Rooftop plant factories: effects on energy use for heating, cooling and electric lighting

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Master thesis in Energy-efficient and Environmental Buildings

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Lund University

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Building Design.

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Abstract

Within the next thirty years, two thirds of the human population will live in a city. This growing urban population requires a major shift in the way we produce and distribute food, since industrial agriculture practices contribute to climate change, biodiversity losses, pollution of waterways, soil degradation, etc. Urban and peri-urban agriculture and forestry (UPAF) represent one of the strategies that can contribute to climate mitigation, adaptation and development. Amongst the urban farming (UF) systems, rooftop plant factories may provide part of the solution for vegetable and fruit production in the city, while solving current problems created by existing flat roofs and saving on arable land outside the city.

This thesis presents a study of rooftop greenhouse (RTG) located on a typical warehouse in Malmö, Sweden (lat. 55.6°N, long. 13.0°E). The goal of the study was to investigate the effect on energy use of building a greenhouse on the roof of an existing warehouse. The study was performed by dynamic energy simulations with the computer program IDA-ICE. The results show that adding the RTG on the warehouse reduces total energy use compared to greenhouse and warehouse as stand-alone structures. Furthermore, the results indicate that the glazing and shading solutions are important aspects determining the energy-efficiency of the integrated system. The energy use for electric lighting is also significantly reduced by the RTG compared to an indoor horizontal farm of similar size illuminated by LED lamps. The main conclusion is that RTGs offer a great potential for food production in the city with the additional benefit of reducing overall energy use of host building and greenhouse. RTGs are also more energy-efficient than indoor farms illuminated by LEDs, when considering all energy end-uses (heating, cooling, lighting, and ventilation).

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Table of contents

List of Tables

List of Figures

Abbreviation

IDA ICE	IDA Indoor Climate and Energy
GDP	Global gross domestic product
GHG	Greenhouse gas
UPAF	Urban and Peri-urban Agriculture and Forestry
UF	Urban farming
URF	Urban rooftop farming
RF	Rooftop farming
RTG	Rooftop greenhouses
CEA	Controlled environmental agriculture
LEED	Leadership in Energy and Environmental Design
COVID-19	Coronavirus disease of 2019
PGF	Plant Growth Facilities
AFNS	Agricultural, Food, and Nutritional Science
UAB	Universitat Autònoma de Barcelona
DLI	Daily light integral
HPS	High-pressure sodium
LED	Light Emitting Diode
PI	Proportional integral
COP	Coefficient of performance
TDLI	Target daily light integral
LE	Light efficacy
LPD	Light power density ($W \cdot m^{-2}$)
OP	Operation time
SHGC	Solar Heat Gain Coefficient

1. Introduction

1.1 Goals

According to Statistics Sweden (2019), the urban inhabitants in Sweden are consistently on the rise, to 87 % at the end of 2018, urban areas have expanded by nearly 11 000 hectare since 2015, which accelerates the loss of agricultural land. Urban agriculture, as a solution to the challenges of food security, has multifunctional benefits (in the social, environmental and economic dimensions) (Appolloni *et al.*, 2021) and produces more than food. Roof plant factories as one of several forms of urban agriculture, contributes to optimization of the urban land use and provide a solution to climate change, soil degradation, biodiversity losses, pollution of waterways, etc. Moreover, some forms of urban agriculture, such as rooftop farming (RF) can result in a saving in the annual energy consumption of the host building (Nadal *et al.*, 2017).

Little research has been conducted on the energy performance of the roof plant greenhouses (RTG), especially in the Nordic region. Therefore, it is of importance to find out the impacts of RTG on energy saving regarding both the host building and the RTG itself. After a review of academic literature concerning existing RTGs, the objectives for the research and detailed research questions and methodology are developed.

1.2 Hypothesis

The roof plant factories can contribute to reducing both heating and cooling demand of the building underneath and itself. The scale of energy saving of RTG depends on various parameters related to various construction parameters such as glazing type and shading devices.

2. Literature review

2.1 Introduction to rooftop plant factories

2.1.1 Global context

About 55 % of all humans currently live in urban areas and this number is expected to increase to 68 % by 2050 (United Nations, 2018). Urbanization, which is the gradual shift in residence of humans from rural to urban areas, combined with the overall growth of the world's population is anticipated to add another 2.5 billion people to urban areas by 2050 (United Nations, 2019). Thus, within the next thirty years, two thirds of the world population will live in a city.

According to the Ellen MacArthur Foundation (2021), 'cities currently account for 85 % of global gross domestic product (GDP) generation, but they are key aggregators of materials and nutrients responsible for 75 % of natural resource consumption, 50 % of global waste production, and 60 % to 80 % of greenhouse gas (GHG) emissions'. In other words, cities are where most materials and food are consumed and wasted. With nearly three million people moving to an urban area every week (UN-Habitat, 2009), the pressure on resources due to urbanization will continue to grow, generating a need to improve local infrastructures at a rapid pace, considering in this endeavour housing, food, water and waste.

2.1.2 Impacts of food production system

According to United Nations (2021), 'food, energy and water: this trio is called 'nexus' of sustainable development'. As the global population has expanded and countries became richer, the demand for these three resources mentioned above increased. Also, they are strongly interconnected: food production requires water and energy, producing traditional energy needs water resources, while agriculture can provide an important energy source through e.g. biomass.

The food production system that currently feeds the human population through agriculture industries is responsible for approximately one fourth of global GHG emissions (Poore and Nemecek, 2018). The FAO (2011) outlined that 'agriculture industries currently withdraw 70 % of global fresh water'. In addition, not less than '50 % of the world's habitable (ice- and desert-free) land is occupied by agriculture operations', according to Ritchie and Roser (2020).

Furthermore, 'agricultural expansion results in the conversion of forests, grasslands and other carbon 'sinks' into cropland or pasture, a process which yields carbon dioxide emissions' (Ritchie, 2019). Data also shows that '78 % of global ocean and freshwater eutrophication (pollution of waterways with nutrient-rich pollutants) is due to agriculture practices' (Ritchie and Roser, 2020). The expansion of agriculture is thus responsible for one of humanity's greatest impacts on the environment. Agriculture has transformed habitats and constitutes one of the major pressures for biodiversity. Together with aquaculture, it is now considered a threat for 24 000 of the 28 000 species threatened with extinction on the (IUCN Red List, 2021).

In summary, our current food production system through industrial agriculture practices is responsible for environmental threats (climate change, pollution of waterways, freshwater shortage, biodiversity losses, etc.). Therefore, a major shift in the way we produce and distribute food to the rapidly growing urban population is urgently needed. This could result in reducing the shortage and pollution of water resources, restoring lands back to grasslands or forests, and protecting the wildlife all over the world. Rizzo *et al.* (2018) emphasized that food security is primarily an urban issue since most people live in cities.

Fortunately, 'increasing attention is paid to the role of cities in contributing to more sustainable and resilient food systems', as expressed by Dubbeling, van Veenhuizen and Halliday (2019). Food systems need to be radically changed in order to be able to withstand and recover from the effects of crises, whether they are natural disasters such as droughts, storms, floods, and pandemics or socioeconomic shocks. According to the World Bank (2010), 'building resilience in a city requires an integrated and, ecosystems-based approach that considers mitigation (e.g., strategies to reduce greenhouse gas emissions), adaptation (e.g., reducing the vulnerability to climate change) and development (such as poverty alleviation, income generation and food security)'. This triple challenge can be met partly through implementation of urban and peri-urban agriculture and forestry, according to Dubbeling, van Veenhuizen and Halliday (2019).

2.1.3 Urban and peri-urban agriculture (UPAF)

Dubbeling, van Veenhuizen and Halliday (2019) claimed that 'agriculture has always been practised in and around cities, but only recently has Urban and Peri-urban Agriculture and Forestry

(UPAF) been formally recognised in international agendas'. According to these authors, UPAF is 'the process of growing trees, food and other agricultural products (herbs, pot plants, fuel, fodder) and raising of livestock (including fisheries) within a built-up area (intra-urban agriculture) or on the fringe of cities (peri-urban agriculture). It includes various production systems such as horticulture, livestock, (agro-) forestry and aquaculture as well as related input supply, processing and marketing activities'.

Under the larger umbrella of UPAF, urban farming (UF) is presented by Rizzo *et al.* (2018), as a solution 'with obvious social, economic, and environmental benefits', which they list as follows:

- 'socially UF will bring people closer to nature and it can become a source of education for local schools and community;
- economically, UF targets the rapidly growing market of premium, fresh, biological food that is proudly produced locally and can be sold to local restaurants and other customers;
- environmentally, UF will decrease our reliance from far away and poorly controlled food chains, while decreasing environmental costs for transportation'.

Rizzo *et al.* (2018) reported a study achieved in Bologna, as attempted to quantify the potential for urban food production. They calculated the food requirement of the city and found that with the implementation on a large scale of their UF model, they could produce up to 12 000 tonne per year of vegetables, which covered 77 % of the food needs in the city, providing tremendous environmental benefits.

2.1.4 Urban rooftop farming (URF)

Among the different UF systems, urban rooftop farming (URF) is one of the most potent solutions as it solves several environmental problems at the same time, while shortening transportation paths. URF, also called rooftop agriculture, 'is the practice of growing plants on top of residential, commercial, and industrial buildings' (Orsini *et al.*, 2017). URF solves several environmental problems at the same time, while shortening transportation paths.

Gasperi *et al.* (2016) claimed that URF is 'a positive utilization of the roof space with ecological, economic and social benefits'. According to Lal (2020), rooftops of buildings as one kind of ‘abandoned or unused irregular city spaces, which have much potential to develop urban agriculture, and increase cities’ resilience to unexpected events such as the COVID-19 pandemic recently, which affect the food transportation and productivity worldwide’. Old buildings can be retrofitted using growing containers, soil-based or hydroponic systems or the like. Even new buildings could be designed with rooftop greenhouses.

URF includes both open-air rooftop farms (RF) and closed rooftop greenhouse (RTG) systems, as outlined by Rizzo *et al.* (2018). RTG is one specific form of controlled environmental agriculture (CEA). It uses soil-less or soil-free agriculture systems to produce food, improving the overall energy performance by integrating with the building (Sanjuan-Delmás *et al.*, 2018). Some of the benefits of RTG are the same as the ones of CEA, i.e. reduction of water use as water can be collected and recirculated, elimination of pesticides since crops are cultivated in closed environments, avoidance of pollution of waterways due to avoidance of pesticides at the source, etc.

2.1.5 From urban flat roofs to green roofs

In many cities around the world, a large quantity of flat roofs covered with a watertight membrane have several negative environment effects.

- Contribution to overload storm water systems since water is drained through pipes and sent directly to the municipal drainage system.
- Enhancement of the urban heat island effect, especially with dark membrane.
- Filling landfills with non-renewable materials, as the membrane needs to be changed every 20 to 25 years.
- High cost in maintenance for inspection and reparation but no revenue.

These flat roofs also have large heat losses in the winter as heat naturally rises and radiates towards the ‘cold’ night sky in the winter. In the summer, these roofs are directly exposed to intense solar radiation all day long and thus create high cooling loads in the building below. On the other hand, these roofs are well exposed to solar radiation and rain, two precious resources for growing crops.

Green roofs have been promoted since the 1990s as a solution to all issues listed above. Green roofs are not only more aesthetically pleasing; the plants on the substrate convert heat into evapotranspiration processes, reduce the roof temperature and mitigate the urban heat island effect. They also contribute to noise reduction, to filtering the air and improving air quality while absorbing CO2 in the city. A study by Fioretti *et al.* (2010) on the thermal effectiveness of green roofs showed that the green roof 'could reduce the daily heat losses through the roof by increasing the thermal mass and insulation'. Green roofs generally stabilize the variation of temperature in the winter and summer, according to D'Orazio, Di Perna and Di Giuseppe (2012). Green roofs also contribute to maintaining biodiversity in the city as insects and birds can dwell on them.

2.1.6 Benefits of urban rooftop farming (URF)

The rooftop plant factories provide many of the environmental benefits of green roofs (water management, reduction of urban heat island effect); they can provide additional multiple ecological, and economic benefits. Similarly to green roofs, rooftop farms provides a solution for temperature regulation, storm-water management, reduction of energy use and greenhouse gas emissions. By covering and protecting the roof from direct solar radiation and natural sunlight, the indoor temperature of the building can be reduced in the summer during the periods of high temperature (Orsini *et al.*, 2017). Greenhouses can also use existing roof space to store water during heavy rainfalls (Mentens, Raes and Hermy, 2006), and reduce runoff by as much as 60 % to 79 % after peak rainfall (Köhler *et al.*, 2002). In addition, taking advantage of the greater exposure to solar radiation on the rooftop instead of using electric lighting indoors, as done in the indoor vertical farm, saves more energy, according to Gupta and Mehta (2017). Finally, Sabeh (2020) outlined that 'waste heat from the host building can be utilized for greenhouse heating by recirculation'. Needless to say, rooftop farms in urban and peri-urban areas shorten the travel distances of vegetables and crops making them more affordable, available (Gupta and Mehta, 2017), and fresher, thus filled with nutrients. Obviously this solution contributes to reducing fossil fuel emissions for transportation.

Besides reducing transportation routes to distribute the produce, rooftop plant factories do not require additional land, which means that the rooftops also indirectly contribute to reducing humans' impact on wild habitats, making rooftop farming one of the most attractive solutions to feed a growing urban population (Sabeh, 2020), while protecting natural ecosystems.

2.1.7 Limitations of rooftop factories

Due to the limitation of roof structure bearing capacity, the depth of soil layer (growing media can weigh 960-1600 $kg \cdot m^{-3}$ when saturated) is generally minimal, meaning that 'limited categories of crops can be cultivated, with a lower production than for ground-based agriculture', according to Ackerman, Dahlgren and Xu (2013). Rizzo *et al.* (2018) also listed the high investment costs, low profit margins on food products as well as long payback times as three major drawbacks of rooftop factories.

2.1.8 Potential of rooftop factories

The potential to develop urban agriculture on rooftops is huge. For example, in New York City, there are almost 15 000 ha of rooftop area, which is 445 times the size of existing community gardens (Ackerman, Dahlgren and Xu, 2013). In Amsterdam, the available rooftop surface is 1 200 ha (Schavemaker and Stremke, 2015), of which available green roof area represents 150 000 m^2, just a fraction in this Dutch capital (Amsterdam University College, 2018). Furthermore, previous research has indicated that approximately 1 200 ha of available rooftop growing space is needed to produce the equivalent to 10 % fresh vegetables of Toronto's supply (Macrae *et al.*, 2010). Moreover, according to Melbourne council, there are 880 ha of roof space in the council's boundaries, the green roofs including rooftop gardens currently only cover 7.8 hectares (Arup, 2019). In summary, the potential for developing and expanding rooftop factories is large in several major cities.

2.1.9 Local policies about rooftop agriculture

Policies are important to regulate rooftop factories implemented on existing buildings due to the change in height of the host building and constitution of interior space (Henckel, 2015). In Germany the Federal Land Use Ordinance defines the volume of structure permitted to construct on a building rooftop (Kment *et al.*, 2017), the structure of any rooftop factories should complied with the Berlin Building Regulation (Henckel, 2015). As the first rooftop farm in Scandinavia, ØsterGRO in Denmark claims that both explicit and implicit policies affect urban agriculture development (Delshammar *et al.*, 2017), regarding the following aspects: legal, economical, educational and urban design (Dubbeling *et al.*, 2010). Rooftop farming is mainly affected by urban spatial planning and urban food strategies on national, regional as well as local levels (Delshammar *et al.*, 2017).

2.2 Worldwide cases of rooftop plant factories

Most of the rooftop plant factories are for commercial production, which ranges from small and medium to large scale farms, applying the engineered lightweight soil directly on top of a soil-ready roof, or using hydroponic systems in greenhouses (Nasr, Komisar and Zeeuw, 2017).

2.2.1 Small and medium scale commercial rooftop farms

Social enterprise ComCrop, Singapore's first and only commercial rooftop farming company, employs a vertical aquaponic farming system atop SCAPE Mall. They pick crops including vegetables, heirloom tomatoes, Italian basil, spearmint and peppermint. By adopting approximately 4.6 m high vertical racks drawing water and nutrients from fish waste in this 560 m^2 farm, as much as 8 to 10 times of produce can be harvested each month in this self-sustaining aquaponics system to fill the plates of local restaurants compared to conventional flat land, soil-based farming (Ee J, 2015; Weise E, 2015; Agri-Food and Veterinary Authority of Singapore, 2018).

Urban Farmers is a technology leader in Aquaponics. Since 2012, Urban Farmers' modular system is supplemented with a 250 m^2 greenhouse called UF001 LokDepot in Basel. It is the first commercial rooftop aquaponics farm in Switzerland, and this is the first commercial aquaponics example across the world. The combination of fish farming and soil-free vegetables farming is performed by using the waste water from the fish to fertilize plants and plant roots cleaning the water for the fish. A prototype study showed that for every 3 m^2 rooftop farm space, 12 % of a person's diet can be met. The LokDepot farm is in full commercial production with harvests of 850 kg of fish and 5 tonnes of vegetables during one year (Bradley, 2013; Graber *et al.*, 2014; Callie, 2016; Thorpe, 2017).

The Blue Sea Development Company constructed a 930 m^2 hydroponic rooftop farm above an eight-story building in the South Bronx in New York City. By collecting rainwater from the greenhouse roof and leftover heat from the building below, 40 % of the produce will be made available to the community annually, according to Serlin (2013).

Australia-based Little Veggie Patch Co.'s backyard Pop Up Patch was built on the rooftop of the Federation Square's car park in Melbourne. The farm covers approximately 1 000 m^2 and encourages local people and restaurants to rent their growing boxes to produce fresh vegetables. The farm provides seeds, seedlings, pots, pest and disease control as well as technical advice (Orsini *et al.*, 2017).

Rooftop Republic has pioneered the rooftop farming movement in Hong Kong five years ago. The rooftop garden was set on the top of the Bank of America Tower, a 39-storey building in the central business district of Hong Kong for food production. It also has educational purpose for Hong Kong Fringe Club (Cam, 2014; Robson, 2017; Ho, 2020).

2.2.2 Large-Scale Commercial Rooftop Farms

Lufa Farms, with four closed-loop hydroponic greenhouse farms, constructed the largest and most ambitious rooftop greenhouse measuring nearly 15 000 m^2 in Ville Saint-Laurent (Lufa Farms, 2021). Their four farms were established on the rooftop of industrial buildings that they optimize by growing crops including lettuce, herbs, microgreens, cucumbers, peppers, tomatoes and eggplants. The farms use half water of comparable farms. Only in cold winter nights natural gas heaters with high efficiency is used (Engler and Krarti, 2021).

A former iconic telecommunications powerhouse Philips called 'De Schilde' in The Hague, Netherlands was transformed into one of the first commercial urban food production facility by Urban Farmers AG in Europe. The rooftop consists of 1 200 m^2 hydroponics greenhouse and a 370 m^2 indoor tilapia farm on the floor below while a 250 m^2 building is used for processing and packaging facility (Chow L, 2016). This farm can serve 900 local families as well as restaurants and a cooking school, with 50 tonnes of vegetables a year (Boztas, 2016).

Gotham Greens as a global pioneer in urban greenhouse agriculture build and operate a state of-the-art agricultural greenhouse facility on the roof at Method's new manufacturing plant, which is the world's first Leadership in Energy and Environmental Design (LEED) Platinum certified manufacturing plant in the Pullman neighborhood of Chicago's south side in 2015. The 7000 m^2 rooftop greenhouse can produce up to around 454 000 kg crops annually (Produce Grower, 2015). The company uses 20 % renewable energy including solar, and recycled water to make more profit (Wharton R, 2015).

There are also traditional open-air farms such as Up Top Acres who transform underutilized rooftops into community-focused farmlands throughout Washington DC and Maryland. Five rooftop farms covering over 8 000 m^2 of space have harvested about 27 000 kg of produce. The harvest was sold to neighbors and restaurants nearby (O'Keefe Kathleen, 2018).

Brooklyn Grange Rooftop Farms built rooftop farms on industrial buildings which cover totally 23 000 m^2 of growing space in New York City is another open air farm. According to Brooklyn Grange's report in 2020, their green roofs collect approximately a combined 19 000 000 liters of storm water each year (Brooklyn Grange, 2021) and use water drip irrigation (Harada *et al.*, 2018).

As the world's largest open air farm by now, a 14 000 m^2 complex urban rooftop farm in Paris has already started to bear vegetables and fruits, served in a farm-to-table mode across the city's Left Bank last year after two months delay due to the COVID-19 pandemic. The Nature Urbaine farm aims to produce about 1 000 kg of 35 different varieties of fruits and vegetables per day. In addition, the farm provides several services such as vegetable garden rentals for the public, visits for education or team-building workshops for firms. This soil-free inner city farm with sustainable and clean agriculture system was achieved by vertical aeroponic farming, with coconut fiber, mist and rainwater, which need 90 % less water than conventional agriculture, but which is rich in organic nutrients and minerals (Henley, 2020; Life & Soul Magazine, 2020; Oliver, 2020).

2.2.3 Rooftop gardens serving a restaurant, institution or shop

The Vinegar Factory is a private grocery store with a rooftop greenhouse located in Manhattan's upper east side in New York City. This 840 m^2 greenhouse offers tomatoes, salad greens and herbs grown traditionally in soil roof greenhouse (Criss, 2013).

2.2.4 Teaching research greenhouses

The Plant Growth Facilities (PGF) of the Department of Agricultural, Food, and Nutritional Science (AFNS) in Alberta, Canada, has nearly 1 350 m^2 of greenhouse space located on the upper floor of the Agriculture and Forestry Centre at University of Alberta, including 15 greenhouses, head house support area, as well as 18 cold frames located on the rooftop, with an additional 150 m^2 of open air growing space besides. This greenhouse is mostly for faculty to support plant growth research and education (AFNS Labs, 2021a, 2021b).

A rooftop greenhouse located in ICTA-ICP building in the Universitat Autònoma de Barcelona (UAB) is a research-oriented greenhouse. This project is set up by Urban Agriculture Laboratory (Manríquez-Altamirano *et al.*, 2020). The rooftop greenhouse uses soilless culture systems with integrating rainwater collection from the roof, residual heat from the building and higher CO2 concentration into the building's metabolism to improve food production and lower building energy use (Sanyé-Mengual *et al.*, 2014).

There are other types of rooftop greenhouses such as the Vida Verde floriculture company in Honselersdijk, the Netherlands. This company built a greenhouse on top of its logistics centre in 2012 for temporary plant nursery storage (Sanyé-Mengual *et al.*, 2015).

2.3 Technology for rooftop greenhouse (RTG)

2.3.1 How do the rooftop plant factories work?

A rooftop plant factory consists of a greenhouse built on the roof (Cerón-Palma *et al.*, 2012) and has similar working principles as conventional greenhouses. It is a structure intended for plant growth and vegetable and/or fruit production. By providing proper light conditions and warm temperatures, this kind of artificial environment even allows growing plants that would not normally survive in the harsh exterior climate, maximizing the "comfort" of plants and creating a favorable micro-climate (Beck, 2018).

Generally, many types of heat exchange occur simultaneously in the rooftop greenhouse (Figure 1). Near-infrared light passes through translucent panels such as glass or clear plastic, it can be absorbed by the plants or the opaque surface inside, and re-emitted as heat (long infrared wavelengths) in this process. The wavelength energy drives photosynthesis in green plants, or create glucose. Once the light is converted into heat, it stays inside the greenhouse and warms up the lower atmosphere. Then the longwave radiation cannot easily escape because the it is reflected by the glazing materials of rooftop plant factories. The trapped heat warms the inside air, raising the temperature in the rooftop plant factory (Beck, 2018; Connick, 2021). This is the process describing how plants receive sunlight and temperatures for growth.

When there is sufficient sunlight, especially in summer, the temperature in the rooftop plant factories may become much higher than the outside. Ventilation is needed for circulating and cooling the RTG throughout vents. When there is no sun, in order to maintain the temperatures in the rooftop plant factory, waste heat from the host buildings underneath can be utilized although additional heat sources are most often needed.

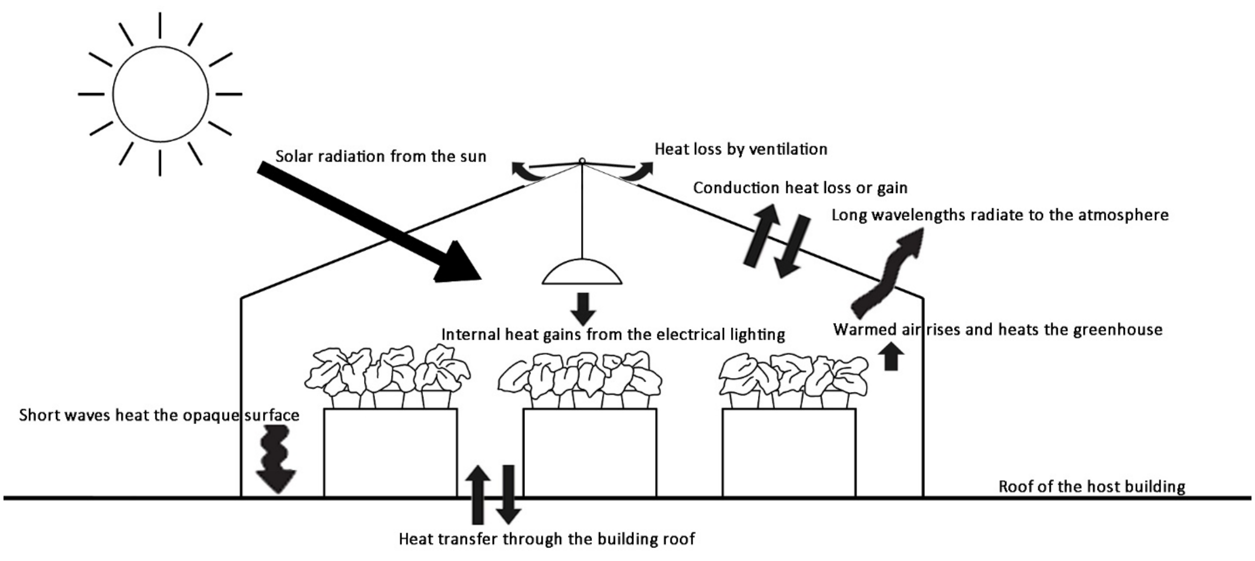

Figure 1: Examples of heat transfers in the rooftop greenhouse.

2.3.2 Ventilation

In practice, greenhouse ventilation provides functions as follows: control temperatures, dehumidification and indoor pollutants elimination (Gates and Duncan, 1999; J. A. Watson, 2019). There are two main ventilation methods. One is natural ventilation, the flow of air through the openings of greenhouses introduced by pressure differences caused by wind or different temperatures indoors and outdoors (Pérez Parra *et al.*, 2004). Another is mechanical ventilation, in which the hot air is replaced with cooler outside air by a number of fans (Flores-Velazquez *et al.*, 2014). Most of the commercial greenhouses use natural ventilation which is cheap and has low maintenance cost (Boulard and Draoui, 1995).

There is an optimum opening area ratio to reach the best air exchange rate. For multi-span/multi-tunnel greenhous structures with vertical sides and interconnected gutters, it ranges between 25 % and 33 % and for tunnels with well positioned openings, this ratio is about 20 % (Wacquant *et al.*, 2000).

During summer, 30 to 60 volume air change per hour is commonly accepted in a greenhouse for temperature and humidity control (Gates and Duncan, 1999; Revathi, Sivakumaran and Radhakrishnan, 2021).

2.3.3 Illumination

Illumination is essential for plant growth. Under a Nordic sky when the solar radiation is insufficient during the winter, greenhouses are equipped with electric supplemental lights to extend the illumination period, in order to improve the quality and production of crops (Nelson, 1991). The amount of light that the crops need varies according to crop category. For leafy greens & herbs such as lettuce, a target daily light integral (DLI) considered is 14-18 $mol \cdot m^{-2} \cdot d^{-1}$ (Runkle, 2021).

On an average day from March to September, natural light is sufficient to produce enough light for leafy greens. The most common high-pressure sodium (HPS) fixtures have efficiencies of1.66 to 1.70 $\mu mol \cdot J^{-1}$ (Nelson and Bugbee, 2014). The efficacy of Light Emitting Diode (LED) chips can reach up to 3.0 $\mu mol \cdot J^{-1}$ (Kusuma, Pattison and Bugbee, 2020), which represents a great optimization of the energy efficiency. According to (Kaukoranta, 2017), the average LED grow light of the leafy greens has a luminous efficacy of 90 to 100 $W \cdot m^{-2}$.

3. Aim of this research project, research questions and objectives

Given the potential of urban rooftop farming (URF) as discussed in the previous sections, it seems imperative to start investigating how this type of solution and technology could be implemented in the Nordic context. This solution is of particular interest for Sweden, as more than 85 % of the Swedish population currently lives in urban areas (URBACT, 2014). Developing rooftop urban farming solutions thus has a potential to provide fresh food to the vast majority of Swedish urban dwellers. Studies indicated that the northern part of Sweden is the region most threatened by disruptions of the food supplier chain as it 'lies in a sub-arctic climate area that is difficult to cultivate during the winter', according to Rizzo *et al.* (2018). The author of this study also claimed that the challenge to produce food within cities located in cold climate regions is greater. However, it can be argued that, on the contrary, that the rather mild summers of Scandinavia provide optimal conditions for growing vegetables, while the winter condition may be mitigated by using closed rooftop greenhouses (RTG), which may benefit from heat losses from the host building, as demonstrated in the present study.

As a key milestone in this endeavour, the next part of this thesis presents a study about rooftop greenhouses (RTGs) in the Swedish climate, focusing mainly on the energy issue. The main goal of this study is to analyse the impact of the RTG on energy use of an existing building, which in this case is a typical large warehouse store. The research questions examined in this project are stated below:

- Does the RTG affect energy use of the host building and to what extent?
- Does the host building affect energy use of the RTG and to what extent?
- Which aspects regarding materials (glazing properties), shading devices (position and properties) yield the lowest energy use?

The main hypotheses of this research are stated below:

- Both systems (RTG and warehouse) benefit from each other in a synergistic manner i.e. the RTG reduces energy use in the host building by providing solar protection in the summer and a heat buffer in the winter.
- On the other hand, the host building contributes to reduce the RTG's heating demand compared to a greenhouse stand-alone (on ground).

- Glazing and shading properties are important parameters affecting energy use of the integrated RTG-warehouse solution.

4. Methodology

4.1 Methodology framework

This study investigates the effect of RTG on energy use, including heating, cooling and electricity lighting, when placed on a typical warehouse superstore. In this case, a warehouse in Malmö was used as a host building. The research methodology consists of various phases: warehouse building model description and validation, greenhouse design and simulation, analysis as shown in Figure 2:

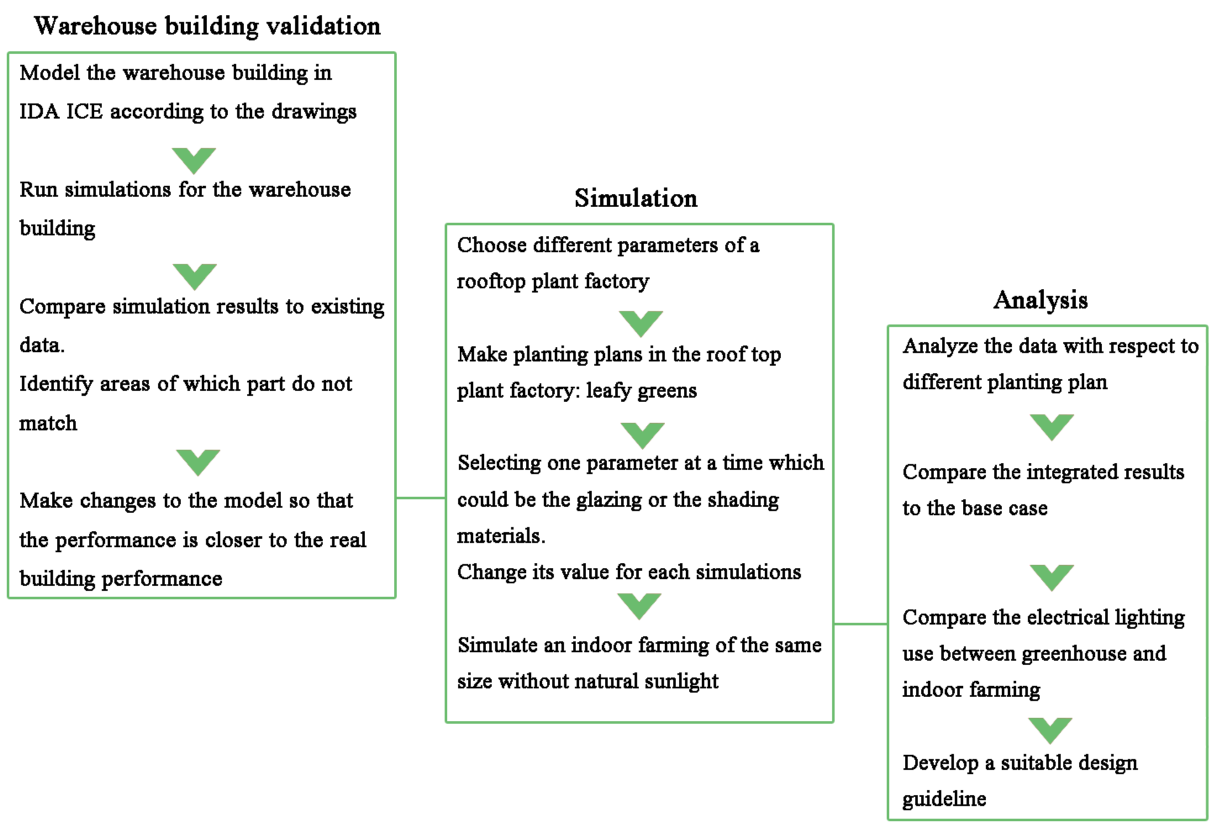

Figure 2: Methodological framework for this study.

This study is mainly achieved using advanced energy simulations. The main purpose of the energy simulations was to study the impact of the RTG on energy use of the host building and that of the RTG on the host building. The simulations considered were thus:

1. Warehouse energy use without the RTG;
2. Warehouse energy use with the RTG;
3. RTG energy use without the warehouse as stand-alone system i.e. on the ground;

4. RTG energy use when located on top of the warehouse.

However, the impact on energy use of RTG depends on various parameters such as insulation, orientation, glazing properties, shading system, ventilation (natural, hybrid), electric lighting, indoor temperature set points, soil depth, vegetation type and design of greenhouse structures. Therefore, several parameters had to be studied and analysed using IDA-ICE energy simulation software to determine the level of impact on a simulated rooftop greenhouse, and the warehouse building underneath. Due to time constraints, a limited number of parameters could be considered in this study:

Type of crop cultivated (which affects electric lighting and temperature set points);

- Glazing materials of the roof;
- Glazing materials of the sidewalls;
- Shading devices (position and properties).

A combination of 18 different RTG were investigated.

4.2 Simulation tools

The IDA Indoor Climate and Energy (IDA-ICE version 5.0) simulation software was used in this study, as it is one of the main building energy simulation programmes available today (Crawley *et al.*, 2008). This program is widely used within engineering practice in Scandinavia. It relies on inputs regarding building geometry, construction materials, HVAC conditions, as well as internal heat loads (mainly referring to lighting, equipment, and occupancy), providing a more detailed calculation of the distribution of solar radiation in and between different zones. According to different weather data, IDA-ICE can calculate the energy use dynamically, which means that input to the program is changing hour by hour and the thermal response is also reacting dynamically, including effects of solar radiation and thermal mass, ventilation, lighting, internal heat loads, etc.

4.3 Climate conditions in Malmö

The simulations were performed using a climate file for Malmö (latitude 55.6°N, longitude 13.0°E). The city of Malmö is located in the southern part of Sweden, and it thus has a relatively mild continental climate compared to most other locations in Sweden. The average temperatures vary from 0°C to 18°C during the year (World Climate Guide, 2021). The sunrise and sunset times differ significantly between seasons (Figure 3) (sunrise-and-sunset.com, no date).

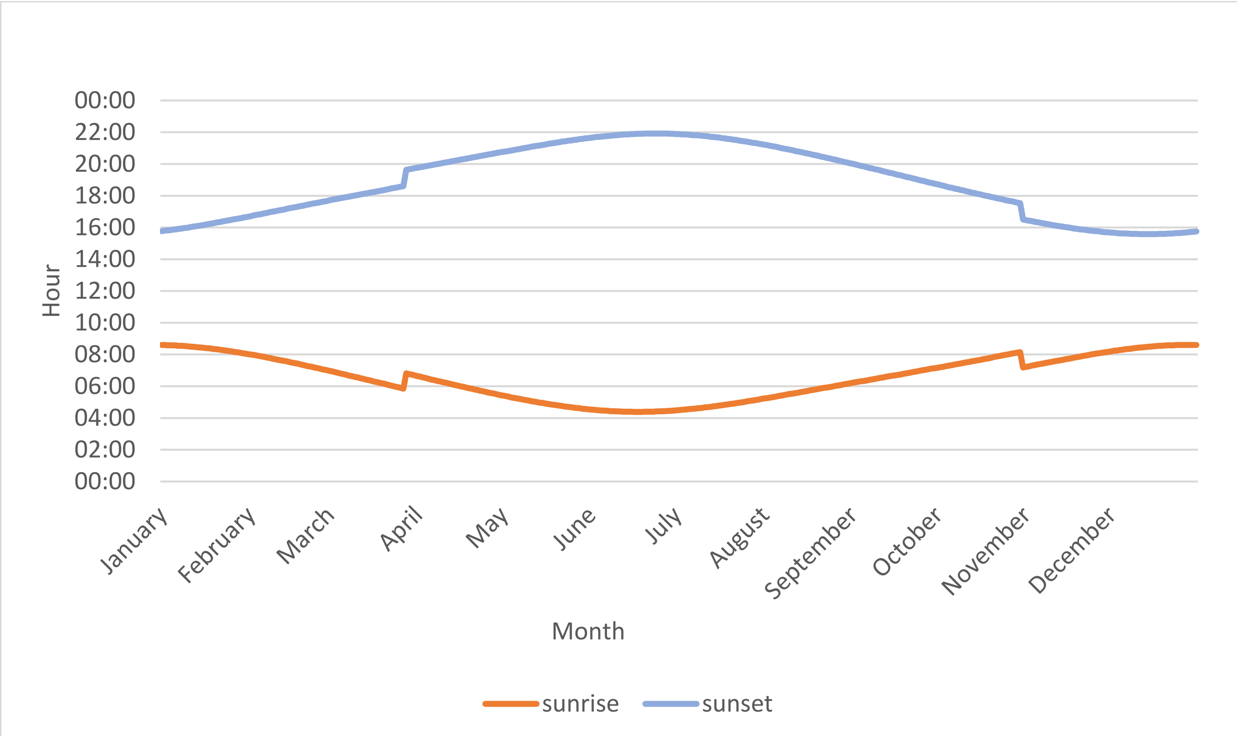

Figure 3: Sunrise and sunset according to civil time, Malmö, Sweden. Irregularity in the curves are due to summer time.

The average outdoor daily integral (DLI) in Malmö during the darkest winter season can be as low as 5.0 mol·m^{-2} on a cloudy day (Table 1, Agronomist, 2021). The DLI describes the number of photosynthetically active photons (individual particles of light in the 400 nm - 700 nm range) that are delivered to a specific area over a 24-hour period (Bula *et al.*, 1991; Faust *et al.*, 2005). This variable is particularly useful to describe the light environment of plants.

Also relevant to the design, it was considered that the prevailing wind directions in the summer in Malmö is from the West (Figure 4), while it is from South- Southwest throughout the whole year. This aspect needs to be considered to provide the best conditions for cross ventilation in the summer.

Table 1: The average outdoor daily integral (DLI) and DLI inside the greenhouse in Malmö, source Agronomist (2021).

	Average Daily DLI (mol·m^{-2})		
	outdoors cloudless sky	outdoors cloudy day	Inside greenhouse at plant canopy, cloudy day
January	8.1	4.4	3.0
February	15.4	8.4	5.7
March	27.6	15.0	10.2
April	42	22.8	15.6
May	53.7	29.2	20.0
June	59.2	32.1	22.0
July	56.5	30.7	21.0
August	46.5	25.2	17.3
September	32.6	17.7	12.1
October	19.1	10.4	7.1
November	9.8	5.3	3.6
December	6.2	3.4	2.3

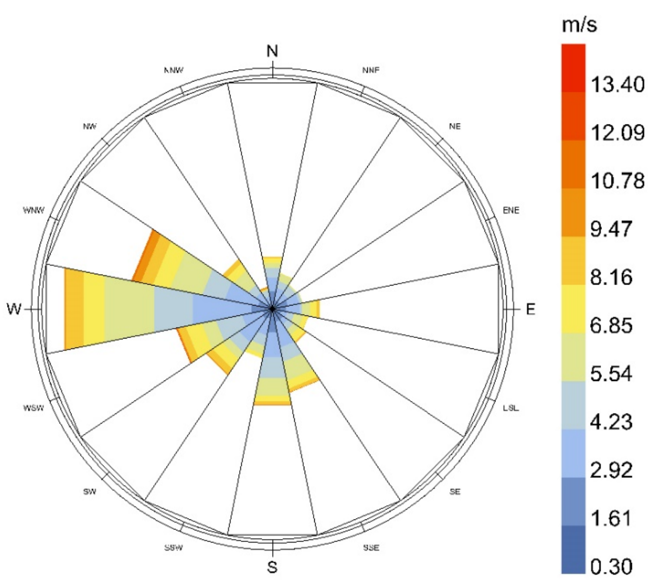

Figure 4: Wind rose for Malmö during summer period.

4.4 Building description and validation

The warehouse studied was a typical, three-storey warehouse type superstore built in 2009, with a total built area of 44 000 m^2 (Figure 5). The warehouse measured 220 m by 134 m on the ground, with the long facades parallel to the East-West axis. The total building height was 39.5 m. This type of warehouse provides a large area to host a RTG. A model of the building (Figure 6) was created accurately in IDA ICE according to the drawings and specifications provided by the building owner.

Figure 5: Warehouse studied..

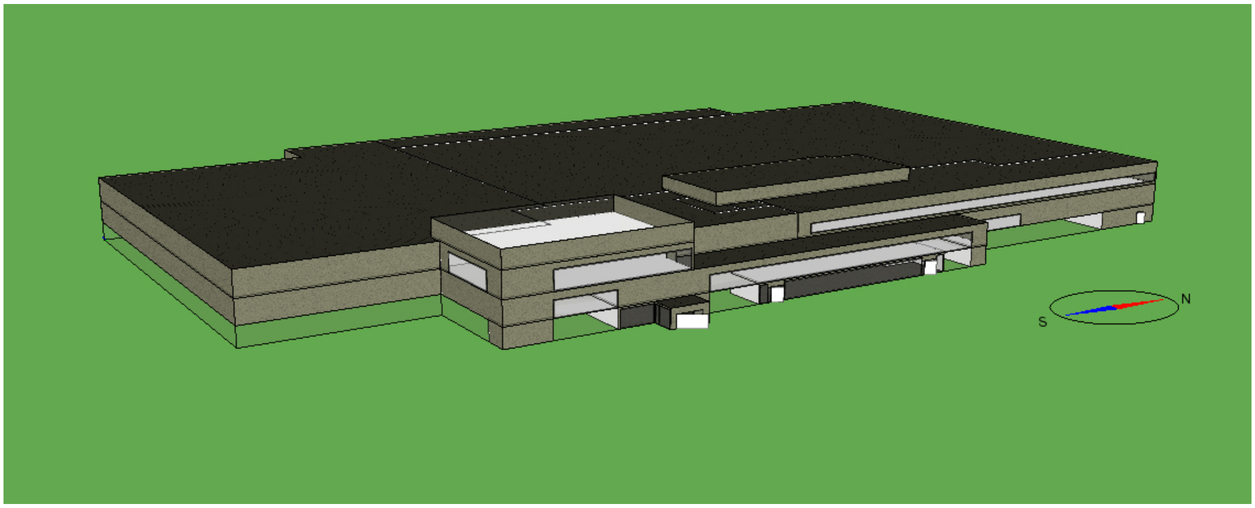

Figure 6: The IDA ICE model of the warehouse.

The base case simulation results were compared to the building energy use data collected for the real building in Malmö. The set points and efficiency of the basic building systems were described in the model as shown in Table 2. The properties of the glazing is shown in Table 3, and properties of constructions are shown in Table 4.

Table 2: Input data of IKEA building model in IDA-ICE.

Climate data	SWE_MALMO-STURUP_026360(IW2)
Wind profile	Default urban
Heating type	Electric (COP=1)
Cooling type	Electric (COP=1)
Domestic hot water type	Electric (COP=1)
Heating setpoint	18.0 °C
	0.0 °C (Freezer zone)
Cooling setpoint	25.0 °C
	5.0 °C (Freezer zone)
AHU type	Variable air volume (VAV)
Occupancy Schedule	Monday - Friday: 10:00 – 20:00
	Saturday - Sunday: 10:00 – 19:00

Table 3: Glazing properties of the warehouse (3 pane glazing, 4-12-4-12-4).

Solar heat gain coefficient (g)	0.49
Solar transmittance (t)	0.27
Visible transmittance (Tvis)	0.27
Emissivity	0.837
U-value	1.3 $W/m^2 \cdot K$

Table 4: Construction details of the warehouse. The U-value of each material is the value of thermal transmittance when the construction is consisted of the one only kind of material (including outside and inside surface resistance in calculation process). The total U-value of each construction takes into consideration of the sum of those of all its layers plus the inside and outside surface resistances.

Name	Material	Thickness [m]	U-value [$W/m^2 \cdot K$]
External walls	Render	0.03	4.82
	L/W Concrete	0.45	0.32
	Render	0.03	4.82
	Total	0.51	0.31
Internal walls	Gypsum	0.03	3.47
	Air in 30mm vert. air gap	0.03	2.79
	Light insulation	0.03	1.00
	Air in 30mm vert. air gap	0.03	2.79
	Gypsum	0.03	3.47
	Total	0.15	0.62
Internal floors	Render	0.04	4.55
	Wood	0.28	0.46
	Total	0.32	0.45
Roof	Concrete	0.15	3.87
	Light insulation	0.17	0.20
	Total	0.32	0.20
Slab towards ground	Wood	0.04	2.38
	Light insulation	0.06	0.54
	Concrete	0.25	3.15
	Total	0.35	0.45

The building was divided into different thermal zones according to different functions (see Appendix A, Figure 18), with different internal loads corresponding to schedules of occupancy, lighting, and equipment. Inputs of HVAC, lighting density and equipment load details are shown in Table 5 - 7.

Table 5: HVAC and schedule of warehouse building inputs.

Zone	Minimum air supply/return [L/s·m^2]	Max air supply/return [L/s·m^2]	HVAC schedule
Entrance	0.35	1	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Hall	0.35	1	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Showroom	0.35	1	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Self serve	0.35	1	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Technical space	0.35	0.36	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Checkout/Exit	0.35	1	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Restaurant	0.35	1	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Kitchen	0.35	1	Monday - Friday: 10:00 - 20:00 Saturday - Sunday: 10:00 - 19:00
Freezer/Refrigerator	0.35	1	Always on
Office	0.35	1	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Stair	0.35	0.36	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Equipment	0.35	0.36	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00

Table 6: Lighting power density and schedule of warehouse building inputs.

Zone	Lighting power density[W/m^2]	Lighting schedule
Entrance	4.6	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Hall	9.9	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Showroom	9.5	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Self serve	4.1	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Technical space	3.0	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Checkout/Exit	9.4	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Restaurant	4.2	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Kitchen	12.0	Monday - Friday: 10:00 - 20:00 Saturday - Sunday: 10:00 - 19:00
Freezer/Refrigerator	2.0	Monday - Friday: 10:00 - 20:00 Saturday - Sunday: 10:00 - 19:00
Office	3.5	Monday - Friday: 10:00 - 20:00 Saturday - Sunday: 10:00 - 19:00
Stair	2.0	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00
Equipment	2.0	Monday - Friday: 09:00 - 21:00 Saturday - Sunday: 09:00 - 20:00

Table 7: Equipment load and schedule of warehouse building inputs.

Zone	Equipment load [W/m^2]	Equipment Load [W/m^2]
Entrance	27.5	Monday - Friday: 10:00 - 20:00 Saturday - Sunday: 10:00 - 19:00
Hall	5.0	Monday - Friday: 10:00 - 20:00 Saturday - Sunday: 10:00 - 19:00
Showroom	5.0	Monday - Friday: 10:00 - 20:00 Saturday - Sunday: 10:00 - 19:00
Self serve	/	/
Technical space	/	/
Checkout/Exit	5.0	Monday - Friday: 10:00 - 20:00 Saturday - Sunday: 10:00 - 19:00
Restaurant	/	/
Kitchen	400.0	Monday - Friday: 10:00 - 20:00 Saturday - Sunday: 10:00 - 19:00
Freezer/Refrigerator	250.0	Always on
Office	3.0	Monday - Friday: 10:00 - 20:00 Saturday - Sunday: 10:00 - 19:00
Stair	/	/
Equipment	5.0	Always on

4.5 Rooftop greenhouse design

The thermal effects of the rooftop and space underneath depend on the percentage of rooftop area covered and on shading throughout the year (Orsini *et al.*, 2017). To reach the highest energy savings for the warehouse, the largest coverage of the RTG was considered in the present study. With regards to greenhouse orientation, according to different studies conducted on greenhouses, an East-West orientation can maximize sunlight in the winter, especially in North Europe due to a better daily light transmission (Bot, 1983), and according to the predominant wind direction of

West in Malmö during summer, this would also contribute to improve cross ventilation. In this study, a prevailing Venlo type structure measuring 73.6 m by 216.0 m with the long axis in an East-West direction was modelled. A setback of 2 m on each side of the warehouse roof edge wasreserved for maintenance (See Appendix B, Figure 19). The total area of the greenhouse was thus 15 898 m^2, which is considered as an ideal size for RTG by Eagle Street Rooftop Farm (Ackerman, Dahlgren and Xu, 2013).

The typical Venlo structure has a standard roof width of 3.2 m, with a 4.5 m post height, and additional 1 m to the gable (Figure 7).

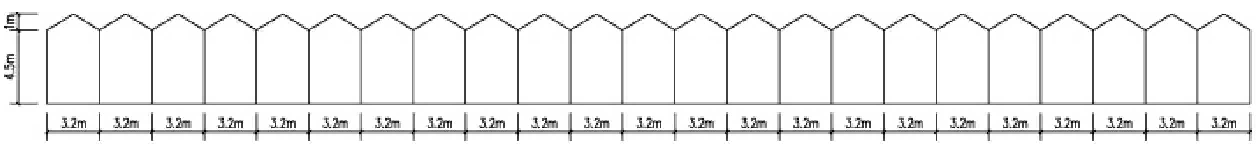

Figure 7: Venlo type structure of the greenhouse.

For the covering materials, single pane clear glass is recommended due to its lightweight and good light transmittance. There are other glazing materials such as acrylic and polyvinyl chloride sheets but these could not be tested due to time constraints.

Therefore, in the base case, the greenhouse was modelled with a single pane, tempered glass roof and double pane, tempered glass sidewalls. The properties of these glasses were the default values in IDA ICE software (Table 9). The frame area was automatically calculated in IDA ICE (10 %). The greenhouse foundation consisted of a 10 cm lightweight concrete slab (Greenhouse Solutions, 2015) with a U-value of 1.2 W/m²·K.

For the leafy greens, the heating and cooling set points were 16°C and 21°C for winter and summer respectively, which is the optimum temperature for crops such as lettuce (Aldrich and Bartok, 1994; Goldammer, 2019). The heating and cooling operation was produced by electricity, with a coefficient of performance (COP) of 1 independent of the mechanical ventilation system. Air exchanges inside the greenhouse were achieved by openings in the ceiling connected with a proportional integral (PI) temperature control system. Forty percent (40 %) of the roof glazing had openings, which allowed using natural ventilation to reduce overheating during the warm seasons. In other words, part of the cooling was achieved using natural ventilation.

Regarding the lighting density, we had to consider that this aspect varies according to type of crops. Leafy greens and herbs were studied in this research. The target daily light integral (TDLI) is usually 14-18 $mol \cdot m^{-2} \cdot d^{-1}$ (Morgan, 2016; Runkle, 2021), and the light efficacy (LE) of LED chips used in greenhouses can reach up to 3 $mol \cdot J^{-1}$ (Kusuma, Pattison and Bugbee, 2020). Assuming an operation time of 12 hours per day, the light power density (LPD) can be calculated with the following equations:

$$LPD = TDLI/LE \qquad (1)$$

$$LPD = 14\ mol \cdot m^{-2} \cdot d^{-1} / (3.0 \cdot 10^{6}\ mol \cdot J^{-1} \cdot 12 \cdot 3600\ s \cdot d^{-1}) = 108\ W \cdot m^{-2} \qquad (2)$$

According to the climate conditions in Malmö, crops receive less than four (4) hours average daily sunshine in the winter. Based on the DLI inside greenhouse at plant canopy, the operation time (OP) of electric lighting (considering the efficiency of 3.0 $\mu mol \cdot J^{-1}$, thus 108 $W \cdot m^{-2}$) for each month during winter was estimated based on the equation provided by Nederhoff and Marcelis (2010):

$$OP = (TDLI - DLI_{\_inside\ greenhouse\ cloudy})/(3.0 \cdot 10^{-6}\ mol \cdot J^{-1} \times LPD_{leafy\ greens} \times 3600\ s) \qquad (3)$$

Where the TDLI value for leafy greens is considered 14 $mol \cdot m^{-2} \cdot d^{-1}$, during heating seasons the mean indoor DLI is the value inside the greenhouse on a cloudy day at canopy level. The cloudy condition was used in the calculations since this climatic condition is dominant in Sweden in the winter (October-March) when electric lighting is needed. The lighting schedule was based on the sunrise and sunset time for Malmö, extending the illumination period from October to March, with the aim to achieve TDLI value for the leafy greens. From these values, the operation time (OP) for electric lighting and schedule was estimated as shown in Table 8.

The main internal gains considered in the greenhouse were gains from the electric lighting. No equipment was considered in this study. Other aspects such as irrigation, plant evapotranspiration and humidification were not either considered in the simulations.

Table 8: Extra illumination needs per day, operation hours and schedule for each month.

	Extra lighting need per day ($mol \cdot m^{-2} \cdot d^{-1}$)	Operation hours of artificial lighting ($h \cdot d^{-1}$) (outdoors cloudy day)	Lighting schedule
January	11.0	9.43	04:30 - 08:30, 16:30 - 22:00
February	8.3	7.12	04:30 - 07:30, 17:00 - 21:30
March	3.8	3.26	04:30 - 06:30, 17:30 - 19:00
April	0.0	0.00	-
May	0.0	0.00	-
June	0.0	0.00	-
July	0.0	0.00	-
August	0.0	0.00	-
September	0.0	0.00	-
October	6.9	5.92	05:30 - 07:30, 18:00 - 22:00
November	10.4	8.92	05:00 - 08:00, 16:00 - 22:00
December	11.7	10.03	05:00 - 08:30, 15:30 - 22:00

For low-density crops, the normal arrangement consisted of main passages of 4 m and secondary passage of 1 m between the rows (see Appendix C, Figure 20). As a consequence, the total coverage of electric lighting fixtures was about 60 %, which means that from the original 108 $W \cdot m^{-2}$ for the leafy greens, only 65 $W \cdot m^{-2}$ (60 % of 108 $W \cdot m^{-2}$) were considered in the simulations. Gómez *et al.* (2013) concluded that the supplementary lighting returns a great share of energy as heat (by 15 % to 41 %). In other studies, it was found that the LED lamps can provide up to 75 % of the heating needs (Castilla, Baeza and Papadopoulos, 2012). Note also that the electric lighting is used only in the heating season. Therefore, a large share of the energy use for lights is converted into heat and saves part of the heating energy demand. This will become explicit in the case of indoor farm presented in the section on electric lighting.

4.6 Indoor farm design

As a measure of comparison, it was then investigated the cultivation of leafy greens in an indoor urban farm on the roof of the warehouse with the same area and volume as the proposed RTG. For these simulations, the U-values of the envelope was the same as the warehouse building. In this case, all illumination needs are covered by electrical lighting due to the opaque envelope. Therefore, under the same arrangement inside the indoor farm, the lighting density is the same as in the greenhouse. The electric lighting operation time was 12 hours per day, from 6:00 to 18:00 hours. The controlled temperature was the same as the RTG, and a mechanical ventilation system was introduced instead of natural ventilation. This additional simulation was conducted to investigate the energy use for lighting in an indoor farm and compare it to the case of RTG.

4.7 Simulation and state variables for rooftop greenhouse

Simulation phase was that phase in which the warehouse was stand alone compared with it was modeled with a RTG, and a greenhouse built on the ground compared with the RTG.

4.7.1 Glazing materials

Several glazing materials were studied. Firstly, different types of roof materials were investigated: single pane, tempered glass, and polycarbonate. Simulations were also performed using glass coated with low emissivity (low-e) reflective coatings, in order to test different insulating properties. The sidewall materials were also changed from double pane, tempered glass to double pane, low-e glass. Note that in these simulations, the effect of different glazing materials with different visible transmittance on LPD was not considered (base case LPD was used throughout the simulations). Additionally, in the first round of simulations, each glazing type was modelled without any dynamic shading device, in order to isolate the effects of different glazing materials.

For the greenhouse envelope material, each greenhouse was named after the U-value of the envelope and the Solar Heat Gain Coefficient (SHGC) in parenthesis. For the glazing material study, the case names are presented as: U-value of the roof (SHGC of the roof)_U-value of the sidewalls (SHGC of the sidewalls). G stands for greenhouse, W stands for warehouse. For example, for the case G_5.8(85)_2.9(76), the number 5.8 represents the U-value of the roof glazing (5.8 $W/m^2 \cdot K$), 85 is the SHGC of the roof glazing, and 2.9 is the U-value of the sidewalls (2.9 $W/m^2 \cdot K$), 76 is the SHGC of the sidewalls. W_5.8(85)_2.9(76) refers to the warehouse integrated with a G_5.8(85)_2.9(76) RTG.

Table 9 shows the properties of different glazing types.

*Table 9: Properties of glazing materials in the simulation. Low-e glass data is taken from Pilkington (NSG Group, no date). Polycarbonate data is taken from Polükarbonaat (*Polükarbonaat.ee - Instructions and certificates*, no date).*

Glazing type	Thickness	Solar heat gain coefficient (SHGC)	Solar transmittance (T)	Visible transmittance (Tvis)	U-value ($W/m^2 \cdot K$)	Emissivity
Single pane tempered glass	4mm	0.85	0.83	0.90	5.8	0.84
Polycarbonate	4mm	0.83	0.79	0.83	4.0	0.92
Single pane low-e glass	4mm	0.77	0.73	0.84	3.7	0.15
Double pane tempered glass	20mm (4+12+4)	0.76	0.70	0.81	2.9	0.84
Double pane low-e glass	24mm (6+12+6)	0.70	0.68	0.76	1.8	0.15

4.7.2 Shading types

After developing the models with different building envelopes, two different shading solutions were studied: 1) light, lightly woven internal screen, and 2) external blind. The shading system was operated when a specific radiation level (100 $W \cdot m^{-2}$) was reached on the outer surface of the greenhouse roof. A total of 12 simulations were performed in this second round of simulations. The properties of shading materials are listed below (Table 10):

Table 10: The properties of different shading materials.

	Light, lightly woven internal screen	External blind
Multiplier for g (Total solar transmittance)	0.71	0.14
Multiplier for T(Short wave shading coefficient)	0.67	0.09
Multiplier for U-value	0.87	1
Diffusion factor	1	1

The parameters indicate the effects of shading solution in combination with the glazing (EQUA Simulation AB, 2013). When the shading is drawn, the effective parameters can be calculated according to equation (4) to (6):

$$g_{effective} = g_{glazing} \times multiplier\ for\ SHGC \quad (4)$$

$$T_{effective} = T_{glazing} \times multiplier\ for\ T \quad (5)$$

$$U_{effective} = U_{glazing} \times multiplier\ for\ U \quad (6)$$

Table 11 shows the summary of all simulations.

Table 11: Summary of all simulations.

	Roof glazing material			Sidewall glazing material		Shading type		
	Single pane tempered glass	Polycar bonate	Single pane low-e glass	Double pane tempered glass	Double pane low-e glass	No integrated shading	Light, lightly woven internal screen	External blind
G_5.8(85)_2.9(76)	■			■		■		
G_5.8(85)_2.9(76)_In	■			■			■	
G_5.8(85)_2.9(76)_Ex	■			■				■
G_4.0(83)_2.9(76)		■		■		■		
G_4.0(83)_2.9(76)_In		■		■			■	
G_4.0(83)_2.9(76)_Ex		■		■				■
G_3.7(77)_2.9(76)			■	■		■		
G_3.7(77)_2.9(76)_In			■	■			■	
G_3.7(77)_2.9(76)_Ex			■	■				■
G_5.8(85)_1.8(70)	■				■	■		
G_5.8(85)_1.8(70)_In	■				■		■	
G_5.8(85)_1.8(70)_Ex	■				■			■
G_4.0(83)_1.8(70)		■			■	■		
G_4.0(83)_1.8(70)_In		■			■		■	
G_4.0(83)_1.8(70)_Ex		■			■			■

G_3.7(77)_1.8(70)			■		■	■		
G_3.7(77)_1.8(70)_In			■		■		■	
G_3.7(77)_1.8(70)_Ex			■		■			■

5. Results and analysis

In the first step, the warehouse was modelled alone as the base case, while the greenhouse was modelled separately as a structure on the ground. In the next step, the greenhouse was built on the roof of the warehouse for the integrated cases.

On completion of all simulations, the heating and cooling demand of the warehouse and greenhouse were analyzed both separately, and then as an integrated model, i.e. as stand-alone structures (greenhouse on the ground, warehouse stand-alone) and as a building-integrated system (RTG integrated with warehouse). An analysis of the stand-alone cases of greenhouse allow for an evaluation of which materials and shading solutions are the most beneficial in terms of energy use. An analysis of the integrated building energy use for heating and cooling indicate whether there is an overall benefit of integrating both structures.

5.1 Base case results of warehouse building

In order to calibrate simulation results of the base case warehouse model, the energy use obtained with IDA ICE (using a climate file for year 2012) was compared to the data from the energy declarations in 2012 (Boverket, 2012). The energy modelling software calculated that the energy intensity of the warehouse was 88 kWh/m^2 in 2012, which represents a 14.2 % deviation with respect to the annual energy use of 77 kWh/m^2 reported in the energy declarations of the same year. This deviation was judged acceptable given the complexity of the model and also, the anticipated differences between simulations and reality (normally at least 20 %). In the energy declarations, the total energy use was 3 216 180 kWh/y, of which 1 040 200 kWh/y was for heating and 887 900 kWh/y was for cooling. The heating demand reported in the energy declarations include zone heating and AHU heating, and the same for the cooling demand. In the base case simulations, the results obtained for total heating demand was 723 846 kWh/y and 654 129 kWh/y for cooling. These results are summarized in Table 12:

Table 12: Base case of warehouse building energy results obtained with simulation for year 2012.

Meter	Energy use [kWh]	Energy intensity [kWh/m^2·y]
Lighting, facility	1 204 986	27.3

Equipment, tenant	979 039	22.1
Zone heating	343 990	7.8
Zone cooling	411 105	9.3
AHU heating	379 856	8.6
AHU cooling	243 024	5.5
HVAC aux	327 719	7.4
Total heating (including zone heating and AHU heating)	723 846	16.4
Total cooling (including zone cooling and AHU cooling)	654 129	14.8
Total	3 889 716	88.0

In the next step, another series of simulations was performed for year 2021, which is a future, typical meteorological year weather data for simulations embedded in IDA ICE. The results are presented in Table 13.

Table 13: Base case of warehouse building energy results obtained with simulations for year 2021.

Meter	Energy use [kWh]	Energy intensity [kWh/m^2·y]
Lighting, facility	1 204 986	27.3
Equipment, tenant	979 039	22.1
Zone heating	340 737	7.7
Zone cooling	410 645	9.3
AHU heating	386 922	8.8
AHU cooling	243 619	5.5
HVAC aux	326 922	7.4
Total heating (including zone heating and AHU heating)	727 658	16.5
Total cooling (including zone cooling and AHU cooling)	654 264	14.8
Total	3 892 869	88.0

5.2 Energy performance of the RTG

After the base case results of both the warehouse stand-alone and greenhouse on the ground were established, the energy intensity of the warehouse plus RTG was examined, using different glazing materials for the sidewalls and greenhouse roof. The results are discussed in the next section.

5.2.1 Effect of glazing materials

Different glazing materials were studied for the greenhouse on the ground and RTG. The results of the simulations indicated that the integrated RTG led to a reduction of the annual heating and cooling demands for the greenhouse itself compared with the case on the ground. For the warehouse, the effect of the RTG was an increase in cooling demand but a reduction in heating demand for the integrated RTG compared to the warehouse as stand-alone. These results are presented in Figure 8 to Figure 11.

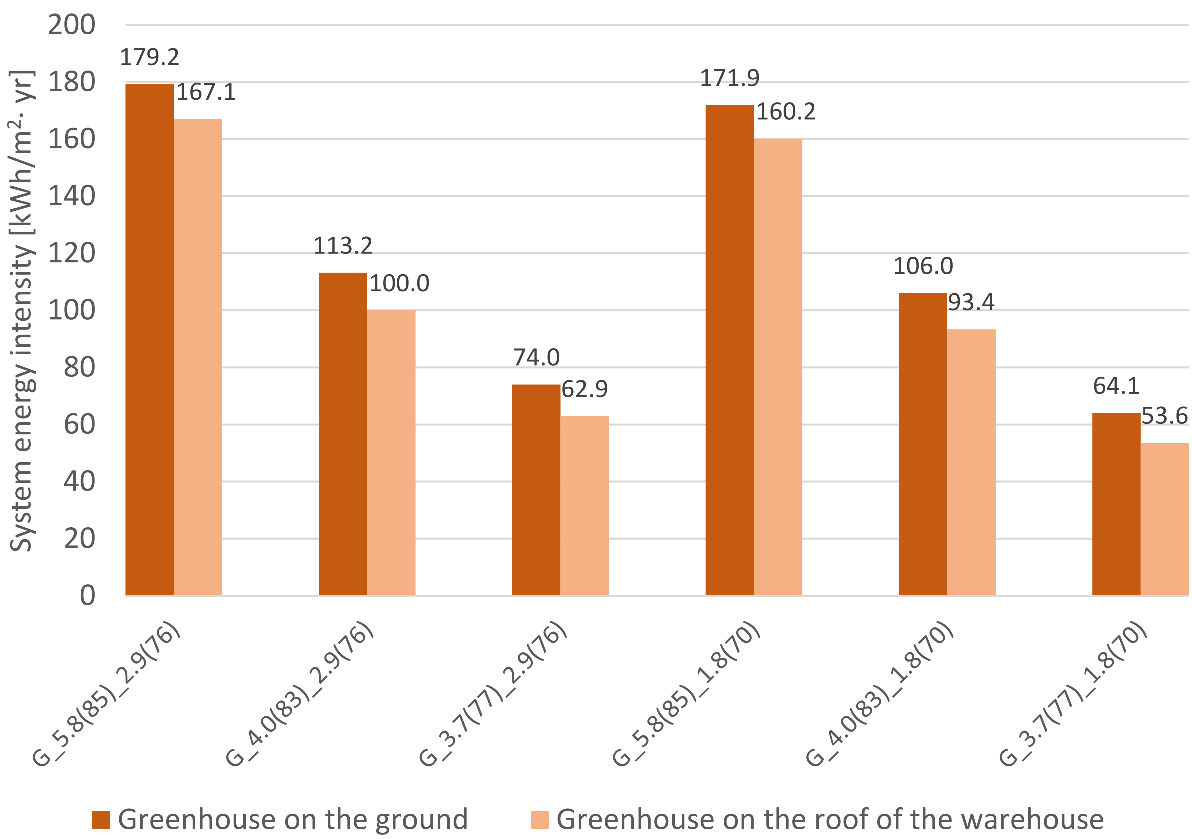

Figure 8: Annual heating demand of the greenhouse stand-alone and as RTG with different glazing materials.

Figure 8 shows the heating performance comparison for greenhouse with different glazing materials without shading devices. These results indicate a reduction of the energy intensity following a similar trend between the cases. This reduction may be attributed to the heat provided by the host building. The results indicate that a RTG with single pane tempered glass roof and double pane tempered glass sidewalls (G_5.8(85)_2.9(76)) resulted in the highest heating demand and allowed savings on the heating demand of around 3 % compared to the case on the ground. On the other hand, a RTG with the lowest U-value (U_3.7(77)_1.8(70)) yielded a significantly lower heating demand, with relative energy savings for heating of 15 % compared to the case on the ground.

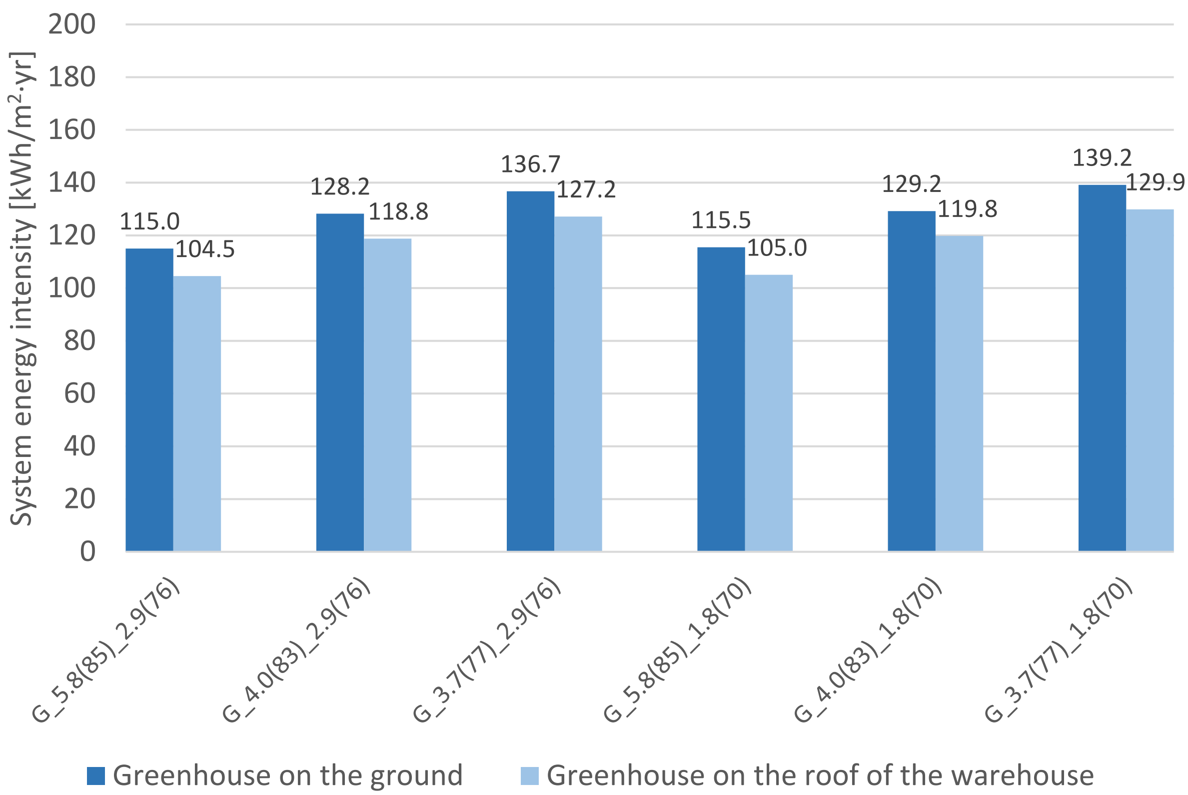

Figure 9: Annual cooling demand of the greenhouse as stand-alone and as RTG with different glazing materials.

Figure 9 shows the cooling energy intensity for the greenhouse with different glazing materials. The cooling energy demand increases with decreasing glazing U-value despite a decreasing SHGC, which is an unexpected result. This means that it is the glazing U-value which is dominating the effect on cooling in this case. In order to test the SHGC effects in cooling demand of the greenhouse, the SHGC of the polycarbonate and the single pane low-e glazing was set to a lower value, from G_4.0(83)_2.9(76) to G_4.0(60)_2.9(76), G_3.7(77)_2.9(76) to G_3.7(40)_2.9(76), the trend of cooling demand reverses (Figure 10).

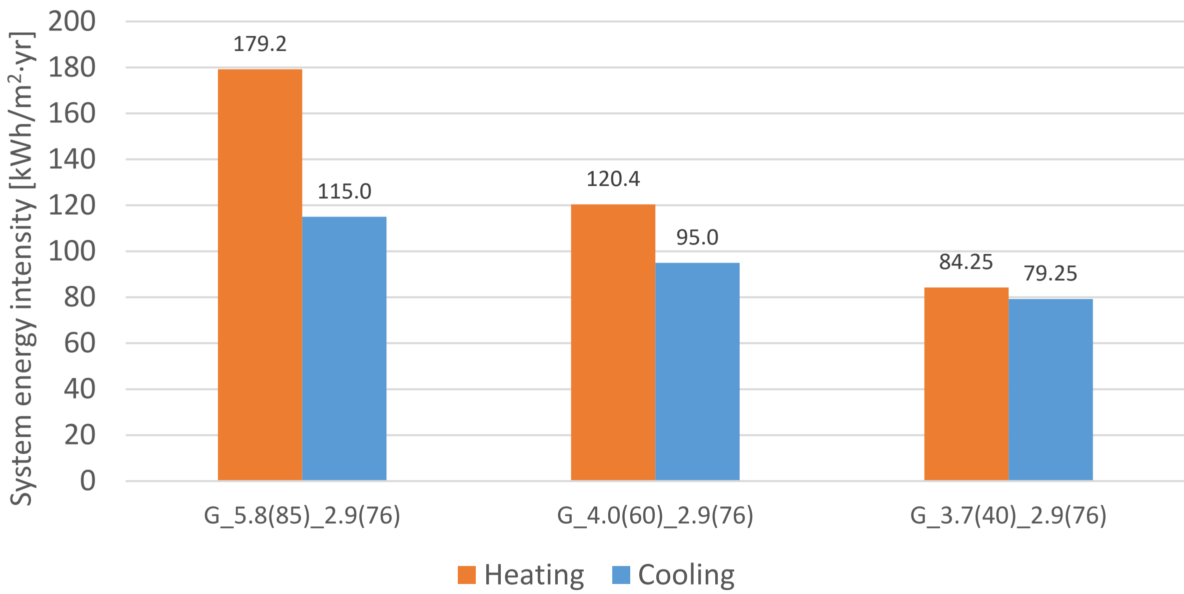

Figure 10: Heating and cooling demand of the greenhouse stand-alone with different glazing materials with a lower SHGC.

The cooling demand depends on the solar heat gain coefficient (SHGC) and conduction heat losses (U-value). Energy balance in a building is the systematic accounting of all energy flows (including heat gains and heat losses). In summer, there is no electric lighting and equipment, the occupancy is ignored in this case, so the main heat gains is the solar radiation. The main heat loss is the conduction between the greenhouse to the outside ambient, besides the natural ventilation. The cooling demand of the greenhouse can be calculated according to equation (7):

$$Q_{cooling} = Q_{solar\ heat\ gains} - Q_{heat\ losses} \qquad (7)$$

where

$Q_{solar\ heat\ gains} = Solar\ radiation \times SHGC \times Area_{glazing}$

$Q_{heat\ losses} = U\text{-}value \times Area_{glazing} \times \triangle T$

Solar heat gains occur during daytime when there is sunlight. Convection, radiation as well as conduction heat losses occur when the outside air temperature is lower than the inside air temperature, especially during night, morning and evening hours. The lower the SHGC, the less solar heat it transmits in the greenhouse. The lower the U-value, the less heat the greenhouse envelope conducts from inside to outside. But the change range of the two variables is not the same. Therefore the cooling demand depends on both the U-value and the SHGC of the glazing materials.

Placing the greenhouse on top of the warehouse yields a 7 % to 9 % reduction of annual cooling demand. This reduction may be due to an increase in wind speed with higher greenhouse position, which is considered in the simulations. This increase in airflow through openings results in a lower cooling demand. In the simulation program IDA ICE, the wind speed is zero on the ground and reaches a higher speed proportional to the height. According to the program information, the wind speed at a certain height is calculated according to equation (8):

$$V = V_{measured} \times A_{0\_coeff} (H/H_{ref})^{\alpha}, \qquad (8)$$

where V is the wind speed in (m/s) at height H in m. $V_{measured}$ is the wind speed for the actual time in the weather file. A_{0_coeff} is coefficient in power law expression for wind speed. α is an exponent in power law expression for wind speed (EQUA Simulation AB, 2013). The openings of the greenhouse were controlled automatically by a PI temperature controller. When the greenhouse is on the roof, the wind speed is higher so the air can move easily and quickly through the roof openings. The natural ventilation of the RTG is more efficient than with a greenhouse on the ground.

Another factor that may influence the cooling demand of the greenhouse is the ground heat transfer. Thermal conductivity of the warehouse roof is generally higher than that of soil, so the warehouse roof functions as a thermal storage, which collects heat during the day and releases it at night. In addition, when the greenhouse is on the roof, the roof temperature is lower due to temperature control inside the building (18°C to 25°C), compared to the temperature of the earth when the greenhouse is on the ground. Nevertheless, these factors need to be further investigated.

The results also show that the low-e coatings of the sidewalls did not yield significant improvements in heating and cooling demands. This solution is not recommended because the solar radiation enters the greenhouse in the morning and illumination is reduced due to the lower transmittance of double pane low-e glass compared to double pane tempered glass, which may affect plant growth.

For the host building, Figure 11 and 12 show changes in energy use with the RTG on the warehouse roof. The annual heating demand decreased by 14 % to 23 % compared to the warehouse stand-alone (16.5 kWh/m^2·y for heating). However, the annual cooling demand of the warehouse increased by at least 4.6 % after it was integrated with RTG. This increase in cooling energy demand may be explained by the heat buffer created by the RTG. In absence of the RTG, the warehouse roof is cooled naturally by airflow passing above while the heat is trapped by the RTG, which reduces the wind cooling effect. However, in the next sections, we present results for a shaded RTG solution, which reverses this trend.

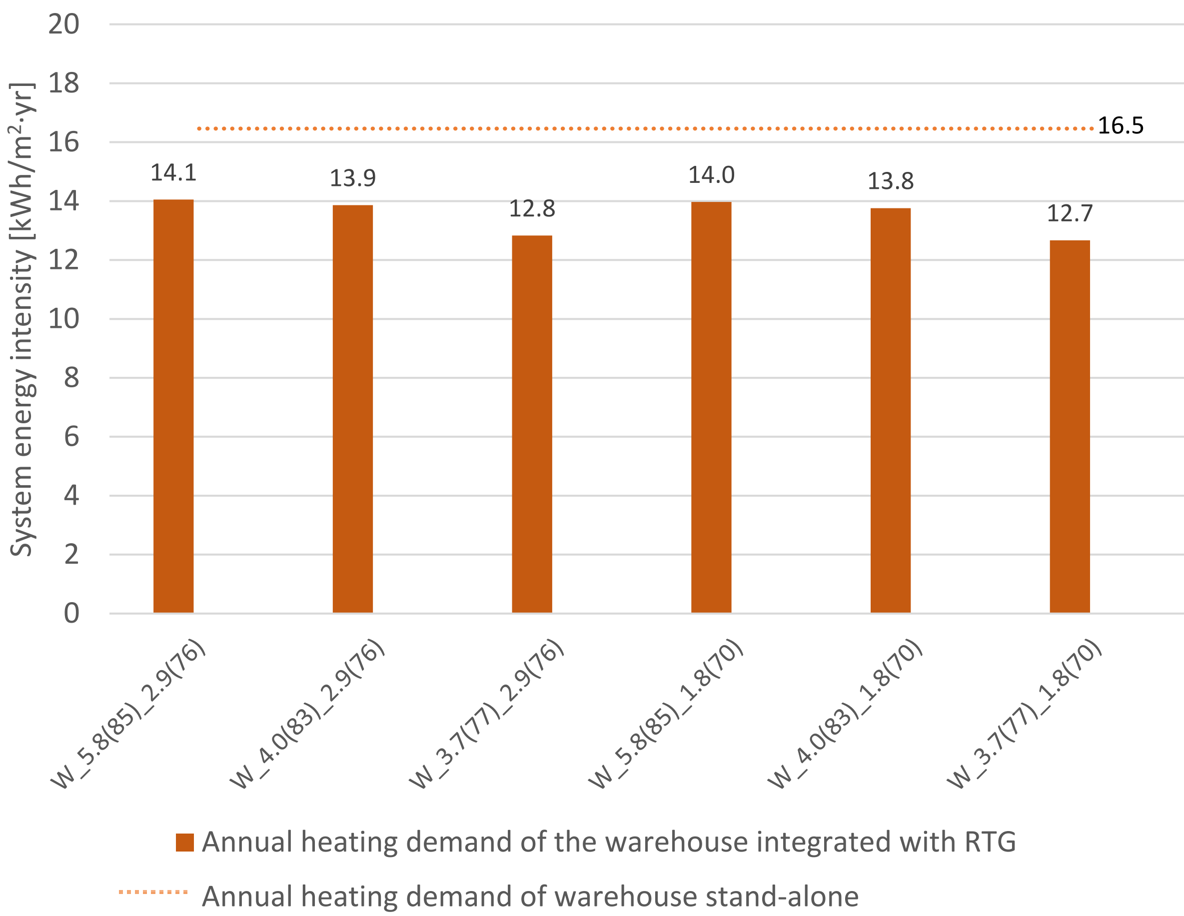

Figure 11: Annual heating demand of the warehouse stand-alone and with the RTG. W stands for the warehouse.

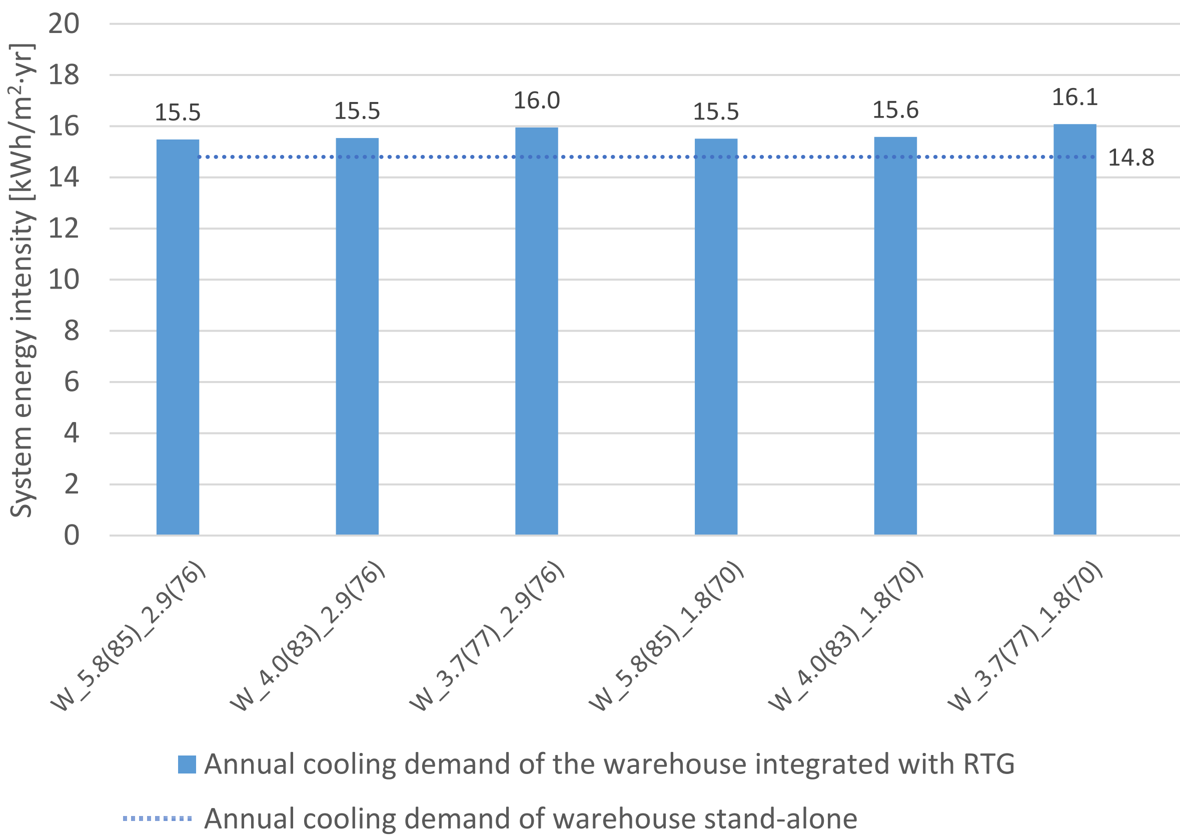

Figure 12: Annual cooling demand of the warehouse stand-alone and with the RTG.

Figure 13 shows that both the greenhouse and the host building obtained the highest cooling demand with the best envelope (G_3.7(77)_1.8(70)). In the summer, the temperature in the greenhouse can be higher than the outside air. An unshaded greenhouse with lower U-value conserves more heat inside. In other words, low U-value envelopes conduct less heat from inside to the outside when the outside temperature is lower than the inside (Sullivan *et al.*, 1993), leading to a higher indoor temperature in the RTG. Some of this heat is then transferred to the host building, which also has a higher cooling demand. The RTG behaves like a thermal solar collector.

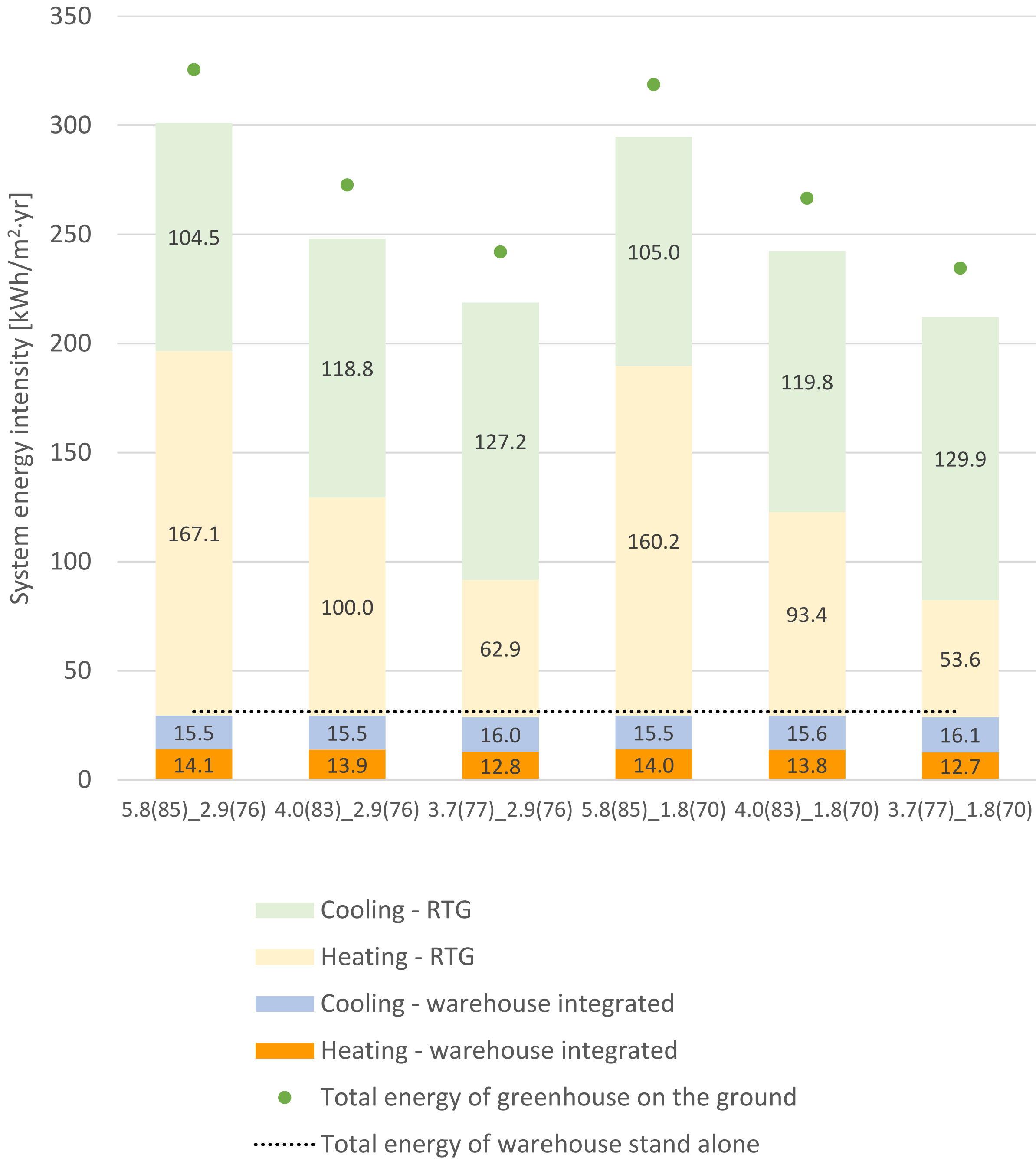

Figure 13: Annual energy use of the warehouse and the greenhouse.

However, the results presented in Figure 13 also show that the total energy use is the lowest with the best envelope, mainly due to a large reduction in heating energy demand, especially evident from the greenhouse part.

5.2.2 Effect of shading devices

In Figure 14, each bar presents the cooling demand of the RTG with different shading solutions. For all cases, there was about a 24 % decrease of cooling demand for the RTG with light lightly woven internal shading, and at least 80 % reduction in cooling with an external shading system compared to the unshaded greenhouse. The results also indicate that the annual cooling demands of each envelope solution are close to each other when the RTG is equipped with external shading devices. In other words, the relative difference in cooling load was negligible. The main factor affecting the total energy demand is the heating demand, which is mainly affected by the U-value of the different glazing alternatives, as shown in the previous section.

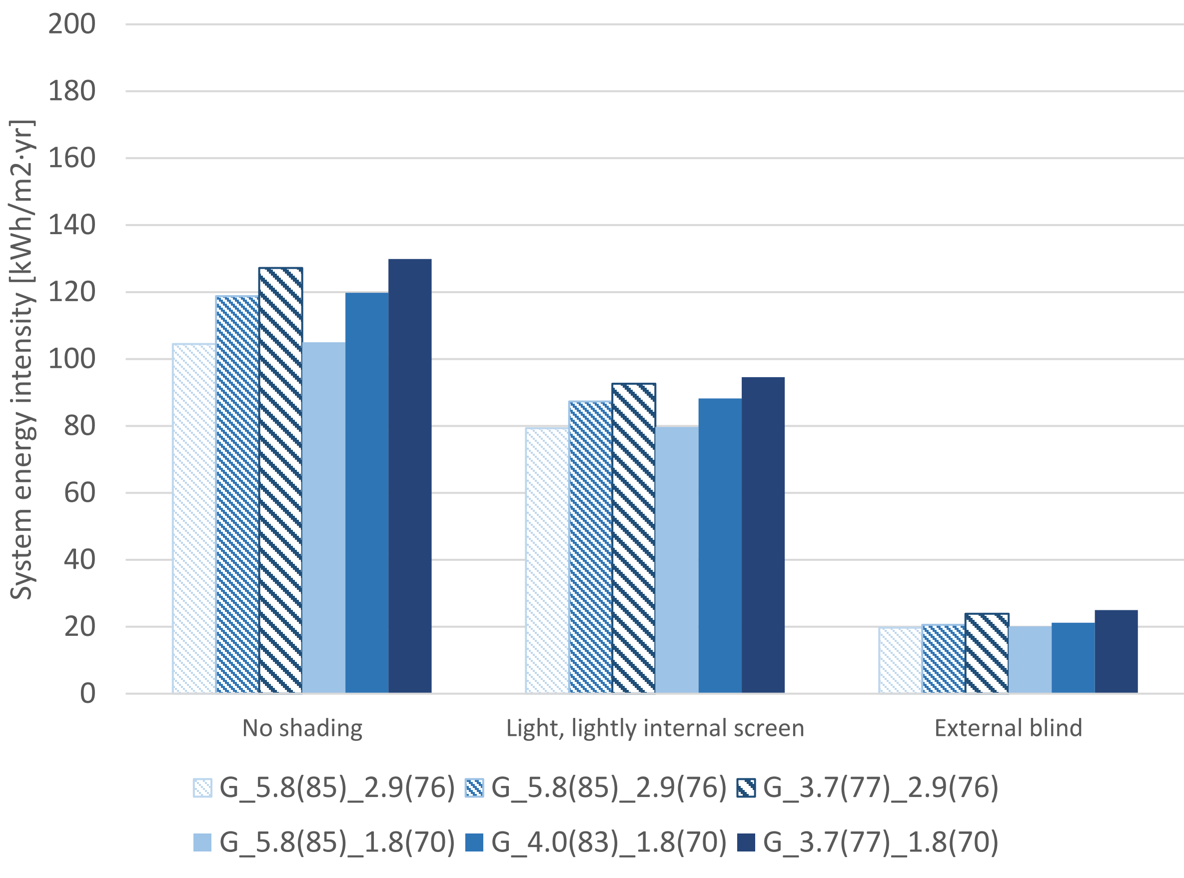

Figure 14: Annual cooling demand of the RTG with different shading solutions.

The slight increase in heating demand after the RTG was equipped with shading devices is negligible so these results are presented in Appendix D, Figure 21 to 26. This increase in heating due to shading is due to the control system, which relies on radiation intensity on the outer surface of glazing (100 W·m^{-2}). It is possible that when the outdoor radiation intensity reaches 100 W·m^{-2}, the shading system automatically closes to prevent solar radiation even in the heating season, which leads to an increase in heating demand.

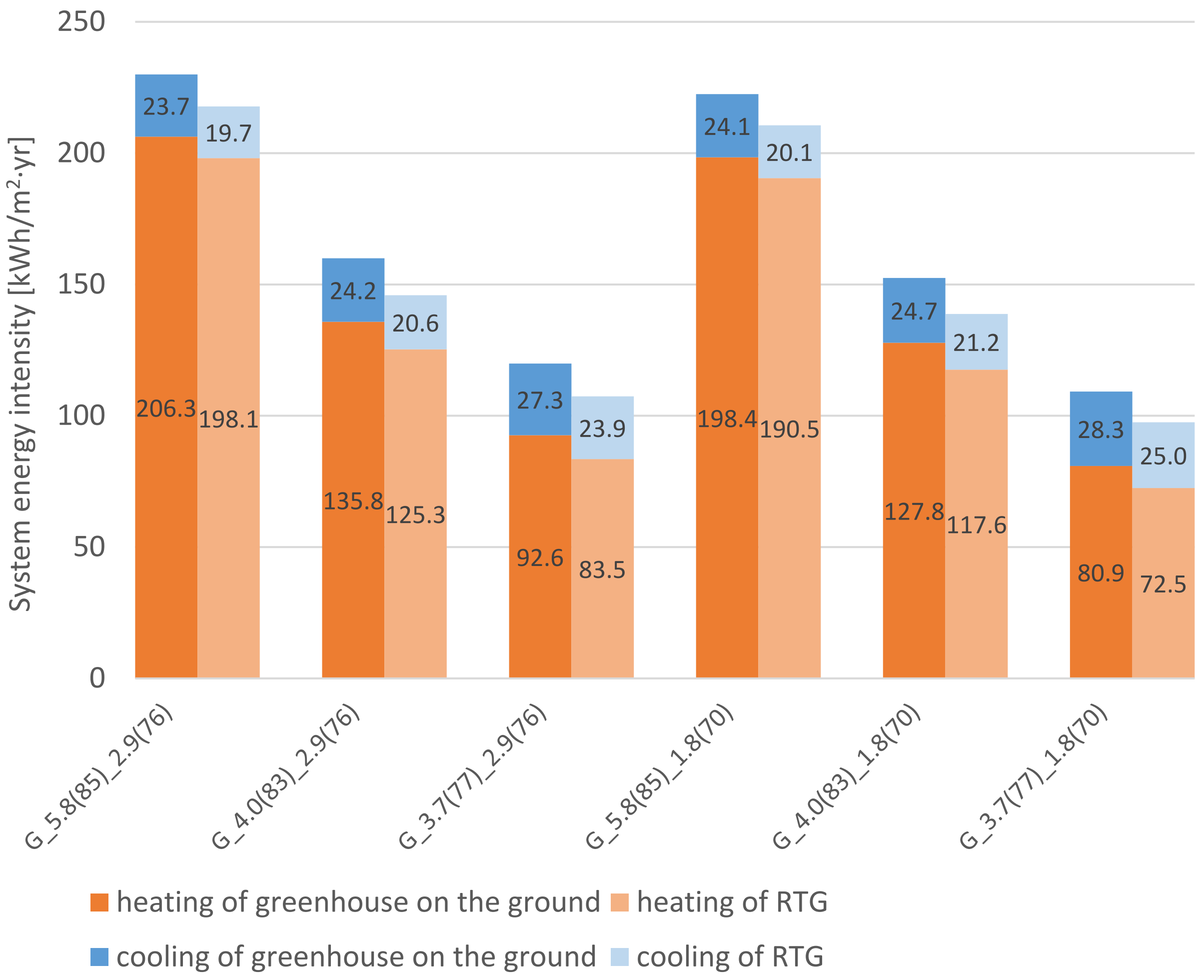

Figure 15: Summary of total energy demand of the RTG with external blind.

Figure 15 presents the heating and cooling energy intensities for the RTG with external blind. Compared to the greenhouse on the ground, both the heating and cooling load of the RTG decreased. The case G_5.8(85)_2.9(76) yielded the lowest cooling demand while the case G_3.7(77)_1.8(70) resulted in the highest cooling demand. However the main factor that affects the total energy use is the heating demand. G_3.7(77)_1.8(70) resulted in the lowest heating demand among different envelope solutions. The external blind shading type can save the highest amount of cooling energy, but this solution may be more difficult to implement in reality due to wind, maintenance, etc.

The internal shading device was inferior to the external shading device in reducing the temperature of the greenhouse, mainly because the external shading can directly prevent the outside heat from entering into the greenhouse, while the internal shading system allows solar radiation to pass through the glass and generates heat inside the greenhouse. Interior shading does not really reduce the temperature sufficiently but it prevents intense exposure to direct sunlight, which could damage plants (Easy Shade Gardening, 2021). According to Ye *et al.* (2016), heat can be absorbed by the internal shading device, which is then radiated as long-wave radiation towards the glass and then reflected back in since glass is opaque to long-wave radiation. This leads to an increase in cooling demand due to secondary radiation and convection.

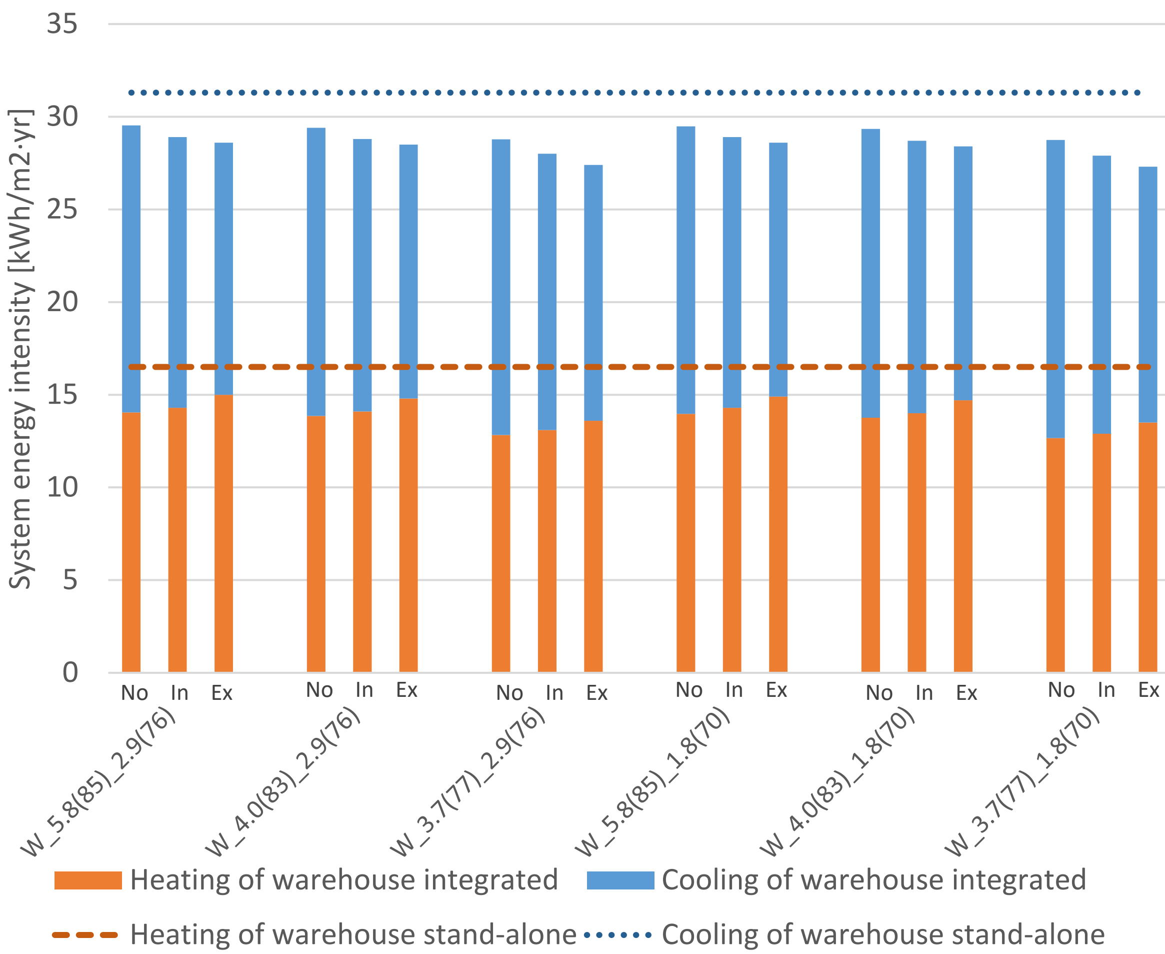

Figure 16:Summary of total energy demand of the warehouse when integrated with different RTG with three shading solutions (No shading, Internal shading, External shading).

Figure 16 shows the annual heating and cooling demands of the warehouse integrated with different RTG solutions. This figure shows that a reduction of heating demand occurs compared to a case without RTG. The integration of RTG on top of a warehouse is thus beneficial in terms of total energy intensity for the integrated system. Total energy demand is reduced by 5.7 % to 12.8 %. Heating demand is reduced by 8.9 % to 21.6 % while cooling demand is changed from 8.8 % increase to 8.1 % reduction (with shading). The warehouse obtained the highest heating demand but the lowest cooling demand when integrated with a RTG with external shading devices. Compared to the warehouse stand-alone, the total heating and cooling energy use reached the lowest when the warehouse was integrated with a RTG with G_3.7(77)_1.8(70) with an external shading system.

Overall, the low-e glazing envelope material used together with the external shading system would provide the best energy performance both for RTG and the host building.

5.3 Lighting energy use

In addition to heating and cooling, electricity is chiefly used for lighting especially in the winter months. Electricity accounts for about 20 % of the total production costs in a plant factory with artificial lighting (Kozai *et al.*, 2020). Figure 17 shows the electrical lighting energy use in the RTG and a comparable horizontal indoor farm.

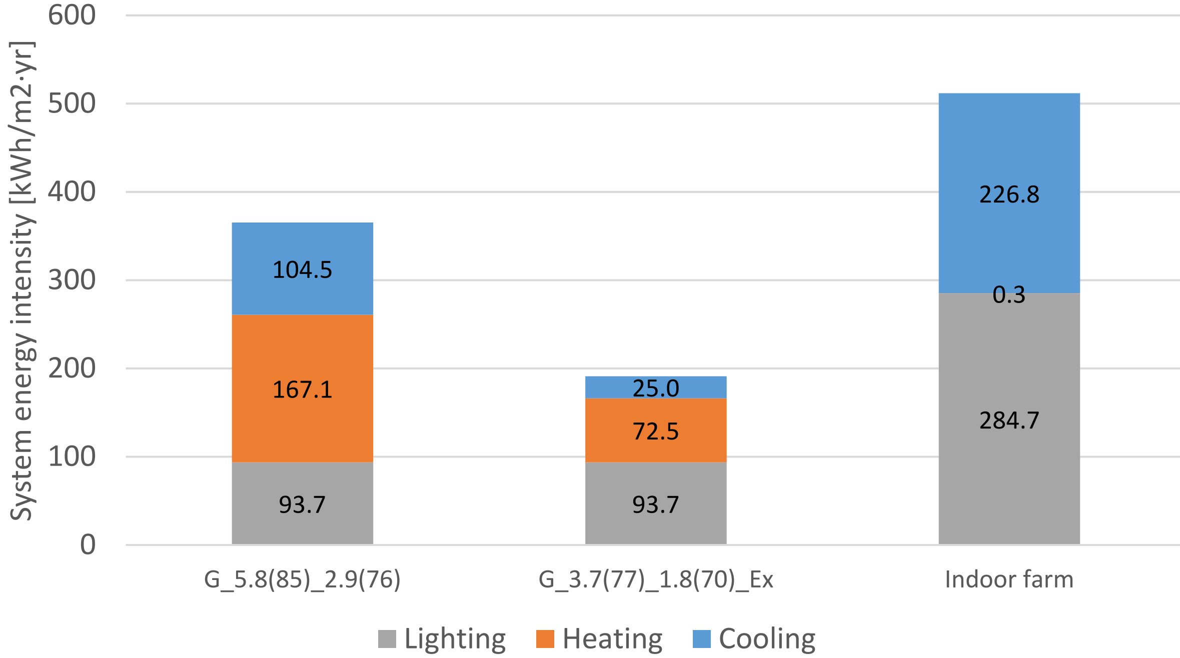

Figure 17: Lighting energy use in RTG with the highest (G_5.8(85)_2.9(76) without shading), lowest (G_3.7(77)_1.8(70) with external blind) total energy consumption, and in an indoor farm.

For leafy greens, the annual lighting energy intensity is 93.7 kWh/m^2 for a greenhouse with natural light. This value is 24.2 % of the total energy use in an unshaded RTG with the poorest envelope (G_5.8(85)_2.9(76)) under natural light, while it is 49 % of total energy consumption in a RTG with the best envelope with external blind (G_3.7(77)_1.8(70)_Ex).

For an indoor plant factory of the same size and horizontal layout of the plants, the annual electrical lighting energy intensity is 284.7 kWh/m^2, which is about three times as much electricity for lighting as a greenhouse with natural light. However, note that the heat converted from the LED lamps almost covers the heating demand in this case, but also yields a significant increase in cooling demand. In the case of the indoor farm, the lighting use is about 55.6 % of the total energy use, see Figure 17. Figure 17 shows that the total energy demand of the indoor farm is more than double the value of the best RTG case (G_3.7(77)_1.8(70)_Ex) and about 30 % higher than the worst case of RTG.

6. Conclusions

This study investigates the impact on the annual heating and cooling energy requirements of an RTG integrated with a warehouse building, as well as the electric lighting use accounted for the total energy use. The results indicate positive trends in providing RTG on a warehouse building. Beyond providing local produce, this study that the integrated RTG can clearly provide is additional value in terms of energy savings.

The integration of rooftop greenhouse (RTG) and warehouse leads to overall energy savings of 10.7 % for heating and 6.8 % for cooling for the warehouse itself and 10.4 % for heating and 11.7 % for cooling for the greenhouse with the best RTG envelope with external shading devices. The integration of both structures is thus beneficial in terms of overall energy efficiency.

By changing the greenhouse envelope, the largest energy savings were for both the host building and the RTG itself when the glazing materials were improved from tempered glass to low-e coating ones. These reductions can lead to 29.5 % lower energy consumption of the RTG-integrated-warehouse system. Although this also led to the highest cooling demands, the total energy use was lowest since heating is dominant.

Using an external shading system for the RTG is the most desirable method to minimize cooling, which can reduce solar heat gains by at least 80 % compared to an unshaded RTG, but this solution may not be realistic due to wind and maintenance considerations.

Therefore, the largest energy savings for a RTG integrated with the warehouse building can be achieved with the lowest U-value of the RTG envelope, and equipped with an external shading system in a heating-dominated climate. The study generally showed that the U-value of the glazing is the dominant glazing property to consider for greenhouse design. The SHGC has a secondary effect on energy use.

The lighting energy use accounts for about half of the total energy use in a RTG with the best envelope and an external shading system. Although the proportion is almost the same as that of an indoor farm, this study showed that a horizontal indoor farm of the same size requires more energy mainly due to electric lighting and cooling to remove the heat generated from lights. We showed that this type of farm would not have any heating demand due to secondary heat gains from lights. The energy use of a comparable indoor farm is about twice as much as that of the RTG with the best envelope with an external shading system and about 30 % higher as the unshaded RTG with the poorest envelope. One conclusion is that RTG may provide significant energy savings in the future compared to indoor farms illuminated with LED lamps.

7. Limitations and future work

The limitations of this study are: lack of data regarding the COP value in the real building, although previous studies have showed that the COP can be influenced by several factors and is not a constant value (Kozai *et al.*, 2020). This shortcoming may lead to different outcomes in actual building energy use, especially concerning the cooling demand, which could have a COP of up tp 3.

Secondly, the lack of data in other climate zones as there are three different climate zones in Sweden. We could obtain a better understanding of the energy performances of rooftop plant factories and host buildings with simulations in other Swedish climate zones.

Moreover, in the simulations of this study, when it comes to the dynamic shading control, solar radiation on the greenhouse roof surface was the only factor considered and temperature of the greenhouse inside was not considered, which led to a little increase in heating demand of the RTG compared to the case without shading. More elaborate simulations with indoor temperature controls could lead to more accurate predictions.

For the parametric study, there was a limit on the number of subset variables, various other materials, as well as the insulation between the host building roof and the greenhouse slab can be tested to show a different impact on energy use.

In addition, the lack of irrigated crops and wet soil in the greenhouse made this research only of theoretical nature. This kind of empty rooftop greenhouse does not represent the real conditions, the results are not indicative of absolute savings in real cases.

Additionally in future work, the greenhouse heating and cooling system should maintain the relative humidity at 60 % to 85 % for crop growth, to maintain hydration and reduce risks for disease, but the dehumidification process is another aspect to include in energy simulations.

Thermal night curtains can be introduced to reduce the heating demand. These were not modelled due to the limitations of the software.

Other climate zones, orientations, solar power integration, shape of the rooftop factory (sloped, flat, height, span) could also be investigated.

It would also be interesting to compare the weather data file to the actual situation at the site. The wind speed at the specific site could vary based on the surrounding buildings and locations. In this case, the wind speed at ground level was set to zero by the program, which is probably unrealistic. There is most probably a little wind flow at the ground level in reality.

Least but not last, it is worth mentioning that this research is only based on energy simulations; future work should also involve measurements in full-scale or mock-up installation. The results presented in this thesis are theoretical and limited by the intrinsic assumptions of the energy simulation program IDA ICE.

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9. Appendix

Appendix A

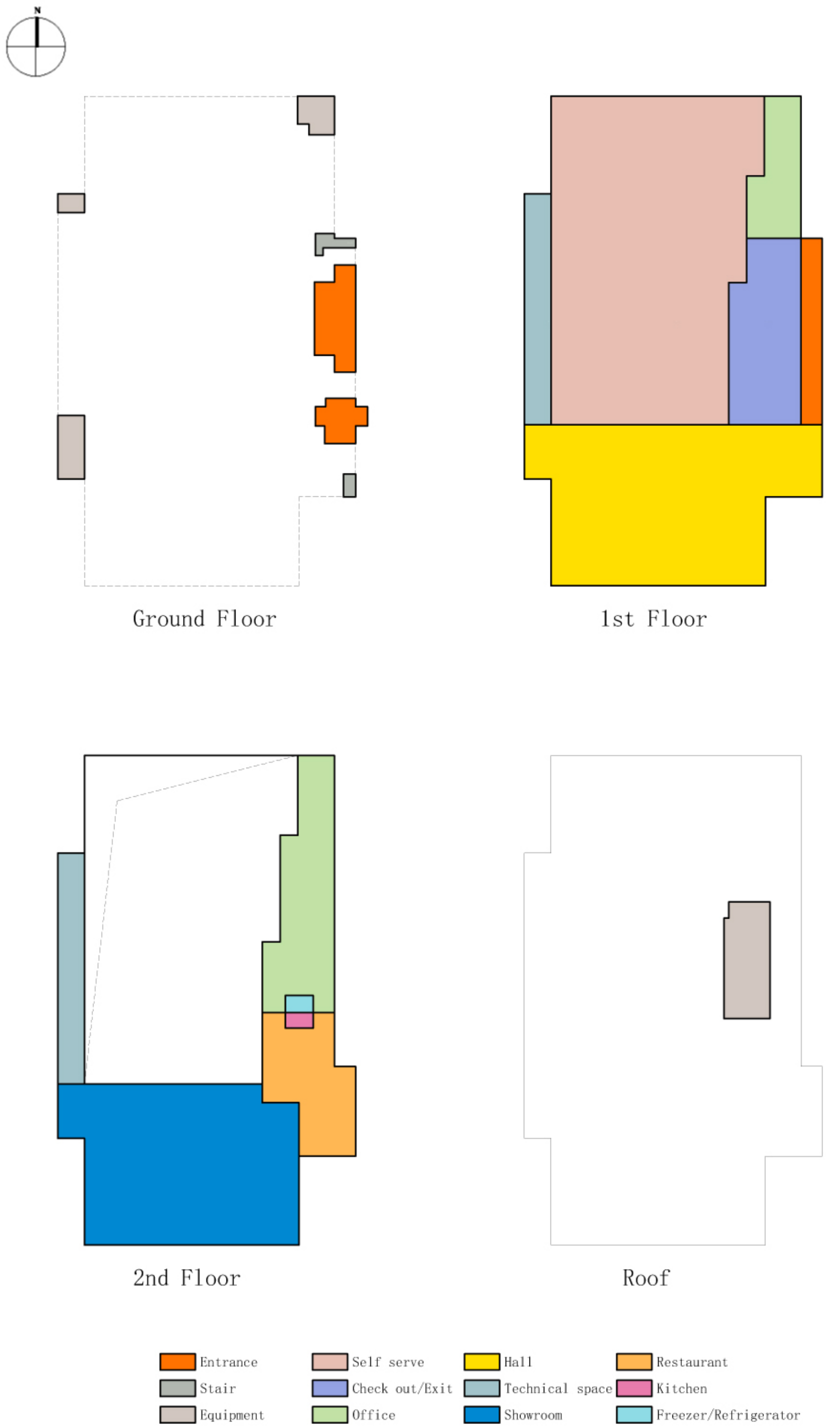


Figure 18: Different thermal zones in the warehouse.

Appendix B

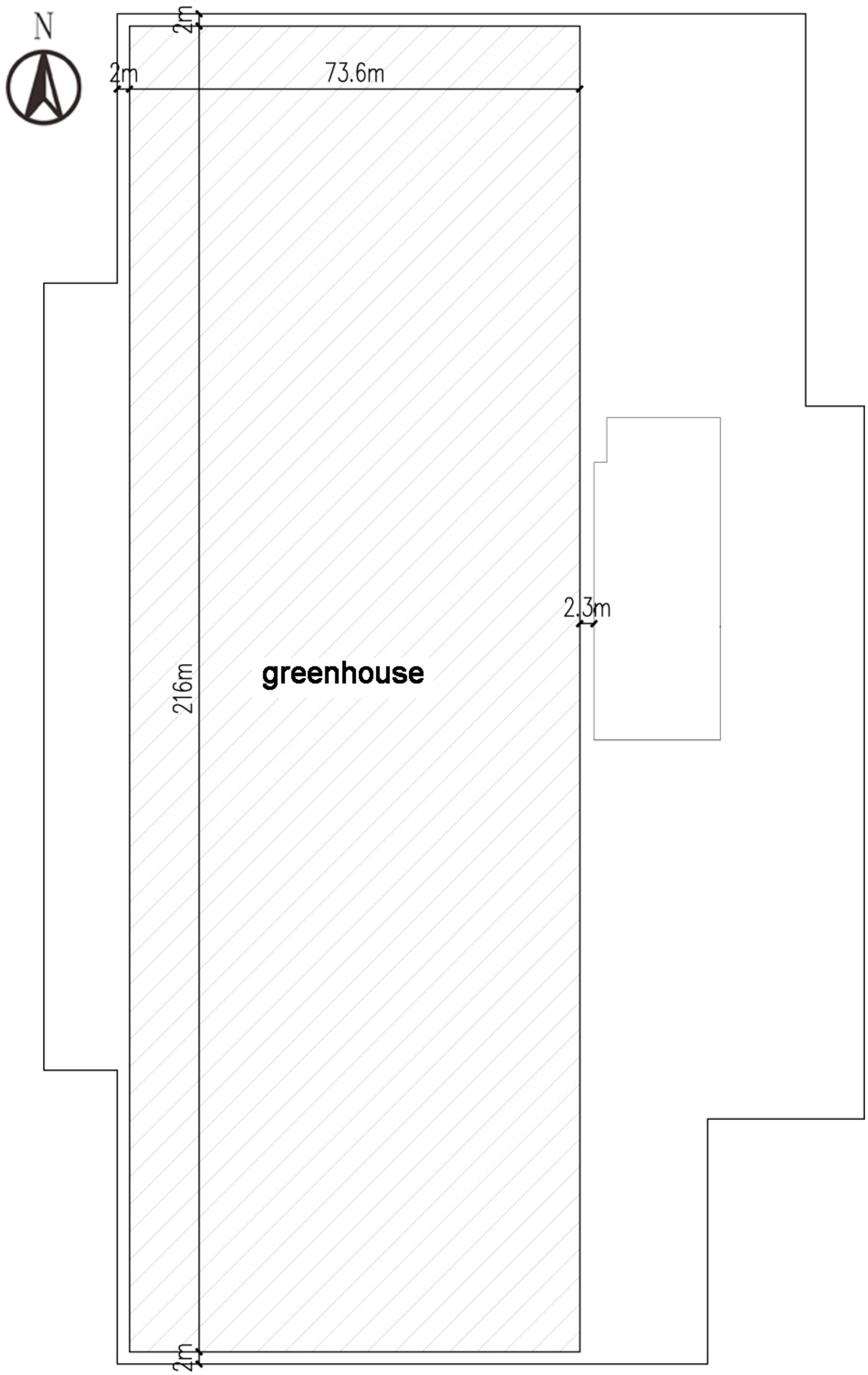


Figure 19: Setback of the RTG.

Appendix C

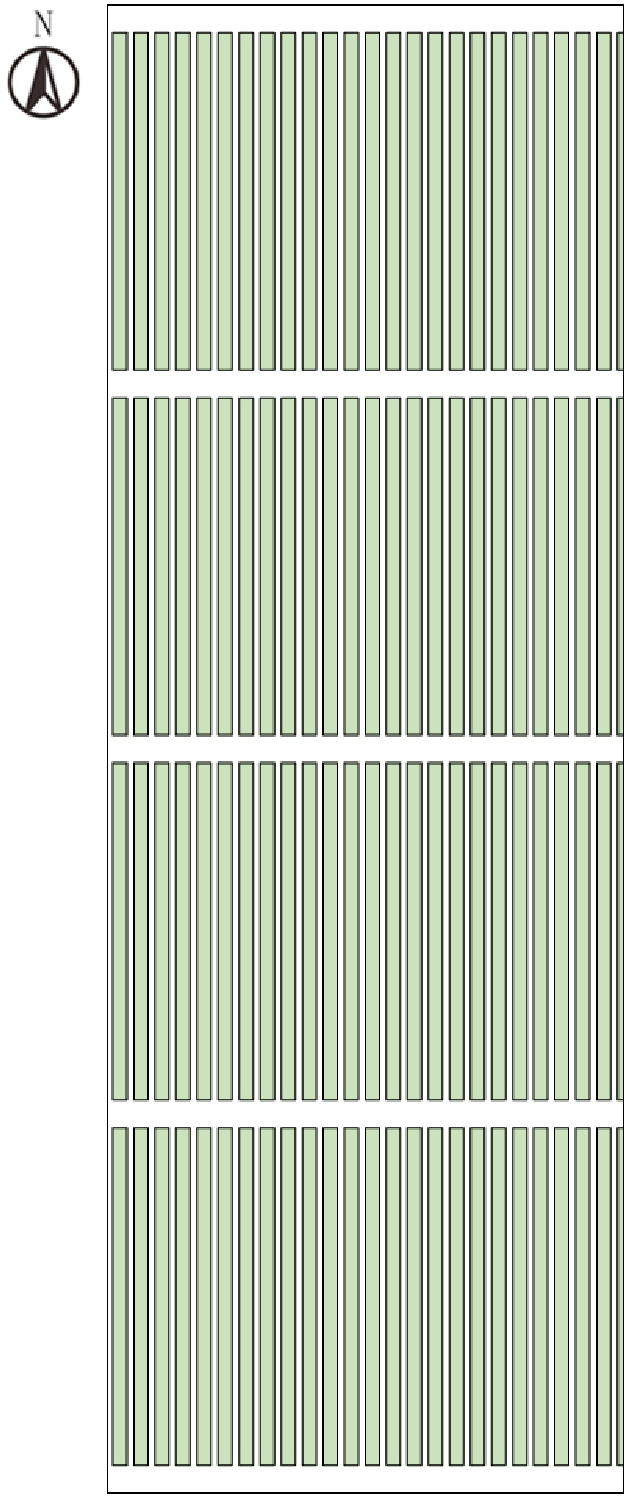
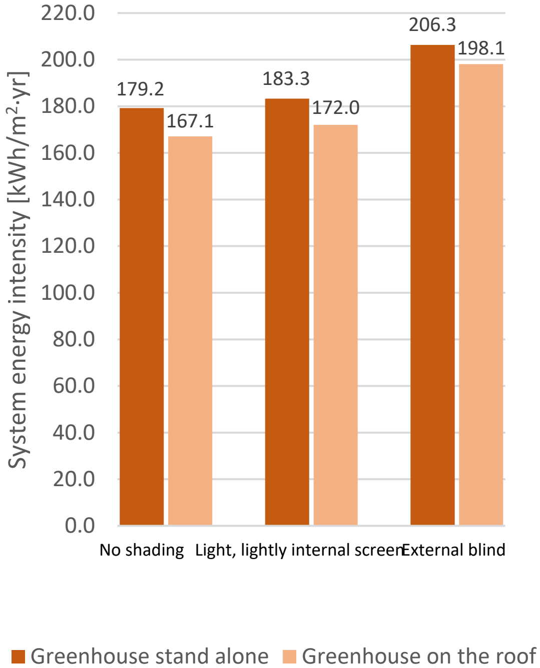


Figure 20: Normal arrangement in the greenhouse and the indoor farm.

Appendix D: Annual heating and cooling demand of the greenhouse.



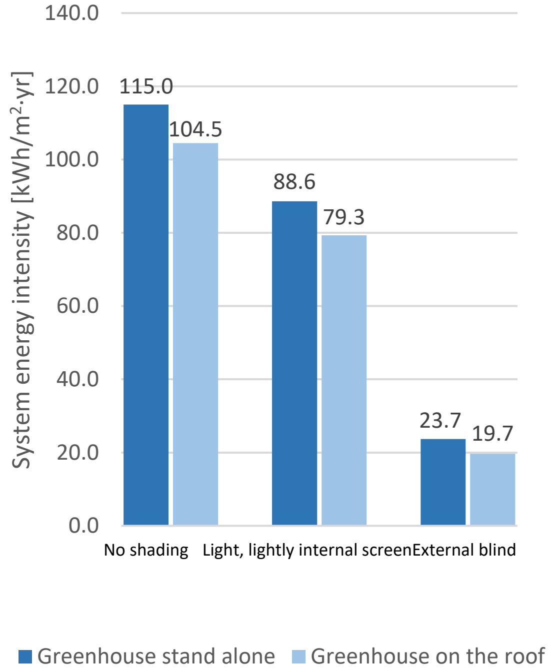
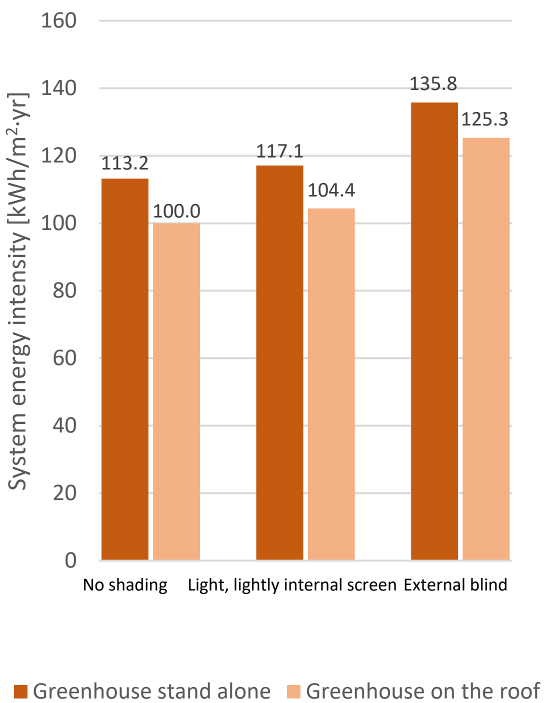


Figure 21: Annual heating (left) and cooling (right) demand of G_5.8(85)_2.9(76).



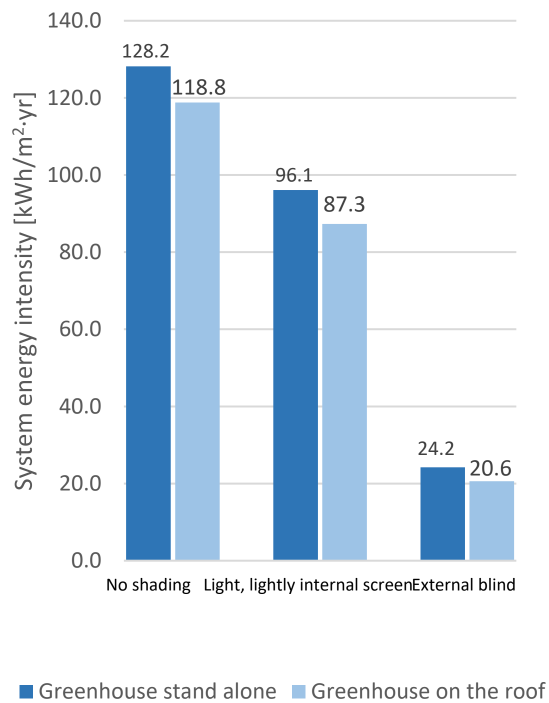


Figure 22: Annual heating (left) and cooling (right) demand of G_4.0(83)_2.9(76).

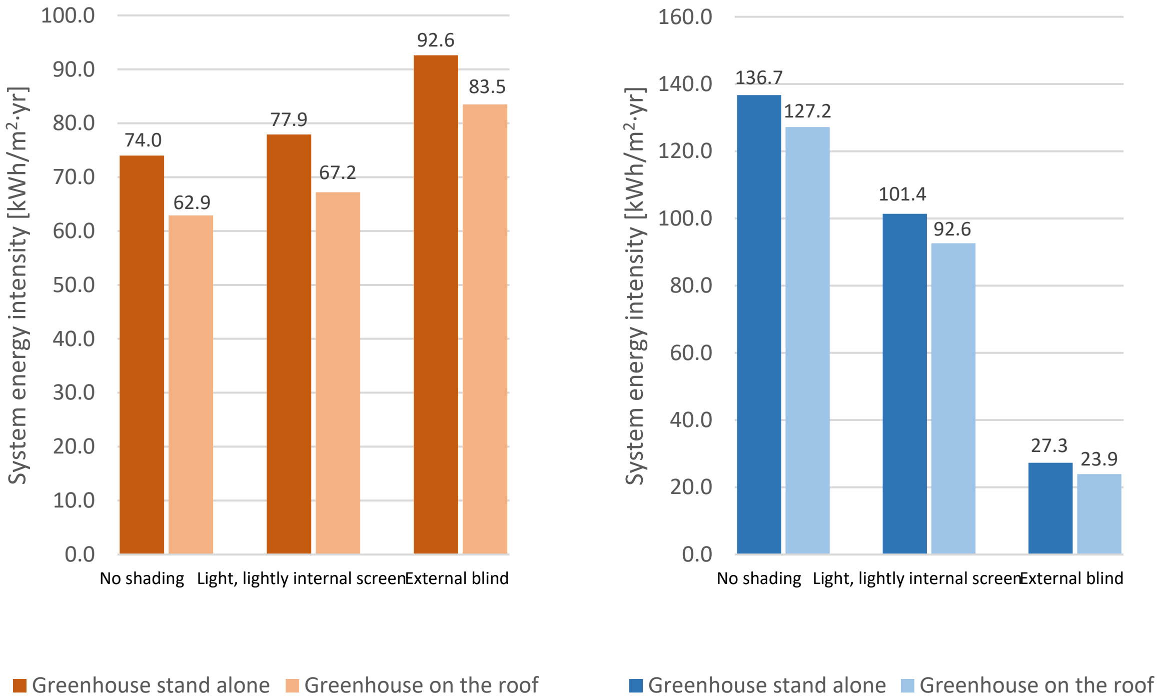


Figure 23: Annual heating (left) and cooling (right) demand of G_3.7(77)_2.9(76).

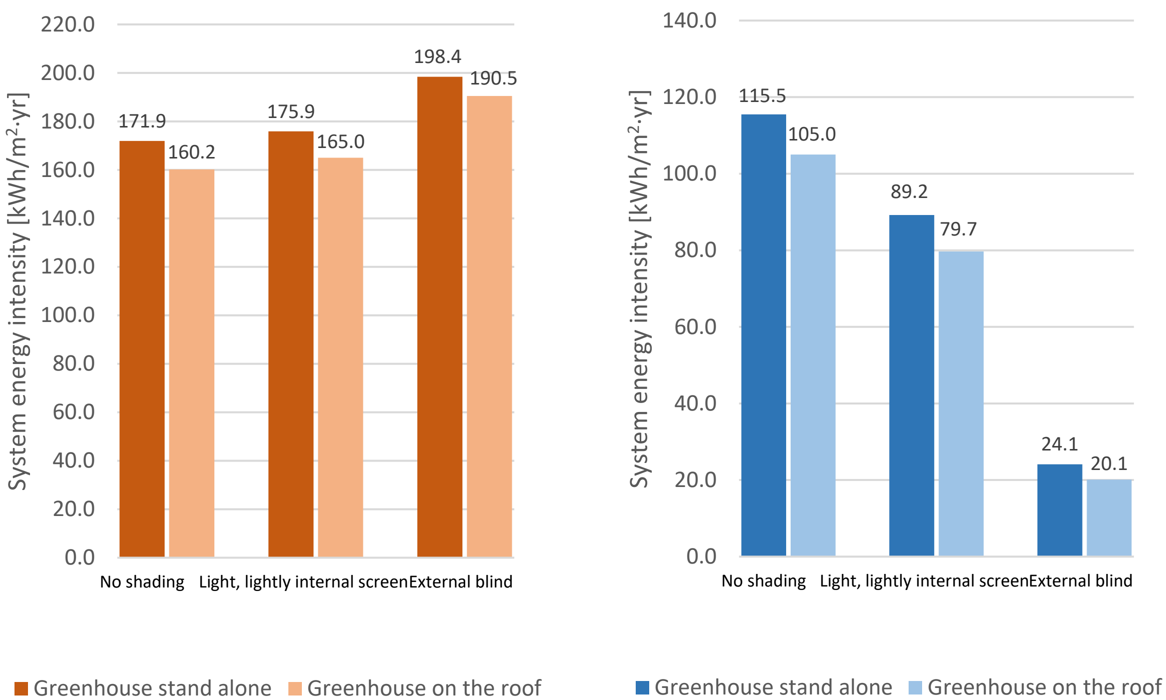


Figure 24: Annual heating (left) and cooling (right) demand of G_5.8(85)_1.8(70).

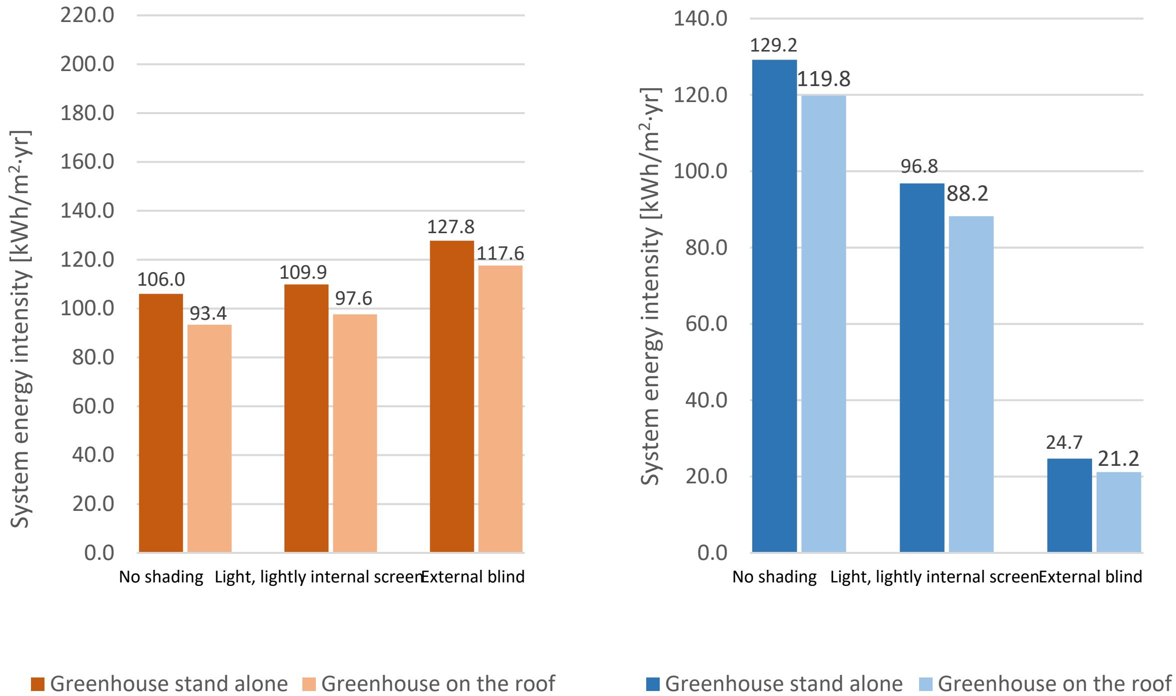


Figure 25: Annual heating (left) and cooling (right) demand of G_4.0(83)_1.8(70).

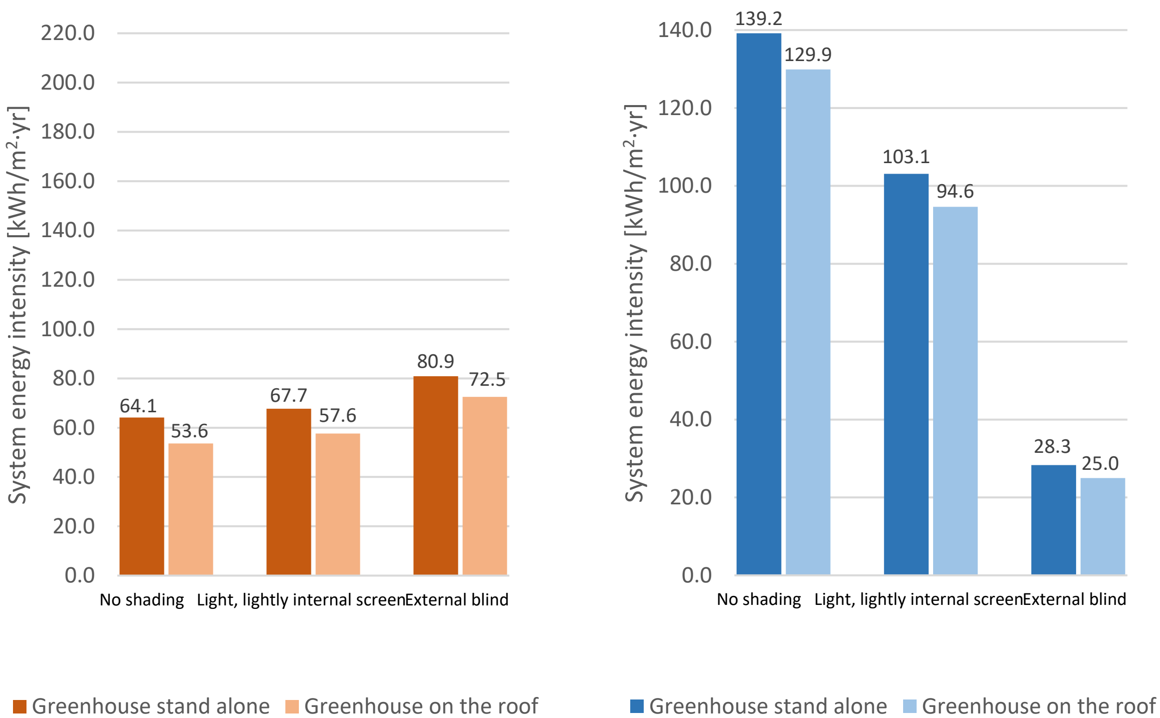


Figure 26: Annual heating (left) and cooling (right) demand of G_3.7(77)_1.8(70).

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