). Regarding designing BIAs such as vertical farming, as they are located in interior spaces surrounded by multiple zones, the impact of outdoor conditions on the loads is restricted, and loads are particularly affected by internal gains. As explained in the sections above (1.2.1 and 1.4.2), in a BIA scheme, the heat gains/losses induced by plants are significant and considered internal loads (Talbot & Monfet, 2020).

Based on different simplifications and assumptions, several load calculation approaches exist to identify the highest applicable energy transfer rate necessary to maintain indoor conditions in the optimal range. The most commonly known are the heat balance (HB) method, the radiant time series (RTS) method, the transfer function method (TFM), and the cooling load temperature difference (CLTD) and cooling load factor (CLF) method (Kavanaugh, 2006). Table 1.2 presents an overview of relevant studies in controlled environment agriculture.

This section briefly characterizes the main components of HVAC systems used in an indoor agricultural environment.

Table 1.2 Overview of recent studies of relevant aspects
Adapted from Ahamed et al. (2023)

References	**ASHRAE climate zone**	**Modelling Tool**	**Type of Agriculture spaces studied**	**Lighting type**	**HVAC System Modeling**
Harbick and Albright (2016)	6A, 6B, 3A, 2B	EnergyPlus	Independent agriculture; Comparison a GH with PF	Calculate the essential supplemental light efficacy without choosing the lighting type.	Air handling unit with economizer control; natural gas boiler and chiller. Evaluation of the impact of using an air-side economizer.
Lalonde et al. (2019)	6A	TRNSYS	A BIA was considered as an interior zone surrounded by different spaces	Determine a specific lighting an input electrical power, use LEDs.	Variable air volume (VAV) recirculation unit with terminal cooling and heating. Evaluation of the impact of using an air-side economizer.
Zhang and Kacira (2020)	7, 4C, 2B, 1	EnergyPlus	Independent agriculture; A warehouse-based plant factory	With splitting lighting portions into PAR, Long-wave radiation and convection lost, use LEDs.	Unitary HVAC system. No dehumidification control.
Graamans et al.(2020)	7, 4A, 1B	EnergyPlus	Independent agriculture; A plant factory	Comparison the opaque and transparent Façade properties, use LEDs for artificial lighting.	Fan coil unit with Air cooled chiller.

Table 1.2 Overview of recent studies of relevant aspects

Adapted from Ahamed et al. (2023) (Continued)

References	**ASHRAE climate zone**	**Modelling Tool**	**Type of Agriculture spaces studied**	**Lighting type**	**HVAC System Modeling**
Liebman-Pelaez et al.(2021)	5A	EnergyPlus	Independent agriculture; A hydroponic container farm	Specify the heat fractions by using LEDs.	A mini-split air conditioning system.
Talbot et al.(2022)	6A	TRNSYS	Independent agriculture, different greenhouse scenarios and a container farm	Determine a specific lighting an input electrical power, use LED and HPS	Mini-split air conditioning system and a stand-alone three-stage dehumidifier.
Eaton et al. (2023a)	3A, 3B, 4A, 4C, 5A	EnergyPlus	Independent agriculture; A plant factory	Specify the heat fractions by using LEDs	Package constant-air-volume (CAV) air handling unit (AHU) and dehumidifier with a closed refrigerant loop and electric reheater within the space. Evaluation of the impact of using an air-side economizer.
Liebman-Pelaez et al.(2021)	5A	EnergyPlus	Independent agriculture; A hydroponic container farm	Specify the heat fractions by using LEDs.	A mini-split air conditioning system.

1.7.1 Ventilation

Passive or active ventilation can help to eliminate moisture and airborne contaminants from indoor spaces while also providing health and comfort to the occupants. Passive ventilation occurs when a building is naturally ventilated through openable fixtures (controlled infiltration) or unwanted gaps surrounding openings (uncontrolled infiltration). The use of mechanical devices for air extraction is called active ventilation. Modern buildings are built so that passive leakage and active ventilation are minimized. Therefore, the potential for illnesses such as Sick Building Syndrome (SBS) increases (Raji et al., 2015). Mechanical and natural ventilation can control temperature and humidity levels and maintain the minimum amount of CO_2 by inducing the outside fresh air into a non-airtight BIA space.

Since the BIAs are usually considered airtightly insulated, a CO_2 enrichment system must maintain the CO_2 concentration between 700 ppm and 1000 ppm (Lalonde et al., 2019). When the infiltration and/or ventilation rate of the airflow is higher than 0.1 ACH, it can lead to pushing the injected CO_2 to the outside. Consequently, the ventilation rate is adjusted to 0.01-0.02 h^{-1} in an airtight space to avoid dilution of the injected CO_2 and reduce the risk of penetrating pests and diseases (Kozai et al., 2020; Talbot & Monfet, 2020). As plants absorb CO_2 from the air and release O_2 through photosynthesis, they may lessen the ventilation requirement, resulting in energy saving (Raji et al., 2015).

The increased air circulation rate is pivotal for extracting moisture and heat from the crops in a controlled environment in a BIA with a controlled environment. This circulated air is then conditioned within the plant factory, eliminating the necessity for introducing fresh external air into the system (Graamans et al., 2017). Because the humidity level in a BIA environment is high, there is a risk of condensation on colder surfaces as the indoor temperature drops and approaches the dew point. (Talbot & Monfet, 2020). A proper air circulation rate (0.5 to 1 $m.s^{-1}$) can decrease condensation on plants' leaves and prevent the growth of bacteria and mold (ASHRAE, 2011; Kozai et al., 2020).

1.7.2 Heating

Heating is mainly used to maintain the dry bulb temperature setpoint within the agricultural space during the respiration or dark period. For a BIA, the most common heating system is electricity-based. In BIA space with only artificial lighting, most of the lighting energy is lost by convention, so even in cold climates, the amount of heating required to maintain the necessary indoor conditions is the lowest value in total energy consumption end use (Graamans et al., 2018; Zhang & Kacira, 2020).

Regarding the comparison of heating demand, Graamans et al. (2018) proposed a plant factory with artificial lighting only and a Standard single glass cover greenhouse. Their analysis was performed on three different climate zones and latitudes (Netherlands, United Arab Emirates, and Sweden). PF has a standard HVAC system with forced ventilation, while GH has natural ventilation with a gas boiler. In all PF scenarios, the heating portion was the lowest and negligible. Zhang & Kacira (2020) did similar research. Still, in three different climate zones in the US, and they indicated that heating only accounted for around 0.01% of total energy consumption, even under cold climates.

On the other side, Harbick and Albright (2016) assumed a constant average value of evapotranspiration rate in their simulation. Plant evapotranspiration and the resulting latent cooling load are essential factors in energy use. The moisture in the air cools the plants and reduces the total sensible load, which is replaced by a latent load. To avoid tip burn and maximize yield, evapotranspiration rates in greenhouse lettuce cultivation must be relatively high. This is frequently accomplished by installing paddle fans to improve air circulation at the canopy. This assumption is considered a disadvantage in the VF domain because almost all of the sensible heat gain from the lights is offset by evapotranspiration, so a low amount of heating is needed.

It is worth mentioning that choosing the heating system is often influenced by the project's location, climate, and economic limitations (Eaton et al., 2023b).

1.7.3 Humidification

Generally, the humidity level in an airtight BIA is higher than the outside air most of the year because of plants' transpiration; therefore, humidification equipment is unnecessary in BIAs. However, some research has shown that adding an economizer to the HVAC system reduces the humidity level due to the high amount of outside airflow into the thermal volume. When the outside weather is colder than inside, economizers are frequently utilized in buildings and BIAs to save energy. Suppose a thermal zone has a cooling load and the ambient temperature falls below the zone set point. In that case, it may be more effective to introduce additional outside air rather than just depending on mechanical cooling. Economizers may depend on humidity, temperature, or both (Harbick & Albright, 2016).

Lalonde et al. (2019) investigated two distinct HVAC system configurations to maintain the indoor conditions of a BIA. The first one is referred to as the airtight system with a variable air volume (VAV) recirculation unit with terminal cooling and heating, and the second system is a VAV with an economizer to provide free cooling and dehumidification when outdoor air was suitable. There was a negligible need for humidification for the airtight system because of the impact of evapotranspiration on the plant. Otherwise, in the second scenario, the higher energy consumption of the humidification system was substantially derived due to the compensation for the humidity losses created by the high outdoor air flow rates required to maintain the CO_2 concentration.

When choosing humidification equipment, a steam humidifier can be appropriate for cold and dry climates because of the possibility of warming air through its process.

1.7.4 Cooling

In BIAs, energy is served predominantly for electrical lighting, then, in order of importance, cooling, dehumidification, and heating and humidification of the air, because of the contribution from internal gains from lighting and plants to the BIA spaces leads to high sensible cooling and latent cooling (dehumidification) demands (Graamans et al., 2018). Regarding the comparison of HVAC energy consumption in an indoor agriculture context, most of the researchers had two options for selecting a suitable cooling system: cooling coil and cooling evaporator (Sethi et al., 2013).

With the legalization of cannabis cultivation, Jonlin & Lewellen (2017) performed a low-energy indoor agriculture approach. For cooling designing, optimization can reduce a significant amount of energy consumption by 20%. For the first cooling stage, they used an air-side economizer with the potential of offsetting all the cooling demand over the year, however, there was a risk of CO_2 dilution due to the high airflow rate. Water-side economizers were proposed as an alternative option with the advantage of constant CO_2 concentration in the absence of dilution. Also, they implemented a novel setup that involves sealed linear light fixtures with clear glass lenses at the bottom. Five fixtures can be linked with ducts, channeling outside air and exhausting it. This method eliminates half of the heat the lights produces, using a small fan, while maintaining a CO_2-rich environment for plant growth. It acts as a simple economizer system, leveraging outdoor air for substantial heat removal throughout the year. However, the glass lenses slightly diminish the light reaching the plants and necessitate regular cleaning.

1.7.5 Dehumidification

Humidity challenges can arise during both phases: dark period and photoperiod. For instance, as the lights are off, the need for air conditioning decreases, resulting in a lack of moisture control. This is the crucial period when an efficient dehumidification system becomes vital, taking charge of managing and regulating the moisture levels (DCA, 2018).

The relative humidity in the air affects the transpiration rate of lettuce. The relative humidity in a plant factory can be as high as 80%. One reason for dehumidification is to prevent the tip burn of lettuces. Studies have shown that decreasing relative humidity during the light period can help increase the calcium concentration in the lettuces and, therefore, delay the tip burn development. However, for the growth of lettuce, low relative humidity causes a reduced growth rate (Zhang & Kacira, 2020).

Usually, a stand-alone dehumidification system, independent of other HVAC systems, is installed within a BIA. A three-stage dehumidifier can be used due to the ability to cool, dry, and heat each stage if needed (DCA, 2018).

1.8 Findings

Certain observations can be made following the literature review conducted in the contexts of Building integrated agriculture, using simulation tools and existing thermal synergy. Few studies have focused on comparing the energy performance of different conditions in BIAs to assess some practical indoor conditions combinations (Carotti et al., 2021; Talbot et al., 2022). On the other hand, there are several approaches for evaluating the energy consumption performance of a VF. These approaches provide a deeper understanding of possible interactions within a protected urban agriculture facility and support the management of choosing optimal indoor conditions to assess the building energy use and peak demand. In the realm of controlled environment agriculture, as explored in the current body of literature, there exists a potential discrepancy in reported data. This research endeavors delves into the energy consumption patterns within building integrated agricultural spaces, particularly under different indoor environmental conditions, while also assessing the effects of integrating agricultural spaces into the existing infrastructure of the host building.

CHAPTER 2

OBJECTIVES AND METHODOLOGY

2.1 Objectives

As the demand for sustainable and efficient agricultural practices intensifies, integrating crop cultivation into building spaces presents a unique intersection of agriculture and architecture. The study aims to evaluate and understand the impact environmental conditions have on the energy consumption and demand of building-integrated agriculture (BIA) spaces and crop growth.

To minimize the impact of cultivating in controlled environment agriculture (CEA) spaces, it is essential to determine the predominant processes and key parameters influencing annual energy consumption, peak demand, and the annual yield of harvested produce. Completing a parametric analysis using environmental or building performance simulation (BPS) tools often achieves this. This study aims to identify the conditions that improve the energy performance of indoor CEA spaces by assessing several influencing parameters, proposed as different scenarios, on the energy consumption of BIA spaces located in colder climates.

This is achieved by comparing different ways of producing crops (lettuce) under different indoor environmental conditions in an urban protected agriculture space, which is integrated into a building. The choice of indoor environmental conditions is assessed based on the energy performance of the BIA space and of the host building in terms of peak demand and annual energy consumption. A crop yield estimation is also completed to assess the productivity of the BIA space.

The BPS model aims to offer an outlook for architects, engineers, and policymakers to optimize the design of BIA spaces, inform on indoor conditions that lead to energy-efficient HVAC systems, and enhance the overall sustainability of integrated agricultural practices within building environments. Through these objectives, the research aspires to bridge the gap between agriculture and building science, fostering a more holistic approach to the design and operation of building-integrated agricultural spaces.

2.2 Methodology

This section describes the general methodology used in this study and details the proposed steps. The methods employed in this thesis aims to comprehensively analyze the impact of crops under various indoor environmental conditions on the energy consumption and peak demand for building-integrated agricultural (BIA) space. To achieve this, an integrated approach is adopted, combining the analysis of several practical sets of indoor environment parameters.

The overall methodology is presented in Figure 2.1. As such, it includes different aspects related to (1) selecting the parameters used to estimate the energy consumption and demand of the BIA space and the host building, i.e., the scenarios to be assessed, (2) developing the BPS model, including the approach undertaken to include the heat gain/loss induced by crops, and (3) estimating the crop yield. This information then establishes different indicators for the BIA space and the host building, such as the production intensity and energy consumption per fresh yield.

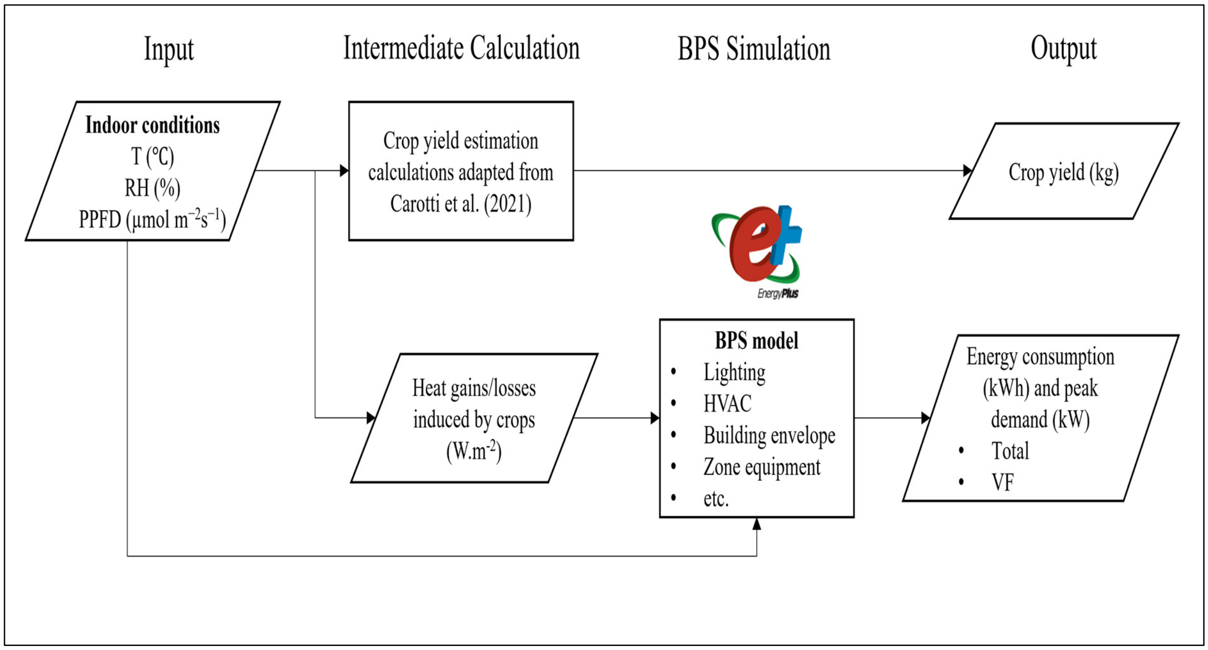


Figure 2.1 Diagram of the methodology

The energy use (consumption and peak demand) is calculated using OpenStudio (Guglielmetti et al., 2011) v3.6, which is one of the graphic user interfaces for EnergyPlus (Crawley et al., 2001). This BPS tool facilitates designing and generating input and visualizing output. EnergyPlus is a dynamic building energy simulation program that incorporates three basic components – a simulation manager, a heat and mass balance simulation module and a building systems simulation module (Graamans et al., 2020).

Sections 2.2.1 to 2.2.3 provides an overview of the scenarios considered in the parametric analysis, a description of the modified BPS model, a presentation of the calculation approach to estimate yields.

2.2.1 Scenarios (indoor conditions)

Several parameters have significant impacts on the overall performance of BIA spaces and yearly yield, as reported by Carotti et al. (2021) and Talbot et al. (2022). These include different combinations of temperature, relative humidity, and lighting characteristics (spectrum, intensity, and photoperiod) to grow lettuces in different CEA spaces such as vertical farms, plant factories, container farms and greenhouses. From an agricultural perspective, light intensity, temperature and CO_2 concentration are vital environmental factors that specify photosynthesis and crop growth and production (Carotti et al., 2021).

In the present study, the impact of different parameters is assessed for a BIA space with artificial lighting only. The considered parameters include temperature, relative humidity, vapor pressure deficit (VPD), lighting intensity and type, PPFD, and the location of the BIA space.

Temperature: To assess the energy efficiency of a Building Integrated Agriculture (BIA) space and understand the impact of integrating green spaces, the main focus is managing the HVAC system's energy use performance. Key components, like cooling and heating setpoints, directly influence the HVAC system's coil cooling and heating processes. In this study, which centers on a vertical farm, manipulating temperature has limitations. Temperature control is crucial for leafy vegetables like lettuce, which thrive within specific temperatures for optimal growth. A detailed assessment is conducted with three temperature settings: 20℃, 24℃, and $28°C$.

Relative Humidity (RH): Moisture content plays a significant role in the productivity of a BIA space. For investigating the impact of RH and temperature simultaneously, the VPD (kPa) is often used, which is the difference between the vapor pressure inside the leaf and the air's vapor pressure as calculated using Equation (2.1).

$$RH = 1 - \left(\frac{VPD}{0.611 \cdot e^{\left(\frac{17.27 \cdot T}{(T+238.3)}\right)}} \right) \times 100 \tag{2.1}$$

In most studies, the VPD was assumed constant between a range of 0.75- 0.8 kPa (Ahamed et al., 2023; Talbot & Monfet, 2020). In this study, the VPD is maintained at 0.8 kPa. This corresponds to relative humidity setpoints of 65, 73 and 78 % for temperature setpoints of 20, 24 and 28℃ respectively.

Lighting intensity and type: It was mentioned that the most energy-intensive part of a BIA is its lighting equipment (Graamans et al., 2018; Talbot et al., 2021). The lighting requirements can be provided using different lighting types, which can lead to a decrease in energy consumption of the installation. As described in section 1.6.3 in Chapter 1, two popular types of artificial lighting are HPS and LED and their pros and cons were explained. One of the influencing lighting parameters is the Photosynthetic Photon Flux Density (PPFD), which links the power intensity with the efficacy of the lamps. Three PPFD levels are assessed in this study: 200, 400, 750 (μmol $m^{-2}s^{-1}$) as described in Equation (2.2).

$$PPFD = q''_{lighting} \times \text{Efficacy} \tag{2.2}$$

Location of BIA space: As specified, two different locations of the BIA space are considered. Since temperature control is vital in CEA spaces, ground-floor locations may offer more stability in temperature regulation than top floors, where temperature variations due to factors like sunlight exposure can be more challenging to manage. On the other side, thermal conductivity of a slab in bottom-floor and thermal conductivity a floor in top-floor scenarios is different, affecting the overall energy performance. This issue can affect the indoor temperature by absorbing more or less heat from adjacent thermal zones.

To thoroughly understand how VF energy consumption relates to various factors, it is essential to organize the variables into clear groups. This creates a logical pattern and streamlines a systematic scientific investigation. Figure 2.2 categorizes the first group of the different parameters into different categories of scenarios.

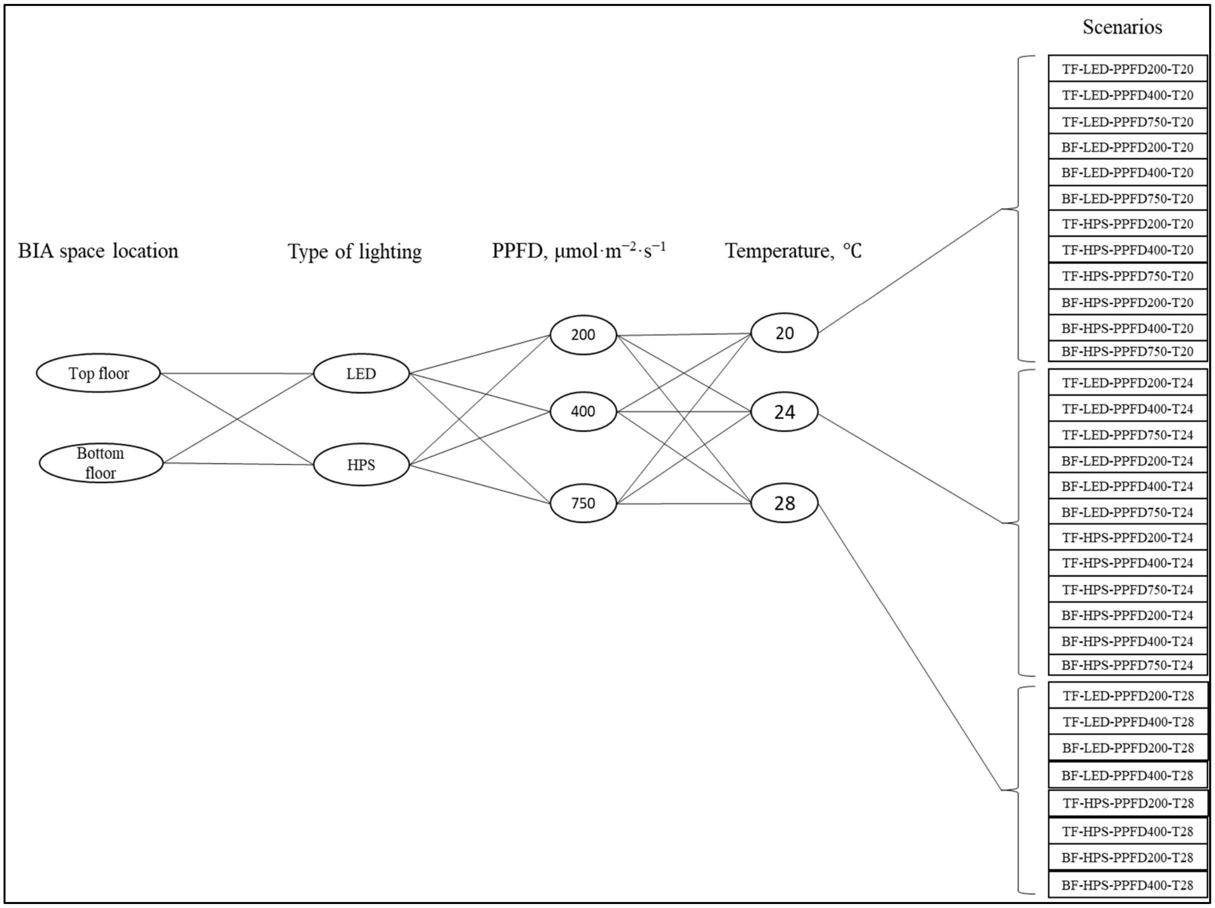


Figure 2.2 First group of proposed scenarios

In the first group, including 32 scenarios, the impact of the location of BIA within a host building, lighting type and intensity, and temperature are assessed. In these sets of scenarios, combinations of temperature 28 ℃ with PPFD of 750 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ due to the high risk of tip burn were not evaluated (Carotti et al., 2021). The second group, with 12 scenarios, as detailed in Figure 2.3, evaluate the location of BIA within a host building, lighting type and temperature with relative humidity while keeping a constant VPD (0.8 kPa).

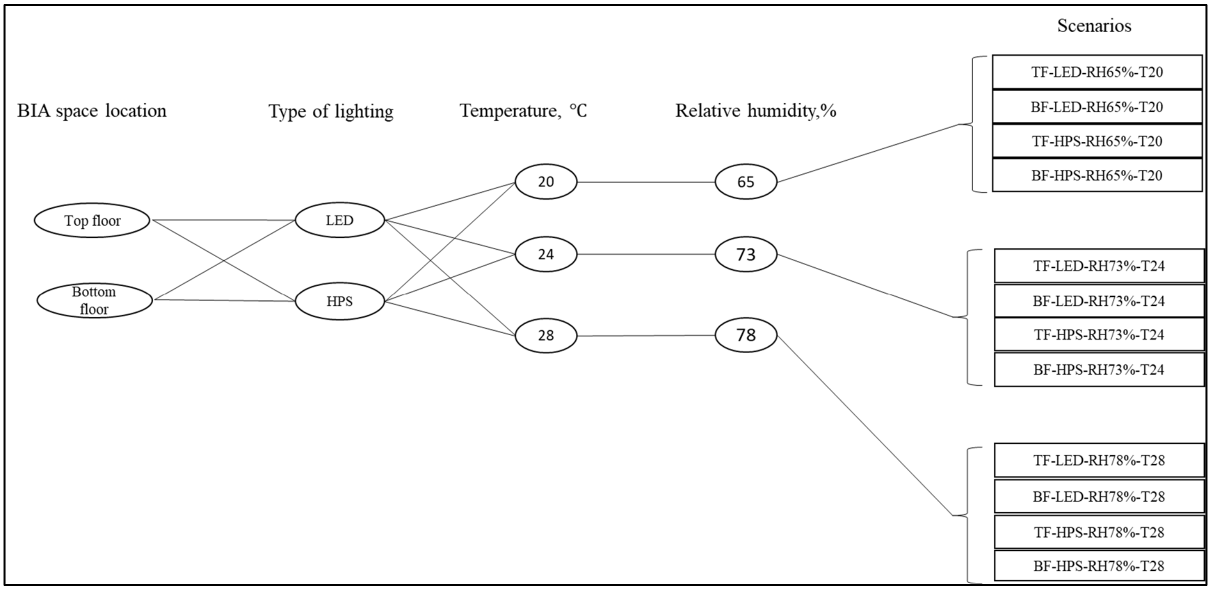


Figure 2.3 Second group of proposed scenarios

To maintain these constant conditions, air is reconditioned and recirculated, and outdoor air infiltration is avoided as much as possible. In the baseline VF, a hydroponic nutrient film technique is used to produce lettuce (photoperiod 16 h) to reach a market size of 250 g. The assumption is made that the air is well-mixed and that the air velocity over the leaves is sufficient for gas exchange. The indoor environment transitions between photosynthesis and respiration states during the light and dark periods, respectively.

Comparing the proposed scenarios allows for exploring a range of efficient combinations alongside less efficient ones. These detailed comparisons serve as a valuable resource for stakeholders, enabling them to make well-informed decisions about adopting optimal indoor environmental conditions. The goal is to steer towards configurations that lead to the lowest annual energy consumption, peak demand, and, simultaneously, the highest annual yield. This nuanced approach ensures that the vertical farm operates at the peak of efficiency, aligning with sustainability objectives and maximizing its potential for productivity.

2.2.2 BPS Model description

In this section, the general assumptions and descriptions of the building and a comprehensive presentation of the studied BIA space are presented. The carried study not only considers the impact of crops (lettuce) as internal loads on calculating the building energy consumption but also provides additional insight by presenting the results of a parametric analysis based on a broad range of proposed scenarios.

2.2.2.1 Site selection

The scenarios in this study are conducted within a hypothetical building located in Montreal. The prediction of the building's energy consumption is carried out using a Building Performance Simulation (BPS) tool, necessitating the inclusion of weather data. In Canadian contexts, simulations commonly use the Canadian Weather for Energy Calculations (CWEC) file, an hourly dataset derived by gathering twelve Typical Meteorological Monthsfrom historical weather data files from 1953 to 1993 (Government of Canada., 2018). While weather datasets can also be calibrated with real monitored data for model refinement (an aspect not pursued in this study), the simulations exclusively employed the CWEC for Montreal (CAN_PQ_Montreal.Intl.AP.716270_CWEC). Montreal's climate is classified as humid continental, characterized by hot and humid summers, cold winters, and 4200 yearly heating degree days (ASHRAE 90_1, 2010).

2.2.2.2 Building specifications

The host commercial building of this case study is a three-story building located in Montreal that originally complied with the 2011 National Energy Code of Canada for Buildings. The BIA space was considered an interior zone surrounded by various spaces. The building has a 49.91 m × 33.27 m footprint, leading to a total area of 4982 m^2.

The National Energy Code of Canada for Buildings (NECB) is a regulatory framework developed by the Canadian Commission on Building and Fire Codes in collaboration with Natural Resources Canada and the National Research Council. It sets forth scientifically to establish minimum energy efficiency standards for new constructions in Canada, encompassing diverse building types. The NECB has evolved over the years, with NECB 2011 establishing the initial benchmarks for energy efficiency in new buildings (Canadian Commission On Building And Fire Codes, 2011).

All the NECB 2011-compliant buildings were generated with the NECB Archetypes generator (NRCAN, 2018). Figure 2.4 shows the building illustration, which has a window-to-wall ratio (WWR) of 47%.

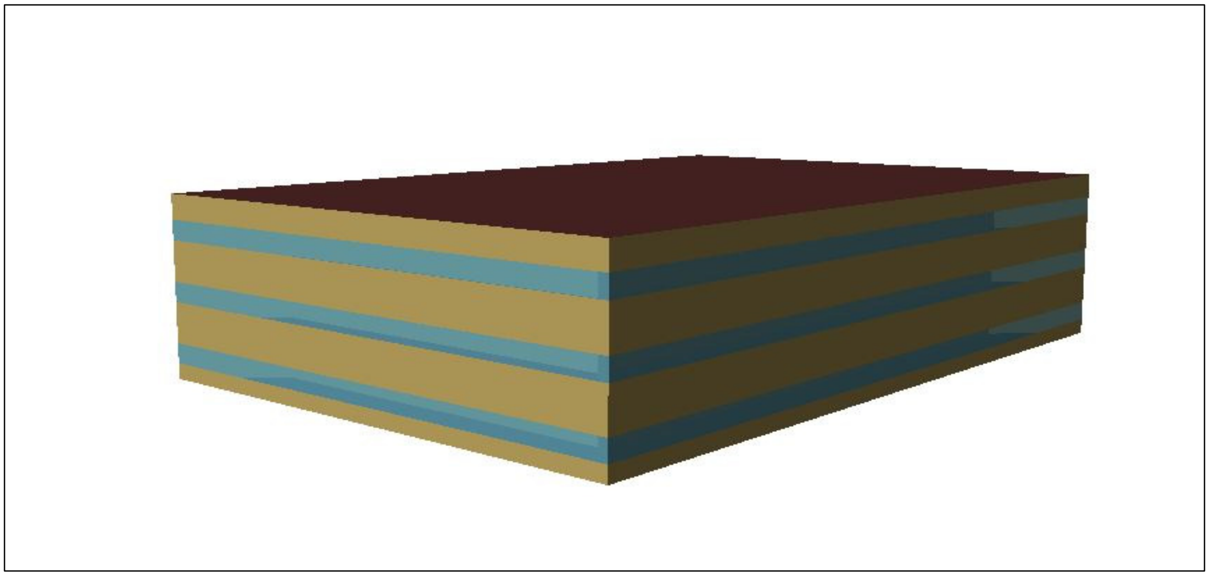


Figure 2.4 General illustration of the host building

The envelope characteristics are modified to comply with the NECB 2015 amended for Quebec as specified in Table 2.1.

Table 2.1 Building envelope characteristics

	Overall U-value, W·m^{-2}·K^{-1}	
	Original - NECB 2011	Modified - NECB 2015 amended
Walls	0.240	0.277
Roof	0.183	0.183
Floor	0.183	0.183
Slab on grade	1.36	0.568

The other building spaces are considered offices with the internal heat gains specified in Table 2.2. The indoor conditions are maintained at average of $24°C$ in cooling thermostat schedule and 22 $°C$ in heating thermostat schedule during the occupied hours per day using a variable air volume (VAV) system with reheat. The cooling system is considered a water-cooled chiller with a COP of 4.5, which can provide 82 tons of cooling capacity. Electric heating coils with an efficiency of 100% provide for the heating demand. The building has 15 thermal zones with different thermostat temperature setpoints divided into specific groups connected to the related VAV duct box provided for each group to regulate the indoor temperature with changing damper position to pass an adequate fresh air flow rate. The infiltration rate for internal zones without contact with outdoor air is assumed to be zero.

Table 2.2 Offices internal heat gains

Internal heat gains	Unit	Value	Schedule for weekdays
Lighting	W.m^{-2}	11	Between 0.3 to 0.9 of maximum capacity during the work-hours
People	W.m^{-2}	6.5	Between 0.3 to 0.9 of maximum capacity during the work-hours (0.5 for lunch break)
Equipment	W.m^{-2}	7.5	Between 0.2 to 0.9 of maximum capacity during the work-hours

2.2.2.3 Building integrated agriculture space specifications

The BIA space is 24.13 m × 40.76 m, leading to a total area of 983 m^2 located in the interior zone of the floor plan, as illustrated in Figure 2.3. A BIA space is integrated into the building twice: once at the top floor of the above three-story commercial building and also on the bottom floor of the mentioned building. The main characteristics of the BIA space are detailed in Table 2.3.

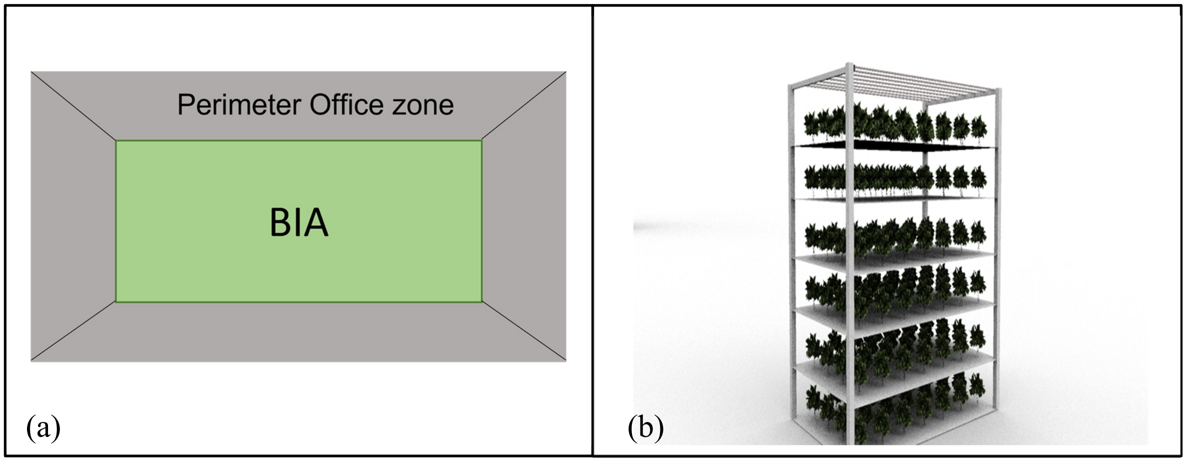


Figure 2.5 Configuration of the BIA space: (a) Building floor plan (b) VF space

Table 2.3 Geometrical and crop parameters of the BIA space

Parameters	BIA space	Notes
Total BIA Footprint, m^2	983	Base on Léveillé-Guillemette (2019)
Cultivated surface area ($A_{cultivated}$), m^2	2358	Each tier has an area of 393 m^2
Growing layers	6	Assumption
Distance between each layer, m	0.46	Based on Kozai et al.(2015) and the height of the floor
Cultivated space	2.4	$CD = \frac{A_{cultivated}}{A_{BIA}}$; (Lalonde et al. (2019))
LAI	2.1	(Talbot and Monfet(2020))
Cultivated area cover (CAC), %	81.35	$CAC = 38.74 \times LAI$; (Talbot and Monfet(2020))
Planting crop density, lettuce.m^{-2}	30	Based on each tier's dimension
CO_2 concentration, ppm	700-1000	BIA space is considered to be airtight; a CO_2 enrichment system is used to maintain optimal range

The Leaf Area Index (LAI) is the ratio of the mean one-sided of leaf area per unit of cultivated area. The LAI was set to the average value of 2.1 to represent a steady state operation with lettuces growing at all development stages simultaneously (Graamans et al., 2018). The LAI is expressed by Equation (2.3) (Talbot & Monfet, 2024).

$$LAI = \mathrm{PCD} \times \mathrm{LA} \tag{2.3}$$

LAI is the Leaf Area Index ($m^2_{\ leaves} \cdot m^{-2}_{\ cultivated}$); LA is the leaf area per plant ($m^2_{\ leaves} \cdot plant^{-1}$); and PCD is the planting crop density ($plants \cdot m^{-2}_{\ cultivated}$).

The cultivated area cover (CAC) represents the fraction of the cultivated area covered with plants and varies with the LAI. The CAC was set to 81.35%, obtained from the linear relationship between LAI and CAC for lettuces (Talbot & Monfet, 2020). This value meant that approximately 20% of the short-wave radiation released from the electrical lighting source did not reach any leaves of plants and was absorbed by the surrounding environment. Furthermore, 5% of the PAR light that reached the leaves was considered to be reflected (Lalonde et al., 2019).

Also, the crop (lettuce) model carried in this study included some simplifications and assumptions(Lalonde et al., 2019);

- The model did not account for the radiative heat transfer from plants to the environment.
- The model did not consider the heat storage in the hydroponic solution.
- The model did not consider the influence of CO_2 concentration on the thermal behavior of lettuces (Graamans et al., 2017). Instead, it assumed that the behavior of plants was primarily influenced by the photosynthetic photon flux density and indoor air conditions (temperature and humidity).
- The model assumed that the air thermodynamic properties remained constant due to the HVAC system maintaining the space conditions.

The simplifications and assumptions made in the lettuce model can impact the reliability of the model in several ways:

- Radiative Heat Transfer: Neglecting radiative heat transfer from plants to the environment may underestimate or overlook temperature fluctuations within the growing environment, affecting plant growth rates and development(Talbot & Monfet, 2020).
- Heat Storage in Hydroponic Solution: Ignoring heat storage in the hydroponic solution might lead to inaccurate temperature predictions, potentially affecting nutrient uptake and plant metabolism, thereby influencing growth outcomes (Kozai et al., 2020).
- CO_2 Concentration Influence: Not considering the influence of CO_2 concentration on thermal behavior of lettuce crop could overlook vital factors affecting photosynthesis rates and plant respiration, potentially leading to inaccurate growth predictions and yield estimations (Talbot & Monfet, 2020).

In the BIA space, Table 2.4 specifies the lighting, equipment, and heat gain/loss induced by crops as internal load gains.

Table 2.4 Internal source of heat gain/loss

Internal Loads		Gain/loss, $W.m^{-2}$		Notes
		Sensible	Latent	
Lighting	LED	168	–	Based on lighting characteristics in Talbot et al. (2022)
	HPS	350		
Plug loads		2.315	–	Based on Maximum heat load
Crops		Variable with T and RH	Variable with T and RH	ANNEXE I

For indoor temperatures fluctuating between 18 and 30°C and a relative humidity (RH) of 70 to 90%, the sensible heat gain (loss) for the lettuce alternated between -68 and -5 $W \cdot m^{-2}$ and between 14 and 129 $W \cdot m^{-2}$ for the latent heat gain according to the model developed by Talbot and Monfet, 2020. The complete set of values used in this study is presented in ANNEX I.

The electrical lighting power input is divided into three components: convective heat gain, long-wave radiation heat gain, and short-wave radiation, also known as photosynthetic active radiation (PAR). The distribution of energy depends on the lighting heat fractions (convective (f_{Conv}) radiative; long-wave (f_{LW}) radiative; short-wave (f_{SW}) radiative), which are unique to the characteristics of the lighting model. Only a portion of the short-wave radiation is captured and absorbed by crops, while the remainder contributes to the heat gain from lighting (Talbot & Monfet, 2024). Table 2.5 lists the lighting features used in this study based on data from Talbot et al.(2022).

Table 2.5 Lighting features
Adapted from Talbot et al. (2022)

characteristics	LED	HPS
Electric power intensity, W.m^{-2}	168	350
PPFD, µmol·s^{-1}·m^{-2} $_{\text{cultivated}}$	434	458.5
Efficacy, µmol·J^{-1}	2.6	1.31
Efficiency, %	52	30
Heat fractions, $f_{\text{Conv}}/f_{\text{LW}}/f_{\text{SW}}$	0.37/0.11/0.52	0.28/0.46/0.26

The specified indoor conditions are maintained using the HVAC system illustrated in Figure 2.6. The main energy source is electricity for all equipment, including heating and dehumidification. The HVAC system includes a variable air volume (VAV) with a recirculation unit, and a zone HVAC dehumidifier (Direct expansion dehumidifier) is provided in the BIA space.

Regarding integrating the plant heat gains into the OpenStudio plugin during the other scenarios, the crop heat loads were taken from Talbot and Monfet (2020) for different static indoor conditions, and the specific crop heat gains/losses compatible with chosen indoor conditions were applied.

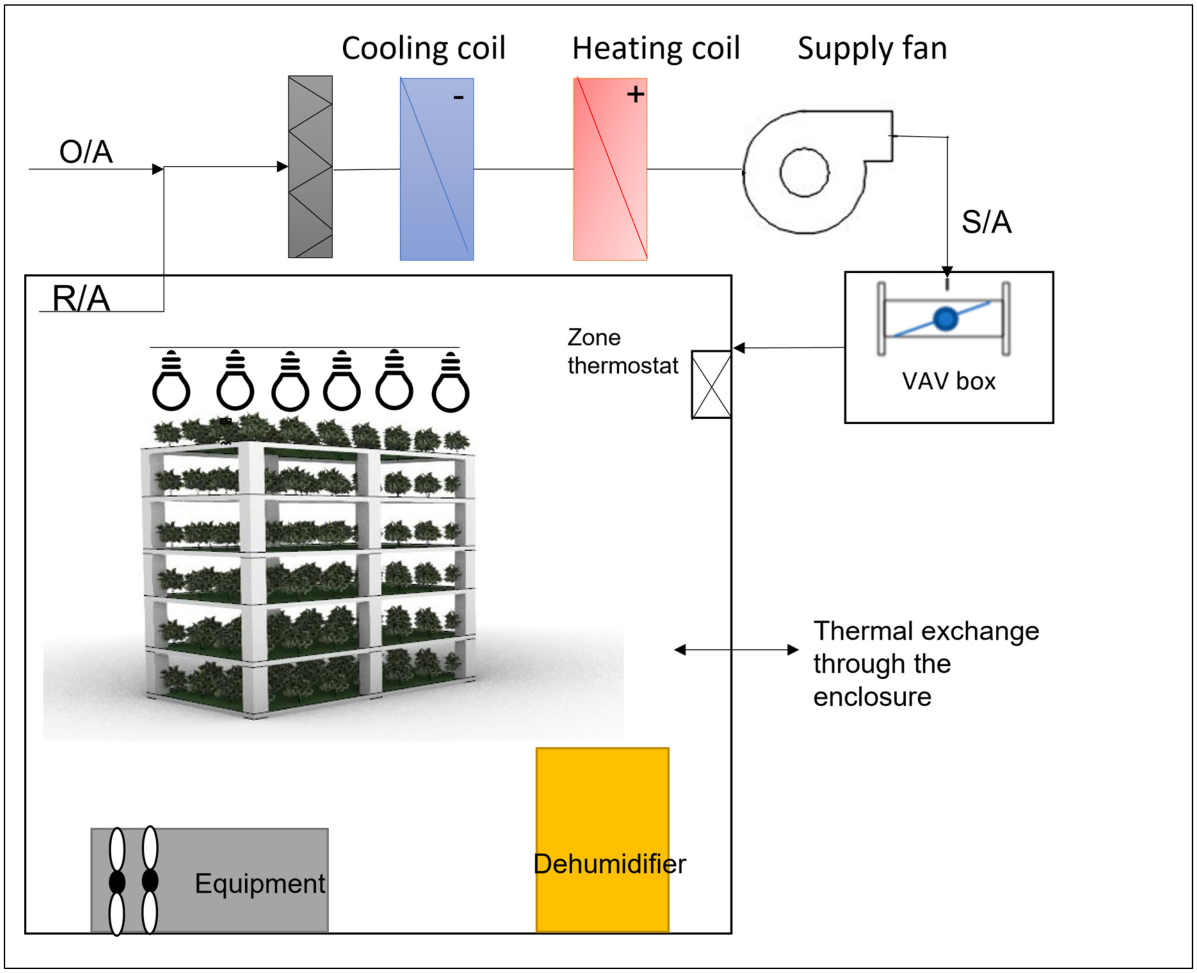


Figure 2.6 HVAC system schematic and energy modelling of BIA space

2.2.3 Crop yield estimation

The annual crop production is estimated according to the fresh weight of produced lettuce using an experimental growth dataset from Carotti et al. (2021). The study by Carotti et al. (2021) presented data on the shoot fresh weight (FW_{sht}) and total dry weight (DW_{tot}) per plant for lettuce grown in a controlled environment agriculture (CEA) facility. The lettuce was cultivated under varying photosynthetic photon flux density (PPFD) and indoor air conditions, with a planting crop density (PCD) of 25 plants per square meter. The study considered a root temperature of 28 ◦C, a vapor pressure deficit (VPD) that alternated between 0.58 kPa and 0.34

kPa during the photoperiod and dark period, respectively, a carbon dioxide (CO_2) concentration of 1200 ppm, and a photoperiod of 16 hours.

Table 2.6 Average duration of growth cycles for different indoor conditions
Adapted From Carotti et al. (2021)

Indoor conditions			Dry weight content at harvest, %	Average duration of growth cycle, days
PPFD ($\mu mol.m^{-2}. s^{-1}$)	DLI ($mol.m^{-2}.day^{-1}$)	Temperature (°C)		
200	11.5	20	2.6	29
		24		25
		28		27
400	23	20	3.8	21
		24		20
		28		24
750	43	20	4.2	19
		24		17.5

For each given set of conditions, Carotti et al. (2021) reported the daily shoot fresh weight of lettuce under different set of indoor conditions from the time of plantation until the end of the growth cycle. For each set of indoor conditions, the number of days for the shoot fresh weight to reach a marketable weight of 250 g, as reported by Carotti et al. (2021), is tabulated in Table 2.6. This value represents the duration in days for each combination of conditions to complete one growth cycle. As an example, for an air temperature of 24 °C and a lighting intensity of 200 $\mu mol.m^{-2}s^{-1}$, it takes 25 days from the time of transplantation for the lettuce to reach a fresh weight of 250 g. The yearly number of cycle (C) is then computed according to equation (2.4).

$$C = \frac{365\ days}{Cultivation\ cycle\ days} \tag{2.4}$$

For the aforementioned example, the total number of cycles is 14 cycles based on the assumption that production starts on the first day of January and ends on the last day of December. For each scenario, the annual crop yield is then estimated by first quantifying the number of planted lettuce heads (H) using equation (2.5).

$$H = \text{PCD} \times A_{cultivated} \tag{2.5}$$

Where PCD is planting crop density (lettuce.m^{-2}), which is equals 30 plants per square meter; and $A_{cultivated}$ is the cultivated surface area (m^{2}), defines as the sum of all horizontal growing beds, which equals to 2358 m^{2} (Table 2.3).

Equations (2.4) and (2.5) are then combined to estimate the annual yield (Y) according to equation (2.6). By understanding the total plants and number of growth cycles over a year, annual harvestable production under each set of combinations is derived by equation. It is assumed that harvest occurs when the fresh weight (FW_{sht}) of the lettuce reaches a value of 250 g which is a reasonable assumption in the Canadian market.

$$Y = C \times H \times \text{FWsht} \tag{2.6}$$

To calculate the annual crop yield under specific indoor conditions, the number of growth cycles over a year per each combination, crop density (lettuce.m^{-2}), and total cultivated area (m^{-2} $_{\text{cultivated}}$) are considered and present in CHAPTER 3.

CHAPTER 3

RESULTS AND ANALYSES

This chapter presents the results of the comprehensive parametric study assessing the impact of crops on the energy usage of a building-integrated agriculture space. The study evaluated various indoor conditions, including lighting type, lighting intensity, BIA space location within the host building, temperature, and humidity levels, to understand their influence on total electricity energy consumption and estimated crop yield. A total of 44 scenarios with diverse inputs were proposed to explore the potential variations in energy usage distribution and crop productivity.

Firstly, the analysis delved into the effect of different lighting types/intensities on energy consumption and crop yield. By simulating scenarios with the most common lighting sources, such as LED and HPS, the study aimed to clarify which lighting configuration optimally balances energy efficiency and crop growth. Secondly, temperature variations were considered to determine their impact on energy usage and crop yield. Furthermore, the investigation extended to examine the role of relative humidity levels for a constant vapor pressure difference (VPD) in influencing energy usage and crop yield. The study aimed to uncover the optimal conditions that balance energy efficiency and crop productivity by manipulating relative humidity and temperature setpoints across different scenarios. The findings from these analyses shed light on the intricate relationship between indoor environmental factors and their implications for energy consumption and agricultural productivity.

3.1 Reference baseline building analysis

Building-integrated agriculture (BIA) significantly impacts the energy consumption and overall performance of its host building. By incorporating hydroponic vertical farming systems into mixed-use buildings such as a medium office building of this study, BIA optimizes space utilization and reduces the need for external energy sources. As seen in BIA, the integration of vertical farms with buildings affects the energy performance and distribution.

To evaluate the synergetic integration of a vertical farm with a 3-storey commercial building, a vertical farming assemblies replaced with one of the interior zones. Firstly, it is vital to determine the total energy consumption and HVAC systems load distribution of the host building as baseline measures to understate the impact of BIA on the host building energy performance. Thus, for this analysis, the area occupied by the BIA space is considered office spaces modelled according to the internal loads specified in the NECB 2011, as specified in Table 2.2.

The studied Medium-Office building is a three-story structure with a total area of 4982 m^2. Each floor has dimensions of 49.91 m × 33.27 m and a window-to-wall ratio (WWR) of 47%. The building's total energy consumption is 569642 kWh. As mentioned in Chapter 2, the primary sources of internal heat gain in this building are people, lighting, and equipment. Figure 3.1 illustrates the monthly distribution of electricity consumption.

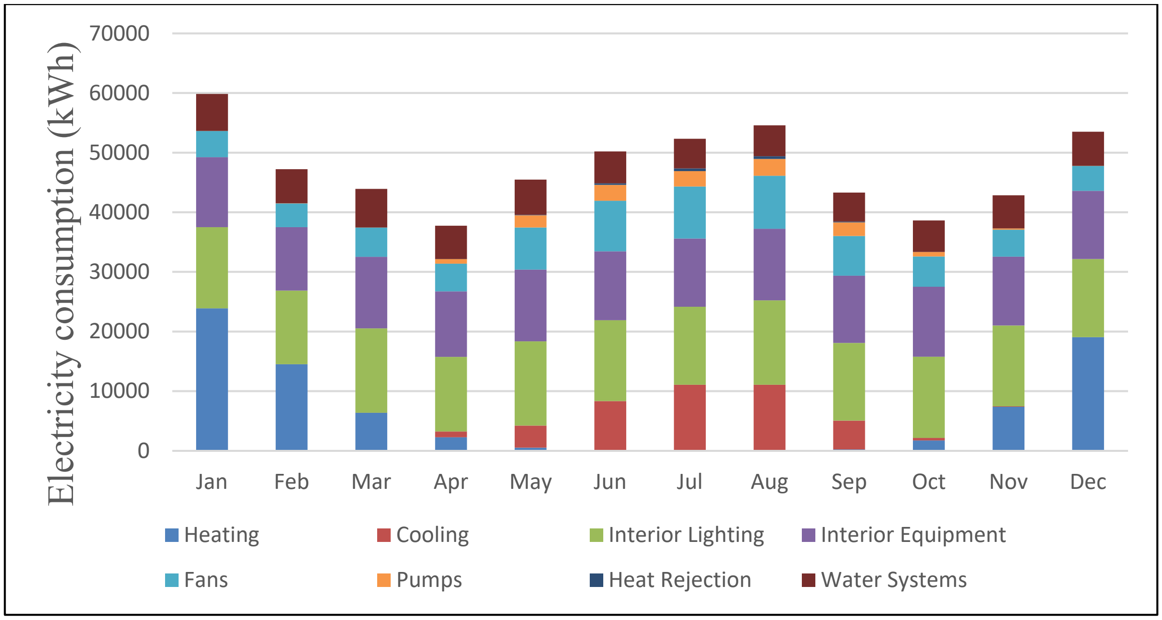


Figure 3.1 Monthly baseline building energy consumption

An end-use graph of building energy consumption loads provides a detailed breakdown of how energy is used within a building. It can reveal the relative contributions of different energy end-uses to the total energy consumption of a building. This information helps identify areas where energy-saving measures can be implemented most effectively. Figure 3.2 shows the end-use division of the host building.

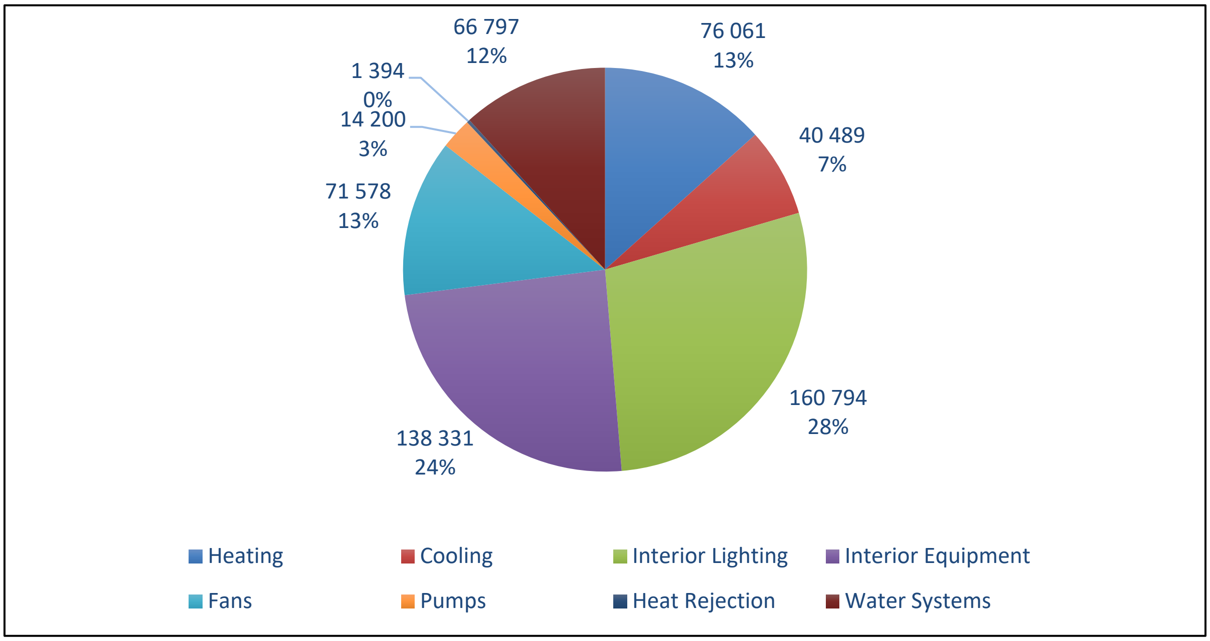


Figure 3.2 Annual baseline building end-use (kWh) distribution

Electricity peak demand is a critical factor in assessing the energy performance of a building. It impacts costs, infrastructure planning, energy efficiency, grid stability, and predictive maintenance, making it an essential metric for building owners and managers to monitor and manage(Avgoustaki & Xydis, 2021). Figure 3.3 shows the peak demand profile over a year.

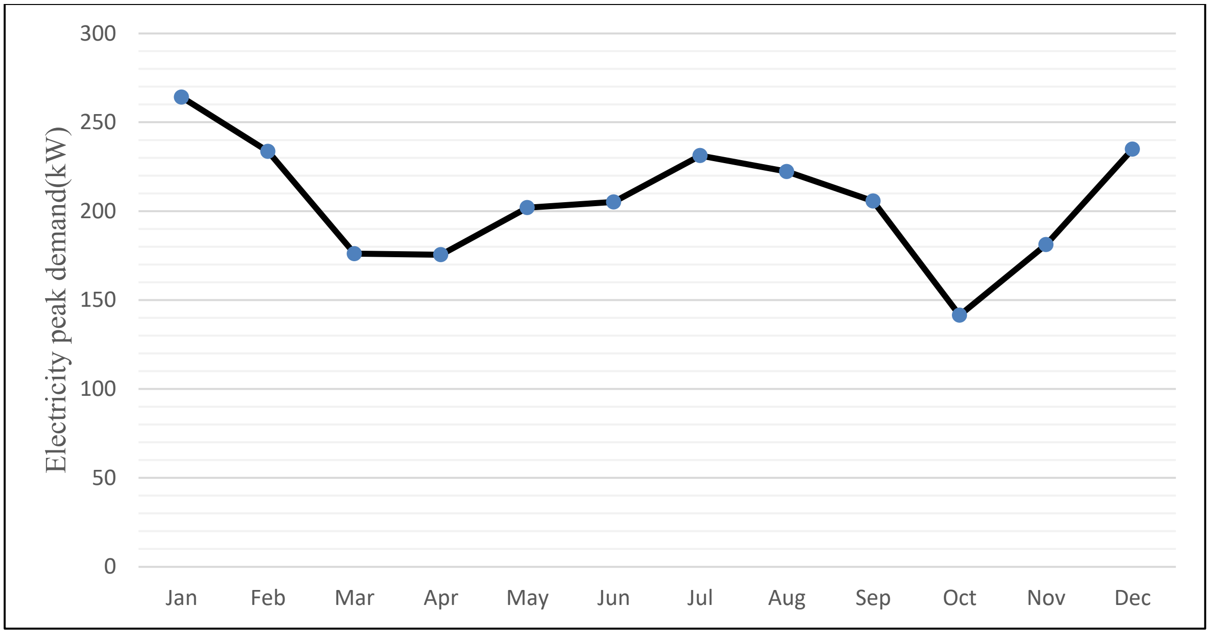


Figure 3.3 Monthly baseline building peak electricity demand

3.2 Vertical farm scenarios analysis

To assess the impact of indoor environmental factors on the energy efficiency of a vertical farm situated within a building, 44 unique combinations were analyzed, categorizing them into two distinct groups. The first 22 scenarios were investigated on the bottom floor of the host building, while the remaining 22 configurations were explored on the top floor. Both sets of scenarios utilized artificial lighting and were characterized by airtight conditions, with no exchange of outdoor (fresh) air. This division allowed for a comprehensive examination of various indoor parameters and their effects on the energy performance of the vertical farm. Figure 3.4 presents the position of the mentioned BIA within the host building.

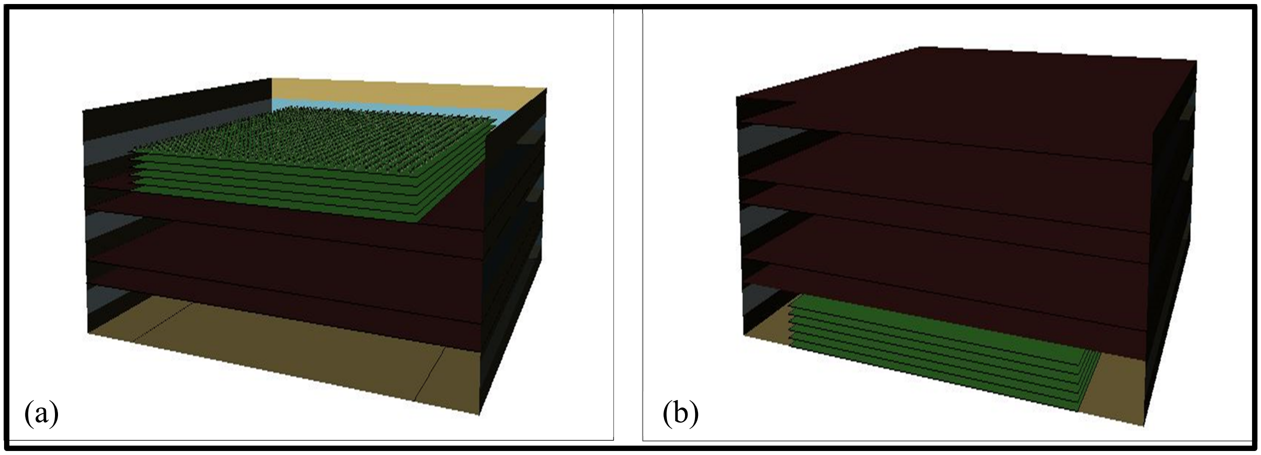


Figure 3.4 BIA location within the host building (a) Top floor (b) Bottom floor

The energy consumption was only estimated for the HVAC and electric lighting systems. It did not consider the energy consumption of other processes, such as the pumping energy of the hydroponic system. By narrowing the scope to these two systems (HVAC and lighting), the study aimed to provide targeted insights into areas with the highest potential for energy savings and efficiency improvements. However, future research could expand the scope to include other energy-consuming processes, such as hydroponic system pumping energy, to provide a more comprehensive analysis of overall energy consumption and efficiency within the studied environment.

3.2.1 BIA space energy consumption distribution

Figure 3.5 illustrates the total energy consumption of the different scenarios. The use of HPS versus LED lighting impacts electricity consumption since they require more energy to perform. The total energy consumption of the main energy uses of the space is the lighting and HVAC system, including sensible cooling, sensible heating, dehumidification, and fan.

Results showed that while the electrical lighting accounted for most of the energy consumption ranging from 45% to 80%, the HVAC systems contributed significantly to the annual energy consumption. For the airtight system, Graamans et al. (2018), Lalonde et al.(2019), and Talbot et al. (2022) have shown similar results for different locations, with electrical lightning accounting for about 57%, 64% and 53% of the total energy consumption respectively. This highlights the need to implement measures to improve HVAC system efficiency to increase BIA viability.

The best scenario with lowest total electricity consumption belongs to combination of BF-LED-PPFD200-T20 (see Figure 2.2) with 999 kWh.m$^{-2}{}_{\text{cultivated}}$ with represented distribution of 55% and 45% for the HVAC and lighting, respectively. The highest energy consumer scenario accounts for the combination of TF-HPS-PPFD750-T20 with individual percentage of 21% and 79% for HVAC and lighting with total electricity consumption of 2935 kWh.m$^{-2}{}_{\text{cultivated.}}$

From a lighting type perspective, it was anticipated that the energy consumption would be lower for the LED since the LED lighting used in this study (Royal Philipps, 2018) has the efficacy of 2.6 µmol·J^{-1} in comparison to 1.3 µmol·J^{-1} for HPS lamps. Higher longwave radiative heat fraction ($f_{\text{LW}} = 0.46$) for HPS compared to ($f_{\text{LW}} = 0.11$) for LED leads to the dissipation of more heat to the environment and increases the cooling requirement to maintain indoor appropriate conditions.

Regarding the location of BIA within the building, the two scenarios with similar indoor conditions, BF-LED-PPFD200-T20 and TF-LED-PPFD200-T20, have approximately the same annual energy consumption (998.7 kWh.m$^{-2}{}_{\text{cultivated}}$ vs. 1002 kWh.m$^{-2}{}_{\text{cultivated}}$). This means that there are no notable advantages in terms of location. As such, the location of the BIA space should be driven by other factors. The slight difference is attributed to the contact surface underneath the BIA, which is an interior floor with a U-value of 0.183 W.m^{-2}. K^{-1} when located on the top floor compared to the bottom floor, which is a slab on grade with a U-value of 0.568 W.m^{-2}. K^{-1}. This higher thermal conductivity for the bottom floor causes a significant conductive heat transfer, resulting in lower cooling demand compared to the top floor scenarios.

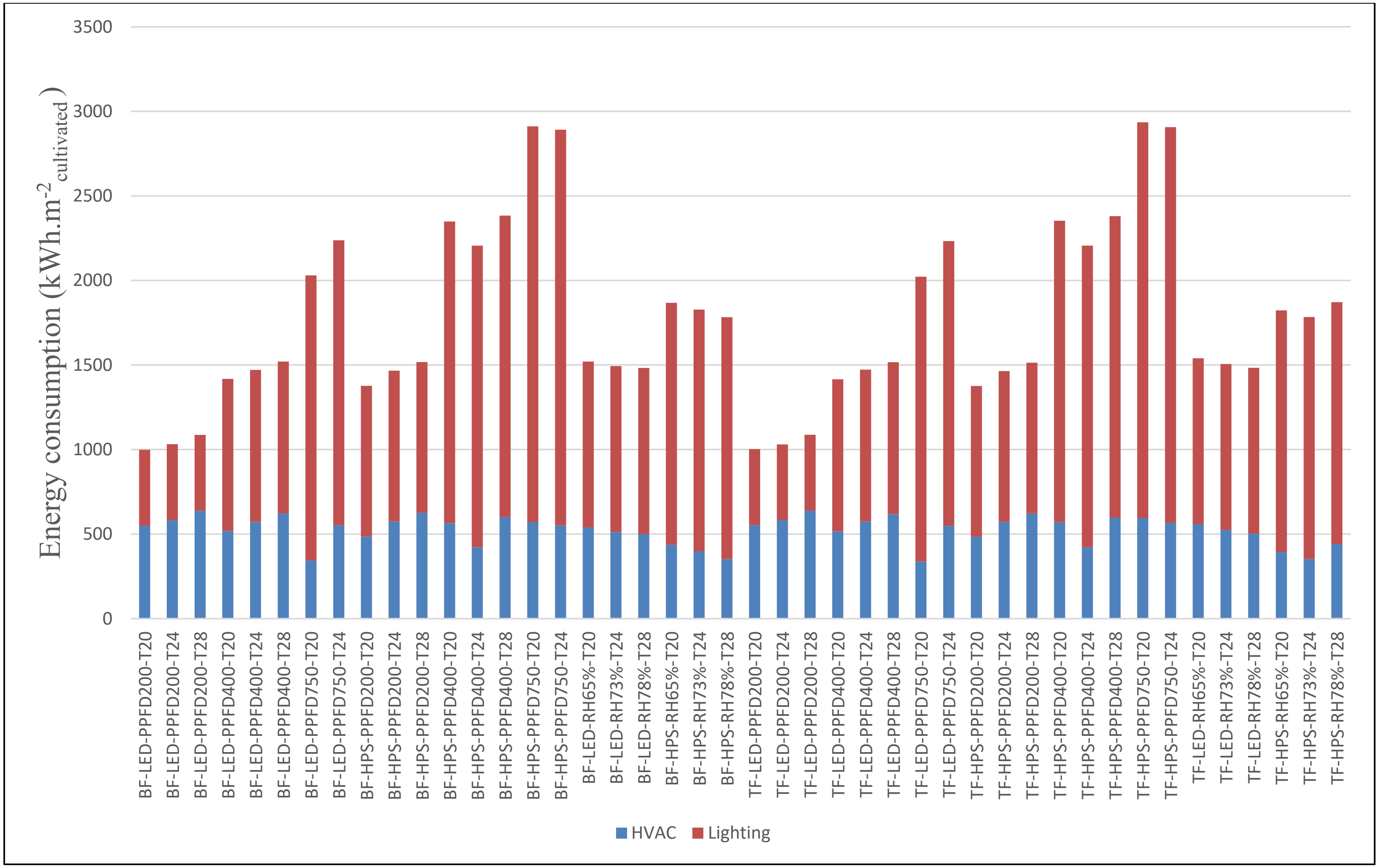


Figure 3.5 BIA energy consumption distribution

3.2.2 HVAC energy consumption distribution

Figure 3.6 presents the energy consumption per year for HVAC systems of every scenario under study. It illustrates the energy consumption of the heating, cooling, fans, and dehumidification systems. Building integrated agriculture (BIA) systems face a significant challenge due to their high energy costs, necessitating a thorough assessment of their energy consumption patterns. It is crucial to delve into the intricacies of the energy usage profile within these spaces to identify optimization and efficiency improvement areas. Particularly in colder climates, where the demand for cooling is lower, leveraging free-cooling methods emerges as a promising strategy to mitigate cooling-related energy consumption. This approach harnesses naturally colder outdoor air to maintain suitable indoor temperatures, thus reducing the reliance on mechanical cooling systems. However, the adoption of free-cooling has its challenges.

Maintaining adequate CO_2 levels within the indoor environment is crucial for supporting plant growth in BIA space. Achieving this balance often necessitates a higher flow rate of outdoor air during the winter months, leading to increased heating energy consumption. Thus, while free-cooling offers potential energy savings on cooling, it simultaneously introduces complexities that influence heating requirements. That is the main reason in this study, the system was assumed to be airtight (no exchange with outdoor fresh air) not only to maintain the CO_2 level constant but also to decrease the need for the heating space significantly. Without free-cooling in this type of system, the provision of cooling needs to maintain an optimal condition was accounted the most energy-intensive parts. One significant benefit of this system was its ability to substantially minimize the infiltration of external airborne pollutants and pathogens into the BIAs while also facilitating CO_2 enrichment (Lalonde et al., 2019)

This highlights the need for a holistic approach to energy management in BIAs, considering both cooling and heating demands to achieve overall energy efficiency. In plant factories, this cooling load results from the relatively high internal heat load from crop transpiration and the inefficiency of the LED fixtures (D’Ostuni et al., 2022).

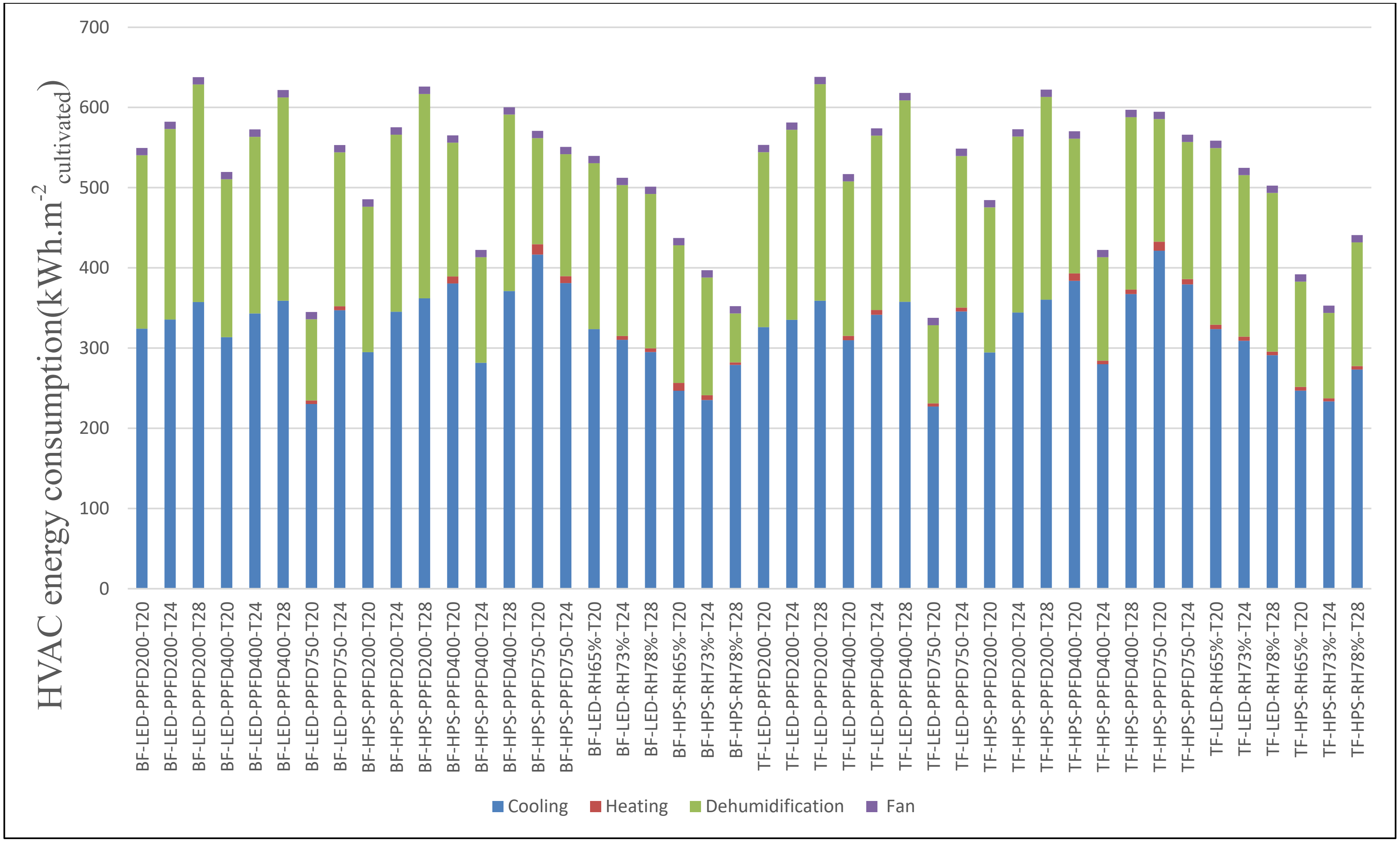


Figure 3.6 BIA annual HVAC energy consumption distribution

An airtight system requires minimal (near zero) humidification because the evapotranspiration plants naturally regulate humidity levels. Since the BIA space in this study is located in a core zone of the bigger fully conditioned floor space, the infiltration rate was calculated at roughly zero and had no impact on the humidity level. As moisture accumulated, the need for dehumidification became significant; in cold climates, dehumidification was estimated to be the second place of the most energy-intensive processes. Conversely, the condensate resulting from air dehumidification could be repurposed for crop irrigation or humidification, especially in arid climates. This consideration is crucial for designing BIAs in regions prioritizing water efficiency(Lalonde et al., 2019).

For the worst scenario with the highest HVAC energy usage, the most significant contributors to energy consumption were cooling and dehumidification, followed by heating and fans. For this combination (BF-LED-PPFD 200-T 28), these energy consumptions represented 73%, 23%, 2% and 2%, respectively. For the most efficient scenario (TF-LED-PPFD750-T20), the distribution represented 67%, 29%, 1% and 3%.

The highest share of the HVAC system, the cooling process, was predictable as the system had to be enabled to cool a large volume of air at low temperatures to help remove moisture content, offset the significant electrical lighting heat gain and reach the desired supply air temperature in variable air volume (VAV) system at (13℃).

As a consequence of the significant impact of heat transfer between the plants (cooling effect of the crops) in high-density cultivated space in this study with the surrounding environment and the fact that the lighting heat gains were adequate to compensate the required heat for conditioning the BIA space inside air, it was expected that the heating energy consumption would belong to the lowest share. However, the highest heating requirements are included in the scenarios with HPS rather than the scenarios with LED, even though HPS lighting releases more heat to the space than LED due to their efficiencies (30% vs. 52%). This contradiction is interpreted by the type of HPS specified in this study, which emitted slightly more PPFD than the LED (458.5 µmols^{-1}·m^{-2} $_{\text{cultivated}}$ vs. 434 µmol·s^{-1}·m^{-2}$_{\text{cultivated}}$). This feature brought crops transpiring more, and it helped plants become cooler (Talbot et al., 2022).

3.2.3 Estimated annual production for the VF scenarios

The yearly yield, based on production starting on the first day of January is determined using data tabulated in Table 2.6 and according to equations (2.4) to (2.6). Table 3.1 and Figure 3.7 presents the estimated annual production of the VF. It is assumed that harvest occurs when the fresh weight of the lettuce reaches a value of 250 g.

Table 3.1 Estimated yearly yield for VF scenarios

Combinations		Average duration of growth cycle, days	Number of cycles per year	Total yield, kg	Yield per cultivated area, kg.m^{-2}
PPFD (µmol.m^{-2}. s^{-1})	Temperature (°C)				
200	20	29	12	212 220	90
	24	25	14	247 590	105
	28	27	13	229 905	97.5
400	20	21	17	300645	127.5
	24	20	18	318330	135
	28	24	15	265275	112.5
750	20	19	19	336015	142.5
	24	17.5	20	353700	150

When other factors are not limiting, production increases with increasing light intensity until the PPFD reaches 750 µmol. m^{-2}.s $^{-1}$ for each temperature. From an electricity consumption view, maintaining the maximum PPFD for each scenario is highly energy intensive, and there is a trade-off between annual high yield and energy usage to be considered.

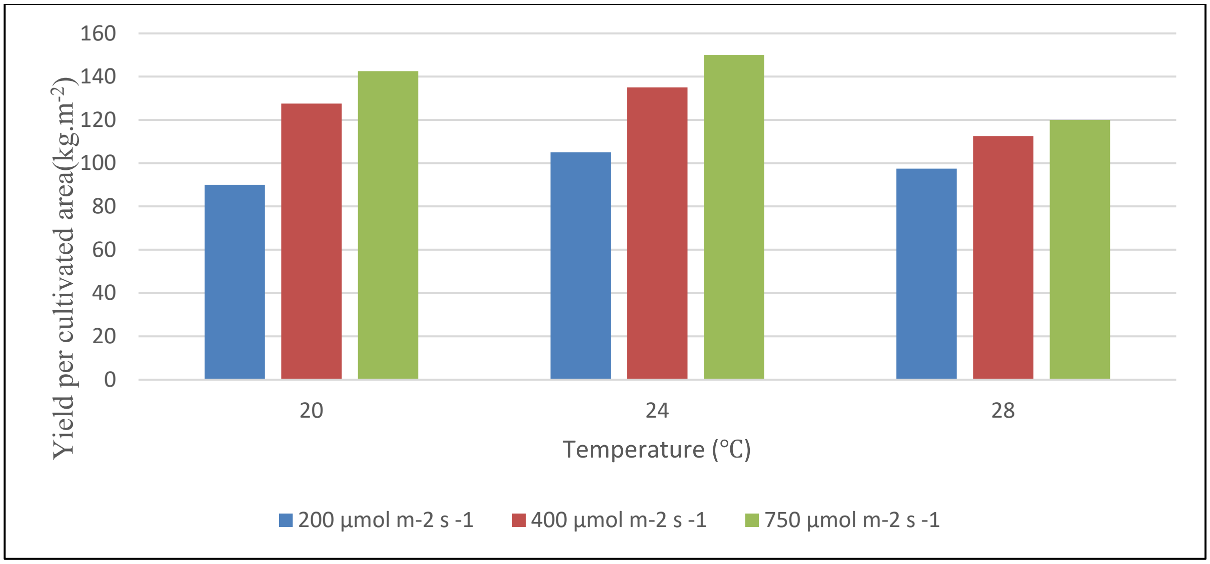


Figure 3.7 Annual yield estimation

The energy consumption per fresh weight produced (kWh·kg^{-1}) often used to compare the energy performance of CEA scenarios is presented in Figure 3.8. Using this metric, the indoor combination of (LED-PPFD 200-T 24) is the most efficient for both the bottom and top floors. It has to be mentioned that the yield calculation, based on what Carotti et al. (2021) did, is compatible with LED lighting with different PPFD values. To evaluate the annual production in all studied scenarios, there is an assumption that crop calculation can be considered valid for HPS lighting, too.

In the Canadian market, the production of fresh lettuce exhibits notable patterns, reflecting both the industry's scale and its responsiveness to consumer demand. Statistics Canada reports a steady increase in greenhouse lettuce production, with over 19.6 million kilograms harvested in 2022 (Over 90% of fresh lettuce produced in 2022 came from Quebec), marking a rise from previous years (Government of Canada, 2023). This uptrend underscores the significance of lettuce cultivation within Canada's agricultural landscape, aligning with its status as one of the most consumed fresh vegetables in the country. Moreover, the geographic diversity of production regions across Canada contributes to the resilience and reliability of the lettuce supply chain, ensuring consistent availability to meet consumer needs.

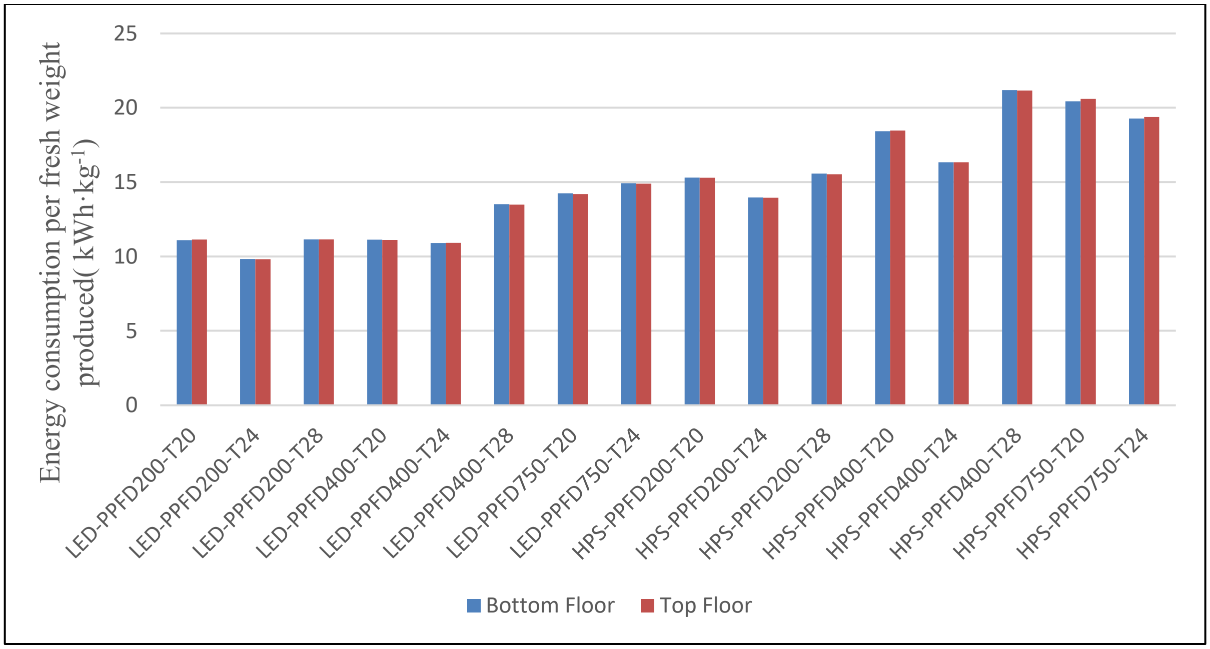


Figure 3.8 VF estimated yearly energy consumption per fresh weight

In terms of energy consumption per fresh lettuce production (kWh.kg^{-1}), understanding the dynamics of this metric provides insights into the efficiency and sustainability of lettuce cultivation practices. As lettuce represents a staple in the Canadian diet, its production demands a substantial amount of energy, primarily driven by the need for controlled environments in greenhouse settings (Pomoni et al., 2023). The energy-intensive nature of maintaining optimal growing conditions, including lighting, heating, and irrigation systems, contributes to the overall energy footprint per kilogram of lettuce produced. By analyzing this energy consumption metric, researchers can evaluate the environmental impact of lettuce cultivation and explore strategies to enhance energy efficiency while ensuring consistent and nutritious food supply to meet the feeding needs of the Canadian population.

In addition to the production trends, examining lettuce consumption statistics provides valuable insights into dietary habits, particularly in Quebec and across Canada. According to data from Statistics Canada, the average per capita consumption of lettuce has shown resilience and growth, reflecting its popularity among Canadians (Government of Canada, 2023). This trend is particularly pronounced in Quebec, where fresh vegetable consumption has increased steadily over the past decade, reaching approximately 69.7 kilograms per person in 2015 (Rousseau, 2018). Such statistics underscore the integral role of lettuce in Quebec's culinary landscape and its importance in meeting the nutritional needs of the population.

3.3 Impact of integrating VF scenarios on energy use of the host building

As illustrated in section3.2.1, a vertical farm requires significant amounts of electricity to power the lighting and HVAC system. Integrating VF scenarios into a host building can increase its overall energy consumption, especially during peak growing seasons when additional lighting and climate control are needed to support plant growth. Integrating VF scenarios into a host building can positively and negatively impact the building's energy use. While VF scenarios can increase energy consumption, they can also lead to improvements in energy efficiency and create synergies with other building systems, ultimately reducing the building's overall environmental impact.

3.3.1 Annual energy consumption

Figure 3.9 presents the building's total energy consumption with VF per year for all designed scenarios and the additional load percentages which are applied to the host building by each scenario. As the derived data for the bottom and top floor had less than 5% differences, annual energy consumption was visualized with disregard to the proposed location scenarios to report more coherently

In terms of total energy consumption over a year, by integrating the scenarios into the baseline building, there is a highly significant increase in building annual electricity consumption. In this study, the impact of using the synergetic interaction between VF and building is not considered. Blom et al. (2023) in their research, designed a pattern to take advantage of a bi-directional interaction between BIA spaces and their host building.

The building with the scenario of HPS-PPFD750-T20 hits the peak of annual energy consumption with the amount of 9053 MWh and applied 1489% additional load compared to the baseline building. The impact on loads indicates how much energy is added to the host building by integrating scenarios in comparison with the baseline building. Using the HPS lighting type with the highest PPFD plays a major role in the highest energy-intensive combination. The best combination belongs to LED-PPFD 200- T20 with a total energy consumption of 2994 MWh and an additional load of 426%. As explained, the differences between lighting type features are considered an important reason.

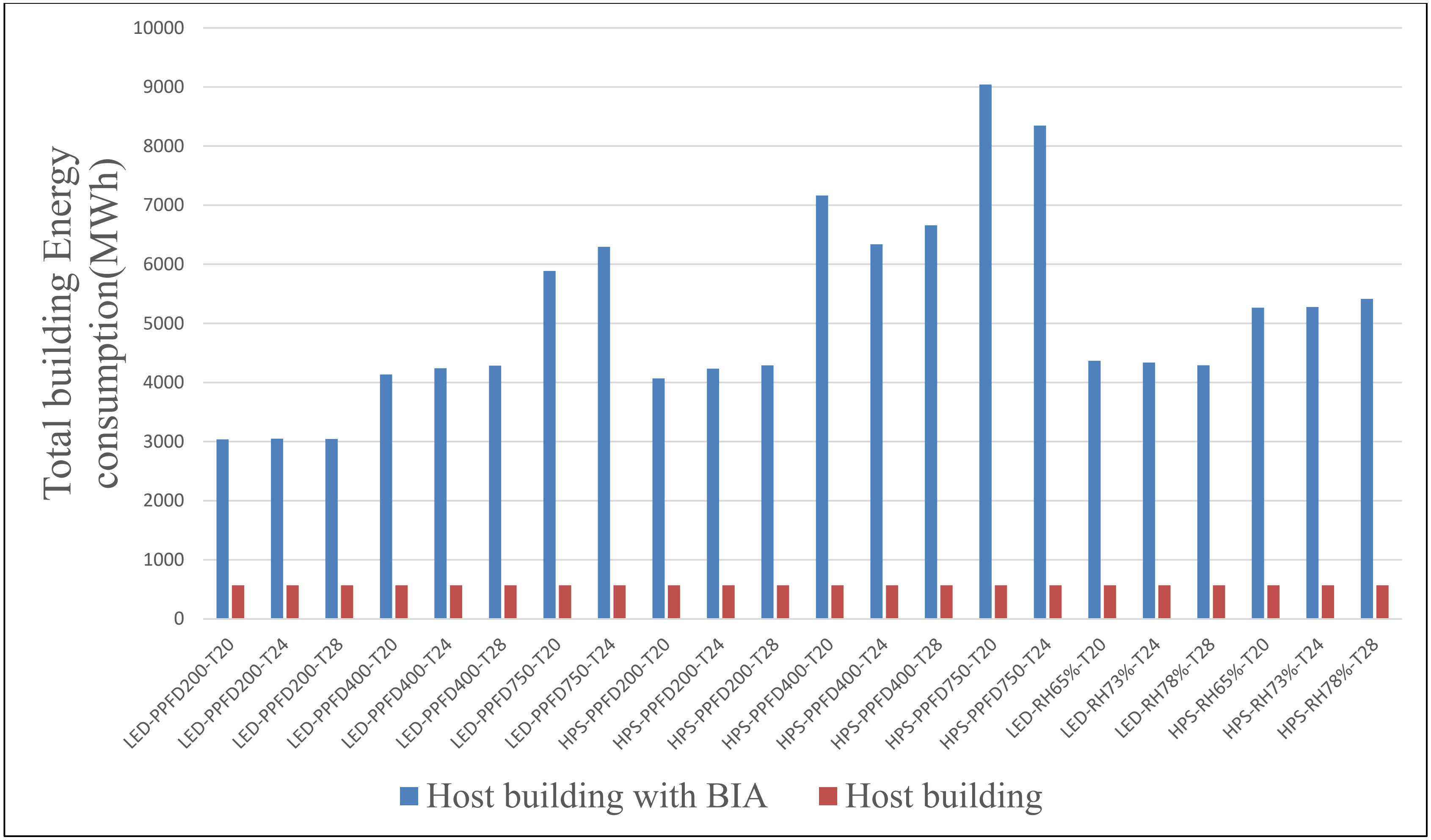


Figure 3.9 Annual building energy consumption with integrating VF scenarios

In terms of heating energy consumption, by adding the VF space, the heating energy consumption is decreased significantly compared to the baseline energy usage. This difference is justified by comparing higher heating demand in the baseline building including people during workdays with BIA space facilities and horticulture lighting. These high internal loads in building with VF caused a lower need to heat the floor space.

Figure 3.10 shows the annual heating energy consumption for the studied building under all scenarios. Generally, scenarios located on the top floor have reduced more energy than the ones on the bottom floor. The best combination is reported for TF-LED-PPFD400-T28, with a reduction load of 78%. The lowest impact belongs to BF-HPS-PPFD750-T20, with a 36% impact load.

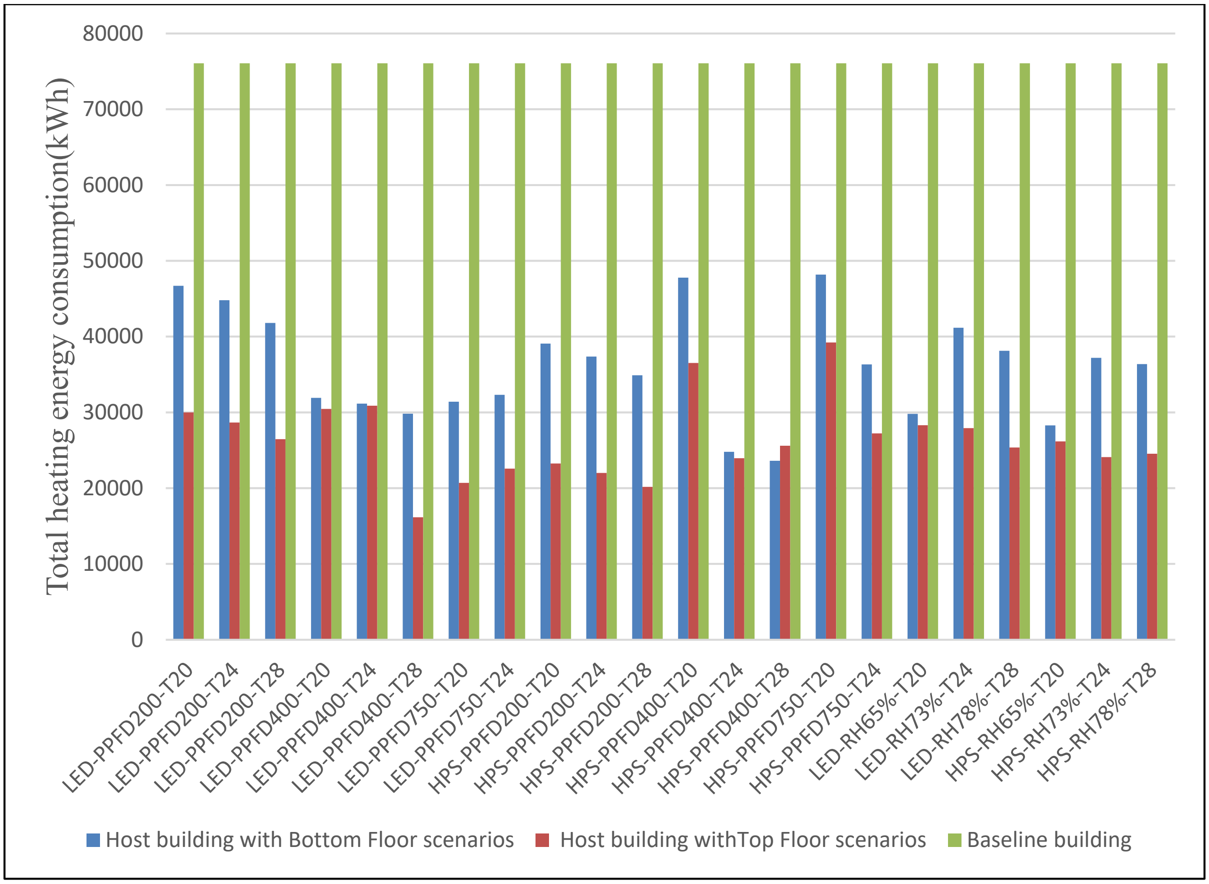


Figure 3.10 Impact of integrating BIAs on annual building heating energy consumption

For the cooling energy consumption, the requirements are much higher with the integration of the VF to the baseline building, crop interactions with the environment, wasted heat generated by artificial lighting and lower cooling setpoint are the main reasons for high cooling demand in BIA spaces. As shown in Figure 3.11, in the best case (TF-LED-PPFD 750-T20), the cooling load is 14 times higher than the baseline, and 25 times for the most energy consuming scenario (TF-HPS-PPFD750-T20).

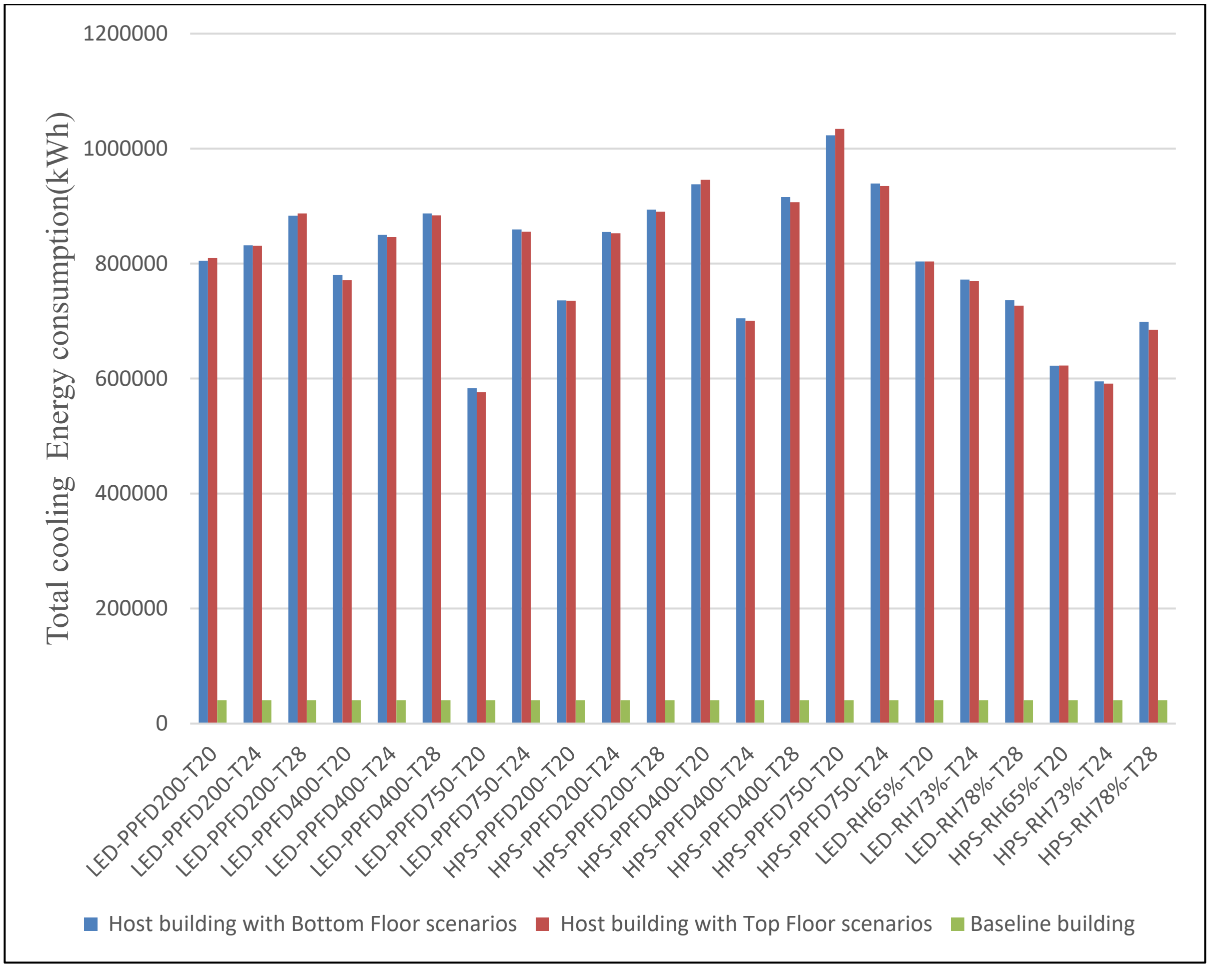


Figure 3.11 Impact of integrating BIAs on annual building cooling energy consumption

3.3.2 Peak electricity demand

Regarding annual peak electricity demand, the impact of adding VF scenarios into the host building is represented regardless of the VF location due to the similar estimated values (Figure 3.12). Due to the similar pattern of peak electricity demand fluctuation in the bottom and top floors, the impact of bottom floor scenarios is assessed only. The highest impact comes from the HPS-PPFD 750-T 20 combination for both the top and bottom floors, which is approximately 7.5 times bigger than the baseline. The most efficient low-impact scenario accounts for the LED-PPFD 200-T28 combination, which is 3.6 times higher than the baseline.

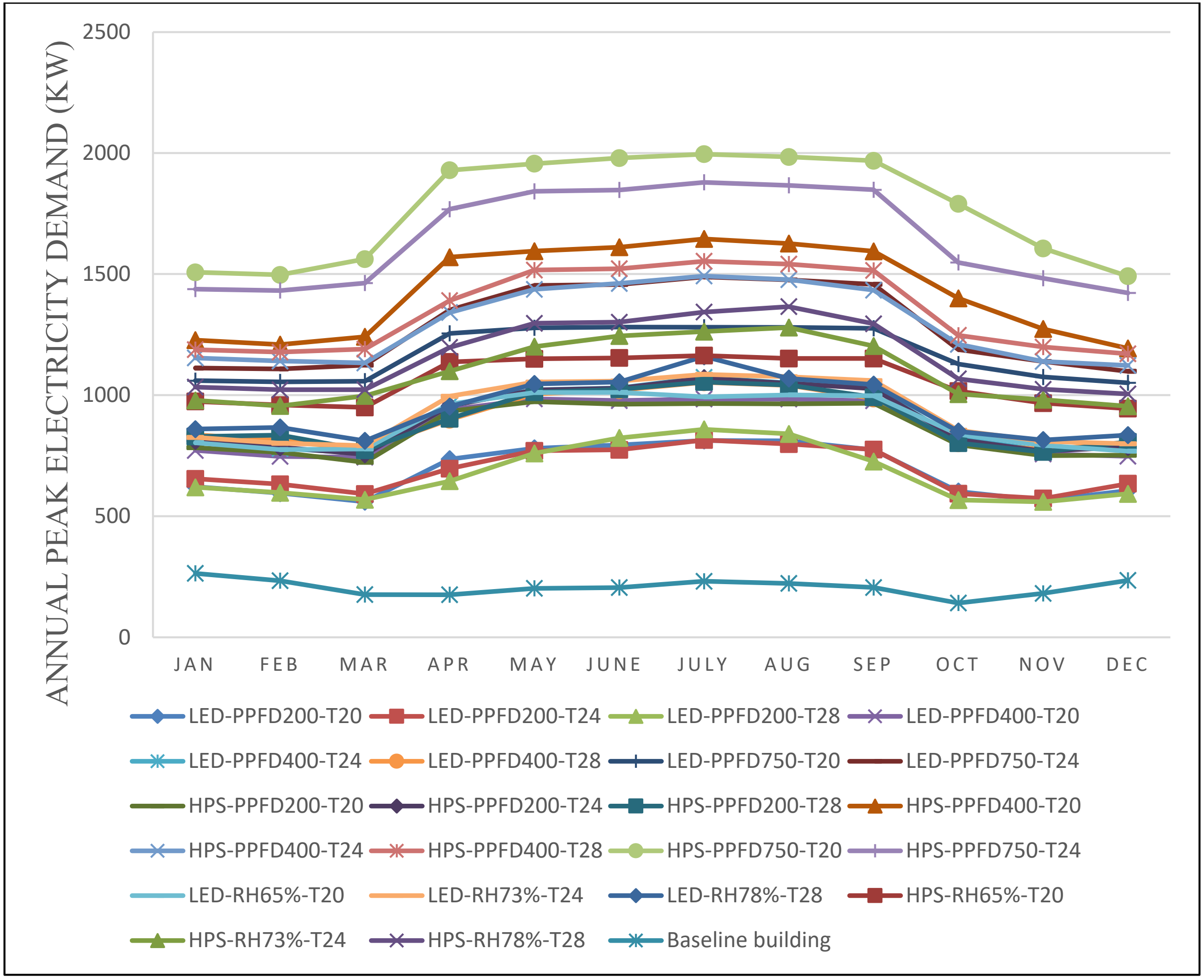


Figure 3.12 Impact of integrating BIAs on annual building peak electricity demand

CHAPTER 4

DISCUSSION

Investigating several combinations for indoor conditions in a vertical farm, the results indicate that in most scenarios, lighting is the highest energy consumer, consuming 50-60 % of the total energy consumption, and the rest of this value belongs to the HVAC system, including the cooling and dehumidification process.

The findings revealed that the thermal interaction of lettuce within BIAs significantly influences HVAC system efficiency. Although Graamans et al. (2018) found no heating necessity, this study and Lalonde et al. (2019) demonstrated that, despite airtight conditions, some heating is essential for BIAs in cold climates during dark winter periods.

The distribution of HVAC systems and artificial lighting within the total electricity energy consumption is compared to the results reported by the most relevant existing research for a similar BIA space located in a cold climate are reported in Table 4.1.

Table 4.1 Total energy consumption comparison with relevant studies

Scenario	HVAC %	Lighting %	Total energy consumption, MWh.m^{-2}
Lalonde et al. (2019)	36	64	1.536
TF-LED-RH65%- T20	36	64	1.540
Graamans et al. (2018)	40	60	1.875
TF-LED-PPFD400-T28	41	59	1.516
Talbot et al. (2022)	48	52	1.046
TF-LED-PPFD400-T24	39	61	1.472

The selected scenarios are the most comparable indoor combinations with the proposed inputs in the literature. Lighting type and intensity are equal; LED with a PPFD of 437 µmol.m^{-2} .

For the cultivated density (CD) of 3, Lalonde et al. (2019) reported that the largest contributor to HVAC energy consumption was dehumidification, followed by fan, heating and cooling. For the proposed scenario in their study with an airtight VAV system, these energy consumptions represented 66%, 15%, 11% and 8% of the total HVAC energy consumption. While for the selected combination in this study, these same processes indicated 39%, 2%, 1% and 58 %, respectively. While in Graamans et al. (2018) study was for a plant factory located in Sweden, which is a similar climate to both studies, i.e., ASHRAE Zone 7, HVAC distribution included only cooling and dehumidification with a share of 70% and 30% respectively. Regarding total energy consumption, lighting accounted for 60% versus 40% for the HVAC.

The yield per cultivated area (kg$_{dry}$·m^{-2}) and the energy consumption per dry weight produced (kWh·kg$_{dry}^{-1}$) are compared to the results reported by Graamans et al. (2018)and Talbot et al. (2022) for a container farm located in Sweden and Montreal respectively, as reported in Table 4.2.

Table 4.2 Energy consumption per yield comparison with relevant studies

Scenario	Yield per cultivated area, kg$_{dry}$.m^{-2}	Yield per cultivated area, kg$_{fresh}$.m^{-2}	Energy consumption over yield	
			kWh.kg$^{-1}_{dry}$	kWh.kg$^{-1}_{fresh}$
Graamans et al. (2018)	5.00	71.42	247	17.30
TF-LED-PPFD400-T28	4.27	112.5	319	13.47
Talbot et al. (2022)	2.86	61.00	386	18
TF-LED-PPFD400-T24	5.13	135.00	287	10.90

These differences may be explained by how the growth model estimated yield. In this study, yield calculation is based on what Carotti et al. (2021) did in their research. They used actual experimental growth model data for lettuce crop growing in a CEA space under different PPFD and indoor air conditions with variable dry matter content ranging from 2.6% to 4.2% for the lowest and highest PPFD, respectively. The growth model was followed until the moment the lettuce's fresh weight reached a marketable weight of 250 g.

In the Talbot et al. (2022) model, yield is influenced by the maintained growing conditions, the crop size at transplant, the harvest size and the dry matter content or based on different assumptions in Graamans et al. (2018). For example, the dry matter content was set to 4.3% while being set to 7% in Graamans et al. (2018). The dry yield per cultivated area for the selected comparable scenario is 44% higher than the value reported by Talbot et al. (2018). This significant deviation is explained by the difference between crop density estimated 18 lettuce.m^{-2} vs. 30 lettuce.m^{-2} in this literature.

For the compared scenario (TF-LED-PPFD400-T28), the dry yield per cultivated area is 14% lower compared to the value reported by Graamans et al. (2018). This is not only explained by the difference in DLI, which was set to 23.04 mol·m^{-2}·d^{-1} for the proposed scenario compared to 28.8 mol·m^{-2}·d^{-1}, but also the results are also influenced by the assumptions made for the dry matter content. The energy consumption per dry weight is 22% higher for the selected scenario, which a combination of factors, such as lower electricity consumption for lighting, but higher consumption for cooling and dehumidification for the scenario of this study can explain. These differences are explained by the different cooling temperature and relative humidity setpoints used, 28°C and 70% for the proposed scenario vs. 30°C and 65% to 90%, respectively, in Graamans et al. (2018). The sensible cooling system and dehumidification COP of this study were also set to lower values than Graamans et al. (2018) values (4.5 vs. 10).

The specific energy use is presented in Table 4.3 for research conducted by Talbot and Monfet (2024) when yield and heat gain/loss from crops are estimated using the experimental growth dataset reported by Carotti et al. (2021) versus the proposed scenarios in this study, while annual yield is assessed using growth dataset reported by Carotti et al. (2021) but the heat gain/loss from crops are valued using static value represented by Talbot and Monfet (2020).

Table 4.3 Comparison with Talbot and Monfet(2024) results

Combinations		Specific energy use, kWh.kg^{-1}$_{\text{fresh weight}}$	Specific energy consumption, kWh.kg^{-1}$_{\text{fresh weight}}$
Temperature (°C)	PPFD (µmol m^{-2} s^{-1})	Talbot and Monfet (2024)	Proposed scenario in this study
20	200	12.08	11.13
	400	17.80	11.10
	750	27.90	14.19
24	200	11.25	9.81
	400	15.83	10.90
	750	27.81	14.88
28	200	11.98	11.15
	400	20.21	13.47

The dynamic crop model developed by Talbot and Monfet (2024) integrates two sub-models: the growth model and the energy balance model. The model estimates the shoot fresh weight (FW_{sht}) and leaf area index (LAI) based on the total plant dry weight. FW_{sht} is utilized to predict crop yield, while LAI is employed to calculate the heat gain/loss from crops and the photosynthetically active radiation (PAR) not absorbed by crops. These two variables are then transferred to the thermal zone model. While, in the proposed methodology in this study, a fixed LAI value of 2.1 is set, indicating the average growth rate. Yield estimation is based on experimental datasets reported by Carotti et al. (2021), which represent relations between the number of days after transplanting and total fresh weight for each combination of PPFD and temperature. Regarding planting crop density, Talbot and Monfet (2024) adjusted 17.6 plants.m^{-2} versus 30 plants.m^{-2} in this study.

The outcomes of this research are challenging to compare with existing literature done by Talbot and Monfet (2024) due to the need for more reporting of specific energy use, unlike specific energy consumption derived from HVAC equipment and lighting usage. The intricate nature of HVAC equipment, influenced by various parameters, makes estimating its energy consumption complex and exacerbates the comparing analyses. The key difference between energy use and energy consumption lies in their scope and focus. Energy use encompasses all forms of energy utilized across different sectors and applications, providing a comprehensive measure of total energy utilization. On the other hand, energy consumption specifically refers to the amount of energy consumed for a particular process or activity, providing a more focused measure of energy utilization for specific applications or sectors.

The findings highlight the significant role of electricity, particularly from LED lighting and the HVAC system, in driving energy demand across various processes. The study also underscores the possible benefits of utilizing waste heat generated by the VF to heat the host building. This is primarily because almost all electricity consumed is ultimately converted into heat, including waste heat from LEDs, equipment, and plant interaction. This heat is then extracted through the exhaust air by the return fan and absorbed by the chilled water system. Most of this heat can be effectively utilized for heating adjunct spaces, thanks to the adequate temperature levels due to the internal heat gains. Furthermore, with a Coefficient of Performance (COP) of 4.5 for the primary cooling system, there's a notable increase in the potential heat quantity, measured in kilowatts, that could be seamlessly incorporated into the building's heating infrastructure. This advantageous outcome in energy conservation for buildings featuring energy-integrated rooftop greenhouses has been substantiated by research examining the thermal dynamics between such greenhouses and the buildings they serve(Ledesma et al., 2022; Muñoz-Liesa et al., 2020).

Vertical farms generate waste heat as a by-product of their lighting and climate control systems. This waste heat can be captured and used to heat the host building, reducing the need for additional heating systems and potentially lowering overall energy consumption. Integrating VF scenarios can create synergies with other building systems, such as HVAC and lighting. For example, the waste heat generated by the VF can be used to preheat water for the building's hot water system, reducing the energy required to heat water. (Blom et al., 2023; M. Martin et al., 2022).

In the realm of vertical farming (VF), two studies have investigated residual heat production. Graamans (2021) found that a non-integrated VF generated 1037 kWh.m^{-2} during a 16-hour photoperiod and 64 kWh.m^{-2} during an 8-hour dark period. The LEDs used in this VF consumed 973 kWh.m^{-2} annually, with a Photosynthetic Photon Flux Density (PPFD) of 500 μmol.m^{-2}. s^{-1}, a Daily Light Integral (DLI) of 28.8 mol.m^{-2}.d^{-1}, and a molar efficacy of 3.0 μmol.J^{-1}. Also, Blom et al. (2023) studied a non-integrated VF that produced 353 kWh.m^{-2} annually. The LEDs in this VF had a DLI of 11.5 mol.m^{-2}. d^{-1} and a molar efficacy of 3.5 μmol.J^{-1}. This study calculated the maximum annual heating energy consumption in the host building with VF at 20 kWh.m^{-2} $_{\text{cultivated}}$, using HPS lighting with a PPFD of 750 μmol.m^{-2}.s^{-1} equal to 43.20 mol.m^{-2}.d^{-1} and an efficacy of 1.31 μmol.J^{-1}. This discrepancy is due to Blom et al. (2023) defining one m² cultivation area as one m² of one production layer of the VF. This implies that utilizing residual heat from a vertical farm (VF) in building energy systems is most advantageous in cold and temperate climates but less so in warm climates where buildings require minimal heating. Additionally, with the broader perspective of Muñoz-Liesa et al. (2020) and urban agriculture, which found that bidirectional energy exchanges between a rooftop greenhouse and an office building in a warmer Mediterranean climate led to energy savings for both heating and cooling the entities (Blom et al., 2023).

The research on building energy integration also acknowledges the potential for integrating vertical farms within buildings, as Shao et al. (2021) highlighted. This study emphasizes the ability of vertical farms to lower CO_2 levels and decrease the energy needed for ventilation in commercial buildings. This indicates a broader potential for integrating vertical farms and buildings to reduce energy and resource usage. Further exploration in this area could significantly advance energy-efficient building design and agricultural practices (M. Martin et al., 2022).

CONCLUSION

This chapter will conclude the study by summarizing the key research findings in relation to the research aims and questions, as well as their value and contribution. It will also review the study's limitations and propose opportunities for future research.

The integration of vertical farms with their respective buildings can serve as a means to advance the decarbonization of buildings and promote the cultivation of fresh produce in urban areas, particularly in colder climates. This is crucial for simultaneously mitigating the environmental and economic repercussions of the building sector and indoor agriculture.

The mutually interactive growth of a vertical farm with its host building to create more “circular urban farming” systems has significant potential advantages for the vertical farm (M. Martin et al., 2022). These benefits extend to the building host, which can achieve substantial energy savings by using the residual heat from the vertical farm for space heating, thereby avoiding the need for conventional heating sources. It was found that integration of the vertical farm with a medium office building as a replacement for one of the floors occupied by typical working people can reduce the heating energy consumption of the host building by up to 78%. It is worth mentioning that this is primarily due to the context location of the study, i.e., Quebec due to significant heating demand in the most months over a year.

The use of the lettuce heat gain/loss inside a BIA indicated to have a substantial impact on HVAC system design and performance due to maintaining an optimal condition for appropriate crop growth. The specific energy intensity of production ranges between 9.8 and 21 kWh of energy consumed per kg FW of lettuce produced.

Regarding a comparison between the most prevalent controlled environment agriculture (CEA) types conducted by Graamans et al. (2018), the greenhouse is more efficient in purchased energy than indoor vertical farming due to the high artificial lighting need. Remarkably, the advantages of solar energy can surpass the demand for a fully-controlled environment, even in harsh climates. In the real world, energy performance is not the only factor determining the system's overall viability. The availability of resources directly affects how healthy production and climate control systems work. Plant factories provide opportunities in areas with limited resources by ensuring efficient water and CO_2 usage, along with high production density. Graamans et al. (2018) have also observed that only a limited number of locations worldwide would warrant the adoption of controlled environments over conventional agriculture. However, ongoing research and advancements in HVAC and electrical lighting system optimization, water use efficiency, crop yield enhancement, and reduced transport costs could potentially transform this concept into a practical reality. Moreover, the ability to enhance energy efficiency and mitigate condensation risks in building envelopes through modelling approaches presents a valuable tool for enhancing the viability of Building Integrated Agriculture (BIAs) in cold climates.

However, further development of the model is facilitated by some recommendations in the context of managing energy performance:

- Improving lighting efficacy can reduce facility energy consumption;
- Introducing an air-side economizer alone reduced HVAC energy consumption through free-cooling;
- Sustaining elevated CO_2 levels and accurately characterizing gaseous exchanges between crops and their environment in BIA production spaces can reduce the need for lighting to achieve desired growth rates, thereby reducing energy consumption;
- Utilizing dynamic crop models can improve HVAC system design and analysis, reducing condensation risks in cold climates and enabling future research to assess cost-efficiency for various HVAC system configurations. This is crucial for demonstrating the economic feasibility of large-scale indoor agriculture facilities.

The findings of this study can enhance our understanding of the environmental impacts of integrating vertical farming into urban settings and buildings, thereby bridging various disciplines like architecture, urban design, horticulture, and industrial ecology. The study offers fresh insights into the environmental effects of the circular development of vertical farms. However, future research should prioritize practical studies involving urban farms to furnish empirical evidence on the potential, feasibility, and additional synergies of such integration.

ANNEX I

ESTIMATED LETTUCE PLANT HEAT GAINS

Table A I-1 Estimated heat gain/loss ($W.m^{-2}$) under photoperiod cycle
Taken From Talbot and Monfet (2020)

T(℃) RH (%)	18		20		22		24		26		28		30	
70	-27	87	-33	93	-40	100	-47	107	-54	114	-61	121	-68	129
75	-16	76	-22	82	-27	88	-33	94	-39	100	-45	106	-51	112
80	-5	65	-10	70	-15	75	-20	80	-25	85	-30	91	-35	96
85	5	55	1	59	-3	63	-7	67	-11	71	-15	76	-19	80
90	16	44	13	47	10	51	6	54	3	57	0	61	-3	64

🟦 Lettuce sensible heat gain ($W.m^{-2}$)

🟥 Lettuce latent heat gain ($W.m^{-2}$)

Table A I-1 Estimated heat gain/loss ($W.m^{-2}$) under dark period cycle
Adapted from Talbot and Monfet (2020) (Continued)

T (℃) RH (%)	18		20		22		24		26		28		30	
70	-42	42	-46	46	-50	50	-55	55	-59	59	-64	64	-69	69
75	-35	35	-38	38	-42	42	-45	45	-49	49	-53	53	-57	57
80	-28	28	-31	31	-33	33	-36	36	-39	39	-42	42	-45	46
85	-21	21	-23	23	-25	25	-27	27	-29	29	-32	32	-34	34
90	-14	14	-15	15	-17	17	-18	18	-19	20	-21	21	-23	23

🟦 Lettuce sensible heat gain ($W.m^{-2}$)

🟥 Lettuce latent heat gain ($W.m^{-2}$)

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