ROOFTOP GREENHOUSES AS ECOSYSTEMS

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LUND UNIVERSITY

SLU

FUTURE FOOD

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PREFACE

This book was written as part of an Interdisciplinary Academy (IDA) project at the Swedish University of Agricultural Sciences (SLU). In this project, we were six researchers from diverse fields, who dedicated one day each week over eight months (2023–2024) to explore the phenomenon of rooftop greenhouses.

The idea to write this book emerged midway through our collaboration, as we began mapping geographic locations and gathering key information on rooftop greenhouses from around the world. We envisioned a resource that could inspire and guide architects, urban farmers, planners, and city officials seeking practical examples of rooftop greenhouse projects in various urban contexts.

Our hope is that this book fulfils that vision—serving as both a source of inspiration and a practical starting point. We aim to encourage professionals to take bold steps in imagining, designing, and implementing rooftop greenhouse technologies. We firmly believe that this innovation has the potential to revolutionize urban food systems, not only in Sweden but globally.

Lund, Sweden
August 2025
The authors

Institut de Ciència i Tecnologia Ambientals (ICTA-UAB), Universitat Autònoma de Barcelona, photo Marie-Claude Dubois

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- Fermes de Gally, Paris, France,
- Ferme des jardins perchés, Tours, France,
- Romain Guillaud (IFSB), Luxembourg,
- Lufa Farms, Montreal, Canada,
- Gotham Greens, Unites States,
- Van Bergen Kolpa Architecten, The Netherlands.

BIGH aquaponic farm, Brussels,
photo Marie-Claude Dubois

INTRODUCTION

Imagine strolling through Malmö or Stockholm on a cold, grey winter day. Rain slicks the pavement, and the air bites with crisp chill. But then, as you glance upward, a warm glow catches your eye—a rooftop greenhouse, its glass panels radiating soft light. Inside, lush green leaves, ripening tomatoes, and trailing cucumbers blossom peacefully in the middle of the urban skyline, a striking contrast to the fast-paced, noisy and hard cityscape below. In that moment, you realize that just a few floors above your gaze, summer is in full bloom. And perhaps, at a nearby store, you could even savour a tomato picked fresh that very morning, with flavours evoking warm, golden summer days.

Rooftop greenhouses are more than just architectural features—they are transformative spaces that blend nature with the built environment. These elevated glass structures repurpose underutilised rooftops into thriving ecosystems, bringing food production to the heart of the city. By reducing the environmental footprint of food, providing fresh produce to urban residents, enhancing food security, and improving the energy efficiency of both the greenhouse and its host building, they offer a multifaceted solution to current urban challenges. More than that, they invite architects to rethink buildings—not just as static spaces for living and working, but as active contributors to a more sustainable and resilient city.

As cities face growing challenges—food security, energy costs, climate change, biodiversity loss, and shrinking green spaces—rooftop gardens and greenhouses offer a potent solution for the future. By transforming unused rooftops into thriving cultivation areas, they provide fresh, local produce while reducing the carbon footprint of food transportation and storage. These green spaces also help regulate building temperatures, improve air quality, and foster a deeper connection between people and nature, all while pushing the boundaries of contemporary architecture.

Beyond sustainability, rooftop greenhouse projects create opportunities for local jobs in urban farming and generate peripheral industries in marketing, distribution, and more. They strengthen communities and open new avenues for education, proving that innovation and sustainability can go hand in hand.

This book is an exploration and inspiration about rooftop greenhouses. It aims to serve as a guide for architects, urban farmers, policymakers, and sustainability advocates. It addresses the technical, ecological, and economic dimensions of these structures, offering insights into design principles, construction challenges, integration with existing buildings, and their broader role in enhancing urban resilience.

For architects, in particular, rooftop greenhouses present an opportunity to push the boundaries of sustainable design, blending aesthetics with functionality, and technology with ecology. Before delving into this topic, let us first explore why urban agriculture is essential and a priority for many municipalities in Sweden and beyond.

A NEEDED TRANSFORMATION OF FOOD SYSTEMS

A compelling argument for urban food production is the pressing need to transform our current food system, which heavily relies on industrial agriculture. This model is a leading contributor of global environmental degradation, driving climate change while simultaneously facing increasing risks. As changing environmental conditions jeopardize the stability of traditional farming, this system's sustainability is increasingly called into question.

A radical transformation of food systems is thus imperative to effectively withstand and recover from various crises, whether they are natural disasters like droughts, storms, floods, pandemics, or international conflicts as well as socioeconomic shocks.

Various sources show that food production, storage, and transportation contribute to roughly one-third of global anthropogenic greenhouse gas (GHG) emissions.[1] Agriculture operations currently occupy over half of all habitable land on earth, converting carbon sinks like forests into cropland or pasture, which leads to GHG emissions.[2] Agriculture industries also consume 70% of the world's freshwater and, together with aquaculture, they endanger biodiversity on our planet by threatening 24,000 of the 28,000 species at risk of extinction in the IUCN Red List.[3] Additionally, industrial agriculture is responsible for 78% of global ocean and freshwater eutrophication,[4] causing a dense growth of plant life and microorganisms leading to toxicity, oxygen depletion, etc. These are pressing environmental issues which must be addressed as population continues to rise, particularly the urban population.

FOOD FOR A GROWING URBAN POPULATION

Since around 2006, the urban popula-

Industrial agriculture

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tion has surpassed the rural one,[5] see Figure 1. The urban population is in fact projected to grow to 6.7 billion by 2050, representing an increase of 50% or 2.5 billion people in 30 years.[6] As more people move to cities, the demand for food increases, which exerts more pressure on existing food systems and all other resources including water, energy, and materials.

Urban populations are increasingly reliant on food produced in rural areas or imported from other regions or countries. The environmental footprint of cities, which primarily rely on resources from rural areas, clearly exceeds their biocapacity.[7] Moreover, as cities develop, the distance between food production and consumption increases, which alters ecosystem services as it prevents nutrient cycling.[8] In other words, through the incessant transportation of food from rural to urban areas, organic matter is constantly moved and most of it is lost, which contributes to soil depletion on the global scale.

The increase in urban population, monetary costs and environmental issues linked to food and nutrient losses are all factors in favour of more local food production, closer to locations where people live. Together with a shift to a plant-based diet, the adoption and promotion of urban and peri-urban agriculture is one way to bring significant changes in food production systems.[9] In the future, cities will play an important role in fostering more sustainable and resilient food systems participating in self-subsistence.

A GLIMPSE AT THE PAST

Many people perceive urban agriculture as a modern innovation. However, a look back at history reveals that food production within cities or their surrounding peri-urban areas was once,

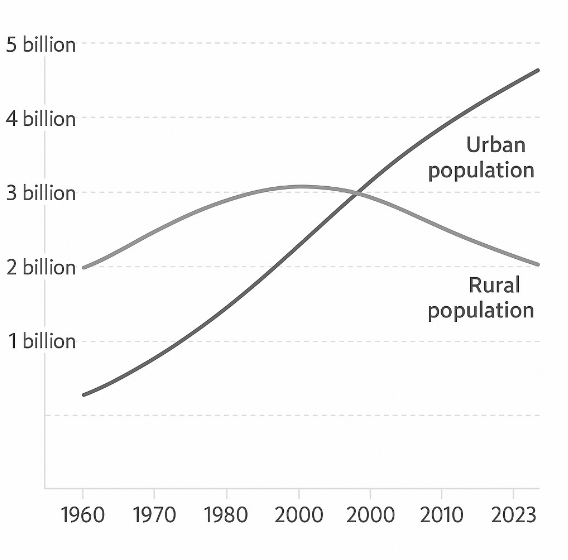

Figure 1
Number of people living in urban versus rural areas, world. Source: World Bank based on data from the UN Population Division (2025), Our World in Data.[111] CC BY. AI generated image from original.

Figure 2
Aerial pictures from the same area of a mid-sized Swedish city around 1960 (top) and 2015 (bottom). Within a few decades, residential buildings and industries have completely replaced the small farms and nurseries in these peri-urban areas. Source: www.eniro.se.

and still is, the norm in many parts of the world. In the past, agricultural products were easily sold in urban markets, while urban wastes such as horse manure and human waste served as valuable fertilizers.[10] Additionally, labor was readily available from urban populations. Farms typically produced a wide variety of goods, from vegetables and fruits to ornamental plants and livestock. A combination of open-field farming, greenhouse cultivation, and hotbeds was often employed to maximize production.

However, with the introduction of better transportation technologies such as railways and cars, along with other advancements like refrigeration and synthetic fertilizers, the natural connection between the city and food production gradually waned during the 20th century. The land in the peri-urban areas was valuable for the city's expansion, prompting production to be relocated to the countryside or even to other regions or countries, as shown in Figure 2.

RESILIENT, SELF-SUFFICIENT FUTURE FOOD SYSTEMS

URBAN AGRICULTURE

Producing food closer to consumption points can significantly reduce GHG emissions, as transport emissions account for about one-fifth of food systems' emissions.[11] Some argue that the cities of the future will thrive by fostering meaningful connections to locally grown food.[12] A concept called 'agrarian urbanism' is gaining attention in city planning. Agrarian urbanism refers to settlements where society is occupied with food at several levels: organizing, growing, processing, distributing, cooking, and eating it.[12]

In more familiar language, the terms 'urban agriculture' (UA) or 'urban farming' (UF) are often used by architects and city planners. They generally refer to activities involving growing crops, trees, herbs, and even raising livestock within or around cities. Urban agriculture can even involve other activities such as waste recycling, processing, and marketing in urban and suburban areas. The promotion of urban agriculture is rooted in the three pillars of sustainability, namely social, economic, and environmental,[13] see box on next page.

Urban agriculture also enhances food security, reduces energy use and carbon footprints, and may offer environmental benefits, such as green spaces highly valued by the community.[13] It can contribute to waste recycling, community building, education, and climate resilience.[14]

Various forms of urban agriculture can coexist in the same city, including community gardens, rooftop farming, and micro-farming. While generally beneficial for the city, the challenges of urban agriculture like limited space, shading from buildings, pollution, and waterborne diseases need to be addressed from early to detailed

- **Socially**: Urban agriculture connects people to nature and provides educational opportunities.
- **Economically**: Urban agriculture meets the demand for fresh, local, and organic food, creating opportunities for local businesses.
- **Environmentally**: Urban agriculture reduces the reliance on long-distance food supply chains, lowering transportation costs and promoting sustainability and resilience.

design stage. Various actors belonging to different disciplines must be involved in planning discussions including professionals of urban planning, horticulture, environmental science, agronomy, economics, etc.[15]

URBAN ROOFTOP FARMING

Urban rooftop farming, along with community gardens, allotment plots, and indoor farms, is a key component of urban agriculture. In cities, spaces for cultivation are limited, which leads to the need for innovative solutions such as rooftop farming (RTF), also sometimes called urban rooftop farming (URF) or rooftop agriculture (RA).

Urban rooftop farming is considered one of the promising solutions for the future because rooftops make up a significant one-fourth of all urban surfaces.[16] The rooftops of buildings are often overlooked or left unused, presenting untapped potential for the development of urban agriculture. Older buildings can be revamped to accommodate growing containers, soil-based or hydroponic systems, and similar setups. The potential for cultivation is thus significant. For example, a study assessing the potential of rooftop farming revealed that cultivating on flat roofs could satisfy a substantial 77% of Bologna's vegetable demand.[17]

Embracing urban rooftop farming comes with a multitude of advantages, ranging from efficient use of space and economic growth to mitigating the urban heat island (UHI) effect and conserving energy. The optimization of space is particularly valuable in regions with limited or no available arable land. Many rooftop farming initiatives refer to their system as 'Zero-Acreage Farming' (ZFarming),[8] which refers to crop production

Rooftops make up a significant one-fourth of all urban surfaces.

By 2050, arable land availability will have diminished to one-third of its 1970 value.

without relying on traditional land or acreage for agricultural activities.

The concept of ZFarming is a significant advancement, especially considering projections indicating that by 2050, arable land availability will have diminished to one-third of its 1970 value.[18] Hence, the adoption of ZFarming not only addresses the current challenge of limited space but also presents a forward-thinking solution to ensure sustainable agriculture in the face of future constraints on available arable land.

OPEN-AIR ROOFTOP FARMS

Rooftop agriculture can take the form of open-air farms or as emphasized in this book, rooftop greenhouses (RTGs), where plants are cultivated in a controlled environment. Open-air farms are more widespread than RTGs. A recent study[19] indicated that 85% of surveyed rooftop agriculture projects consisted of open-air farms. It also revealed that only a few of these projects had a commercial focus. Instead, most were designed to enhance quality of life and serve social or educational purposes.

A few notable open-air farm projects, most of which integrate food production with events, education, social outreach, or other community initiatives, are listed below:

- **Østergro** (Copenhagen) – Supports 16 families and supplies a restaurant, Figure 3 (top).
- **Brooklyn Grange** (New York City) – A 5.6-acre organic urban rooftop farm.
- **Dakakker** (Rotterdam) – The largest rooftop farm in the Netherlands (1,000 m²), located on top of the Schieblock.
- **City Farm** (Tokyo) – Encourages urban residents to engage with food production while helping combat rising city temperatures.
- **Boston Medical Center** (Boston) – Provides fresh produce for the hospital kitchen.
- **Hotel Yooma** (Paris) – A 1,000 m² farm growing 20,000 plants, supplying a restaurant and a few families.
- **Pakt** in Antwerp, Belgium, see Figure 3 (bottom).

Due to the roof's limited bearing capacity, the soil layer in open-air farms is generally shallow, often not exceeding 40 cm. This is because growing media can weigh between 900 and over 1600 kg/m³ when fully saturated. Since substrates in open-air farms become completely saturated at certain times of the year, this must be factored into the structural load calculations for the growing system. The thin substrate layer also means that irrigation is almost essential, and only a limited range of crops can be cultivated, typically with lower yields compared to ground-based agriculture.[20] Additionally, key chal-

Figure 3
Top: Østergro, Copenhagen, photo: Nicholas Wakeham; Bottom: Pakt, Antwerp, Belgium. Photo: Paul G. Becher.

lenges in developing successful rooftop farms include high initial investment costs, low profit margins on food products, and long payback periods.

URBAN ROOFTOP GREENHOUSES

Urban rooftop farming encompasses both open-air rooftop farms and enclosed rooftop greenhouses,[14] as shown in Figure 4, both of which fall under the broader category of 'building-integrated agriculture' (BIA), see Figure 5. BIA involves integrating farming systems into mixed-use buildings to maximize synergies between agriculture and the built environment. While it may seem like a modern innovation, BIA dates back as early as 600 BC, with the Hanging Gardens of Babylon serving as a historical example.

Unlike open-air rooftop farms, rooftop greenhouses are classified under 'Controlled Environment Agriculture' (CEA), a method that enables localized urban food production while enhancing biosecurity, resilience to pests and drought, and consistent, year-round crop yields. Rooftop greenhouses are particularly valuable in temperate and cold climates, as they regulate temperature, humidity, and light to create optimal growing conditions. Their key advantage thus lies in their ability to sustain food production throughout the year, something that open-air rooftop

Figure 4
Open-air and enclosed rooftop greenhouse farm combined on the same roof.
Photo: Courtesy of Ferme Les Jardins Perchés, Tours, France.

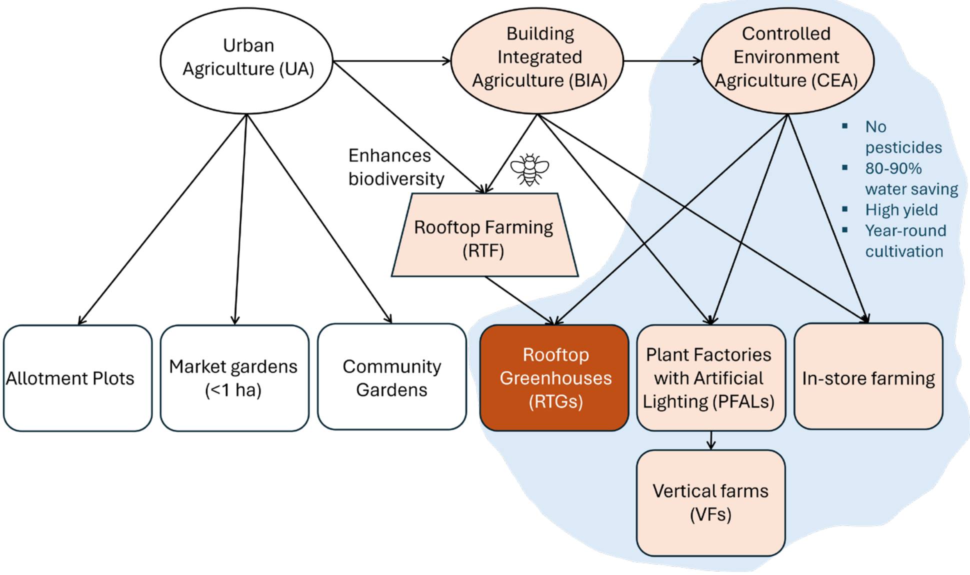

Figure 5
Diagram showing the conceptual associations between rooftop greenhouses, BIA and CEA.

farms in colder regions cannot achieve.

RTGs can be found on a variety of building types, including commercial, industrial, and residential structures. They can be either permanent or temporary installations, utilizing diverse cultivation technologies such as hydroponics, aeroponics, aquaponics, and vertical farming (VF). Hydroponic and aeroponic systems are particularly well-suited for rooftop greenhouses due to their light weight and efficient water use.[21][22] Some of the most advanced rooftop greenhouses, such as 'De Schilde'[23] and 'Urban Farmers AG'[24] in The Hague, 'Ferme Abattoir' in Brussels,[25] and 'Sky Greens' in Singapore, incorporate aquaponics—a system that uses fish waste to fertilize crops—sometimes in combination with rooftop gardens, further enhancing sustainability and productivity.

The benefits of RTGs align closely with those of CEA, including reduced water consumption through collection and recirculation, minimized pesticide use due to indoor cultivation, and decreased contamination of waterways.[26]

Other forms of CEA include conventional greenhouses, vertical farms (VFs), and plant factories with artificial lighting (PFALs), also known as closed plant production systems. In the recent decade, research on CEA has largely focused on VFs,[27] as these can boost crop yields by 10 to 100 times compared to traditional farming, making them ideal for space-constrained

Figure 6
In-store farming (vertical) integrated into a supermarket, Coop, Lund, Sweden. Photo: Marie-Claude Dubois.

urban environments.[28] However, one key drawback of PFALs is their high energy consumption due to their reliance on artificial lighting[29] as shown in Figure 6-7. This drawback must be taken seriously, especially as electricity becomes an increasingly costly resource, which is in competition with other sectors such as e-mobility.

Implementing RTGs requires collaboration among multiple stakeholders, including building owners, architects, construction firms, and policymakers. In addition, recruiting skilled staff is essential for successful implementation.

A key factor supporting the positive development of open-air rooftop agriculture and RTGs is the shifting perspective of municipalities on the city's role in the food system. Major North American cities, such as New York and Toronto, are actively promoting urban agriculture through targeted policies and initiatives.[20] These municipalities recognize the need for comprehensive food system strategies to combat food insecurity, with RTGs playing a crucial role in building more resilient urban food networks.[30] These examples demonstrate how municipal governments can drive change by positioning cities as central actors in the development of sustainable food systems.

CHALLENGES AND GROWTH OF ROOFTOP GREENHOUSE PROJECTS

Market growth and RTG construction can be challenged by physical constraints such as building structure and accessibility, as well as legal requirements related to technical standards and fire safety regulations. Structural limitations must be carefully evaluated to accommodate the extra weight imposed by the greenhouse. These factors can, in turn, impact the economic competitiveness of RTGs compared to conventional ones.[31 32]

Other challenges of RTG technology include high infrastructure investments and energy costs for equipment and lighting. Construction and maintenance expenses can also be considerable, along with ongoing costs for energy, staffing, and maintenance. Additionally, structural reinforcements and specialized environmental, water, and resource management systems may also be necessary. These factors are critical, as microclimatic variations can affect plant productivity; precise management is therefore necessary to ensure optimal growing conditions.

Efficient water management is essential for RTGs, given their limited access to water sources. A comprehensive sustainability approach should also address energy use and waste management. Key design considerations include low solar transmission due to additional structural elements, limited availability of flat roofs, and

Figure 7
Hydroponic production of lettuce in a vertical farm. Photo: Karl-Johan Bergstrand.

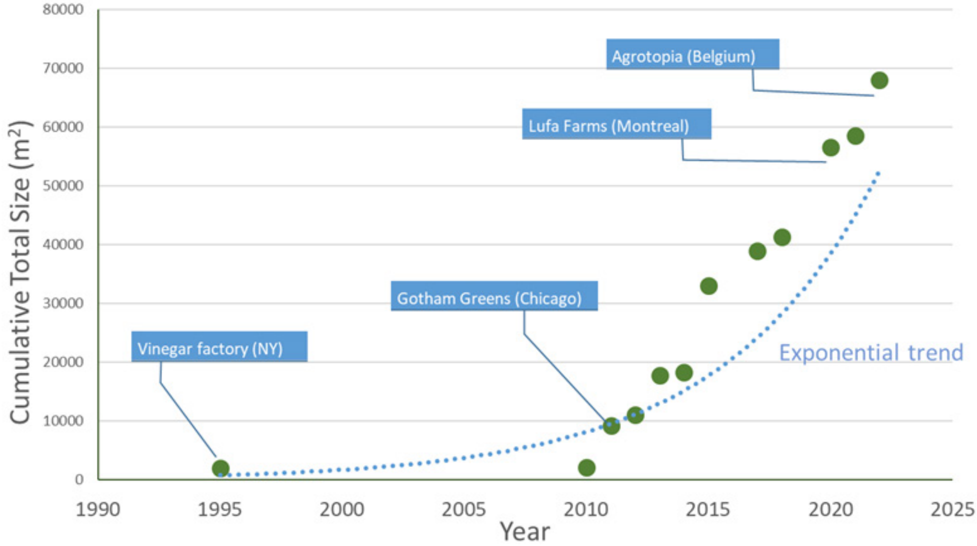

Figure 8
Cumulative area (m^2) of rooftop greenhouses on a global scale, according to data from Drottberger et al (2023).[112]

the need for staircases or elevators for accessibility. Note that transporting supplies and produce from and to the roof can be more labour-intensive and time-consuming than in traditional ground-based agriculture.

Despite these challenges, RTG technology has gained significant momentum, with numerous full-scale implementations over the past decades. A recent analysis of global RTG projects shows that the total surface area has been growing exponentially since one of the first projects, the Vinegar Factory in New York, began operations in 1995 (see Figure 8). Notably, this growth accelerated around 2010. Today, RTG technology is proving commercially viable in major cities, with several companies scaling up their projects to capitalize on economies of scale.

CONTEXT FOR ROOFTOP GREENHOUSE IMPLEMENTATION

GEOGRAPHIC DEPENDENCIES OF ROOFTOP GREENHOUSE PROJECTS

The geographic location and context can significantly impact the economic viability and success of a RTG project at various levels. At a specific site, the characteristics of

Challenges or constraints of rooftop greenhouses

- Physical constraints of existing building (building structure, accessibility, etc.)
- Legal requirements related to technical standards, fire safety, urban planning
- Costs for infrastructure, maintenance, energy, and staff
- Need for additional structural reinforcement due to application of building codes
- Need for specialized environmental, water and resources management systems
- Limited availability of flat roofs

the building providing the rooftop surface directly affect the RTG implementation, including factors such as load capacity, roof construction, available roof area, and indoor space.

Additionally, the surrounding urban features play a key role in shaping the potential for RTG development. Important variables to consider include proximity to transportation networks, local population density, nearby commercial actors, and the size and global location of the city itself. Regional geography also matters, as the advantages of urban food production—without expanding land-use—can depend on factors like the distance to, transportation costs of, and availability of agricultural land outside the city. Variations between countries and even continents further influence these considerations.[16]

Studies focusing specifically on geographic dependencies in rooftop greenhouse food production projects are limited. However, a few reports on the broader concept rooftop agriculture (RA) are available. RA projects can serve as commercial food production businesses, as well as recreational and social spaces. These projects are found worldwide, with 69% located in temperate regions, and fewer RA projects in subtropical (19%) and tropical (11%) areas. Data shows that the number of RA projects at the country level is positively correlated with the Human Development Index (HDI)[33], while at the city level, the frequency of RA projects is linked to factors such as city size, population density, and overall population[8 20]. While the number of rooftop farming projects has surged in recent years, the development of supporting policies and regulations varies across countries.

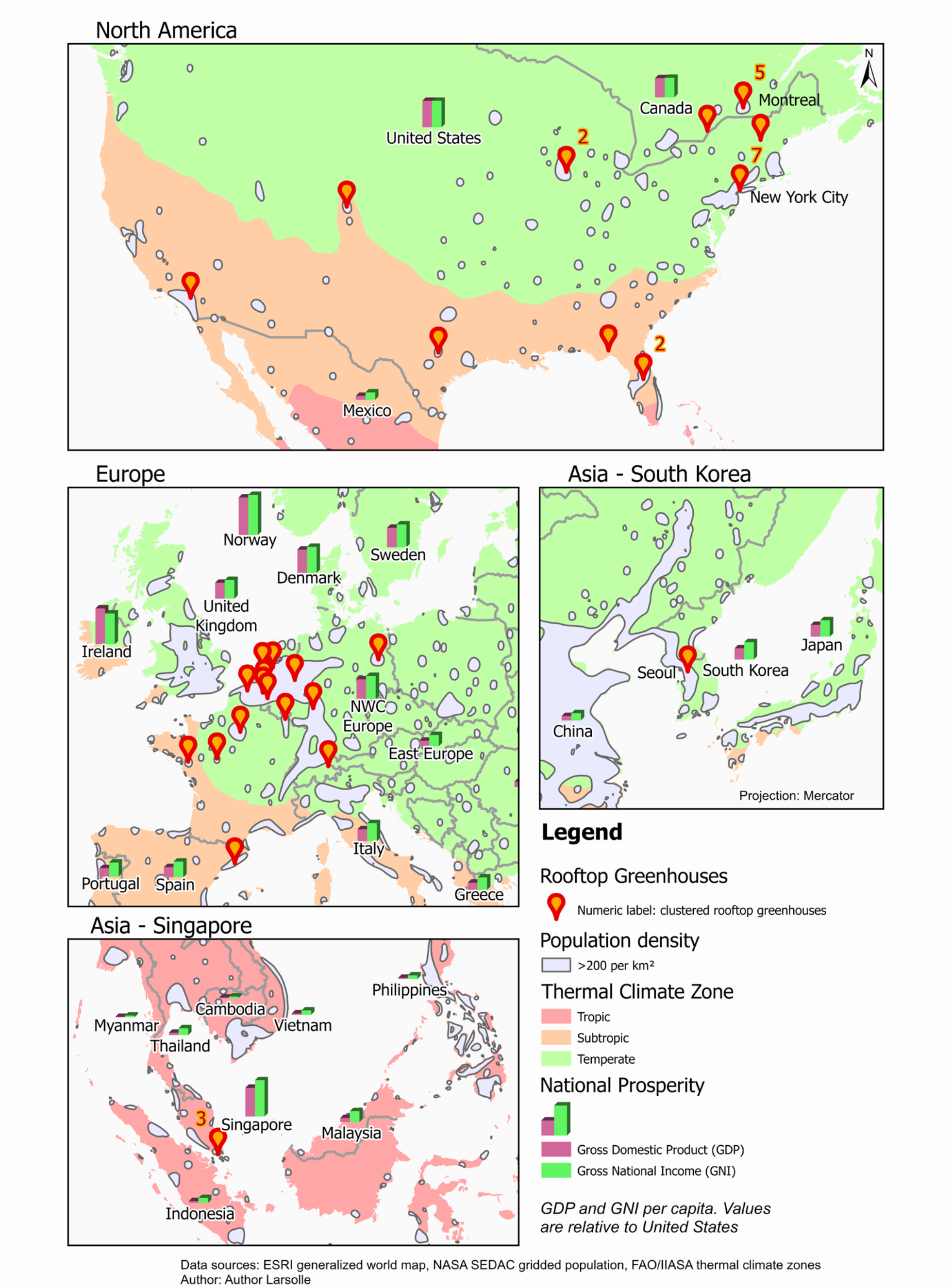

Figure 9
Geographical position of RTG projects. RTGs located in the same city are grouped under a single symbol. The number next to the symbol indicates how many projects were found in that location. Author: Anders Larsolle.

The global distribution of RTG projects differs significantly from that of the broader category of RA projects. A 2021 review[20] found that 76% of all RTGs were located in North America and Europe, accounting for 22 out of 29 total projects. The remaining RTGs were scattered across Asia, South America, Africa, and Oceania, with only 1 to 3 projects per continent. However, our own research reported further down, has identified up to around 100 projects located mostly in Northern Europe and the North American east coast.

GEOGRAPHIC POSITION OF ROOFTOP GREENHOUSES

While some studies and initiatives have reviewed existing RTGs, no global geographic visualization has been published. The Groof project[34] initiated an analysis of RTG distribution, which we have further expanded in this book. Our research identified nearly 100 RTG projects worldwide, concentrated in three main clusters: North America (Montreal, New York), Northern Europe (Belgium, the Netherlands, Germany), and Asia (South Korea, Japan) (see Figure 9). Additionally, emerging projects are beginning to appear in California, the southern United States, and Spain.

A comprehensive list of existing rooftop greenhouses (RTGs) was compiled from published sources and online platforms, including RTG businesses, architectural firms, media articles, and city tourist guides. The geographical locations of these projects were determined using publicly available address information and online mapping services. This overview includes food production RTGs that were operational as of March 2024.

Figure 9 presents a map of RTG distribution, with the number of projects indicated by a numeric label. Additionally, the map highlights areas with a population density exceeding 200 inhabitants per square kilometer (based on gridded world population data from CEISIN/NASA-SEADAC)[35] and thermal climate zones (derived from FAO/IIASA raster data, 2007).[36]

Figure 9 reveals that most RTGs are concentrated in North America and Europe, with fewer projects in Asia. A clear correlation exists between RTG presence and densely populated urban areas, particularly in larger metropolitan regions. Another key factor is national prosperity—countries with RTGs generally have higher Gross National Product (GNP) and Gross Domestic Income (GDI) compared to other countries.

Additionally, nearly all RTGs are located within the temperate climate zone, with Singapore being a notable exception. Despite its tropical climate, Singapore hosts three RTG projects, likely driven by its significantly higher GNP and income levels compared to surrounding countries.

The prevalence of RTGs in economically developed countries may be attributed to their advanced food production technologies and a higher proportion of high-end consumers. In subtropical and tropical regions, open-air rooftop farming is more common, as the warm climate reduces the need for controlled greenhouse environments.

In developing countries, urban food production is often driven by different factors, such as limited access to agricultural land and the need for affordable food. Here, crops are frequently grown on available urban surfaces for self-sufficiency or small-scale commercial purposes.

BUSINESS MODELS AND INNOVATION IN ROOFTOP GREENHOUSE PROJECTS

BUSINESS MODELS

In the Global North, particularly in North America and Europe, several well-established commercial soilless RTG firms operate in urban areas. The growing number of these businesses suggests that RTGs are becoming an integral part of the urban food system, with strong consumer and stakeholder demand for their produce.

For RTG firms to succeed, remain cost-effective, and deliver value, their business models play a crucial role. Analyzing existing RTG companies reveals a wide variety of business models, each adapted to local market conditions and policies. To illustrate different approaches, three case examples are discussed below:

- Case 1: Integrating an RTG with a supermarket
- Case 2: Selling RTG produce via an online marketplace
- Case 3: Partnering with local restaurants

Case 1 illustrates the integration of a RTG with a supermarket, exemplified by the recently opened REWE store in Wiesbaden-Erbenheim, Germany, see Figure 10. From the initial planning stages, the greenhouse was designed as an integral part of the building, aligning with the retailer's sustainability strategy. The rooftop farm, managed by ECF Farmsystems in partnership with REWE, primarily cultivates leafy greens and, later, fish. The produce is sold directly in the supermarket, supporting a vision of a more sustainable food system. This concept emphasizes self-sufficiency, circular water use, local production, freshness, and reduced plastic packaging. Additionally, the cultivation method, based on aquaponics, eliminates the need for pesticides and synthetic fertilizers.

Case 2 is exemplified by Lufa Farms, a leading Canadian RTG company. Lufa Farms designs, builds, and fi-

Figure 10
RTG on REWE Supermarket, Wiesbaden-Erbenheim, Germany. Source: Wikipedia CCO 1.0.

nances its own RTGs, primarily on existing urban buildings, with recent expansions integrating greenhouses into new constructions, see Figure 11. The company's goal is to position RTGs close to consumers, aligning with sustainability principles such as fresh, local, and responsible food production.

Beyond cultivating RTG vegetables, Lufa Farms has developed an online marketplace and logistics platform. This e-commerce system allows customers to purchase both Lufa's produce and goods from other local producers, offering a wide range of food categories. Customers can either pick up their orders from designated locations or opt for convivial home delivery. Lufa Farms exemplifies a business model where the RTG is integrated into a broader food distribution and packaging system. More recently, the company has also expanded into indoor farming to complement its RTG operations.

Case 3 highlights a collaboration between a RTG and a restaurant as host building, see Figure 12. This RTG, operated by JFS Altius Farms, is in Denver's Sustainability Park—a mixed-use development integrating housing, urban farming, and commercial spaces. JFS Altius Farms cultivates vegetables using an aeroponic system, producing lettuce, herbs, and edible flowers. The company serves a diverse customer base, supplying local restaurants (including the high-end restaurant within the building), food services, citywide markets, and nearby residents.

Private customers can purchase produce through a 'Community Supported Agriculture (CSA)' program, which offers subscription-based deliveries at regular intervals. Additionally, surplus produce not sold to restaurants or CSA members is made available through pop-up sales. During warmer months, the farm supplements its RTG production with vegetables grown in an adjacent outdoor space. Beyond food production, the company also rents out this gated garden for private dinners, social events, and meetings, further integrating urban agriculture into the community.

In this case, the firm emphasizes values such as hyperlocal sustainable farming, reduced water use, year-round production, non-GMO crops, and CEA. It also highlights key qualities like consistency, pesticide-free cultivation, health benefits, high quality, freshness, and superior taste. Additionally, the company promotes its contribution to the local community by creating job opportunities and making efficient use of land. By requiring less space, the RTG model enables food production in urban areas, supporting a more sustainable and localized food system.

These three cases demonstrate the diverse ways in which commercial RTG business models can be structured to attract customers, deliver val-

Figure 11
Lufa Farms in Ahuntsic-Cartiervill, Quebec, Canada. Courtesy of Fermes Lufa, Montreal, Canada.

Figure 12
Japanese restaurant UCHI in Denver, Colorado. Source : Tres birds workshop. Photograph James Forio.

ue, and achieve profitability. To further explore the development of an RTG business model, various tools are available. One widely used framework is the Business Model Canvas (BMC), by Osterwalder & Pigneur (2010), which helps structure and analyze different strategic paths and the necessary resources. The BMC provides entrepreneurs and stakeholders with an accessible way to map out key elements, including customer segments, customer relationships, value propositions, channels (distribution/sales), key resources, key activities, key partners, revenue streams, and cost structure.

Growing vegetables in a hydroponic system is significantly more productive than traditional soil-based cultivation.[37] However, the initial costs of these technology-driven systems are higher, particularly due to the construction of the greenhouse structure.[34] Empirical data on costs is limited, making precise calculations difficult, but installation costs are typically around 1,000 euros per square meter[20] compared to 300-500 euros per square meter for a conventional ground-level greenhouse. Once established, the economic viability of hydroponic systems largely depends on yield, market prices, and local conditions. Additionally, reductions in transportation and packaging costs have been identified as key factors that contribute to economic profitability.[32]

Conventional greenhouse production is typically located outside cities and depends on transportation to reach retailers, distribution centers, and consumers. In contrast, RTG systems, situated on rooftops in retail or residential areas, have shorter distribution chains, which can reduce costs. Recent studies suggest that once operational, RTGs may lower consumer prices compared to conventional greenhouses.[32 38]

Roof space can be used for multiple

purposes, leading to competition between RTGs and alternative uses, such as energy generation. When comparing these systems, considering factors like ownership, community benefits, financial returns, and local job creation, RTGs were found to offer more advantages than energy generation.[39] Additionally, RTGs can provide increased revenue for the host building owner by leasing roof space for other activities (meetings, education, and more).

RTGs differ not only from traditional green roofs but also from most open-air farms, as their primary goal is commercial viability. To ensure sustainability while remaining financially feasible, the commercial model must be strategically developed and integrated from the start. This requires moving beyond solely providing services for the common good and instead focusing on marketable and profitable concepts. These may include food production as well as additional services such as social events and educational activities. The importance of this multifunctional approach was recently highlighted by Appolloni and colleagues (2021)[20] who consider it a key advantage of RTGs over purely commercial farming enterprises.

PRODUCE AND MARKET

Rooftop greenhouses are ideal for urban locations, particularly near retailers, restaurants, and residential areas. By supporting short value chains and urban food systems, RTGs offer several benefits, such as reducing transportation and creating local job opportunities. Additionally, placing production closer to where people live, or work enhances communication between growers and consumers. Currently, many consumers are unaware of how food is produced, which is seen as a problem. Increased interaction and communication raises awareness about food production, aligns production with demand, and sparks greater interest in the food sector. This, in turn, may elevate the value placed on food.

> Rooftop greenhouses allow cultivating delicate and unique varieties addressing qualities linked to taste and appearance or varieties unsuitable for long-distance transportation, increasing the competitivity of RTG produce.

The food system, compared to other sectors, lags in innovation and product development and struggles to attract young people into the industry. Given the multifunctionality of RTGs, these systems have the potential to inspire young entrepreneurs and increase interest in food production.

Currently, soilless RTG firms primarily grow herbs, leafy greens, and tomatoes[20]—like conventional greenhouses. However, RTGs offer greater flexibility to tailor their crop selection to local demand. They can also cultivate delicate and unique varieties addressing qualities linked to taste and appearance or varieties unsuitable for long-distance transportation. RTGs can thus provide produce not typically available through conventional agriculture, which can increase their competitivity. Additionally, RTGs can support the production of medicinal plants, berries, edible flowers, cut flowers, mushrooms, and ornamental plants, further expanding their market potential.

Beyond their diverse production potential, RTGs contribute to sustainable food systems by growing vegetables, one of the most climate-friendly food categories.[40] [41] As environmental and health considerations continue to shape consumer preferences, demand for RTG-produced goods is expected to rise.

Although consumers are often hesitant about technology in food production,[42] hydroponics enjoy high acceptance.[43] However, awareness remains low—according to a recent Swedish study,[44] only 48% of respondents were familiar with hydroponics. This highlights the need for better communication, especially given that nearly all greenhouse-grown vegetables sold in European supermarkets are already produced using this method.

ROOFTOP GREENHOUSE ARCHITECTURE

Throughout history, humans have tried to outplay nature's cycles by cultivating plants in controlled environments, a practice apparently dating back to the Romans.[45] The Romans are said to have created simple greenhouses from skins mounted in wooden frames. In Europe, the first 'orangeries' were built in medieval times, and later developed as the first commercial greenhouses. From around 1900, the greenhouse industry has expanded all over the world and been extremely successful in this endeavor.

Greenhouses have completely altered our diet, from meat, cabbage, root vegetables and preserved vegetables, to including fresh vegetables year round, even in colder countries. With the introduction of greenhouse production, crops such as tomato and cucumber, once reserved for the nobility, have become staple food even for low- or medium income families.

In the Nordic countries, an outstanding early example of large greenhouse is the Palm House (Figure 13), at the Natural History Museum of Denmark in Copenhagen, built by Carlsberg Breweries in 1874. Designed in the Victorian style, this greenhouse was inspired by the Crystal Palace, an iron-and-glass structure erected in London in 1851 to house the World's Fair.

During the Industrial Revolution, advancements in float glass technology and cast-iron structures made greenhouses more accessible to the growing middle class, particularly in England. One of the most magnificent greenhouses from this era is the

Figure 13
Palm House, Natural History Museum in Copenhagen, Denmark. Photo: Marie-Claude Dubois.

Palm House at Kew Gardens outside London. From this point in time, the availability of cheaper glass technology made it possible for smaller, self-assembled greenhouses to appear in the gardens of middle-class homes.

Greenhouses cover today a substantial land area, where the largest concentration (roughly 30 000 ha) can be found in Almeria, Spain,[46] see Figure 14. The Food and Agriculture Organization (FAO) estimates that there are 405 000 hectares of glass and plastic covered greenhouses in the EU.[47] Other data from Eurostat reports that 135 000 hectares of glass covered greenhouse cultivation takes place in the EU, which includes vegetables, flowers and permanent crops under glass from EU-27 in the period 2007-2013.[48] In the last two decades, the construction technology and agricultural production in advanced greenhouses has made significant progress, involving modifications in the design, materials, and cultivation techniques.[51]

We may speculate that the simple idea to place greenhouses on top of buildings started with the New York City-based Arthur Ross Greenhouse located on the rooftop of Milbank Hall at Barnard College, New York City, see Figure 15 (top). The College's first greenhouse was built on the rooftop

Figure 14
Greenhouses in Almeria region, Spain. Source : NASA. Wikipedia (2025), Creative Commons.[113]

site as a research facility around 1912-1913. The idea to utilise roof spaces for more valuable activities than just air-conditioning or technical facilities is not an entirely new idea. Le Corbusier conceived flat roofs as a fundamental component of the modern city where the roofs could be seen as the fifth façade of the building; a surface that should not be neglected but instead used for social interaction, experiences and connection to the sky above.[49]

Today, RTGs can be crafted from a diverse array of materials, modules, shapes, and sizes, showcasing their versatility and adaptability within urban environments. Examples of smaller-sized double-sloped rooftop greenhouses have been found atop existing residential buildings such as in the case of Symbiose, Nantes (Figure 16, bottom). Meanwhile, large-scale RTGs, situated on single-floor warehouses, showcase a repetitive modular greenhouse structure covering large surfaces (> 10 000 m^2), such as in the Lufa Farms in Laval near Montreal, Quebec, Canada (Figure 15, bottom). Other examples combine modularity above smaller scale buildings or simpler structures made from plastic materials.

SHAPE AND ROOF SLOPE

In general, RTGs have a square or rectangular plan adapted to the shape of the host building's roof. Examples of dome-shaped RTGs have also been

Figure 15
Arthur Ross Greenhouse, Milbank Hall, Barnard College, New York City, CC BY-SA 4.0, photo Barnardgreenhouse (top); Lufa Farms, Laval, Quebec, Canada, Courtesy of Lufa Farms (photo Fadi Hage, bottom).

Figure 16
Oberhausen job centre. Photo: Sara Spendrup (top); Symbiose, Nantes, France. Photo: Valery Joncheray (bottom).

Figure 17
RTG as a dome structure at MKB Greenhouse, Malmö, Sweden. Photo: Marie-Claude Dubois.

Figure 18
Standard greenhouses in the Westland region, The Netherlands. Source: Wikipedia, CC by 2.0.

found, as shown in Figure 17. It is optimal if the greenhouse completely covers the roof surface to maximize the heat exchange between the greenhouse and host building. RTGs often come in modular systems, like prefabricated ground-based greenhouses, with a series of glazed gable roofs with ridges and creases at regular intervals. In Central Europe, the prevailing structure is the Venlo type, which has a 22° symmetrical roof slope,[50] see Figure 18.

The roof slope has an impact on light transmission. One study investigated the impact of roof slope on light transmission by computer simulations for greenhouses located at latitudes 25°N, 37°N and 45°N. Greenhouses with a 10° slope had the poorest light transmission (67%) at the winter solstice and latitude 25°N, while the one with a 40° slope had the highest light transmission (77%). Differences were small for slopes of 20° or higher. At higher latitudes, the 30° roof slope returned 73% light transmission for latitude 37°N and 68% for latitude 45°N. In general, a 30° roof slope is suggested as an acceptable trade-off between light transmission and construction costs, and it is a recommended slope when plastic is used as cover material in urban greenhouses.[56]

ORIENTATION

Studies conducted on conventional greenhouses show that east to west orientation (E-W) of the greenhouse (long axis) is preferable over north to south orientation (N-S). A Dutch study[51] reported 45% daily light transmission for E-W orientation of a typical Venlo greenhouse versus 35% for a N-S orientation at the winter solstice. Another study conducted in Mediterranean conditions (lat. 37°N) also indicated that the E-W orientation provided up to 15% increase in light transmission at the winter solstice (30° roof slope). As the roof slope decreases, the effect of orientation also decreases, and for 10° roof slopes, the effect of orientation on light transmission is negligible.

What happens is that shadows produced by N-S parts move along the day while shadows from E-W parts remain in almost the same position all day long. Therefore, structural parts should be avoided and if possible, the broader structural elements should follow the N-S orientation, which provides more uniform light conditions in the greenhouse.

BUILDING ENVELOPE

TRANSPARENT AND TRANSLUCENT PARTS

Greenhouses must maximize the transmission of natural light, which can be more challenging for RTGs as they must comply with stricter building regulations often resulting in more structural elements against wind, earthquakes, etc. RTGs also sometimes have a denser urban context all around, which requires a careful analysis of shading from adjacent

Figure 19
Fermes de Gally, Saint-Denis, France, showing a mix of polycarbonate (walls) and ETFE (roof). Photo: courtesy of Fermes de Gally.

buildings. Additionally, RTGs can be shaded by air conditioning equipment from the host building (ducts and pipes), which can significantly reduce the light transmission to the crops.[56]

TRANSPARENT MATERIAL

The most common cladding materials used in RTGs for walls and roofs are:

- Rigid plastic made of polycarbonate (PC),
- ETFE (Ethylene tetrafluoroethylene),
- Polyethylene film,
- Fiberglass,
- Glass panes (single and double).

Some projects use a combination of materials for the transparent parts. For example, the RTG of Fermes de Gally in Saint-Denis, France, has polycarbonate walls with roof cover of double-skin inflated ETFE, see Figure 19. The advantage of ETFE is the high transmissivity, especially in the ultraviolet (UV) range, which is beneficial for the plants. ETFE lets full spectrum light into the growing area, which increases crop yield and speed of growth, while improving qualities of the produce such as taste, plant health and vigour. Unlike other plastic materials, ETFE is a very specialised fluoropolymer, which is incredibly strong. It does not degrade over time from exposure to UV radiation. ETFE is also recyclable and potentially reusable; it can be melted down and turned into new fluoropolymer products including film.

The transparent materials need to have optimal optical properties to maximize daylighting and optimize crop yields, while minimizing energy use for heating the greenhouse. In addition, stricter building regulations (compared to rural ones) also translate into higher requirements related to fire safety. In greenhouses with a risk for shocks or falls, the transparent layer must also be tempered to prevent accidents. The optimum properties of transparent materials for RTGs are summarized in the box below.

Regarding far infrared radiation (FIR), it is necessary to have a high reflection of FIR from the greenhouse covering material towards the interior to avoid large heat losses at night. This property is compulsory in unheated greenhouses to avoid large drops in nighttime temperatures. In the summer, the greenhouse must also be protected against high solar heat gains, which involves installing shading curtains with high reflectivity. Recent examples in north Europe within the Groof project show the use of double pane glass to conserve heat during night time, see Figure 20.

SOLAR SHADING

Rooftop agriculture is a great means to fight climate change in densely built environments, since it protects the roof from direct solar radiation. It shields roofs from the scorching sun, especially when we plant crops or create green roofs outdoors. These green layers not only soak up sunlight but also cool the building below by releasing moisture into the air. This is

Optimum properties of transparent materials for RTGs

- Minimum absorption and reflection of the solar spectrum
- Maximum transmission of photosynthetically active radiation (PAR)
- Colour should not be affected by light transmission
- Materials must be resistant to Ultraviolet (UV) radiation to avoid degradation (yellowing)
- Maximum reflection of far infrared (FIR) radiation, which helps maintain a higher indoor temperature in the RTG at night but can be difficult to obtain with commercial transparent materials
- Minimum transmission of FIR, which limits heat penetration in the summer
- High diffusion (haze), but it should not reduce PAR transmission in the solar spectrum. Most plastics have a haze factor larger 30%

also true with green roofing and outdoor rooftop agriculture, where the combined crop and soil layer contributes to solar reflection, absorption and temperature reduction through evapotranspiration by crops, thereby minimising the accumulation of heat in the roof materials and structure.

However, in RTGs and rooftop gardens, there are no trees or bushes to provide shade, so we must be extra careful about how much sunlight we let in. It is all about finding the right balance between sunlight exposure and shading to keep plants in optimal conditions for growing without overheating. Solar shading is a critical element of RTG design.

Movable screening is a natural part of all modern greenhouses. The screening system in a greenhouse serves several purposes, namely:

- Shading to reduce the solar heat load,
- Reduction of heat losses (mostly at night),
- Prevention of light pollution,
- Conservation of humidity,
- Control of the photoperiod in the greenhouse.

Different types of screens are avail-

Figure 20
IFSB, FRESH, Luxembourg. Photo: courtesy of IFSB (Romain Guillaud).

able that will serve one or several of the mentioned functions. Two or three screens are commonly installed to optimally address these different functions. Screens primarily designed to reduce energy losses during day- and night-time and to conserve humidity are made of 100% polyethylene and have a light transmission of around 75-90%.[52] Screens for the primary purpose of reducing solar heat gains are made of polyester and polyolefin with strips of aluminum woven into the material. They can have a closed or open structure enabling humidity and air to pass through. The latter will also be of use for reducing heat loss during night-time, with a reduction of heating energy by up to 40% reported in some study.[53] These types of screens will typically have a light transmission of 20-50%.[58] Screens designed to prevent light pollution, and for photoperiodic control ('blackout screens'), are made of polyolefin and polyester and have a light transmission of 0%.[58]

Shading screens should be dynamic or movable to adjust to the specific conditions required at different times and seasons. While reducing solar energy transmission into the greenhouse by shading improves thermal and hygrometric conditions, it can also result in a significant reduction in incident radiation on the crops, which in turn leads to a loss of photosynthetic assimilation and consequently, less production. Therefore, the screens must be movable.

Some screens can have the dual function of reducing solar radiation during the day and reducing radiative heat losses to the sky at night, which also prevents thermal inversion. On clear nights, when a large amount of radiant heat is sent back to the sky, the greenhouse air can be cooler than required and there is a risk of dew forming and dripping over the crops. One study showed that an aluminized screen placed inside the greenhouse at gutter height provided the greatest temperature increase at night.[54] This study in single pane, soil-based greenhouse led to the conclusion that external or internal screens can help to increase the sustainability of greenhouse production in areas with mild climates by enhancing the use of solar energy stored in the greenhouse soil during the day and released at night.

STRUCTURAL CONSIDERATIONS OF ROOFTOP GREENHOUSE PROJECTS

STRUCTURE OF THE HOST BUILDING

Making sure a building can handle the weight of a greenhouse on its rooftop is crucial to keep everyone safe and protect the building itself. But not every rooftop is up to the task—some need upgrades or reinforcements to handle the added weight. Guidelines usually detail what the host building needs: like how steep the roof should be and how much weight it can bear. These technical specifications are vital for ensuring the safety and stability of the whole system.

The minimum load capacity for RTG is in the range 150-200 kg/m^2 depending on the type of culture[55] and a roof slope no greater than 10% is required.[56] This implies that buildings with a concrete or composite (steel and concrete) structure are more appropriate for the implementation of RTGs. The load calculated in the IFSB (Institut de formation sectorielle du bâtiment) in Luxembourg (Figure 20) was 500 kg/m^2 but this was an extreme case,[57] while it was less than 250 kg/m^2 in the EBF (Energy, Biosphere, Food) RTG in Bürstadt, Germany.[63] On the other hand, soil-based projects would add an extra load of 800-900 kg/m^2, which is why cultivation in soil is seldom considered in RTG projects. Note that the weight from hydroponic systems is relatively small i.e., 40-50 kg/m^2.

Like green roofs or other types of rooftop technologies, load calculations should include:[58]

- dead loads (weight of greenhouse structure and cladding),
- live loads (weight of people, plants, hydroponic or other system, etc.),
- transient live loads (not a permanent part of the structure or of permanently in-place load),
- snow and rain loads,
- wind loads, and
- seismic loads.

The US National Greenhouse Manufacturers Association (NGMA) refers to collateral loads (irrigation equipment, including water, mechanical equipment, permanently mounted service equipment like heaters, fans, water lines, etc.) instead of live loads.

For snow loads, the NGMA provides detailed calculations differentiating between a continuously heated, intermittently heated or unheated greenhouse.[59] The calculation entails a thermal factor, which varies between 0.85-1.2, where the lower bound is for continuously heated greenhouses. The snow load is linearly dependent on this thermal factor, meaning that the snow load requirement will be less in the case of a continuously heated greenhouse since snow is melting in this case. Moreover, an increased greenhouse roof slope and the avoidance of snow accumulations may lower the snow loads.

When greenhouses are located on roofs, wind speeds are generally higher due to the higher vertical elevation of the greenhouse with respect to the ground. It is well known that the wind profile follows a logarithmic function depending on terrain roughness, with a rapidly increasing wind speed from the ground and stabilization after a certain height. Further, the greenhouse changes the aerodynamic shape and may cause uplifting wind forces. Thus, due consideration of wind loads, their load path to the foundation and a solid anchoring are required. Otherwise, rooftop greenhouses could be a risk for pedestrians and surrounding buildings.

The additional loads and change of use require a structural assessment carried out by qualified engineers subjected to structural codes and standards in the respective countries. The structural assessment can be performed with semi-probabilistic assessment procedures or on the basis of structural reliability. In both cases, structural testing procedures can be used to activate passive safety to be able to fulfil the design and reliability checks. In case these checks do not work, strengthening and structural modification should be considered.

STRUCTURE OF ROOFTOP GREENHOUSES

Greenhouse structures should be designed according to international and national building regulations. Rooftop greenhouses normally have more structural elements than conventional ground-based greenhouses to comply with building construction codes, which are generally stricter than agricultural codes.[56] It is important to try to minimize the size of structural elements as much as possible as these increase shading, which is detrimental for crop growth. The most common structural materials used for RTG is galvanised steel although examples with wood structures have been found.

REFURBISHMENT: GREEN ROOFS VERSUS ROOFTOP GREENHOUSES

Retrofitting existing structures for installation of a green roof is a possibility and since green roofs are normally heavier than RTGs, we can deduce that it is also possible to retrofit the structure of the host building to accommodate an RTG. Basic structural strengthening techniques can be used. As for green roofs, one item to note is that a transient live load must be considered as part of the structural engineering load combinations.[64] Additional planning regarding drainage and fire safety considerations are needed. Relocation of the rooftop's mechanical equipment is also often advisable when possible.

ACCESS AND SUPPORT FUNCTIONS

Most RTGs will require staircases and a large elevator to transport crops and equipment vertically, along with additional storage and handling space beneath the RTG for packaging and logistics. The size of this area depends on the business model, thus the importance of defining the business model at the early design phase. For instance, a CSA-focused RTG would need a large packaging room, while one supplying a restaurant or supermarket directly below could minimize packaging space.

ENERGY AND SYSTEMS

ENERGY FOR HVAC SYSTEMS

When compared to energy use in open-air cultivation, greenhouse production is considered as one of the most energy-intensive sectors of agriculture production.[51 60] In the EU, greenhouse production includes both advanced, energy-intensive structures with indoor climate regulation, as well as simpler structures looking more like open-air systems. The great variation found in data on greenhouse energy use depends on several factors including climatic and socio-economic conditions.

The most energy-intensive systems (i.e., around 15 000 GJ/ha or 420 kWh/m^2)[51] are primarily found in northern Europe. In these regions, greenhouses normally involve highly controlled indoor climate, where operation energy is primarily for heating and cooling processes. In south Europe, low energy systems are dominant and normally involve a mix of energy end-uses: heating, cooling, irrigation, lighting, fertilizers, and pesticides. Greenhouses also exhibit great variations in size from large-scale, commercial systems to small-scale subsistence systems, which also influences their design, structure, energy systems, and energy sources.

A large proportion of greenhouses in south Europe are not heated, while in temperate and cold climates, greenhouses normally have a high heating demand, which is the main energy end-use. A variety of systems and energy sources are used for heating greenhouses, including electric air heaters, central heating through pipes, boilers, cogeneration, natural gas heaters, heat pumps, etc.[51] Cooling, is achieved through a variety of systems and solutions, such as shading, white-washing, natural or mechanical ventilation, evaporative cooling, etc. Cooling often involves one or a combination of these passive and active systems in areas with high temperatures throughout a large part of the year.

Indirect energy use of greenhouses, which is much less documented, will also certainly be considered in the future as societies are moving towards climate neutrality in buildings and infrastructures. This indirect energy use normally refers to embodied energy and their related GHG emissions for constructing the greenhouse as in the production, transportation, assembly, and even dismantlement of building materials. This calculation may even include energy-related impacts of greenhouse machinery, and energy needed for producing the fertilizers and pesticides.[51]

Several studies[30 61 62 63 64 65 66 67 68] show that RTGs provide significant benefits compared to conventional ground-based greenhouses, particularly when considering operational energy use of

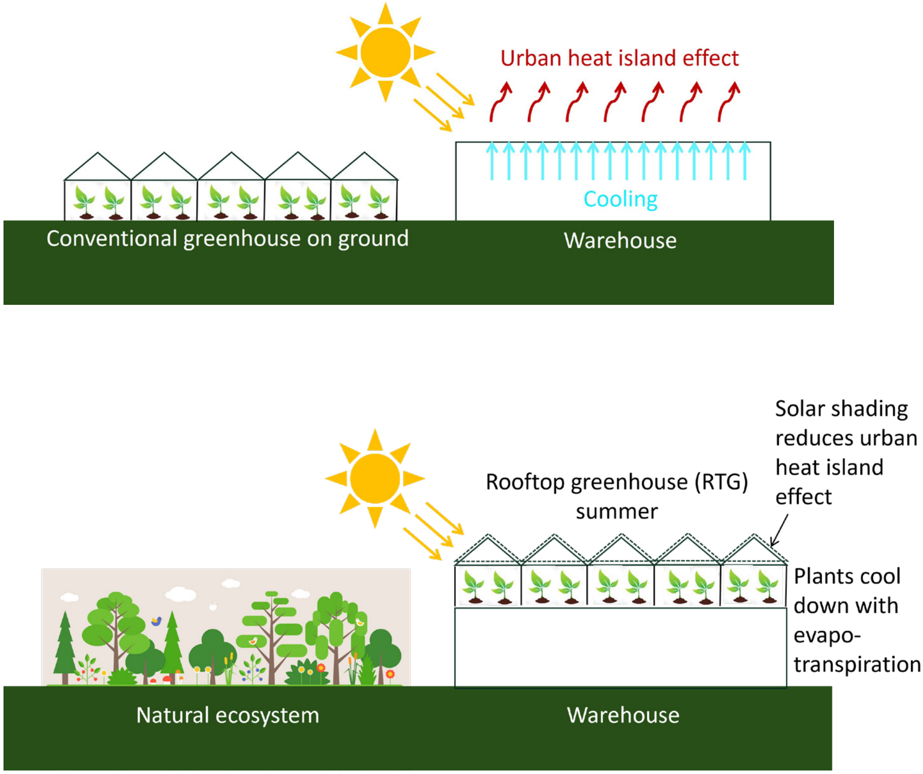

Figure 21
Energy symbiosis of host building and RTG during the cooling season.

both greenhouse and host building. This occurs first by reducing the exposure of the host building's roof surface to solar radiation in the warm season. The roof temperatures and internal air temperatures of the greenhouse are decreased through shading and evapotranspiration of crops, which also reduces the host building's cooling demand. One condition for this to occur is that the RTG is well ventilated so that any overheating is directly released to the outdoor air (Figure 21).

In the cold season (when heating is needed), the greenhouse effect produced by the RTG brings reductions in the heating demand of the host building. The RTG then performs like a Trombe wall[1] and heat buffer, reducing heat losses through the host building's roof, which can be quite important (Figure 22). Reductions of heating demand of 14-23% compared a stand-alone warehouse host building have been re-

1 A Trombe wall is a passive solar design technique that utilizes indirect-gain principles. It works by allowing sunlight to hit a solar collection surface that is in contact with a thermal mass. The thermal mass absorbs the sunlight, converts it into heat, and gradually releases the warmth into the living space.

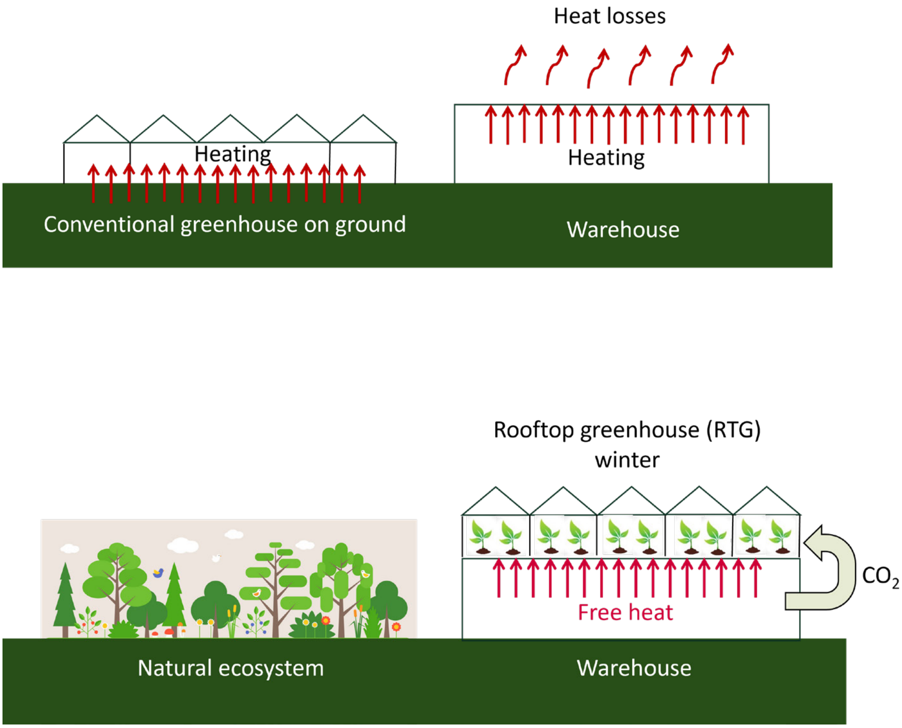

Figure 22
Energy symbiosis of host building and RTG during the heating season.

ported in a Swedish study.[30] Another study conducted in Barcelona showed that the RTG's surplus heat saved up to 79% of the heating requirements of the single-story host building.[69]

More recently, South Korean researchers have shown through measurements and simulations that the heating demand of the host building and RTG can be reduced by 18-25% and 0.7-6.3% respectively.[70]

The heating demand of the RTG is also significantly reduced compared to that of a ground-based greenhouse, since the RTG uses the low-grade heat losses from the host building as a heat source (Figure 22). This heat source is especially important if the host building is poorly insulated. It could cover up to 50% of the heating demand of the greenhouse, according to the owners of Lufa farms in Montreal.[71] However, the Swedish study conducted on a relatively well insulated host building showed that the reduction in heating for the RTG was only 3-15% (depending on glazing assemblies) compared to a similar ground-based greenhouse.[30]

In the warm season (when cooling is needed), the RTG benefits from standing on the host building as this provides higher natural ventilation rates compared to a ground-based greenhouse, see section on natural ventilation. The RTG also benefits from standing on a concrete floor (compared to soil), which is more efficient to store solar energy during the day and release it at night. The specific heat capacity and thermal conductivity of concrete is higher than that of soil, which makes concrete a better material than soil to regulate indoor temperatures.

The indoor climate of a RTG and an on-soil greenhouse were compared in a Spanish study[60], which showed that the concrete floor surface temperature at night was typically up to 6°C higher than the greenhouse temperature at the beginning of the night and around 4°C higher at sunrise. Heat transfer calculations indicated that the heat released from the concrete floor to the RTG air was on average around 30 W/m^2, while in commercial on-soil unheated greenhouses, this heat transfer has been reported to be around 20 W/m^2.[60] The authors thus concluded that the concrete floor is a more efficient thermal storage material than most soils.

Apart from operation energy, other benefits of connecting RTG with host building include water conservation and CO_2 harvesting.[56] The last years have seen the emergence of so-called integrated rooftop greenhouses or IRTG, which means that, besides conduction processes, the RTG is also partly heated by CO_2 filled exhaust air coming from the host building. This provides the additional benefit of enhancing plant growth.

The greenhouse can also potentially be used as the host building's air purification and oxygenation system, but further studies about allergens and air quality need to be conducted to ensure that this does not jeopardize the health of the host building's occupants. Moreover, precautions must be taken regarding crop sanitation, pest, and disease management to prevent the dispersion of harmful substances in the host building.

In summary, recent developments in RTG technology such as IRTG promise to deliver higher energy savings, while providing other benefits such as enhanced photosynthesis by CO_2 enrichment. More recently, more advanced control systems used in so-called intelligent rooftop greenhouses (iRTGs) can also enable temperature mitigation for the RTG and host building.[72 73 74]

NATURAL VENTILATION

Natural ventilation is the most cost-effective and passive method for ventilating a greenhouse, which is driven by pressure differences generated by wind (cross-ventilation) or temperature differences (stack or chimney effect), expelling excess heat. Ventilation openings are typically located on the roof, with additional openings sometimes in the side walls. The airflow is regulated by adjusting the opening angles, a process that is usually automated for efficiency. Research shows that wind driven ventilation prevails over thermally driven ventilation, even when the wind speed is as low as 2 m/s.[75] With wind driven ventilation, air changes depend on the ventilator's opening size, and it is directly proportional to outside wind speed.

Wind directions perpendicular to roof vent openings provide the highest ventilation rate. The orientation of the greenhouse (W-E/S-N) influences the ventilation rate, which is another element to consider at the design stage. Air streams directly on the crops should be avoided as this would not only damage them, but it could also increase needs for irrigation.

A combination of sidewall and roof ventilation is the most effective ventilation strategy. The architect or planner should also consider that the roof slope influences the air change rate, where a minimum roof slope of 25-30° is recommended for adequate ventilation.[56] Additionally, the greenhouse depth affects ventilation efficiency. A maximum depth of 50 m is recommended to prevent warm spots in the middle of the greenhouse.[56]

The different wind speeds of RTGs compared to on-ground greenhouses imply that RTGs present a higher potential for wind-driven ventilation as air change rate indoors is directly proportional to exterior wind speed. In large cities with roughness length of 1.6 m, the wind speed at 10 m height is 5 m/s, while it is 8 m/s at 30 m, and 9.5 m/s at 50 m above ground.[56]

A Swedish study[30] performed by computer simulations showed that installing the greenhouse on the building roof contributed to increased natural ventilation compared to the ground-based greenhouse, which resulted in lower temperatures and cooling demand for both RTG and host building. One consequence of this is that RTGs may need smaller ventilation openings than ground-based greenhouses to achieve a similar air exchange rate.

However, greenhouse ventilation can also increase the risk of introducing plant-damaging pests, harmful microorganisms, and outdoor air pollutants into the production area. Additionally, pollinating insects and biocontrol agents used within the greenhouse may inadvertently escape into the surrounding environment.

Clearly, rooftop greenhouse production is vulnerable to risks of plant damage from pests and pathogens. Innovations in indoor farming systems introduce new considerations for plant protection.[76] The extensive knowledge gained from traditional greenhouse production provides a strong foundation for developing current and future strategies and technologies that enable efficient and sustainable plant protection in rooftop greenhouses.

The entry of airborne pests and pathogens, as well as the escape of beneficial organisms, through the ventilation system can be minimized by using physical barriers such as netting or filters, which obviously slow down the airflow. Various types of plastic screens and fabrics are available, differing in thread thickness and mesh density.[77] Generally, smaller mesh sizes provide better protection against small pests but can reduce ventilation capacity.

Forced ventilation, or creating overpressure by pushing air into the greenhouse, has been found to reduce the entry of certain pests and help alleviate heat stress on crops.[78] However, active ventilation requires energy and additional investment. Hybrid systems that combine passive and active ventilation offer a balanced solution for cooling the greenhouse on hot days.[79] Shading cloths or reflective screens can further reduce heat buildup from solar radiation. Ideally, these installations should be designed to avoid obstructing airflow or ventilation.

Climate control systems are essential for greenhouses, particularly in managing high exterior temperatures and solar radiation. Effective greenhouse ventilation is critical to promote healthy plant growth. For RTGs, proper ventilation is even more crucial, as these structures are typically integrated with the host building, and elevated greenhouse temperatures can lead to increased cooling demands for both the greenhouse and host building.

Managing temperature and humidity is vital to optimize plant growth conditions while preventing the development of diseases, such as fungal pathogens. Additionally, it is important to ensure that the indoor climate is comfortable for employees, supporting a productive and safe working environment.

HUMIDITY

In conventional ground-based greenhouses, the soil is often an important source of humidity. One potential problem of RTGs is the low relative humidity, which is a consequence of higher ventilation rates on the roof, the soilless cultivation techniques used, and the concrete floor.[80] Urban air may also be drier compared to air in rural areas, where vegetation and surface water are sources of water vapour. The relatively low humidity of RTGs can be associated with problems regarding pollination, fruit development, and plant growth, while leading to higher water consumption.[56]

Therefore, having humidity sources within the RTG and an appropriate irrigation system are two important aspects to consider. Note that some ground-based greenhouses also use plastic or similar cover on the ground so the difference in humidity might not be as large as reported in previous studies. The transpiration from the plants is a more important factor driving the humidity levels. Modern greenhouses are often equipped with a misting system to maintain humidity. Also, thermal management using shading systems helps to minimize humidity losses through ventilation.

ILLUMINATION FROM NATURAL LIGHT

A minimum solar irradiation of 1900-2000 MJ/m² (528–556 kWh/m²) per year or 13–14 MJ/m² (3.6–3.9 kWh/m²) per day[62] is required for productive greenhouse cultivation. For RTG projects, it is thus imperative to verify at the early design phase that shading by adjacent buildings or by the greenhouse structural elements do not interfere with crop cultivation. A high transmission of covering materials and avoidance of ventilation ducts or thick structural elements are two key aspects to consider in the design.

As mentioned earlier, RTGs contain more structural elements than conventional ground-based greenhouses due to stricter building compared to agriculture regulations. They can also be shaded by neighbouring buildings or the host building's air conditioning or plumbing system (ducts, etc.), which may lead to a substantial illumination loss. For example, in the ICTA-RTG,[56] the substantial drop in light transmission was due to the RTG's structure and ducts dedicated to the host building.

Some measures can be implemented to mitigate the generally poorer light transmission of the RTG compared to conventional greenhouses, such as the use of reflective surfaces (white painted or aluminised screens) in surrounding walls and opaque areas, which are often needed on RTGs' sides to accommodate supporting functions. RTGs are also often narrower compared to conventional ground-based greenhouses, which is advantageous from the point of view of daylighting since it provides more illumination from lateral walls compared to deeper greenhouses.

Compared to indoor PFALs, one of the main advantages of RTGs is the daylight harvesting potential, which greatly reduces the need for electric lighting. Electricity accounts for about 20% of the total production costs in a PFAL.[81] This figure can be greatly reduced through daylight harvesting in the RTG, which requires at least 50% less electric lighting compared to a PFAL of the same size.

This aspect was investigated by simulations in a Swedish study,[30] which showed that a PFAL had an annual electrical lighting energy intensity of 285 kWh/m². This figure was about three times higher than in the RTG exploiting natural light. However, note that the heat converted from the LED lamps almost covered the heating demand in the PFAL, but also resulted in a significant increase in cooling demand. In the case of the PFAL, the lighting energy use was about 55.6% of the total energy use. The total energy intensity of the PFAL was more than twice as high as that of the most energy-efficient RTG design and about 30% higher than the least energy-efficient RTG design. However, despite energy use per square meter being high in a PFAL, one should consider that production per square meter is also high. Therefore, it is important to also consider the energy use per produce unit, which was not investigated in the Swedish study.

ARTIFICIAL LIGHTING

Soon after the invention of electric lighting, it became clear that artificial light could be utilized to drive photosynthesis in plants. Incandescent lamps were less suitable for this purpose due to their heat radiation. However, they were found to be useful for photoperiodic lighting, which was introduced in the 1950s. With the advent of fluorescent and mercury lamps in the 1930s, the commercial implementation of artificial photosynthetic lighting became feasible. In the 1960s, high-pressure sodium (HPS) lamps were introduced, originally for use in street lighting, but they proved to be well-suited for photosynthetic lighting. They have been the light source of choice for greenhouse growers until the LED-based lighting systems were introduced around 2010.

For northern latitudes, natural radiation is only sufficient to support full plant growth for around four months per year. During the remaining eight months, supplementary light is needed to reach the plant's full photosynthetic potential.

Light in greenhouse conditions is usually measured using the unit $\mu mol/m^2s$. Typical values for supplementary lighting in greenhouses range from 200 to 300 $\mu mol/m^2s$, while light intensity outside on a sunny summer day can reach more than 2000 $\mu mol/m^2s$. However, from the perspective of plant growth, the daily light integral is more relevant than light intensity. The daily light sum achieved per square meter is expressed as mol/m^2day, with typical values inside a greenhouse in Scandinavia ranging from around 2 to 3 mol/m^2day during winter and up to 35 mol/m^2 day around the summer solstice. Crop needs range from around 15 mol/m^2day for leafy crops up to around 25 mol/m^2day for fruit-bearing crops. Typically, up to 12 to 20 mol/m^2day needs to be supplied artificially during the darkest time of the year.

The best available LED lamps as of today produce up to 4 µmol/J, corresponding to a daily electricity consumption of 1.4 kWh/m^2day to achieve 20 mol/m^2day. Older HPS lamp types can reach an efficiency of only 1.5-2.0 µmol/J.

The light spectrum utilized by the photosynthetic apparatus of plants is roughly the same as that which is visible to the human eye, i.e. 400 to 700 nm. However, light of shorter wavelengths (UV-light, 100-400 nm) and longer wavelengths (far red light) also affect plants, influencing processes such as pigmentation, elongation and leaf expansion, and photoperiodic regulation (flowering, dormancy, etc.). While light in the blue and red parts of the spectrum has traditionally been considered most valuable to the photosynthesis, it has become evident in recent years that wavelengths in the green-yellow part of the spectrum also play a significant role. A complete spectrum, including green-yellow light as well as UV and far-red light, is essential for plant lighting, especially when used in combination with little or no natural light. Modern LED lamps can be designed to meet these requirements. The light spectrum might be modified to adjust the red/blue balance, red/far red balance, etc., which affects plant elongation, pigmentation, generative/vegetative growth, and more. Research is also ongoing on how to utilize light quality to affect product properties such as taste and shelf life.

LIGHT POLLUTION

Artificial light at night (ALAN) is an irreplaceable technology for our cities and transport infrastructures supporting human activities at night, primarily in urban settings. ALAN is also essential for safety and to highlight the beauty of certain sites, parks, monuments, or historic buildings. However, this indispensable technology of modern times is associated with some detrimental effects. One of them is light pollution, which is increasing at an alarming rate (3-6% per year)[82] on a global scale.[83] It is estimated that more than 60% of the human population is now living under light-polluted skies, while 99% of Europe and the USA cannot see a pristine night sky.[84]

At high latitudes, supplemental electric lighting is needed in greenhouses to extend the growing season, as discussed earlier. In some cases, artificial lighting may be needed for as

Figure 23
A greenhouse in Quebec city, Canada, creating light pollution for the residential building located behind. Photo Marie-Claude Dubois.

long as between 4 AM and 11 PM.[85] However, this has the disadvantage of environmental light pollution (Figure 23). The consequences of this pollution may range from irritated neighbours to municipal regulations prohibiting electric lighting during certain hours or during the whole night.[86]

Recent research uncovers significant effects of ALAN on nocturnal wildlife, including insects, fish, amphibians, birds, and mammals (including humans). These effects include changes in behaviour and health.[87] One study showed that ALAN alters the sexual behaviour and fertilisation success of the common toad.[88] In humans, exposure to ALAN has been associated with breast and prostate cancer,[89] circadian phase disruption and sleep disorders.[90]

Until now, the effect of artificial light on wildlife has focused on street lighting and much less attention has been devoted to the effect of greenhouses, which are large light emitters. In greenhouses, the use of shades at night is strongly recommended or even required to reduce light pollution in the form of sky glow.[91] Skyglow, which adds to the light pollution from point light sources (streetlights or light from greenhouses), is today considered one of the most important alterations of the biosphere.[92] It is a phenomenon at the scale of the landscape which can affect larger areas and can be perceived from a distance.

Most species require alternating light and darkness to maintain their circadian clock or as signal for behaviour and reproduction (e.g. bud burst, flowering, dormancy, leaf abscission in plants, sexual behaviour,[88] migration and diapause in animals).[91] Therefore, illumination around the clock is not required or even desirable from a biological perspective. Recommendations and regulations normally address the lighting period. In general, artificial lighting should obviously be switched off when not needed, to limit light pollution and save electricity.[93] This is possible with smart and flexible lighting systems allowing to control artificial lighting more precisely.

The spectral power distribution of light sources also has significance for light pollution since it is now acknowledged that illuminants rich in short wavelength (blue) light more strongly suppress melatonin production in higher vertebrates including humans. This may result in a disruption of the circadian cycles leading to a general dysregulation of organisms. This blue-enriched light spectrum also attracts many insect species and generally contributes to sky glow pollution more than other light emitters, since blue light is scattered more in the atmosphere.[91]

It is worth mentioning that light actively attracts certain pest insects, which increases the risk for pest introductions and crop damage in greenhouses. Covering of cultivation facilities with UV-absorbing plastic films has been shown to prevent various pests from getting into greenhouses.

ALAN has documented effects on wildlife and one of the affected groups of animals are birds, who use singing to attract mates and defend territories.[94] A Polish study[85] in non-urban settings showed that birds exposed to greenhouse lighting start dawn singing and calling earlier and stop dusk vocalization later, particularly before the breeding season in the second half of February. This study indicated that even short-duration light pollution from greenhouses in a non-urban context affects bird vocalization in the breeding season.

This relatively recent body of research about light pollution emphasizes the need to move greenhouses from rural areas, which may contribute to the preservation of natural ecosystems for light-sensitive species in natural environments. Research has also suggested that urban citizens were more tolerant than rural citizens, as they are already used to a higher level of light pollution in the city.[95] This does not mean that citizens should not be protected from light pollution. In urban contexts, an improved understanding and awareness of light pollution effects is needed to yield appropriate regulations, provide guidelines to builders, and more sophisticated solutions that prevent light pollution for urban citizens, birds and insects. These solutions should encompass measures described in the box below.[91]

Light should generally be directed where it is needed, and spillover (trespass) should be avoided. The International Commission on Illumination (CIE)[93] recommends a maximum illuminance on the surface of a window to limit light trespass into a building, as well as a maximum upward light ratio to limit sky glow. The use of shield baffles and louvers in the light fixture can reduce the spillover around the target for illumination. Protection from light emission can also be provided in the form of walls, vegetation such as edges or opaque shad-

Measures to prevent light pollution from RTGs:

- Habitat conservation in protecting species-rich areas free from artificial lighting (mainly for rural sites or parks)
- Determination of thresholds and upper limits for light emitters
- Environment-specific brightness levels adapted to surrounding areas
- Temporal control of light emission and diurnally adapted colour spectra
- Reduction of light trespass

Figure 24
Example of cultivation in pots in a rooftop greenhouse project located in Oberhausen in Germany. Photo: Sara Spendrup.

ing curtains, especially in the case of greenhouses, which are large light emitters. The advantage of blackout screens used at night is that they also reduce heat loss from the greenhouse, contributing to a reduction in nighttime heating demand of the greenhouse or to maintain a higher temperature in non-heated greenhouses.

Methods to limit the detrimental effects of light pollution on nature and species including humans can be relatively inexpensive and easy to implement, but this aspect must be budgeted and planned at the early design phase of any RTG project. In the future, the LED technology, which makes it possible to vary light colour and intensity, could produce an illumination matching natural diurnal changes, mimicking sunset or the blue hour (period of twilight in early morning and evening).

CULTIVATION TECHNIQUE, YIELD, AND PLANT PROTECTION

Once the RTG is strategically located in the appropriate urban context and on the right building with the right business model, architecture and energy systems, several key aspects of the cultivation system must be carefully planned. These include the cultivation technique, expected yields, types of produce, and plant protection measures. The following subsections provide detailed insights into these topics.

Figure 25
Example of cucumber production at Agrotopia, Belgium. Photo: Paul G. Becher.

Figure 26
Float hydroponics, rooftop greenhouse atop a job center in Oberhausen, Germany. Photo: Tobias Emilsson.

CULTIVATION TECHNIQUES

Crop production in rooftop greenhouses is inherently hydroponic, as hydroponics is defined as any cultivation done ex-situ. In hydroponic systems, all essential nutrients—comprising 13 key elements—are delivered to plants through the irrigation water as a nutrient solution. Rather than growing in soil, plants are cultivated in a confined soil-like substrate such as peat, rock wool, perlite, or pumice (solid hydroponics), or directly in the nutrient solution itself (liquid hydroponics).

In solid hydroponics, the growing medium is typically contained in plastic containers or bags, with volumes ranging from 0.5 to 50 liters per plant, depending on the plant type and size, see Figure 24. For crops like herbs and ornamental plants, which are sold with the pot, peat-based substrates in plastic pots are commonly used. The nutrient solution is absorbed via capillary action. For longer-growing crops like cucumbers and tomatoes, mineral-based substrates such as rock wool or volcanic materials are preferred, with the nutrient solution delivered through drip irrigation, see Figure 25. The solution is usually prepared on-site from stock solutions using a fertilizer mixer, with a typical over-supply of 20-30% to ensure consistent delivery. Excess runoff must be collected and reused. To prevent the spread of phytopathogenic diseases, the recirculated nutrient solution should be disinfected. Common disinfection methods include UV treatment, pasteurization, and biofiltration.

In liquid hydroponics, little to no substrate is used, and the nutrient solution is supplied continuously or at regular intervals. A simple approach to liquid hydroponics is the static aerated technique (SAT), often called 'float hydroponics'. In this method, plants are placed on Styrofoam rafts that float on a container filled with aerated nutrient solution, as illustrated in Figure 26.

In the Nutrient Film Technique (NFT), plants are positioned in gutters

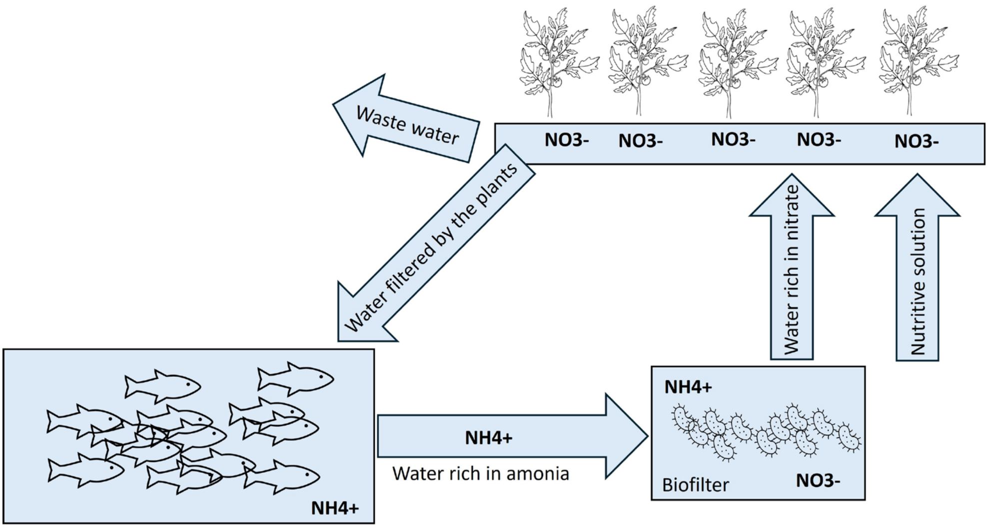

Figure 27
Conceptual drawing of the aquaponic system at Ferme Abattoir Bigh, Brussels. Adapted from https://circulagronomie.org/en/ferme-abattoir-bigh-en/.

or pipes through which a continuous flow of nutrient solution circulates. Over time, the plant roots develop into a mat, which helps retain some of the nutrient solution if there is an interruption in supply. NFT systems are particularly well-suited for shorter crops, such as lettuce and herbs, due to their compact growth habits.

Aeroponics represents the most advanced form of liquid hydroponics, where plant roots are suspended in the air and periodically misted with a nutrient solution. A variation of aeroponics, often referred to as fogponics, uses ultra-fine mist for nutrient delivery. While aeroponics has primarily been used for research purposes, it holds significant potential for rooftop greenhouses due to its lightweight design and minimal reliance on solid materials.

Hydroponic systems typically rely on mineral fertilizers, except for aquaponic systems, where a portion of the nutrients is provided by fish. Mineral fertilizers are concentrated, which means that relatively small quantities are required. In high-intensity production systems, such as greenhouses, approximately 1 kg of fertilizer per square meter per year is needed. These fertilizers are derived from mineral resources (excluding nitrogen fertilizers, which are typically obtained from atmospheric N2), then processed industrially to remove impurities and enhance solubility and ease of use.

Integrating plant production into urban areas could allow for the use of nutrient-rich waste streams, such as food waste, as fertilizers.[96] This would help close the nutrient loop, reducing the need for transportation, reliance on mined resources, and nutrient runoff into sewage systems. However, a hygienization process, like anaerobic digestion, is necessary to ensure safety.[101]

Aquaponics, which combines aqua-

Table 1
Advantages and disadvantages of the different types of hydroponic systems.

Solid hydroponics	**Liquid hydroponics**
+ Suitable for all crops	+ Requires no growing medium
+ Low energy requirement	+ Low weight
+ Buffer of nutrient solution	- High energy use
- Requires a growing medium	- Sensitive to technical failure
	- Not suitable for longer crops

culture and hydroponics, has gained significant attention in recent years. The concept involves integrating a land-based fish farm (a recirculating aquaculture system, or RAS) with a hydroponic production system, either in a coupled or decoupled configuration, see Figure 27. In this system, the fish provide essential nutrients, primarily nitrogen in the form of ammonium, to the water. This nutrient-rich water is then circulated to the hydroponic system, where plants absorb the nutrients, effectively removing excess levels that could be harmful to the fish. To prevent ammonia toxicity to both the fish and plants, a biofilter is often used to convert ammonia into less harmful nitrate. While fish feed is the primary source of nutrients for the plants in an aquaponic system, occasional supplementation with mineral fertilizers may be required.

Table 1 summarizes key advantages and disadvantages of different types of hydroponic systems.

YIELD AND PRODUCE

Building a greenhouse is one of the most effective ways to enhance land productivity, particularly in terms of plant biomass. Compared to open-field systems, greenhouse environments can be up to ten times more productive (in terms of plant biomass production per square meter per day).[97] This increased productivity is due to the controlled climate within the greenhouse, which includes higher average temperatures,

Table 2
Typical fruits and vegetables grown in rooftop greenhouses.

Firm	Crops
Lufa Farms	Cucumbers, tomatoes, lettuce (Boston Lettuce, Sweet Crisp Lettice, Baby Romain Lettuce, Arugula), fennel, kohlrabi, green onions, kale, mustard leaves, herbs, microgreans, sprouts, aloe vera
Rewe	Herbs (basil)
JFS	Lettuce (Lollo Rosso, Romain green, Brassica mix, Green Butter, Red Butter, Red Oak), microgreens, herbs (basil, etc.)
Gotham Greens	Sallad, herbs
Sky	Lettuce (Nai Bai, Cai Xin, Xiao Bai cai), Chinese Cabbage, Spinach
Ecco Jäger	Lettuce, herbs (basil)

Compared to open-field systems, greenhouse environments can be up to ten times more productive.

increased humidity, reduced crop damage from wind and precipitation, and better control over irrigation, nutrient delivery, and CO_2 concentration. On average, urban greenhouses can yield 10-50 kg of fruits and vegetables per square meter per year.[98] Common crops grown in rooftop greenhouses include tomatoes, leafy vegetables, and herbs. The use of artificial LED lighting in rooftop greenhouses further boosts productivity. A life-cycle analysis of rooftop greenhouses in Spain revealed that spring tomatoes had the lowest climate impact (kg CO_2 equivalent per kilogram of produce), while leafy vegetables like spinach and arugula had higher impacts.[99] Additionally, crop diversification across seasons proved to be the most effective strategy for minimizing the carbon footprint while maximizing the nutritional value of the produce, with a value of 3.18×10^{-3} kg CO_2/kcal. Currently, the produce sold by existing soilless rooftop greenhouse operations primarily consists of herbs, leafy greens, and tomatoes,[20] which are like the types of crops typically grown in conventional greenhouses. Table 2 provides an overview of various crops produced by some of the well-known firms operating RTGs.

PLANT HEALTH AND PROTECTION

Both abiotic and biotic factors play a role in regulating plant growth, but they can also negatively impact plant health. Climatic conditions such as high temperatures, air stagnation, and elevated humidity increase the risk of plant diseases. To prevent the build-up of excessive heat during warmer seasons, both rooftop and soil-based greenhouses must be properly ventilated. This subsection focuses on the fundamentals of plant protection in greenhouses, considering ventilation as a key challenge for RTG production in maintaining plant health.

Plant pests and pathogens, which naturally occur in gardens and fields, can also pose a threat to the production of vegetables, fruits, and ornamental plants, even in greenhouses. The controlled environment inside a glasshouse offers ideal conditions not only for crops but also for unwanted pests such as insects, mites, fungi, and other nuisances. During the 20th century, the widespread use of chemical plant protection products in orchards and fields led to pesticides becoming the standard method for controlling pests and pathogens even in greenhouses.[100] However, the negative consequences of pesticide use—such as the development of resistance, toxicity to non-target organisms, and health risks—prompted researchers, growers, and policymakers to seek alternative approaches. This led to the development and adoption of Integrated Pest Management (IPM) strategies, which now dominate both ground-based and rooftop greenhouse production.[101] At the core of IPM are practices designed to prevent the emergence and establishment of pests and pathogens, prioritizing non-chemical control methods. This approach is particularly relevant for RTGs, commonly located in densely populated urban areas, where pesticide-free production is both practical and often mandated by authorities.

The use of certified healthy and, when available, disease-resistant plant material, combined with strict sanitary standards, is a common practice to prevent the introduction and establishment of pests and pathogens in urban horticultural production systems such as vertical farms and RTGs. Despite strict preventive measures, the movement of materials (e.g., growing media, substrates, and plant material), air and water flow, and human traffic in and out of any production system pose significant risks of introducing pests and pathogens. While airlocks, decontamination areas at entry points, and filters or netting at ventilation openings help mitigate these risks, they cannot entirely prevent plant pests and diseases from entering the production area. Many plant-damaging organisms are small or even microscopic, with pests often being mobile and naturally attracted to plant materials. As a result, continuous monitoring and effective pest control are essential to minimize plant damage and ensure a profitable harvest. Tools such as colored sticky traps and pheromone traps aid in pest monitoring, while continuous and careful visual inspection of plants is crucial for early detection and prevention of pest and disease outbreaks. Advanced monitoring solutions, including camera and software-based systems, are already available and will increasingly support greenhouse managers in ensuring timely and effective pest control measures. While IPM prioritizes minimizing chemical pesticide use, intensive greenhouse production systems still rely on chemical plant protec-

Figure 28
Syrphid fly maggot feeding on aphids. source: Beatriz Moisset, Creative Commons Attribution-Share Alike 3.0 Unported.

tion products when necessary. These pesticides can be applied through spraying or by incorporating granular or liquid formulations into soil or nutrient solutions. Various sprayers enable high- or low-volume applications, while advanced precision application systems can detect and target pathogens and pests with high efficiency, reducing overall pesticide use.

In modern production systems, automated processes are increasingly integrating pest and disease monitoring, prescription, and application of plant protection products, including biocontrol agents, such as shown in Figure 28. Biological pest control—the use of living organisms to manage harmful pests—is a widely practiced and effective approach in both ground-based and rooftop greenhouses. A variety of beneficial insects, predatory mites, insect-pathogenic nematodes, fungi, and bacteria are commercially available year-round in many countries.

However, like chemical pesticides, using biocontrol agents effectively requires proper training. Additionally, regulatory constraints or a limited availability of biocontrol products and services can pose challenges to implementation. That said, the market for biological pest control is expanding, offering sustainable alternatives to traditional chemical plant protection. Advisory services, provided by farmer organizations or private companies, can assist with pest diagnosis, management strategies, and tailored solutions.

SUSTAINABILITY OF ROOFTOP GREENHOUSES AND ROOF GARDENS

Historically, green roofs have been a feature of Scandinavian buildings (Figure 29). However, the modern green roof movement—where vegetated roofs are designed to mitigate the negative effects of urbanisation—began in Germany in the mid-1980s. Initially driven by stormwater management and aesthetics, biodiversity has become an increasingly important benefit of green roofs over the past 20–25 years.

RTGs differ from traditional green roofs, representing a new urban surface that impacts all aspects of sustainability. As previously discussed, they enhance local food production, create jobs, and—depending on design and goals—improve the health of urban citizens as well as environmental performance of buildings and food systems. One study[44] indicated that high-tech, conditioned rooftop greenhouses could be more sustainable than conventional, unconditioned greenhouses for crop production. The same study also revealed that high-tech rooftop greenhouses generate more jobs and have a lower global warming potential (GWP) compared to conventional rooftop photovoltaics. RTGs address several of the United Nations (UN) sustainable development goals (SDGs) as outlined in Table 3.

In dense city centres, RTGs offer an innovative way to utilize otherwise

Figure 29
Green roofs on older houses, Lofthus, Norway, photo Marie-Claude Dubois.

underutilized rooftop space. Roofs are often overlooked as valuable spaces and are primarily used for technical installations like ventilation and air conditioning units. It is even relevant to consider that flat roofs—especially those with dark, waterproofing membranes—do contribute to environmental issues, as outlined in the box below. Failure to consider these aspects and remediate existing urban and peri-urban flat roofs creates environmental pollution in various ways. Flat roofs (Figure 30) are not only challenging from an urban heat perspective but also with respect to building energy balances. During winter, most flat roofs lose energy as heat rises and radiates to-

Environmental issues created by flat roofs with waterproofing membranes:

- Increased stormwater runoff contributing to combined sewer overflows or pluvial flooding
- Increased urban heat islands (UHI) effect due to increased energy storage and reduced reflection from dark coloured membranes
- Waste generation from membrane replacement every 20-25 years
- Increased heat exchange driving the heating and cooling demand of buildings.

wards the 'cold' night sky. During summer, these roofs are directly exposed to intense solar radiation during the day and thus create high cooling loads in the building below. This intense solar radiation also accelerates the degradation of waterproofing membranes, necessitating their replacement and contributing to increased toxic waste in landfills. While flat roofs are widely used, their environmental impact is significant, and they will require future remediation to mitigate these effects.

IMPACT ON URBAN HEAT ISLAND

One important benefit of green roofs is the urban heat island mitigation through increased evapotranspiration and altered reflection, improved noise insulation, and enhanced thermal performance depending on building insulation. One study[102] found that green roofs reduce daily heat loss by increasing thermal mass and insulation. By stabilizing membrane temperature variations, green roofs significantly impact both urban and building energy balance.

Like green roofs, rooftop farms can contribute to improving the thermal urban environment, depending on their design and materials. For open-air farms, their impact on urban ecology is influenced by the extent of the growing surface, substrate thickness and quality, as well as the type of vegetation and cropping system used. RTGs require shading devices to protect the crops, which also reduce the amount of sunlight hitting the roof membrane, thereby contributing to a

Figure 30
Flat roof with dark waterproofing membrane contribute to environmental pollution in several ways. Photo: Marie-Claude Dubois.

decrease in the urban heat island effect. Additionally, the crops located in the greenhouse also contribute to passive cooling through evapotranspiration.

IMPACT ON BIODIVERSITY

While RTGs provide advantages for food production, they do not directly create natural habitats or contribute to biodiversity conservation in the same way that open-air rooftop farms do. However, RTGs contribute indirectly to preserve biodiversity by optimizing land use. They help preserve open land for natural ecosystems outside urban areas, allowing it to remain undisturbed by development. Additionally, because RTGs are based on CEA, they typically reduce the need for pesticides, which indirectly supports biodiversity conservation.

ENERGY PRODUCTION ON ROOFS

The last years have seen a strong interest and policy development pushing for renewable energy production in general but also on urban buildings. The trade-off between renewable energy (e.g., photovoltaics - PV) and agricultural production on urban rooftops involves considerations such as energy efficiency, economic viability, spatial conflicts, and environmental benefits. PV systems are more energy-efficient and financially lucrative compared to agricultural systems, but high-value rooftop farming can still provide additional economic benefits and in particular other services such as local food production. Spatial conflicts may arise when allocating limited rooftop space.

Companies striving for climate neutrality are increasingly viewing roof spaces as untapped resources, with regulations underway that will mandate the installation of PVs in new construction and renovation projects. The proposed Energy Performance of Buildings Directive (EPBD), for example, will emphasize PV installation. A key future challenge will be how to combine these systems effectively, as both PVs and RTGs offer environmental benefits and present unique challenges.

One study[44] comparing PVs with RTGs found that, when factoring in financial returns and local job creation, food production from RTGs was more beneficial than energy generation from PVs, both for system owners and local communities.

Technological advances, such as integrating semi-transparent solar cells (STPVs), could help minimize the trade-off by enabling the generation of both food and electricity on the same roof, while protecting crops from overheating. However, the impact of STPV on yield has yet to be studied in the Scandinavian climate.

ROOFTOP GREENHOUSE OPERATION AND ENVIRONMENTAL EFFICIENCY

While RTGs offer numerous advan-

Table 3

Summary of sustainable development goals (SDG) addressed by RTG projects.

2 ZERO HUNGER	• By increasing access to food in city centres • By fighting food deserts
3 GOOD HEALTH AND WELL-BEING	• By providing fresh, healthy produce to urban citizens • By focusing on plant-based diets
6 CLEAN WATER AND SANITATION	• By harvesting rainwater, which reduces water use and burden on storm water systems • By recirculating water in the hydroponic system
7 AFFORDABLE AND CLEAN ENERGY	• Through energy conservation of host building and greenhouse • By exploiting daylighting for food production instead of relying only on artificial lighting
8 DECENT WORK AND ECONOMIC GROWTH	• By providing job opportunities in cities where people live • By contributing to the development of peripheral businesses in marketing, distribution, selling, etc.
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	• By promoting innovation in food production
11 SUSTAINABLE CITIES AND COMMUNITIES	• By increasing social, economical and environmental sustainability of urban areas
13 CLIMATE ACTION	• By mitigating the urban heat island (UHI) effect • By reducing energy use and GHG emissions from buildings • By reducing emissions from transportation of food
15 LIFE ON LAND	• By optimizing land-use through preservation of land outside the city • By reducing pesticide use, which preserves biodiversity

tages, they are not yet perfect ecological systems. Currently, they still depend on fossil fuels across the supply chain and face environmental challenges at various stages of operation.[103]

However, the broader societal efforts to reduce fossil fuel use and transition to renewable energy will also impact the future environmental performance of RTGs. The location of the growing facility atop a building significantly impacts the overall environmental efficiency of the operation. One key aspect is energy performance, as waste heat from the building below can be recovered to reduce building energy consumption. Compared to plant factories, another form of building-integrated agriculture, RTGs benefit from their rooftop placement, which provides greater exposure to solar radiation and thus free illumination.

RTG operations also offer indirect benefits for the urban environment. By reducing the need for transportation to consumers, rooftop farms help minimize transportation routes, thereby lowering carbon emissions. Furthermore, the transportation and storage of nutrients or pest control chemicals—while minimized—must be carefully managed to reduce their environmental impact. Like any technology, there are obstacles and challenges to improving system performance. Increasing food production within urban areas also presents its own set of difficulties.

WASTE MANAGEMENT

Developing urban agriculture will also place demands on local infrastructure and waste management systems within cities.[104] Increased agricultural activities will generate new types of waste and resource streams, particularly in the form of organic waste. While some of this waste can be managed onsite, a significant portion will need to be transported offsite for processing. This will require logistical solutions for removing material from the rooftops, as well as transportation to treatment facilities. However, as the concept of RTGs continues to grow, these challenges are likely to be addressed or mitigated. There are already ongoing tests and developments aimed at internal recycling of the organic fraction within RTGs.[110]

At Lufa Farms, a well-known RTG company located in the heart of Montreal, Canada, special attention is given to minimizing waste. Vegetables are harvested only once they are ripe and ordered by customers, a strategy that, like other modern greenhouse operations, significantly reduces produce waste at the source while ensuring maximum freshness for consumers. Additionally, when plants reach the end of their productivity, they are removed and replaced with new seedlings to begin the next cycle. Waste at Lufa is carefully monitored through smart sourcing and thorough sorting. As part of their sustainable practices, Lufa is developing a system to compost all production-related materials, such as substrate, stems, and leaves. Moving toward a circular approach is possible when every aspect of the operation is considered, including both input materials and the handling of waste products. Lufa not only focuses on converting waste into compost and recycling nutrients but has also reduced its use of plastic in growing supplies and twine. By replacing plastic accessories with compostable alternatives, a larger portion of materials can be composted, reducing plastic waste and further advancing their sustainability efforts.[105]

WATER SUPPLY AND CONSERVATION

RTGs function differently than open-air rooftop farms, as their outer surface is a sealed hard layer, leading to nearly complete and direct stormwater runoff. However, RTGs have significant potential when combined with rainwater harvesting systems, which can reduce and delay almost all rain events. Some studies[104] suggest that this can reduce runoff by as much as 60-79% after peak rainfall. The actual impact on stormwater depends on the installed system and the capacity of the rainwater storage.

Since RTGs typically use hydroponic cultivation techniques, they consume significantly less water—over 70% less than conventional soil-based systems. An American study[106] found that one hectare of rooftop vegetable farm can save the equivalent of 20 hectares of rural land, with each hectare saving an average of 74,000 tons of freshwater per year. In their survey of the environmental impacts of growing tomatoes, the study revealed that the freshwater consumption of RTGs was only 16% of that required by conventional farms.

Harvesting rainwater from an RTG roof is relatively easy, as rainwater is generally of good quality. However, storing it presents challenges, as it requires containers and additional space, which can be particularly difficult in retrofit projects. Nonetheless, there is significant potential in optimizing water use by modelling RTG water consumption against local rainfall patterns to determine the ideal collection area and tank size for meeting the greenhouse's primary water needs.[107]

In some regions or during certain times of the year, rainwater alone may not be sufficient, requiring the use of tap water, which increases operational costs. Several projects harvest rainwater to use in the hydroponic system. For example, the greenhouse of the Arbor House (Figure 32) uses water harvested from the greenhouse roof for irrigation purposes.[108] When greenhouses are installed in series, as in the Agrotopia project shown in Figure 31, the overall configuration creates creases that are most often used to collect rainwater used in the hydroponic system or for other domestic water uses such as toilets, washing, etc.

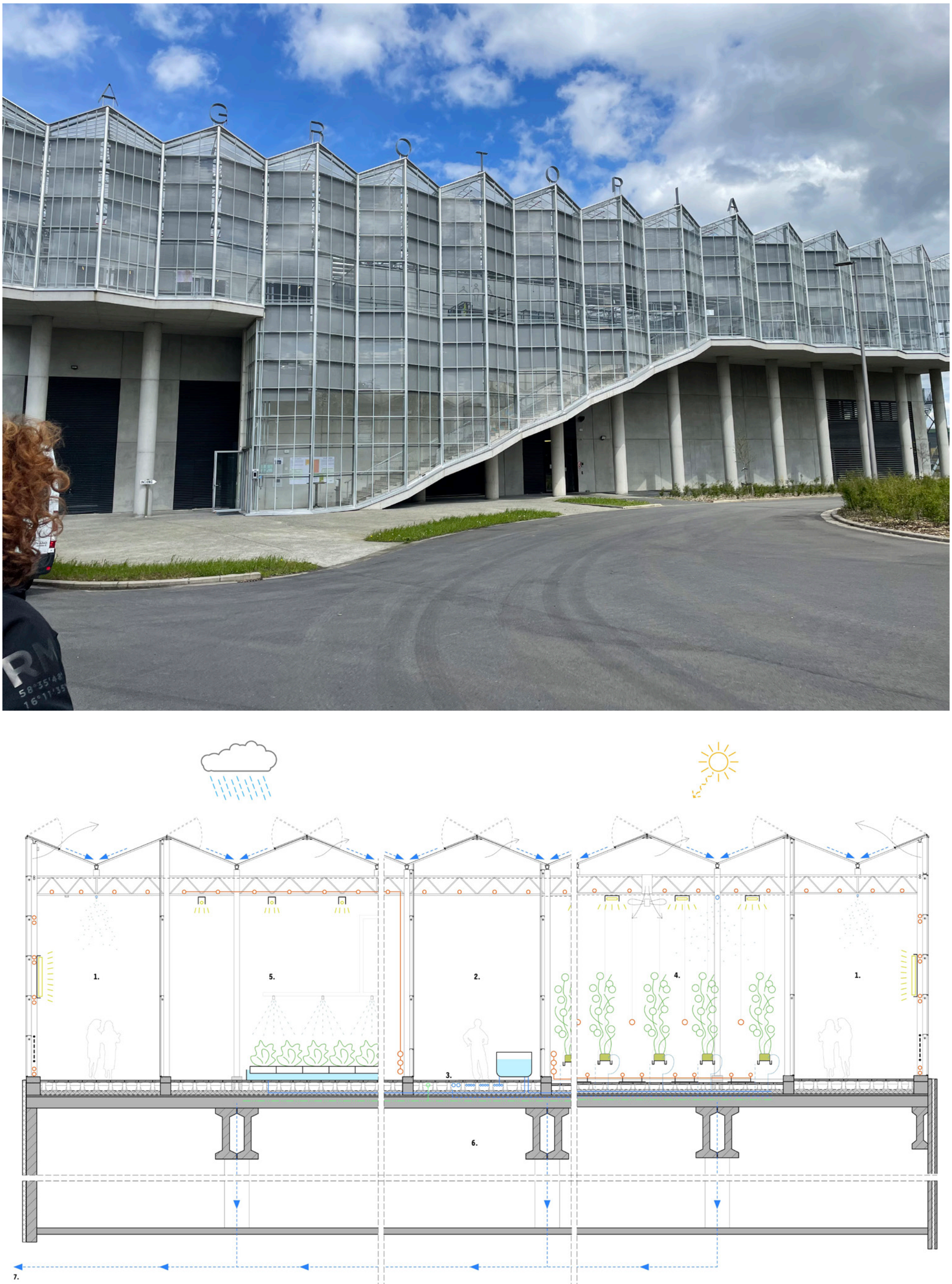

Figure 31
Agrotopia, Rosselaere, Belgium, photo Anders Larsolle (top); drawings: Courtesy of design offices van Bergen Kolpa Architecten and META.

Figure 32 Arbor House, Bronx, New-York, photo Bernstein and Associates.

SOCIAL SUSTAINABILITY

Social values have been driving the installation of many of the RTGs globally. Several projects have been built with objectives related to social values or community building. For example, the Arbor House (Figure 32), which is an affordable housing development in the South Bronx, New York, features a 930 square meters rooftop farm.[108] The farm provides fresh, healthy vegetables to the building's tenants and the surrounding community, aiming to make an impact on food access and public health in the neighborhood. Arbor House provides 124 energy-efficient housing units for citizens earning 60 percent or less of the area's median income, while offering an environment for a healthier lifestyle.[109] The farm, which is operated by Sky Vegetables, ensures that 40 percent of the produce is available to the community including the residents, schools, hospitals, and markets. Arbor House was also designed to meet New York City's Active Design Guidelines, which promote physical fitness and target reduction of obesity.

In Europe, the project 'J'habite mon Jardin', shown in Figure 33 created by Tours Habitat is a social housing organization in the city of Tours, France. In this case, the greenhouse was intentionally designed as a tool for social inclusion, while the produce (vegetables and fruits) is mainly intended for future building inhabitants.[110] The production also includes training, animation, and communication to a broader audience, from student groups to urban farmers. According to a recent study[62], a minimum area of 50 m² and a maximum of 100 m² are needed for socio-educational purposes, as the primary goal is self-consumption. A minimum of 50 m² allows for the development of educational and nutritional school projects in limited spaces, while the 100 m² upper limit is recommended to prevent excessive labour demands for crop maintenance.

In conclusion, we should emphasize that the promotion of social values is not always fully compatible with commercial production. Therefore, RTGs must be specifically designed and implemented to foster and support social engagement while balancing practical constraints.

CONCLUSION

This book has explored the immense potential of rooftop greenhouses in shaping sustainable cities, feeding growing urban populations, and combating climate change. By integrating agriculture into the built environment, we can create resilient food systems that reduce transportation emissions, enhance building energy-efficiency, and make efficient use of underutilized urban spaces.

Advancements in cultivation techniques, AI-assisted farming, and circular economy principles are driving rooftop greenhouses toward greater efficiency and sustainability. These innovations not only optimize food production but also contribute to climate adaptation, energy conservation, and waste reduction. The impact on a city's roofscape can be transformative, turning barren surfaces into thriving ecosystems that benefit both people and the planet.

We hope this book has inspired you to take action—whether by advocating for policies that support urban agriculture, initiating your own small-scale rooftop project, or supporting businesses that integrate rooftop gardens and greenhouses into their operations. Small steps taken at the local level can lead to widespread change, creating healthier, green-

Figure 33
Project « J'habite mon jardin », Tours, France. Courtesy of the farm.

er, and more self-sufficient cities. A powerful example of this transformation is Lufa Farms in Montreal. By pioneering commercial-scale rooftop agriculture, they have redefined the city's foodscape, proving that urban farming can be both economically viable and environmentally beneficial. Their success is a testament to what is possible when innovation meets determination, and it serves as a model for cities around the world to follow.

Beyond their practical benefits, rooftop greenhouses also offer an opportunity for a deeper reconnection with nature, community, and the origins of our food. They challenge us to rethink the way we design buildings and cities, transforming them from concrete jungles into vibrant, living ecosystems. In the end, rooftop agriculture is not just about growing food—it is about reshaping our relationship with the environment and fostering a more sustainable future for generations to come.

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ABBREVIATIONS

AHU	Air handling unit
ALAN	Artificial light at night
ARQ	Architecture Research Foundation (Sweden)
BIA	Building-integrated agriculture
BMC	Business model canvas
CBC	Center for Biological Control
CEA	Controlled environment agriculture
CIE	International Commission on Illumination
CSA	Community supported agriculture
EBF	Energy, Biosphere, Food
EPBD	Energy performance of buildings directive
ETFE	Ethylene tetrafluoroethylene
EU	European Union
FAO	Food and Agriculture Organization
FIR	Far infrared radiation
GDI	Gross domestic income
GHG	Greenhouse gas
GMO	Genetically modified organism
GNP	Gross national product
HDI	Human development index
HPS	High-pressure sodium
HVAC	Heating, ventilation and air conditioning
ICTA	Institut de Ciència i Tecnologia Ambientals
IDA	Interdisciplinary Academy
IFSB	Institut de formation sectorielle du bâtiment
IPM	Integrated pest management
iRTG	Intelligent rooftop greenhouse
IRTG	Integrated rooftop greenhouse
IUCN	International Union for Conservation of Nature
LED	Light emitting diodes
LTH	Lunds Tekniska Högskola (Lund Institute of Technology)
NFT	Nutrient film technique
NGMA	National Greenhouse Manufacturers Association
NIR	Near infrared radiation
PAR	Photosynthetically active radiation
PC	Polycarbonate
PFAL	Plant factory with artificial lighting

RA	Rooftop agriculture
RAS	Recirculating aquaculture system
RF or RTF	Rooftop farming
RTG	Rooftop greenhouse
SAT	Static aerated technique
SDG	Sustainable development goal
SLU	Swedish University of Agricultural Sciences
SPD	Spectral power distribution
STPV	Semi-transparent photovoltaic
UA	Urban agriculture
UHI	Urban heat island
UF	Urban farming
URF	Urban rooftop farming
UV	Ultraviolet
VF	Vertical farming

GLOSSARY

Abiotic
Abiotic factors refer to non-living environmental elements that affect plant and animal life. These include temperature, light, humidity, soil type, air quality, and water. Essentially, abiotic factors are the physical and chemical components of an environment.

Aeroponics
A plant cultivation technique in which the roots hang suspended in the air and a nutrient solution is delivered to them through a fine mist.

Aquaponics
A plant cultivation technique where fish or other aquatic creatures are farmed and supply the nutrients for plants grown hydroponically. In this system, the plants can utilize fish waste as fertilizer and at the same time purify the circulating water.

Biosecurity
Procedures or measures designed to protect the population against harmful biological or biochemical substances.

Biotic
Biotic factors refer to the living components of an environment that influence organisms. These include plants, animals, fungi, bacteria, and other microorganisms. Biotic factors can affect organisms through interactions such as predation, competition, and symbiosis.

Carbon footprint
A measure of the amount of carbon dioxide released into the atmosphere as a result of the activities of an individual, an organization, or a community.

Climate neutrality
Reduction of emissions through measures or climate actions to ensure no net effect on the climate system.

Daily light integral
The number of photosynthetically active photons that are delivered to a specific area over a 24-hour period. It can also be thought of as the measure of usable light that plants receive over the course of one day.

Diapause
A period of suspended development in an insect, other invertebrate, or mammal embryo, especially during unfavourable environmental conditions.

Dormancy
The state of having normal physical functions suspended or slowed down for a period or the state of being temporarily inactive or inoperative.

Embodied energy
The sum of all the energy required to produce any goods or services, considered as if that energy were incorporated or 'embodied' in the product itself.

Eutrophication
A process in which nutrient accumulate in a body of water, resulting in an increased growth of organisms that may deplete the oxygen in the water. It can occur naturally or because of human activities like the use of fertilizers in agriculture.

Far-red light
The wavelength just above the visible spectrum (700-780 nm) which is important for plants in relation to stem elongation and flowering regulation. Note that in physics, the term near-infrared radiation (NIR) refers to the region of the spectrum extending from about 700 nm to 2500 nm, while far-infrared radiation (FIR) means radiation between 3 and 1000 μm.

Gross domestic income (GDI) index
A measure of the incomes earned, and the costs incurred in the production of gross domestic product (GDP). It is an alternative way of measuring the nation's economy by counting the incomes earned and costs incurred in production.

Gross national product (GNP)
The total value of all the final goods and services produced by a nation's economy in a specific time (usually one year).

Growing media
A substrate (organic or inorganic) used to support the roots in hydroponic production.

Habitat
The natural home or environment of an animal, plant, or other organism.

Hotbeds
A bed of soil enclosed in glass, heated by fermenting manure, for raising or forcing seedlings.

Human development index (HDI)
A statistical composite index of life expectancy, education and per capita income indicators, which is used to rank countries into four tiers of human development.

Hydroponics
A cultivation technique involving growing plants, usually crops or medicinal plants, without soil, by using water-based mineral nutrient solutions in an artificial environment. In this system, plants are grown ex-situ, and water and nutrients are brought to the plants by an irrigation system.

Hygienization
The process of eliminating harmful pathogens, microbes, or contaminants from a substance to make it safe for use.

Leaf abscission
When a plant drops its leaves.

Mechanical ventilation
System that circulates air using ducts, fans, and air handling units (AHU) rather than relying on airflows through openings in walls or roof.

Nursery
A commercial producer of horticultural produce.

Optical properties
Properties of a material defining how it interacts with light. It includes, for example, the reflection, transmission and absorption of visible light.

Passive systems
A system requiring little or no external (artificial) energy to operate. Passive systems can rely on natural energy flows as when there is natural convection by a stack effect (warm air rising) or cross ventilation. Passive solar heating is a typical passive system.

Pheromone
A chemical substance produced and released into the environment by an animal, especially a mammal or an insect, affecting the behaviour or physiology of others of its species.

Photosynthetically active radiation (PAR)
The part of the electromagnetic spectrum (400-700 nm) which is active in the plant's photosynthesis.

Resilient
A person, animal or plant capable of withstanding or recover quickly from difficult conditions.

Spectral power distribution (SPD)
Measurement describing the power per unit area per unit wavelength of the electromagnetic spectrum radiated by the sun, a lamp or other source.

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INDEX

SUMMARY

Agriculture in industrialized countries faces numerous challenges: an increasing urban population, erratic weather patterns stemming from climate change, a decreasing number of farmers and loss of arable land. Current practices in industrial farming exacerbate environmental degradation, contributing to greenhouse gas emissions, habitat destruction, water contamination, and the loss of biodiversity. Urgent action is imperative to address these issues, necessitating a fundamental transformation in food production and distribution methods, particularly considering escalating urbanisation trends.

Urban agriculture plays a crucial role by repurposing city spaces for farming, preserving natural environments beyond urban boundaries, and providing local food access to consumers. Rooftop greenhouses emerge as a particularly promising solution in temperate and cold climates, extending the growing season for various vegetables such as tomatoes, salads, herbs, and cucumbers, even during the winter months. Additionally, rooftop greenhouses facilitate water harvesting and maximize the utilization of free sunlight, covering approximately half of their lighting requirements. Furthermore, they contribute to energy efficiency by reducing heating and cooling demands for both the greenhouse itself and the host building.

This book delves into rooftop greenhouse technology, a promising frontier for future urban food production. It conducts a thorough examination of its benefits and limitations, addressing pivotal factors for planners, engineers, urban farmers, and architects. These encompass the necessity of a robust business strategy, streamlined produce distribution, and technical intricacies like cultivation technique, building structure, access, glazing, and shading to mitigate overheating, and light pollution. Moreover, it addresses horticultural aspects such as cultivation systems and plant protection. Additionally, the book explores social and sustainability aspects, alongside urban planning considerations. In summary, it furnishes a comprehensive overview of rooftop greenhouse technology and its ramifications for urban landscapes.