Urban Vertical Garden

Ways to Improve Living Conditions by Applying Green Façades in Buildings Refurbishment at Semi-Arid Climate

Doctoral Dissertation

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Urban Vertical Garden

"Ways to Improve Living Conditions by Applying Green Façades in Buildings Refurbishment at Semi-Arid Climate"

by

Faezeh Bagheri Moghaddam

Submitted to the Department of Architectural Representation;
Requirements for the Degree of Doctor of Philosophy in
Architectural, Civil and Urban Heritage and Refurbishment of Existing Buildings

Abstract

This dissertation aims to improve work conditions in office buildings by implementing vertical greenery systems such as green façades and living walls in semi-arid climates. Since building energy performance is characterized by their electrical systems and thermal exchanges through the building envelope, which are primarily defined by glazing systems in the façades, covering glazed façades with a vegetation layer can play a key role in energy saving and thermal comfort of buildings.

This research evaluates, through building simulation method, the influence of green façades in thermal comfort, energy consumption, and the heating and cooling loads of an office building in Denver city with a semi-arid climate condition. Furthermore, the psychological and physical performance of vertical gardens as a nature-based solution and, from the perspective of biophilic cities and philosophy has been assessed through a review of previous studies related to the effect of greenery systems in office buildings. A green façade can also be used as a retrofit option for office building refurbishment. A case study was created as a building model to investigate the influence of green façades and green façade configuration on their performance prediction in semi-arid climates. Additionally, for a better understanding of vertical garden performance in semi-arid regions, simulation case studies in Barcelona with a Mediterranean climate (as articles) and Denver with a semi-arid climate as the context of this dissertation were conducted and their results were compared together.

The information generated from the simulation of bare and green façade configurations as a double-skin façade was incorporated into qualitative theories trying to predict human comfort aspects in the work environment. For balancing energy-saving measures through green façade refurbishment, four qualitative criteria serve as the foundation occupant psychological and physical comfort, and its impact on productivity has been established. These criteria are: the requirement for appropriate indoor air temperature, indoor air quality, daylight availability for the psychological performance of users, and perceived control over the façade by a vegetation layer in workplaces.

Finally, a new concept of vertical gardens was introduced by integrating biology and technology in architecture, which may solve the issue of weather conditions and water scarcity in some climates, such as semi-arid climates, for implementing vertical gardens.

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Publications:

- F. Bagheri Moghaddam, J. M. Fort Mir, A. Besné Yanguas, I. Navarro Delgado, and E. Redondo Dominguez, *"Building Orientation in Green Facade Performance and Its Positive Effects on Urban Landscape Case Study: An Urban Block in Barcelona,"* 2020, doi: 10.3390/su12219273.

- F. Bagheri Moghaddam, J. M. Fort Mir, I. Navarro Delgado, and E. Redondo Dominguez, *"Evaluation of Thermal Comfort Performance of a Vertical Garden on a Glazed Façade and its Effect on Building and Urban Scale, Case Study: An Office Building in Barcelona,"* 2021, doi: 10.3390/su13126706

- F. Bagheri Moghaddam, J. M. Fort Mir, I. Navarro Delgado, and E. Redondo Dominguez, *"Understanding the Performance of Vertical Gardens by Using Building Simulation and its Influences on Urban Landscape Case study: An Office Building in Barcelona"* 2021,

- F. Bagheri Moghaddam, S. Banihashemi, J. M. Fort Mir and I. Navarro Delgado, *"Blending digital fabrication and photosynthetic microorganisms as green façades structure"*, 2021 (Writing) (Chapter 5, Future research)

Acronyms and Abbreviations:

ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CBECS	Commercial Buildings Energy Consumption Survey
CO	Carbon Dioxide
DOE	U.S. Department of Energy
EER	Energy Efficiency Ratio
GF	Green Façade
GFTs	Green Façade Technologies
HVAC	Heating, Venting, and Air Conditioning
HSPF	Heating Seasonal Performance Factor
LW	Living Wall
PBA	Principal Building Activity
SHW	Service Hot Water
VGS	Vertical Greenery System

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Chapter One: Introduction

1.1. Definition

Building façades as vertical surfaces are a characteristic of urban environments that can be used creatively for sustainable [1][2] and biophilic [3] solutions in architecture by incorporating a plant layer on these surfaces. Vertical gardens as a vertical greenery system have a lot of advantages over conventional green façades because they can integrate new materials and technologies to improve sustainable building functions.

This thesis aims to investigate the performance of vertical gardens in refurbishment office buildings with glazed façades in semi-arid regions to reduce environmental issues, energy consumption, and also improving occupant comfort. As a vegetation layer configuration, the vertical garden is intended as a refurbishment alternative to enhance the condition of existing office building façades (glazed façades). It is investigated as part of a refurbishment option that can be implemented while maintaining the building's occupancy and, as a result, improving the occupants' comfort. These interactions between the vegetation layer and the behavior of buildings can help to improve living conditions.

In the sense of this study, semi-arid regions occupied 15% of the earth's land surface and supported 15% of the global human population [4][5] (Table 1.1). In these regions, the environment is extremely fragile and vulnerable to severe interactions between human activities and climate change [6][7][8]. Furthermore, the long-term global warming trend is accelerated in these areas [9]. These regions are currently confronted with significant environmental issues such as high air pollution, and as their populations grow, they will face increased energy consumption demands.

The built environment is a major consumer of energy, such as power, while also helping to mitigate environmental concerns. Improving the efficiency of the building stock provides an opportunity to improve both energy awareness and real environmental issue mitigation.

In semi-arid areas, building occupancy coincides with the warmest air temperatures and maximum direct solar radiation on the building façade. Air conditioning systems are used to provide thermal comfort and improve efficiency. Green facades are intended as an energy-conscious façade refurbishment alternative that passively reduces environmental and climatic effects on office building occupants in this context. There are several studies on the efficiency and visual impacts of using green façades in moderate and cold climates, with more than a few publications on the performance of green façades in semi-arid climates.

Table 1.1: Statistical Profile of the Dryland System *(Area from Deichmann and Eklundh 1991; global area based on Digital Chart of the World data (147,573,196.6 sq. km; the year 2000 population from CIESIN 2004))*

Subtypes	Aridity Index	Current Area		Dominant Broad Biome	Population	
		Size	Share of Global		Total	Share of Global
		(mill. Sq. km.)	*(percent)*		*(thousand)*	*(percent)*
Hyper-arid	<0.05	9.8	6.6	desert	101,336	1.7
Arid	0.05-0.20	15.7	10.6	desert	242.780	4.1
Semi-arid	0.20-0.50	22.6	15.2	grassland	855.333	14.4
Dry sub humid	0.50-0.65	12.8	8.7	forest	909,972	15.3
Total		**60.9**	**41.3**		**2,109,421**	**35.5**

1.2. Research Hypotheses

The primary aim of this dissertation is to upgrade existing office buildings in semi-arid regions that have glazed façades. The vertical garden, as a vegetation layer on the building's exterior, is thought to have a major influence on the city's environment, building activity in hot and cold weather, and occupant living conditions. By examining vertical gardens from the past (3000 B.C.) to the present (explained in chapter 2), it is possible to demonstrate the use of vertical greenery in architectural design. Four hypotheses are tested to evaluate the performance of vertical gardens in refurbishing existing glazed office buildings in Denver, Colorado (a semi-arid region) as a double-skin façade configuration:

Hypothesis one: Beyond aesthetically and psychologically, investigate the performance of vertical gardens at building and urban scales. (explained in chapter 3)

Hypothesis two: Investigate the connection between nature and architecture. (explained in chapter 3)

Hypothesis three: Improving thermal comfort and saving energy in the transparent façade through applying vertical gardens, with no alterations to the architectural configurations, will reduce the cooling and heating loads of buildings in semi-arid regions. (explained in chapter 4)

Hypothesis four: Investigating the most recent vertical greenery generation, which has no weather restrictions for use. (explained in chapter 5)

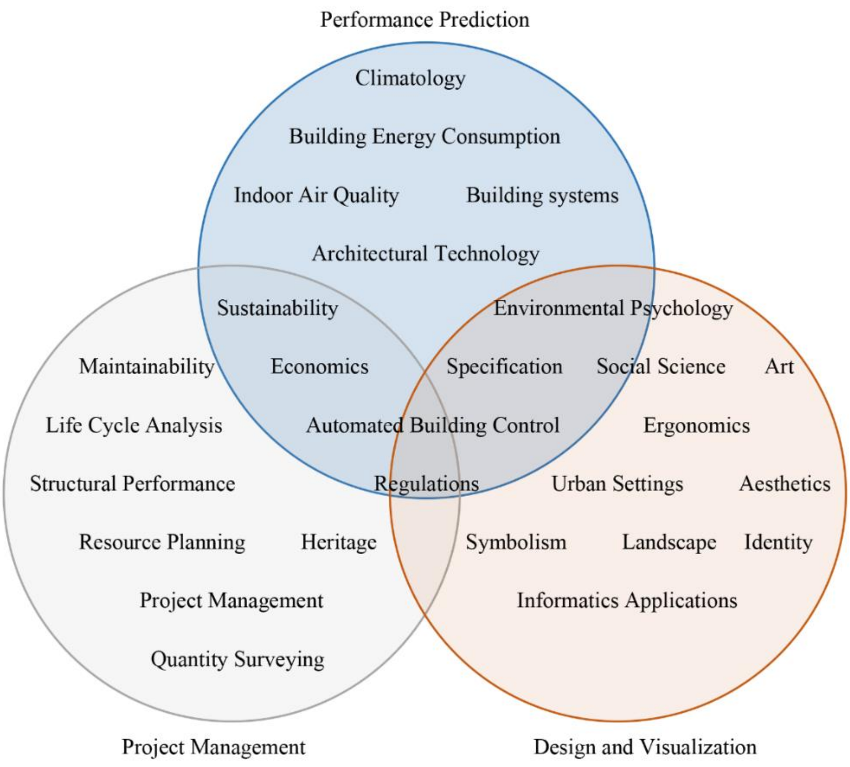
1.3. Research Objectives and Scope

The aim of the study is to find a balance between using vertical gardens and improving the environmental psychological aspects of the building while lowering energy consumption and improving living conditions in a semi-arid climate.

The objectives can be divided into five categories. The first category examines the history of vertical gardens from the past to the present. Finding the connection between vertical gardens and architecture industrialization, and then contemporary architecture, has played a crucial role in the development of this section. Furthermore, from the viewpoint of biophilic cities, vertical gardens as a part of nature in cities. The second group of objectives is driven by the need to understand the reality of contextual forces in the semi-arid regions that lead to the shaping of building façades and their physical state and configuration. The third group, deals with quantifying the predicted reductions in energy consumption and also improving living conditions by applying vertical gardens in semi-arid regions. The fourth group is proposed a new concept of vertical gardens which could make a revolution in vertical greenery by blending architecture with technology and biology in which cyanobacteria as a plant species is constructed with 3D printed structure as their container on the façade. The fifth group is dedicated to outline future research efforts based on limitations faced throughout the study.

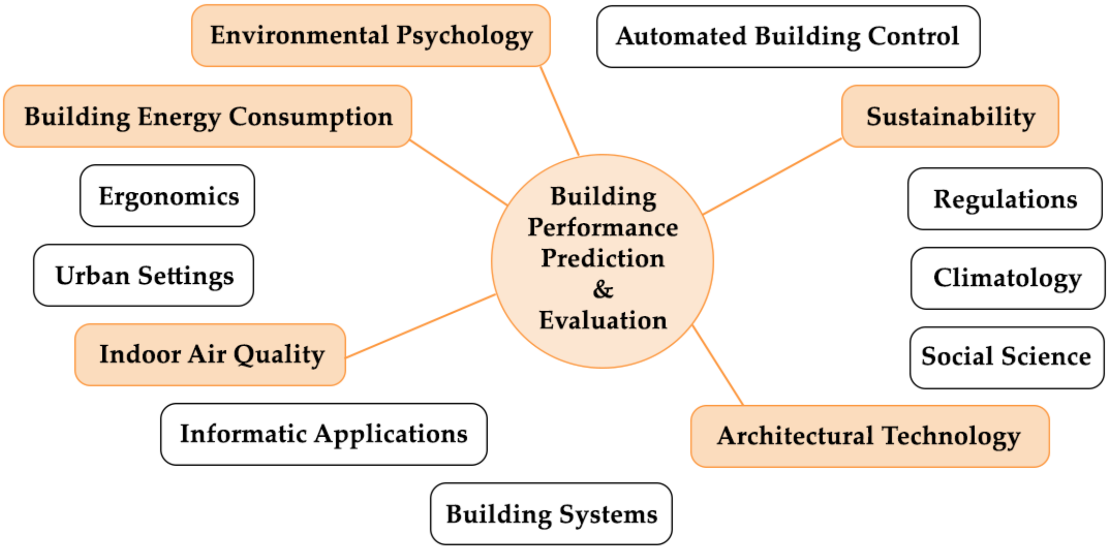
An overview of the related domains was defined to determine the scope of this study. The Venn diagram (Figure 1.1) depicts the numerous information domains that this study considers as part of the final realization of a holistic building design, whether for new construction or renovation. Building visualization, building output estimation, and project management were the three major domains in which these variables were grouped.

Figure 1.1: Linked knowledge domains for the realization of a holistic building.



There are several disciplines involved, and due to the time constraints of this study, a concentrated relationship between three variables of building technology, resources, and environmental psychology is explored in detail (see Figure 1.2).

Figure 1.2: Variables dominating the thesis scope.



In semi-arid climates, properties such as façade shading systems and glazing are used in a variety of ways to mitigate the effects of the atmosphere on indoor comfort. Green façades were implemented as an architectural technology that can be used to renovate the facades of existing buildings while also serving as a solar shading device.

The most contentious issue surrounding green facade building is its economic viability. The opinions vary from "a waste of money" to "viable due to energy savings" [10]. Although the economic feasibility of green façades as an architectural technology is not examined in this study, despite the fact that it is a significant factor in the decision-making process.

Green façade as a second skin construction is based on very specific technical requirements. Fixation of elements on the exterior and inner façades, inlet and outlet configuration and location, forms and sizes of openings for natural ventilation and night purge, early fire warning system installation inside the cavity, and fire and sound transmission control inside the cavity are only a few of the requirements. These factors are not part of the main body of building simulations discussed in the thesis sense, despite being mentioned in the discussions that support the conclusions.

1.4. Dissertation Overview

This Chapter describes the research process flowchart that serves as the foundation for the investigation. The research case is based on explaining the motivation for considering green facades as double-skin facades for refurbishing Denver's existing stock of office building facades, as shown in Figure 1.3 demonstrates the dissertation breakdown and relevant research methods used. In addition, the hypothesis that underpins the structure and direction of analysis in this study is explained. The chapter concludes with a discussion of the research's purpose, scope, and limitations.

Chapter two discusses the state-of-the-art of this research, including typologies, functionalities of vertical gardens, and their advantages at the urban and building scale. In addition, a performance assessment of vertical gardens is provided, which considered both urban quality and building performance. The aspect of vertical greenery in sustainability was seen at the end of this segment.

Chapter three focuses on the research foundations and validations of studies in terms of biophilic architecture, philosophical notion, nature-based solution, inner and outer building's spaces interaction and also considering as a façade retrofit solution by implementing vertical gardens on the façade. This chapter also looks at modes of energy consumption in office buildings. The reasons behind buildings being a major energy consumer within the building environment are explained concerning their environmental, urban, climatic as well as occupancy patterns.

Due to the context of semi-arid regions, urban configuration, and its climatic and environmental characteristics, this chapter looks at the wider context of requirements and expectations from a green façade but focuses on the green façade’s role as a climate-environment moderator. It is argued that occupant’s satisfaction with the green façade underpins indoor comfort and affects productivity. In this context, the impact of the green façade on indoor thermal comfort is discussed. This discussion feeds into the functional values chosen for the office building simulation and finally on concluding on the green façade could balance both reductions in energy consumption while providing user’s comfort. In end, this chapter ends by introducing the energy-saving performance of vertical gardens.

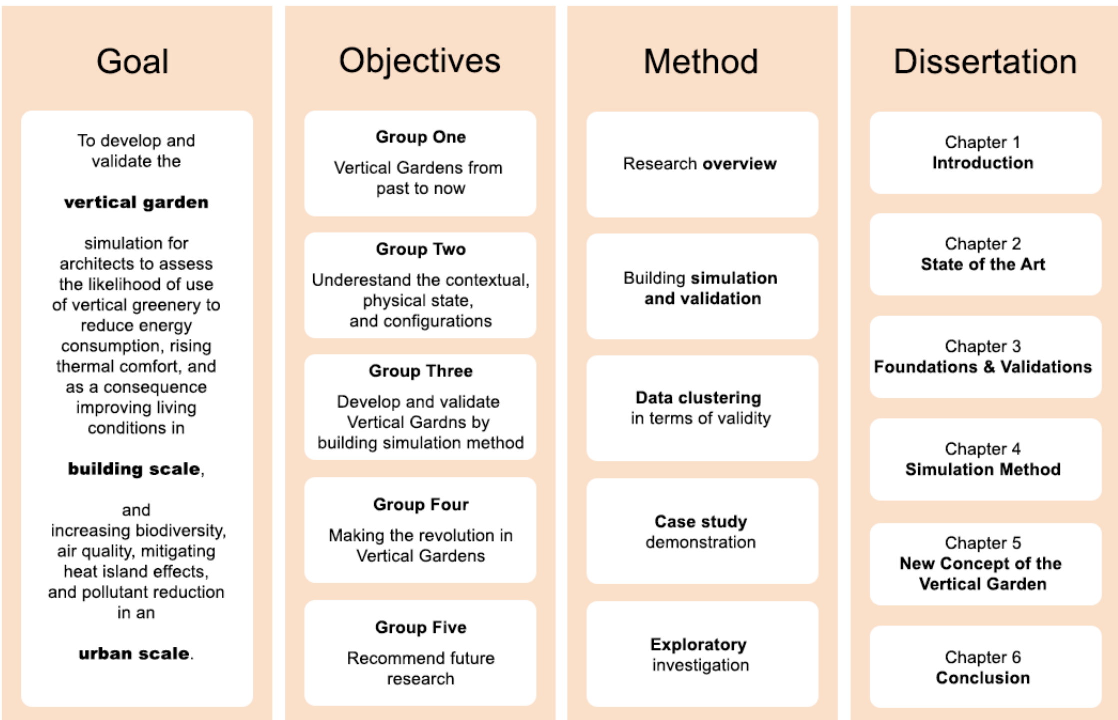
Chapter four focuses on explaining the simulation process for energy usage and thermal comfort efficiency of vertical gardens by using the IESVE building simulation tools. The information collected was analyzed. The results are used to create the green façade structure of the base case (the unit of measurement), which will be used to test and assess the green façade variables defined in this part. Variables are divided into dependent and independent variables. The dependent variables are specific building modes of operation, while the independent variables are green façade systems under review. The various calculation techniques are examined in order to assess the accuracy of various variables. The rationale for using simulation as a means of testing the study hypotheses is shown. The simulation's overall structure and model are then quickly clarified.

This chapter also connects green façades as an architectural technique to refurbishment as a sustainable solution for maintaining the functionality of existing stock. The process of deciding whether or not to renovate an office building is addressed.

Chapter five propose a new concept of the vertical garden by blending architecture with technology and biology. Cyanobacteria as a plant species play a key role in this chapter, which is implemented on the façade by using 3d printed technology. This chapter investigates typologies and biological functionalities of cyanobacteria, the application of 3D printing with different materials in the facade, and also explains in detail the simulation results of this concept as refurbishment scenarios.

The conclusion chapter (chapter six) concludes this work by revisiting the hypotheses and showing successful implementation, while also showing potential areas of development and limitations of vertical gardens, along with recommendations for future directions.

Figure 1.3: Research Process Flowchart.



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Chapter Two: State of the Art

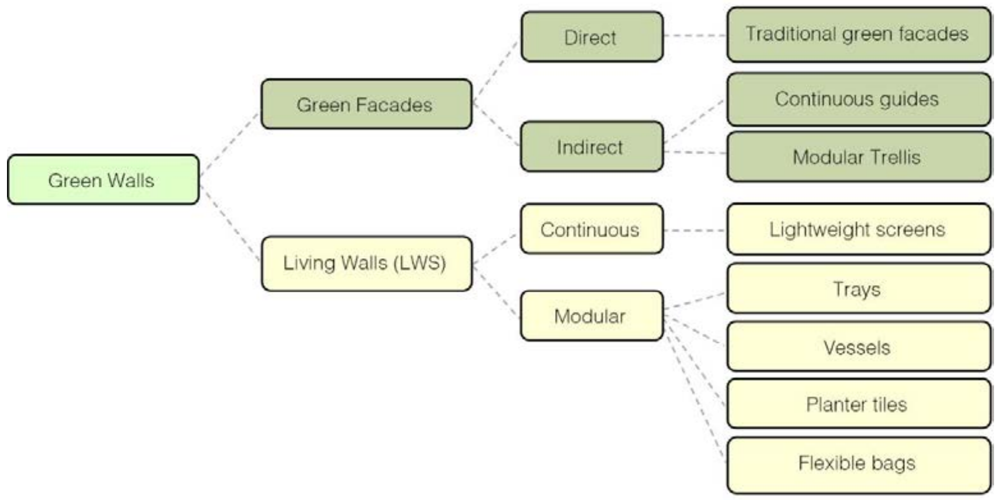
2.1. *Overview*

Urban sprawl and resource use are growing at an unsustainable rate, resulting in serious societal and environmental consequences. Climate change, health problems, the loss of natural habitats, and the increasing risk of natural disasters are only a few of the many threats we face, prompting a sense of urgency in preserving nature in built environments [1]. Nature-based Solutions are successful mitigation strategies that aid in the resolution of these problems. These developments are carefully designed based on a thorough understanding of how nature works, allowing for urban regeneration. Rain gardens, street trees, urban drainage systems, green roofs, and green walls are examples of nature-based Solutions that can work together to solve various problems. [2].

Due to the lack of available land in highly urbanized areas, green walls may be preferred over other Nature-based solutions, but they also provide multiple ecosystem services [3], such as air pollution absorption [4], indoor and outdoor temperature control [5], urban noise absorption [6], biodiversity recovery, and urban wildlife safety [7]. These solutions, which include runoff management [8], flood prevention [9][10] and sponge city interventions [11], help to create a sustainable drainage network. Aside from the environmental and ecological advantages, social advantages include improved quality of life and public health [12], attractive leisure areas, and improved aesthetics [13][14]. These solutions improve building performance from the perspective of building users and potential investors by protecting and increasing the longevity of wall claddings [15], reducing energy consumption [16][17][18][19][20], increasing the efficiency of photovoltaic panels [21][22], and reducing sound propagation [23][24][6].

Green walls are multi-layered systems that develop vegetation in the building envelopes. Green walls come in a variety of shapes and sizes (Figure 2.1) [25]. Each technology can incorporate a variety of design elements, such as different plant species and substrate compositions, to name a few. These various technological options have an effect on the final solution's results. Major research efforts have been made within the framework of reviews for describing green walls in terms of their key features, following the historical analysis of their use [26][27]. Many researchers have examined the social, environmental, and economic advantages of this technology [25][28][29][30], as well as the fundamentals of its use, performance, and implementation challenges [31].

Figure 2.1: Classification of green walls, according to their construction characteristics. *(M. Manso, J. Castro-Gomes / Renewable and Sustainable Energy Reviews 41 (2015) 863–871 Green)*



2.2. *Vertical Garden in History*

By looking at design theory during 2000 B.C.–2000 A.D. can understand how little has changed in the long history of gardens and gardening in these years [32]. As seen from behind in the history of vertical garden shows that vegetated façades are not a new technology (Figure 2.2); however, they can provide multiple benefits as a component of popular urban design. The vertical garden has been used in the building envelope for centuries to shade building walls and atriums, protect buildings from the wind, and grow agricultural plants. The first vertical gardens were created in the Mediterranean region around 3000 B.C. Grapevines (Vitis spp.) were and still are very popular food crops in the region, so they were commonly grown in fields, homes, and gardens all over the place. Some vines were planted to grow food, while others were planted to provide shade in areas where planting trees was not a choice. Above is an image of a Vitis vinifera plant that is currently being cultivated in Greece (Figure 2.3).

Figure 2.2: The history of vertical gardens, including a timeline and examples of contemporary conceptions.

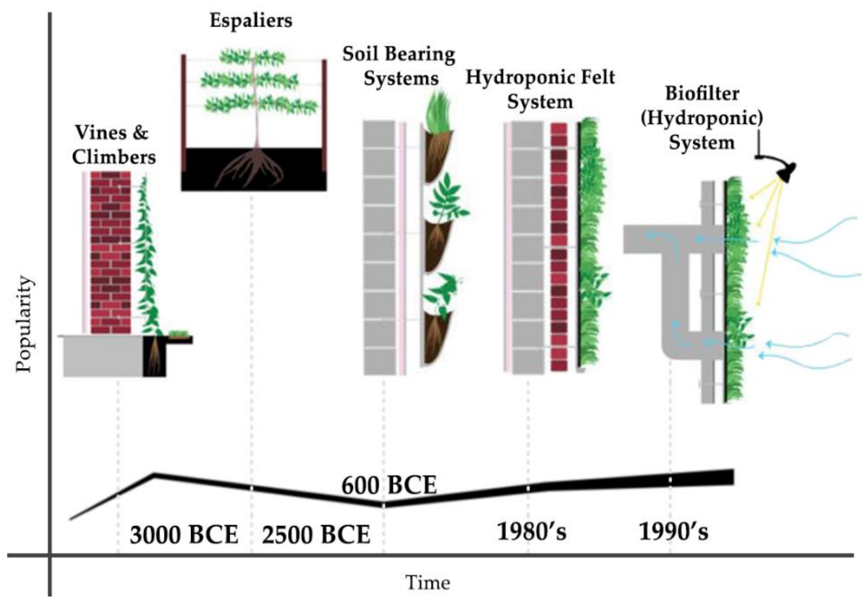
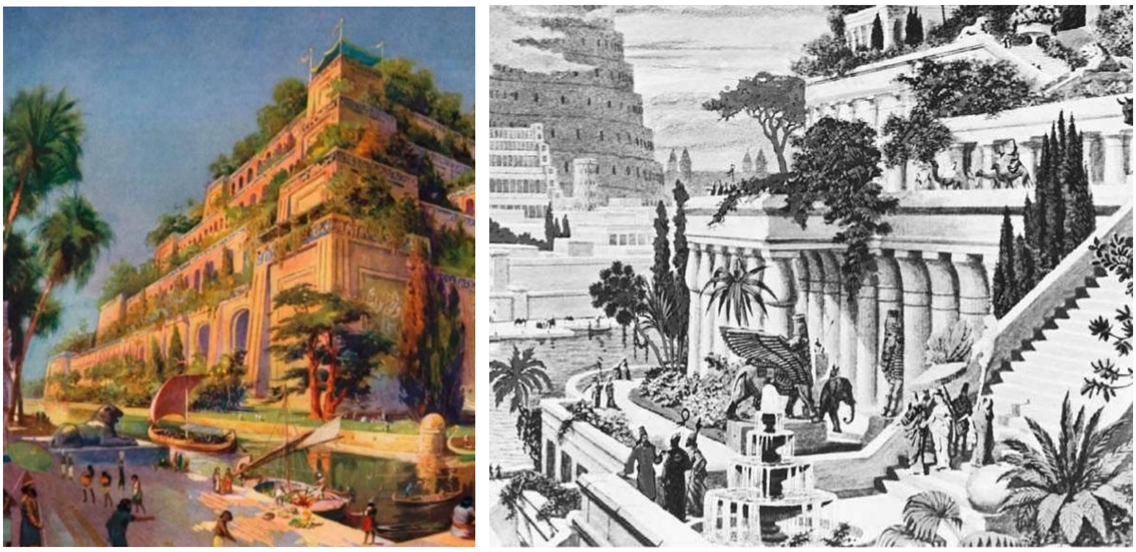


Figure 2.3: Vitis vinifera on the façade of an old house in Greece.

Many researchers have shown that the initial idea of vertical vegetation, including the widespread use of green walls, can be traced back to Babylon's Hanging Gardens [27], one of the seven ancient wonders of the world, dating from between 600 to 800 B.C. (Figure 2.4).

Figure 2.4: Hanging Gardens of Babylon, constructed between 600 to 800 B.C.



Vertical gardens during Design philosophy 2000 B.C - 2000 A.D:

A garden is "a piece of ground fenced off from cattle, and appropriated to the use and pleasure of man: it is, or ought to be, cultivated" [33]. At 10,000 B.C., people started to enclose outdoor areas. West Asia started farming, settlement, and gardening. The first cities have grown here. This course of garden evolution moved north and west for 4,000 years before it reached the coasts of California. The eastern and western traditions, as well as the social, artistic, and philosophical frameworks that regulate the creation of gardens, began to converge at this stage. According to garden theory, there are six compositional elements for outdoor design which 1) Landform; 2) Vertical structures; 3) Horizontal structures; 4) Vegetation; 5) Water; 6) Climate [32].

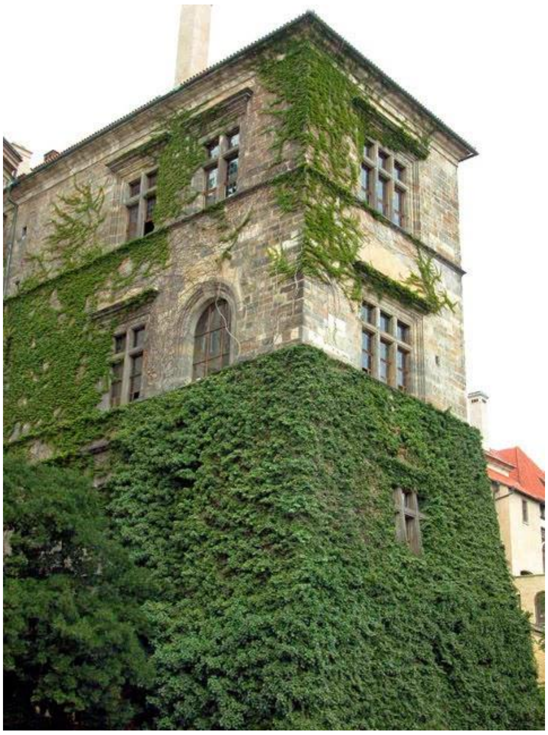
During 2000 B.C - 2000 A.D, Palace gardens was built by kings and nobles as an addition to their living quarters. It was natural to gather officials and hold parades in such places, which became known as the court (or hof) [32]. Figure 2.5 shows the vegetation layer on one of the building façades of the Horse Guards Parade that is a historic building in the City of Westminster, London. It was built in the mid-18th century.

Figure 2.5: Horse Guards Parade, London.

Vertical gardens in Medieval gardens 600 A.D-1500 A.D:

The Middle Ages are among the most important in the history of the garden, but in many respects frustrate the scholar. The fascination with symbols in the Middle Ages stemmed from philosophy: 'nature seemed to the symbolical imagination to be a kind of alphabet by which God spoke to men and revealed the order of things'. Europe's Middle Ages, which lasted a thousand years, had periods of stability and prosperity that could have been used to build magnificent gardens. Castles and towns lacked internal spaces, but extensive gardens, similar to the gymnasiums and groves of Ancient Greece, could have been built outside fortifications. The Prague Castle is an example of Medieval gardens in which vertical greenery was applied on the part of the castle's façade (Figure 2.6). Ornamental climbing plants and fruit tree trellis (trees trained to grow against flat support or wall) were popular in the courtyards of castles and palaces in Medieval Europe to provide shade and harvest fruits and vegetables in limited horizontal space [34].

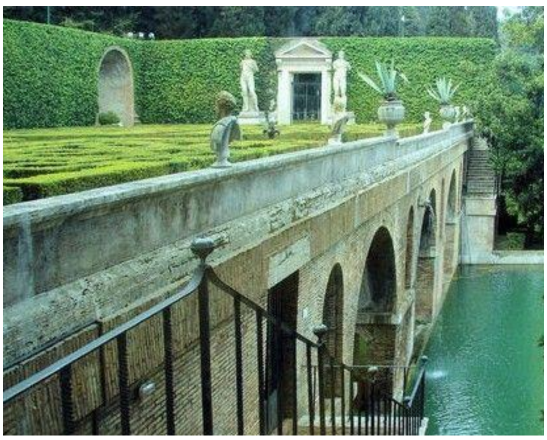
Figure 2.6: Prague Castle was built during the Medieval gardens 600 AD-1500 AD.



Vertical gardens in Renaissance garden 1350–1650:

Religion had dominated medieval thought, as had monastic gardens. The reason was set on a path by Renaissance philosophy to reclaim its classical status as the supreme criterion of reality, rather than as a help for faith. In history of garden design during the renaissance between 1350–1650, can be seen in the use of vertical greenery on the buildings' façades [32], as an example Villa Madama, Roma, Italy (Figure 2.7). The Villa Madama was influential due to its high quality and the fact that it was designed by Raphael, whose art was regarded as the peak of Renaissance beauty before its 'descent' into mannerism and baroque. Madama was one of the very first High Renaissance villas constructed in 1518 outside of Rome, Italy.

Figure 2.7: The started to build in 1518 and finished in 1525 as a renaissance architecture style in Roma, Italy.



Vertical gardens in Eclectic gardens 1800 to 1900:

Around 1800, garden design theory ran into an issue that is still being debated today. According to Gothein's study, practitioners had stopped 'looking for art at all,' so that 'the entire nineteenth-century could complete its tale of sins before the foundations are broken.' Architecture from the nineteenth century met a similar fate. Vertical greenery can also be seen in the Eclectic gardens style during 1800 to 1900 (Figure 2.8).

Figure 2.8: Chateau de Courances was built in 1630 and its garden recreation of the style of Le Nôtre in 1870 by Duchêne during the Eclectic gardens period in France.

Vertical gardens at the beginning of 18th century:

At the beginning of the 18th century, turf or sod (a top layer of soil consisting of grass and roots) was widely used as a façade or roof material in many northern countries, and vegetation cladding was also incorporated into the building practices. The Vikings used turf to cover building roofs and façades, which provided more protection against extreme cold [35] (Figure 2.9).

Figure 2.9: Icelandic turf houses.

Vertical gardens during Abstract and post-abstract gardens 1900 - 2000:

In the 19th century, woody climbers (trees and shrubs with self-supporting, rigid, erect stems) were commonly used as a coating layer for plain facades in many European and North American cities. The vision to conduct nature in cities was born out of Central Europe's rising interest in environmental issues in the 1980s. Many German cities created incentive schemes, some of which aided residents in planting and preserving climbing plants in their façades and backyards. Plants' insulating performance on façades, their ability to mitigate dust, the cooling effects of plants' evaporative, and the development of habitat for urban wildlife such as birds, spiders, and beetles have all been studied since the 1980s. Berlin is a good example, with about 245.584 square meters of green façades built between 1983 and 1997 [27]. Two Ph.D. dissertations have been completed on the ecological functions of green facades in Germany by Friedrich Bartfelder and Manfred Köhler in 1987 [36] and Thoennessen in 2002 [37]. A third one is focused on the social and economic aspects of green facades by Tobias Chilla 2004 [38]. While the vertical garden has the potential to boost urban microclimate and buildings' ecological footprint, it has yet to gain widespread adoption in most semi-arid climates due to a lack of water and climate conditions, as well as the lack of implementation guidelines and incentive programs.

In addition, in the 1980s, world-renowned French botanist Patrick Blanc started experimenting with his signature hydroponic method, Mur Vegetal, which he has since applied to large-scale, internationally acclaimed green wall projects all over the world [39][40]. His first major project was completed in 1996, and he has since collaborated with some of the world's most well-known architects. Blanc's gardens are the most well-known style of the vertical garden among the general public. Amazingly, his lush designs are supported by a growing medium made up of just two thin sheets of felt with a total thickness of just a few millimeters. This implies that the device is both light and soil-free. Hydroponically grown green walls are less vulnerable to pests and need fewer structural changes to support the weight due to the lack of soil (Figure 2.12) [41]. The major highlights in green walls history show in Table 2.1 [42].

Many artists turned away from abstraction during the closing decades of the 20th century. With classical order, the architects resumed their filtration; garden designers were inspired by meanings, iconography, and allusions; the concept of the garden came back with wild animals and plants. Since both of these developments took place after the void of abstract modernism, they can be classified as post-abstract or postmodern. Modernists believed in purity, simplicity, and abstraction from context; postmodernists believed in complexity, pluralism, conceptualism, layering, and re-contextualization. During this period, vertical greenery has perfectly developed. In the meantime, the use of vegetation as the key feature of "Hundertwasser's projects" can be seen in Figure 2.10, 2.11 which shows some of his projects which his radical integration of gardens with architecture is overtly anti-modern [32]. At that time, architects demonstrated the possibility to combine ecological compatibility with modern technologies.

Figure 2.10: Residential building of the city of Vienna, HUNDERTWASSER-HOUSE, constructed in 1983 - 1985.

Figure 2.11: The Hundertwasser House is an apartment house in Bad Soden that the house was built in the 1990s; it has 17 completely different apartments.

Table 2.1: Highlights in green walls history.

Year	Description
1920s	The Garden city movement in the UK and North American is promoting the incorporation of houses and gardens by means of features like pergolas, trellis systems, and self-clinging climbing plants.

1988	A cable system for green facades in stainless steel was introduced. The early 1990s: The North American market was opened by cable and wire-rope net systems and modular trellis panel systems.
1993	The first big use of the Universal CityWalk trellis panel system in California.
1994	The Canada Life Building in Toronto, Canada, installed an indoor living wall with a bio-filtration device.
2002	In Zurich, Switzerland, the MFO Park, a 300-story and 50-story high park building, has been opened. More than 1300 plants were part of the project.
2005	A major bio-lung exhibition, the central feature of Expo 2005, in Aichi, Japan, was funded by the Japanese federal government. The wall has 30 separate modular green wall systems.
2007	The Green Factor, which includes green walls, is implemented in Seattle.
2007	Green Wall Design 101 launched full day by GRHC; the first subject in North America.
2008	The Green Wall Excellence Award and Green Wall Research Fund were launched by the GRHC.

Figure 2.12: The green wall on the Quai Branly Museum designed by Patrick Blanc in 2005 in Paris.

Another notable advancement in vertical gardening technology occurred in the 1990s at Guelph University's Humber Campus in Toronto, where a team of researchers designed and tested a hydroponic vertical garden that doubled as a giant air filter [43] (Figure 2.13).

Figure 2.13: University of Guelph-Humber Campus Biowall, designed by Nedlaw.

Various climbing plant species are grown along with building envelopes and above atria to shade the façade from direct sun exposure and to cool the air in many countries with different climates (Figure 2.14).

Figure 2.14: Potted plants covering the walls of Spanish patio.

As previously mentioned, vertical greenery gardening has slowly spread across the world in recent years, with the majority of them being vine-based gardening, helped primarily by the garden city movement. The Garden City aimed to incorporate nature into the city, and since vertical gardens on grade need a small footprint, they quickly became a simple and relatively inexpensive way to green many cities. Virginia Creeper (Parthenocissus quinquefolia), English Ivy (Hedera helix), and Boston Ivy (Parthenocissus tricuspidata) are among the most widely planted vine plants in the past. These plants are still commonly used today because of their ability to thrive in a variety of climates and attach themselves to building facades without the use of a trellis.

The relationship between humans and nature is more critical than ever before when more than half of the world's population now lives in cities, where the natural environment replaces the man-made [44][45]. The fact that buildings near natural areas, such as parks, have higher real estate prices than those without such amenities demonstrates this [46].

The environmental sustainability movement has sparked a renewed interest in structures that incorporate plants into their design. Building designers and architects have recently advocated for the incorporation of plants into building envelopes, such as roofs and exterior walls (Figure 2.15,2.16), which account for a significant portion of a structure's surface area. The integration of plants into vertical elements of architecture has evolved into the idea of green walls, which has gained popularity in recent years thanks to French botanist and designer Patrick Blanc's "vertical gardens" [41] (Figure 2.17).

Figure 2.15: Athenaeum Hotel, London.

Figure 2.16: Consorcio Santiago Building, Chile.

Figure 2.17: Vertical garden designed by Patrick Blanc in Caixa Forum, Madrid.

Green walls have been used in a variety of forms from the past to the present, and their typology includes green façades, living walls, vertical gardens, hanging gardens, bio-shades, and bio-façades. Green walls have become a common design element for many architects and artists, who incorporate them into existing façades as well as new commercial, residential, and public building construction with great creativity.

2.3. *From the Horizontal Garden to the Vertical Garden*

The concept of a garden is a green place that is restricted on one side but stretching across a horizontal surface. Since the beginning of human existence, gardens have existed as humans-built shelters to protect themselves from various scenarios, including inclement weather conditions. The "green" element has always been present throughout human history. In fact, green spaces and gardens have always been present in human's life and, as a result, were part of the environment into which human was inserted. All across history, the garden has been proposed as an artistic composition or as a complement to the city or architecture [47]. There are many references to gardens in biblical texts, the most notable of which is the Garden of Eden, that is correlated with paradise.

The development of Gardens was accompanied by theories of vogue and had various goals: sacred spaces, spaces for leisure, healing spaces; architectural elements for the identification of the outdoor spaces; areas of research and experimentation [48][49]. Progressively, horizontal gardens gained many dimensions, as did the modelling of the land that became art through "land art" and "earthworks" [49] (Figure 2.18). Horizontal gardens also gradually showed "Green," together with a diverse and abundant vegetable layer, was the target for rotations and twists. The acquired condition of horizontality was quickly called into question by opening a path to vertical plans. As a result, horizontal gardens gave way to the vertical garden, implying that it is no longer limited to the soil substrate to be a part of the building.

Figure 2.18: l'Orangerie Palace of Versailles, France is a good example of land art of gardens.

The green space we call a garden is one more compositional element that has been added to the architectural grammar that also appeared as a novel architectural element in the 20 and 21 centuries, which is called green façades (Figure 2.19). Vertical greenery in architecture is enhanced by this new element, which is more than just a new material; it is a novel way of doing architecture that reconnects humans to nature. Horizontal coverage with plants was an experimental "ground," a new challenge for architecture to absorb and respond to, and with the creation of vertical gardens, there is wide and diverse use of vertical greenery as new architectural elements, based on accurate engineering solutions, which allow mitigating unfavorable environmental conditions, as well as the creation of a new language, either through new construction or through reuse. Furthermore, historical and heritage buildings can be refurbished and tried to intervene in using this new, interdisciplinary architectural language.

Figure 2.19: Green façade as a vertical greenery system designed by Patrick Blanc in Madrid, Spain.

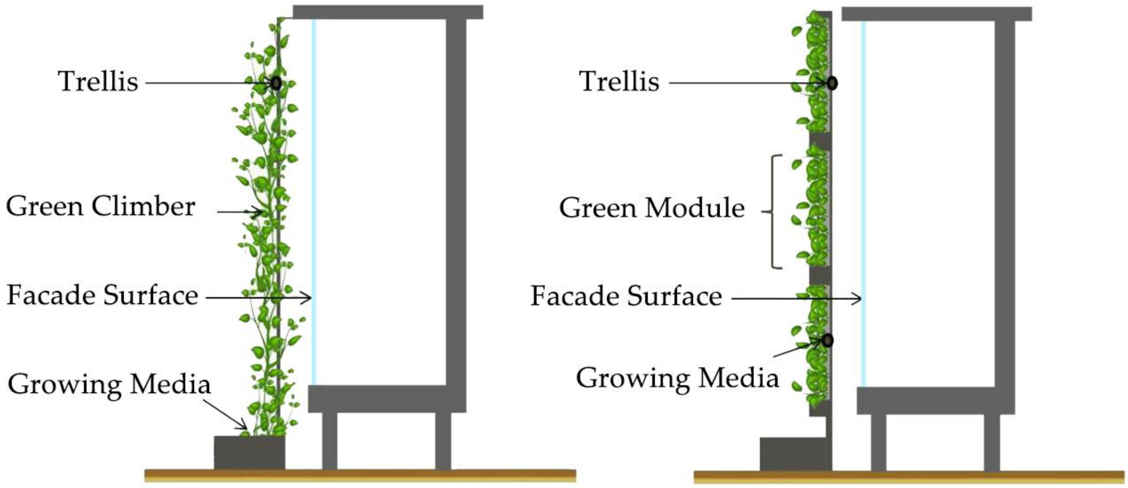
It is well known that green spaces such as parks and vertical greenery systems like green façades in urban areas have a significant impact on citizens' quality of life. Citizens will benefit from urban renewal policies that include guidelines for the installation of gardens, both horizontal and vertical.

2.4. *Typologies of the Vertical Garden*

The "green façade" or "vegetated façade," as established by the Council on Tall Buildings and Urban Habitat (CTBUH), is a system in which plants grow on a vertical surface such as a building façade in a regulated manner and with regular maintenance [34]. Climbing plants naturally acclimate to building facades by binding themselves to surfaces using a variety of mechanisms. Self-clinging climbers and self-supporting woody plants may bind themselves to the surface of the façade or expand along with it without the need for additional support. To encourage or maintain vertical development, other plant species, such as climbers with aerial roots, suckers or tendrils, twining climbers, and lax shrubs (ramblers), need additional support such as trellises, netting, or wires connected to the façade surface. As a result, the most important components of vertical greenery systems such as green facades and living walls are (Figure 2.20):

- Plants
- Planting media
- Structures that support and attach plants to the façade
- The irrigation system

Figure 2.20: Green façade systems (left) and living wall systems (right).



Multiple types of vertical greenery systems can be distinguished based on the plant species, planting media, and support structures used, and are generally categorized into four categories:

- Façade-Supported Green Wall
    - Metal Mesh Green Wall
    - Cable-Supported Green Wall
    - Rigid Green Wall
- Façade-Supported Living Wall
    - Vegetated Mat Living Wall
    - Hanging Pocket Living Wall
    - Modular Living Wall
- Stepped Terraces
- Cantilevering Tree Balconies
- Other Types (Green wall types can include exterior walls covered with a layer of moss or grass, and even entire trees.)

2.5. *Vertical Garden in Semi-arid regions*

2.5.1. *Semi-arid regions characteristics*

Semi-arid and arid zones, also known as drylands that are areas where gross surface evaporation and plant transpiration outnumber precipitation on an annual basis. According to reports, they cover roughly 15% of the Earth's land surface [50] and play an important role in global climate change as a regulator of patterns and variability in atmospheric carbon dioxide (CO2) concentrations [51]–[54]. Researchers found that the mean sink, trend, and interannual variability in CO2 absorption by terrestrial ecosystems was affected by a variety of biogeographic regions, with semi-arid ecosystems having the greatest effect on the sink's trend and inter-annual variability [51]. Also, carbon pools in semi-arid biomes drive the global carbon cycle inter-annual variability [54]. These areas are ideal for activities with lower annual production and are more vulnerable and rapid in response to external forces due to a lack of water sources, low vegetation coverage, and a fragile ecological climate.

The semi-arid regions have experienced the greatest land temperature rise and area expansion over the last 100 years [55][56]. According to climate forecasts [57][58], the situation is expected to worsen, resulting in a rise in aridity, warming, land degradation, and desertification in developing countries' drylands [56]. Drylands would also be affected by climate change as a result of emissions from humid lands [56][59].

The vegetation of the semi-arid zone is heavily influenced by the spatial and temporal differences in water availability. These variables reveal apparent connections between hydrology and ecology in these areas, where precipitation varies more dramatically over time than in other areas at different scales (diurnal, seasonal, and inter-annual) [60]. In general, precipitation bursts end dry periods by triggering a cascade of pulsed ecosystem responses. In the meantime, they can cause a rapid increase in evapotranspiration, which is made up primarily of evaporation from plant and soil surfaces, as well as plant transpiration by leaf stomata. As a result, if the water added is sufficient to wet the root areas, as indicated by surface/sub-surface soil moistures, transpiration will contribute significantly to total evapotranspiration [52],[61]–[64]. Because water is the main constraint on plant productivity in these regions, evapotranspiration is an important predictor of vegetation tolerance and resistance to drought conditions [65][66]. Evapotranspiration is a key mechanism in the hydrological cycle that connects the energy, carbon, and water cycles [67].

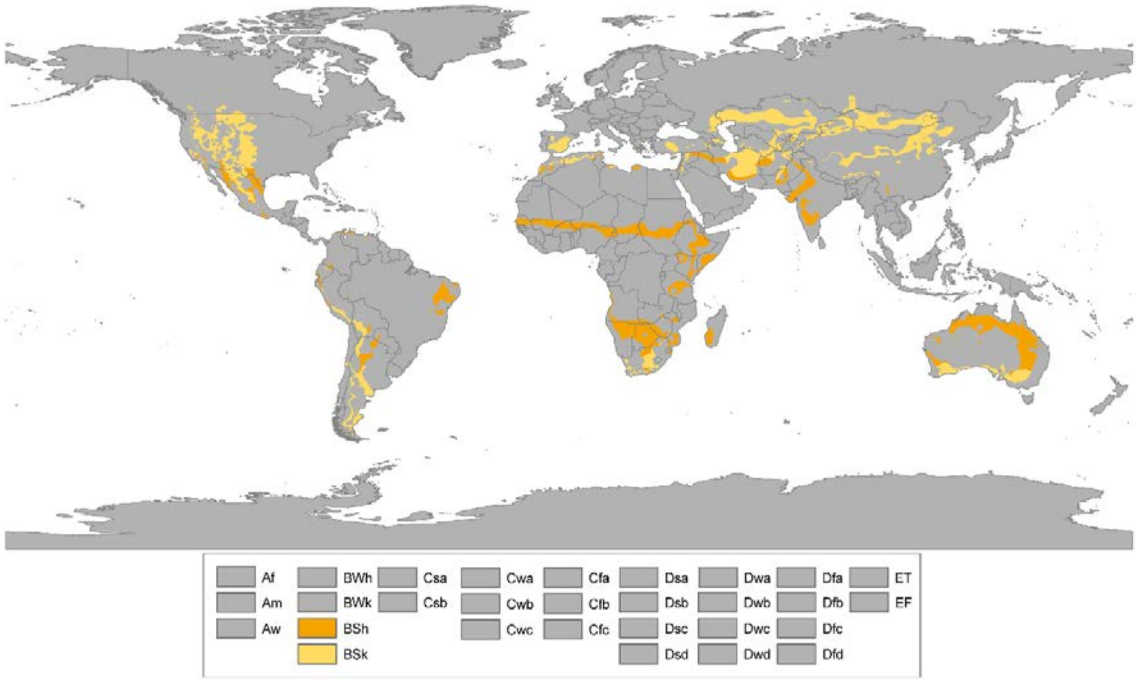
Small Shrubs, Trees and Plants:

Due to a lack of precipitation, these regions are normally unable to support forests or significant vegetation. The vegetation of semi-arid regions is dominated by small plants, such as grasses, shrubs, and small trees. Certain plants in semi-arid regions may have some of the same adaptations as desert plants, including thorny branches or waxy cuticles that may adapt to reduce evaporation and water loss through their leaves.

2.5.2. *Semi-arid climate classification*

Semi-arid climates are also known as steppe climates which these regions are the world's second driest climates, after deserts, which are noted for their dry, arid climates. Figure 2.21, according to the Köppen climate classification (see Appendix F for further information about the Köppen climate classification), shows semi-arid regions in the world map. These areas receive up to 20 inches of rain each year, which is twice as many as desert regions. Semi-arid climates can be divided into two categories: hot and cold.

Figure 2.21: BSh (Hot semi-arid climate) and BSk (Cold semi-arid climate) regions in the world according to the Köppen climate classification.



Hot semi-arid:

In the tropics or subtropics, hot semi-arid climates can be found, sometimes on the outskirts of the subtropical desert. Summers are extremely hot, and winters are mild or warm. Most of the Australian outback, as well as parts of southern Africa and a wide region of land on the southern edge of the Sahara Desert, have these climates.

Cold semi-arid:

Cold semi-arid areas are more likely to occur inland, away from large bodies of water, and are located in temperate zones. Summers are usually hot and dry, and winters are often cold enough to produce snow. The Great Plains of North America, as well as large parts of Mongolia and Kazakhstan, have cold semi-arid climates. Many semi-arid regions, such as the Great Plains of North America, have grassland areas, while others have plants with glossy leaves.

2.5.3. Vertical Garden Studies in Semi-arid Regions

The vertical garden has many uses and benefits in different climates, both at the urban and building scale mentioned at the outset of this chapter. Among these benefits, energy efficiency and thermal comfort are studied more than other aspects in arid and semi-arid regions, and due to the fact, that in these regions the use of energy is very high because of high temperature and having dry and hot summers and also cold winters. There are limitations and conditions for applying vegetation layer on the facade in these climates due to lack of water and poor conditions for plants which discussed in this section.

In semiarid regions, several researchers have shown that green walls are able to influence heat transfer between the internal and the external environment of a building in these areas as its energy efficiency. The following are the key external factors that influence heat transfer through a building's façade: (i) solar and thermal radiation from the atmosphere and the ground, (ii) air temperature, (iii) relative humidity, and (iv) wind speed. The impact of these climatic influences on the exterior wall surfaces is reduced by plants and other components of green walls, such as planting media or supporting structures, leading to a reduction in heat transfer through the façade and a reduction in heating and cooling energy consumption. In order to determine the impact of a green wall on building thermal efficiency and potential energy savings, it is critical to first understand the energy balance of a vegetated wall as well as the individual thermal-physical processes [34].

In a five-story brick building in Thessaloniki, Greece, via an experimental-based study by Evmorfopoulou et al. in 2009, assessed the effects of wall vegetation on the thermal activity of the East Façade, with the area of the glass of 15% on the floor [68]. On the second floor, the vegetation-covered area was contrasted to the barren area on the third floor. The ambient air temperatures outside and indoors, surface vegetation temperature, surface façade temperature behind the vegetation, and room surface interior temperature were calculated. When covered with vegetation, particularly on warm days, the surface of the façade temperature was significantly reduced. Behind the foliage, the facade temperature was 1.9°C to 8.3°C (average 5.7°C) below the bare facade surface temperature.

Huang et al. in 1987 by simulation-based research has examined how the impact of the trees on shade, reduction in wind and air cooling with the evapotranspiration procedure affects building cooling [69]. The researchers used DOE-2.1C software to model the cooling energy consumption of a traditional, air-conditioned one-story, wood-framed house in a semi-arid environment (Sacramento, CA, USA) with various amounts of tree area coverage (10%, 25%, and 30%). The simulation calculated the impact of the trees on the annual energy consumption of buildings, peak cooling loads, and costs. The results were compared with a typical, moderately isolated home, the performance of a base case. The simulation showed that the annual cooling requirements have been significantly reduced. For 10% of the tree area, energy reduction was 18.4% for 25% of the tree area, 42.5% less, and for 30% of the tree area, energy decrease 53.3%. in Sacramento, USA.

Kontoleon et al. in 2010, used a one-dimensional circuit model with resistors reflecting the thermal resistance of the wall assembly layers to investigate the effect of plant cover on building thermal efficiency [70]. They created a model of a one-story square brick building in Thessaloniki, Greece, that measured 10 meters by 10 meters in the plan, stood 3 meters tall, and had no windows. A bare facade wall model was compared to a vegetated facade's canopy model. The study examined the effects of the building's orientation, insulation layer positioning, and vegetation coverage as well as measuring ambient outdoor and indoor air temperatures, surface vegetation temperature, surface façade temperature, the room's interior surface temperature, and reduced building cooling ability.

The results showed that for the vegetation-covered façade and the room surface temperature was lower than the bare facade. The mean temperature of exterior surface difference was 1.73°C in the north-facing wall, 10.53°C in the east-facing wall, 6.46°C in the south-facing wall, and 16.85°C in the west-facing wall. The average temperature of the interior wall surface difference was 0.65°C in the north-facing wall, 2.04°C in the east-facing wall, 1.06°C in the south-facing wall, and 3.27°C in the west-facing wall. In the east and west façades, the temperature difference was particularly significant. Fluctuation of the façade surface temperature during vegetated facades (on average 1.09°C, on the western façade max 2.42°C) as for bare façade (on average 10.97°C, on the west façade a maximum of 19.27°C). Finally, it was found that when vegetation on the façade was used, the building cooling load was lower.

The addition of a vegetation layer reduced the building cooling load for the north-facing wall by 4.56%, for the wall to the eastern side by 18.17%, for the wall to the south by 7.60%, and for the western side by 20.08%. Some of results of the experimental and simulation studies are summarized in Table 2.2.

Table 2.2: Summary of studies on thermal effects of vegetation.

Ref & Year	Location	Climate Zone*	Period	Duration	Green Wall Description	Façade Orientation	Façade Surface ∆T(decrease)	Cooling Savings (%)	Ambient Air ∆T(decrease)
[68] 2009	Thessaloniki, Greece	Semi-arid	Jul - Aug	1 Month	Plant-covered building façade	E	1.9°C – 8.3°C	-	1°C - 2°C
[71] 1987	Sacramento, USA	Semi-arid	-	1 Year	Building shaded by trees	All	-	18.4 – 53.3	-
[70] 2010	Thessaloniki, Greece	Semi-arid	-	1 Year	Plant-covered building façade	N	1.73°C	4.7	-
					Plant-covered building façade	E	10.53°C	18.2	-
					Plant-covered building façade	S	6.46°C	7.6	-
					Plant-covered building façade	W	16.85°C	20.1	-

* Köppen Climate Classification

2.6. *Functionalities of Vertical Garden*

Plants are the foundation of all life on Earth and a necessary resource for human survival. Although there are strong links between plants and our daily food for survival, we are yet to establish strong links between plants and our built environment. Plants and their biological roles in the landscape and built environment were once thought to be limited to "romantic gardenesque" applications. Many people, understandably, still hold this viewpoint due to the aesthetic qualities of plants. Beyond its aesthetic value, greenery's biological versatility is crucial in developing useful applications and identifying sustainable approaches in any built environment. Previously unfavorable areas can be planned, constructed, and installed to build more livable spaces by incorporating greenery into the built environment.

Improving a facade's thermal efficiency and reducing building energy usage.

Thick vegetation can act as an envelope insulator and shader, preventing heat and cool air from escaping into the atmosphere through the building envelope and restricting solar gain to the exterior surface of a wall or through the glass. In summary, green walls can help insulate a building in cold climates while also providing shade in tropical climates. In arid and semi-arid climates, environmental transpiration also creates small zones of cool air, especially between the green wall and the building envelope, but also in some cases along the building's exterior, which aids the envelope's thermal transmittance. For example, the Consorcio project in Santiago, Chile, which has vertical greenery covering 43% of its west façade (Figure 2.22), records 60% less solar radiation and 48% reduce energy use than ten other comparable buildings nearby.

Figure 2.22: The 43% west façade greenery coverage of Consorcio project in Santiago, reduces solar gain by 60%, and the structure of green façade of Consorcio project.

Protecting façade materials from degradation because of natural factors such as driving rain, solar and UV radiation, and extreme temperature fluctuations.

It stands to reason that covering a façade with plants would shield the materials behind the façade from the effects of the climate. However, the roots and stems of the plants themselves, particularly those climbing plants that connect themselves to the surface, can lead to the degradation of the facade materials beyond, and may even lead to structural damage if not managed.

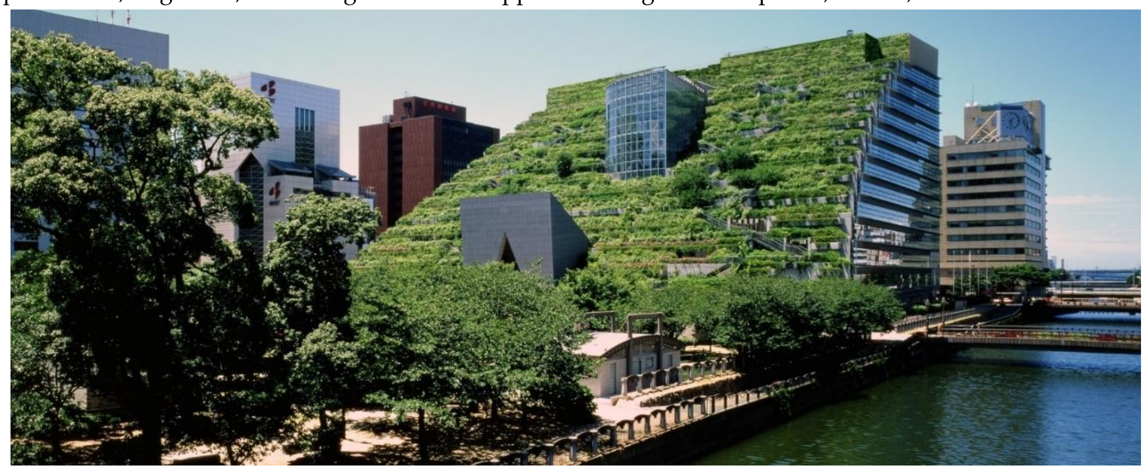
Improving the quality of indoor or outdoor air.

Plants are well known for their ability to enhance the air quality of their surroundings. On both an urban and a building scale, the photosynthesis process produces oxygen and sequesters carbon dioxide. Leaves have a large surface area that can absorb airborne particulates and prevent them from entering building systems, where they can be collected and recirculated to cause damage.

Creating more temperate microclimates near outdoor areas.

Plants can significantly reduce the temperature of the immediate area around them by shading and atmosphere transpiration. For an instance, The ACROS project in Fukuoka, Japan, showed a difference of up to 15 °C between the surface temperatures of the greenery area and the adjacent concrete. Because of the project's morphology, a dense layer of greenery was present on both horizontal and vertical surfaces, and its proximity to a park meant that greenery was the dominant feature of the immediate area (Figure 2.23). This illustrates one of the larger-scale goals of green walls in general, to lower temperatures and boost the microclimate around the project, as well as the city as a whole, by reducing the urban heat island effect. Obviously, combining multiple green walls, horizontal greenery areas, and parks would greatly increase the gain by capturing more solar heat and producing more oxygen.

Figure 2.23: ACROS, Fukuoka, is located next to a park and a waterway, raising the chances of cross-pollination, migration, and living inside the stepped terrace garden for plants, insects, and wildlife.



Improving the building's architectural appearance and increasing the presence of nature for both building inhabitants and the general public.

Obviously, buildings are stronger aesthetically with vertical greenery than without. A green wall on a building's exterior is a "breath of fresh air" in the landscape. This isn't a flimsy advantage. The appearance of greenery has been shown to increase human psychological well-being, and the use of a building as a "green billboard" is likely to have a perceptible, if not easily observable, impact on the bottom line for retail and commercial establishments like hotels.

For an instance, at Pasona Headquarters in Tokyo, the impact has actually been calculated by the use of post-occupancy surveys and other monitoring techniques (Figure 2.24). Employees at Pasona have seen a 12 percent increase in productivity and a 23 percent decrease in attendance-related illnesses.

Figure 2.24: Pasona Headquarters, Tokyo.

Providing space for urban agriculture as well as the inhabitants of buildings.

Green walls have the ability to increase the variety of agricultural food sources available and minimize "food mileage," or the distance that food must travel from point of origin to point of need, resulting in fossil-fuel emissions and greenhouse gas emissions. This is possible because of the enormous amount of effort needed to find plants that will thrive in a given environment, let alone produce edible food, particularly when that environment is largely vertical.

For example, the edible product of the green walls at Pasona's Tokyo headquarters is one of their distinguishing features. Besides abundant indoor hydroponic facilities, the green wall grows edible fruits (plums, oranges, peaches), vegetables (pumpkins, tomatoes), and rice, which are harvested and cooked in the building's cafeterias.

Creating a suitable habitat for wildlife in urban areas.

Ken Yeang, one of the early pioneers of vertical greenery in building facades, was particularly vocal about the potential for vertical greenery to function as a "land bridge" or "eco-corridor" that could serve as a primary home for the plant, insect, and wildlife or a vehicle for migration and cross-pollination of plant, insect, and wildlife species (especially primary in reducing plant monocultures). For an instance, the Solaris project in Singapore, that is one of the Yeang's project, embodies this idea in the most concrete sense, as the building is encircled by a gently sloping green ramp that runs from subgrade level to the roof garden (Figure 2.25). The landscape's consistency is crucial in this regard. When the landscape is continuous, airborne seeds and insects will cross-pollinate across species within a larger vegetated field.

Figure 2.25: Solaris, Singapore, Yeang’s own project.

Creating a barrier between parking garages and the outside view, reducing vehicle-generated air pollution.

Car parking is a requirement for the fact of life in many cities, even where development preference is for high-density living and transit access. Many high-rise buildings are constructed as towers that sit atop car parking podiums; wider, squatter buildings that also contain ramped parking. Since these structures are lower to the ground, they are the most open and visible component of the building to passers-by. The ability to screen unwanted building uses from view as well as absorb the noise, fumes, and airborne particulates resulting from cars navigating the parking structure make this an ideal opportunity to cloak the building in greenery.

Also, the major source of waste heat in buildings are garages, because of auto exhaust and the thermal retention properties of concrete. A green wall can absorb excess heat from the garage while also preventing the garage from retaining solar radiation, which can heat car interiors to uncomfortably high, even harmful temperatures.

Green walls were used to secure parking facilities within some projects, such as PARKROYAL on Pickering and Newton Suites in Singapore; the Met and IDEO Morph 38 in Bangkok. At PARKROYAL in particular, the architects went to great lengths to turn a utilitarian parking facility into naturalistic, sculptural features festooned with overhanging planting (Figure 2.26).

Figure 2.26: PARKROYAL on Pickering, Singapore.

lowering the amount of street noise.

The amount of traffic and other sources of urban noise, such as construction work, has risen dramatically in recent decades in the urban world. A dense layer of vegetation, as well as the planting medium that supports it, can have sound-deadening properties besides visual appeal. This benefit of vertical greenery is cited as a reason for green wall schemes being implemented in a number of hotels and offices. For example, the green wall in the InterContinental, Santiago hotel, along the building's most active road, leads to a sound obstacle for guestrooms (Figure 2.27).

Figure 2.27: Hotel InterContinental, Santiago.

Supporting and promoting sustainable green technologies.

"Sustainability" has been embedded in the lexicon of both a business and civic policy, and the term has become so overused that it risks diluting its meaning. Green walls, which place the enterprise of sustaining life directly in the line-of-sight of building inhabitants and passers-by alike, will help to alleviate this situation. Green walls can be an outstanding educational tool, incorporating topics like the urban heat island effect, nutrient mileage, CO_2 levels, street noise abatement, and biodiversity into the everyday experience of building residents.

2.7. The Benefits and Effects of the Vertical Garden

There are several advantages of designing a green façade. These advantages vary based on a variety of variables, including geographic location and environment conditions, building morphology, orientation, plant types, and green façade components and systems. The benefits are divided into two categories: “Urban Scale” (benefits to the urban population outside the building) and “Building Scale” (benefits to the building's users and owners).

2.7.1. *Urban Scale:*

- Reducing the impacts of the Urban Heat Island (UHI)
- Improving air quality
- Carbon sequestration
- Aesthetic appeal
- Psychological impact on urban dwellers
- Providing biodiversity and establishing natural animal habitats
- Soundproofing

2.7.2. *Building Scale:*

- Increasing the energy efficiency of buildings
- Internal air quality, air filtration, and oxygenation
- Health Advantages
- Safety of the envelope
- Reduction of interior noise
- Agricultural advantages
- Increasing the value of properties
- Obtaining credits from a sustainability ranking system
    - Sustainable sites development
    - Water conservation
    - Energy and the environment
    - Materials and tools
    - The efficiency of the indoor climate
    - Organizational and design innovation

Additionally, the effects of the vertical gardens can be inspected in terms of different topics such as microclimate, human well-being, urban ecology, insulating function, Life cycle extension-protection of building fabric, stormwater management, and Urban development (Table 2.4). The investigates effects of vertical gardens reveal that the highlighted benefits will become more important as global temperatures rise and the need to regenerate densely populated urban areas grows.

Table 2.3: Effects of Green Walls.

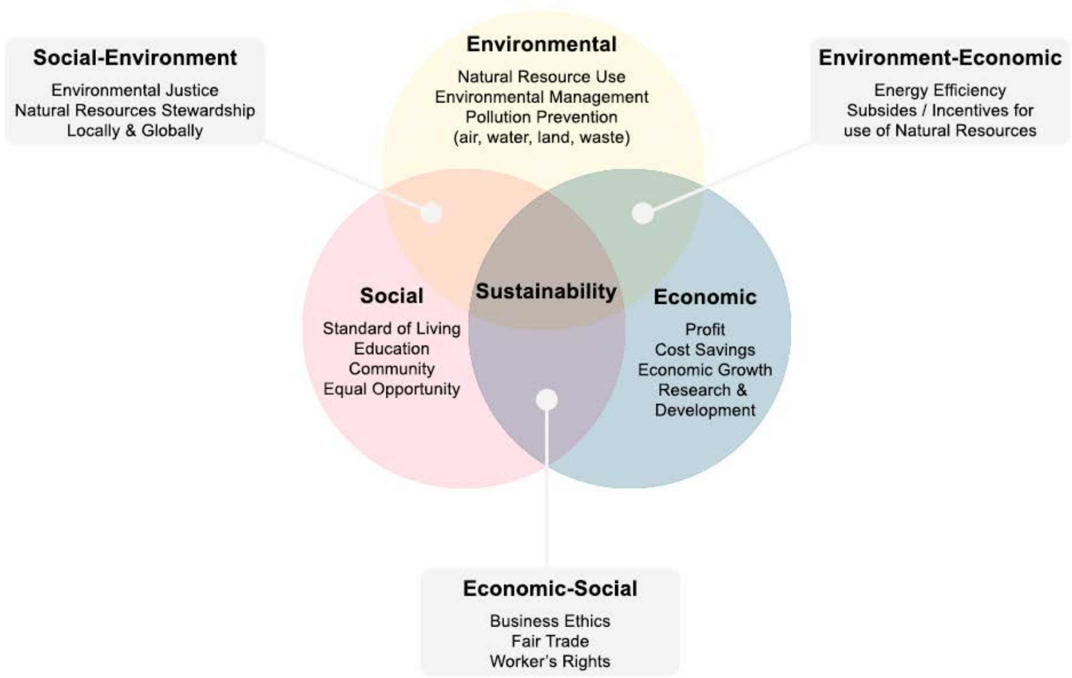
Topic	Function	Effects / Values
Microclimate	Evaporation	Increased humidity Reduction of the physiological equivalent temperature (PET) to a max. of 13 K/ reduction of UHI-effect
	Air improvement	MA 48 greening ˜ oxygen production for 40 peoples
	PM-Suppression by leaf surface	1.7 kg/m²a (1000 m² * 20 cm Hedera helix)
	Evaporative cooling	MA 48 greening cooling capacity ˜ app. 712 kWh
Human well-being	Thermal comfort	Reduction PMV-value by 1.5 points
	Noise protection	Noise reduction by 1-10 Db
	Comfort	Feeling of safety – Aesthetic effect
Urban ecology (flora & fauna)	Habitat creation	Habitat connectivity
	Biodiversity	Space for “urban wilderness
Insulating function	Reduction heat loss	Heat transfer reduced by 0.19 W/m²
Life cycle extension – protection of building fabric	Physical material protection	Protection of mechanical & chemical environmental influences Woodpecker holes Vandalism (graffiti) Lower remediation costs

Stormwater management	Backing, Storage, Evaporation	Stormwater overflow Reduced costs (stormwater charge) Reduction of consequences from stormwater events
Urban development	Use of remaining areas Aesthetics	Increase of vegetation areas Revaluation of building fabric

2.8. *Sustainability*

Sustainability is comprehensive and a complex subject which has become a driving force to renew urban areas and also represented as a synergy between society, economy, and environment (Figure 2.28). It is vital importance to all because it deals with the survival of human species and almost every living creature on the planet. Sustainable and eco-friendly architecture is one of the main aims that humans for creating a better life have made as the ultimate model for all their activities. For this reason, moving towards a greener architecture is well-thought-out the main goal of the present architecture of our time [72].

Figure 2.28: Sustainable development. (Adopted from University of Michigan Sustainability Assessment,2002)



Vertical gardens are a branch of green architecture as well as green infrastructure. Green infrastructure is important for environmentally friendly urbanization in developing countries, so it is difficult to achieve urban development without considering green infrastructure [73].

The long-term viability of a green vertical structure must be thoroughly investigated. Some aspects that should be considered important for assessing the sustainability of green vertical systems in a technical standard [74], [75]. They have identified forty environmental standards to be considered for the entire building process by following CEN/TC 350 – “Environmental sustainability of construction works.” The key environmental conditions for green vertical systems have been established and shown in Table 2.4, based on the studies reviewed in [76].

Table 2.4: Main environmental requirement for vertical greenery systems.

<table>
<tr><th>ENVIRONMENTAL REQUIREMENTS FOR THE MANUFACTURING OF
VERTICAL GREENERY SYSTEMS</th></tr>
<tr><td>

Minimizing the thicknesses and weights of the materials used to build the structure

Increasing the use of materials manufactured using low-impact techniques
Increasing the amount of recycled materials used
Making the most of natural materials
Maximizing the use of locally manufactured materials
Increasing the use of materials of similar lifetimes

Increasing the use of goods that can be useful in a variety of fields
Maximizing the use of reuse building structures which coming from partial or total demolition

</td></tr>
<tr><th>ON-SITE INSTALLATION</th></tr>
<tr><td>

Using modular and prefabricated components to their full potential
Getting the most out of elements with a simple installation
Increasing the use of devices with interoperability for the use of sources (water, electricity ...)
The usage of renewable-energy-based energy conversion systems

</td></tr>
<tr><th>USE AND MAINTENANCE</th></tr>
<tr><td>

Selecting plant species that are easily adapted to the climate zone (saving water and fertilizer)
Choosing environmentally friendly fertilizers (i.e., organic fertilizers over mineral ones)
Choosing cutting-edge and high-performing irrigation technologies (i.e., reuse of water technology, automatic systems)
Choosing high-performance solutions from a variety of perspectives, including capacity, acoustics, and indoor air quality

</td></tr>
<tr><th>END OF LIFE</th></tr>
</table>

- Maximizing the use of elements while allowing for simple disassembly
- Making the most of recyclable goods
- Making the most of reusable products

To be sustainable, a construction product must be economically viable in order to be competitive. Perini and Rosasco [77] conducted a “cost-benefit analysis” of different green walls placed in Mediterranean climates, taking into account costs and benefits for people (real estate, heating, and air conditioning savings, cladding longevity, and tax incentives) and society (air quality improvement, carbon reduction, habit improvement, and tax incentives) then have concluded that the direct green façade is, therefore, the most economically sustainable scheme. Moreover, they discovered that in the Mediterranean environment, economic sustainability is only achieved if taxes are reduced, after considering eight different scenarios in terms of life span (25 and 50 years), economic benefits, and disposal at the end of the life span [78]. Ottelé et al. [79]; found similar findings, demonstrating that living walls made of felt have a high environmental impact, while those made of planter boxes do not, since the materials have a positive impact on the system's thermal resistance. Oquendo-Di Cosola et al. [80] have also demonstrated the effect of felt-based living wall systems on life cycle assessment. The study discovered that felt-based living walls have a greater effect in the manufacturing, building, and repair stages than plastic-based living walls.

In recent decades, a new environmental assessment approach is known as "emergy evaluation" has been adopted; it considers some complementary information that allows assessing design sustainability by considering both "environmental costs" and "benefits." Pulselli et al. [81] used this approach to show that ‘benefits' do not cover ‘costs' within a fair lifetime for a living wall and a green wall built on a large envelope, since the Cost to Profit Ratio (CBR) is CBR47 = 1 for the living wall and CBR151 = 1 for the green wall. These figures are based on a ratio of "initial emergy expenditure" (without renewables or human labor) to "yearly energy gain." This result is mostly due to a lack of water supply. Rainwater harvesting systems may thus be beneficial.

The most important factor in the long-term viability of vertical greenery systems is water consumption; Perez Urrestarazu et al. [82] only found that the amount of water required is dependent on the substrate type and emitter flow rate. Only if designers and industry build systems that consider not only materials but also rainwater storage tanks and water content sensors can the design become fully sustainable [83].

There are a few key considerations when it comes to maintaining a green wall. In reality, Manso et al. [25] pointed out that it is difficult to restore the consistency of the green surface and for climbing plants when certain plants must be replaced; it is also difficult to ensure the absence of gaps in the facade for the spontaneous growth of the vegetation.

The maintenance cost of green systems is influenced by the selection of plants that are appropriate for the environment. For a Living wall in a cold environment, Mrtensson et al. [84], emphasize the importance of selecting evergreen plants that can easily adapt to excessive or inadequate irrigation as well as frigid temperatures.

Definitely, a green system can contribute significantly to the growth of the construction industry by enabling the creation of open, safe, and healthy built environments, but it must adhere to certain constraints during its life cycle in order to be a sustainable solution. This means that the design must ensure low energy, water, and raw material impacts. Finally, in light of the risks, it is worth noting that the development of international technical standards can play an important role in improving product features and design.

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Chapter Three: Research Foundations and Validations

3.1. Introduction

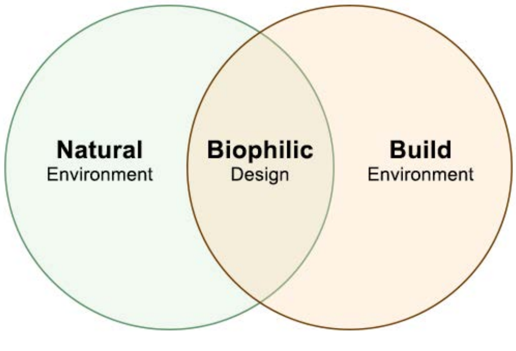
Growing urbanization, altering disease scenarios, and current climate change predictions necessarily require innovative methods of providing healthy and sustainable urban areas. Stress is a common and latent disease, and dealing with stress and stress-related diseases is a growing problem in both developed and developing countries, with enormous costs for individuals, businesses, and societies. Studies of stress and well-being in the workplace tend to focus on psychosocial influences in the work environment. Multiple claims and empirical findings suggest that workplaces should be healthier (both psychologically and physically) and more productive than conventional buildings. There is wide agreement on the beneficial effects of nature exposure in the workplace, which has been proposed as a cost-effective approach to promoting employee health.

The goal of this chapter is to investigate scientific evidence as foundations and validations of this research on the effectiveness of vertical greenery systems such as green façades and green walls in promoting mental health, well-being and improving conditions among actual employees in actual workplace settings, as well as to improve the built environment in terms of occupant comfort. The outcomes of this chapter were classified into five categories: (i) Vertical gardens from the standpoint of biophilic cities, (ii) Philosophical perspective of vertical gardens, (iii) The relation of vertical gardens with Nature-based solution, (iv) Vertical gardens as a retrofit solution, and (v) Vertical gardens interaction with workplaces as a psychological tool, indoor environmental quality and occupants' comfort. Ultimately, the concept of vertical gardens as a passive energy source was discussed.

3.2. Vertical Garden in Biophilic Cities

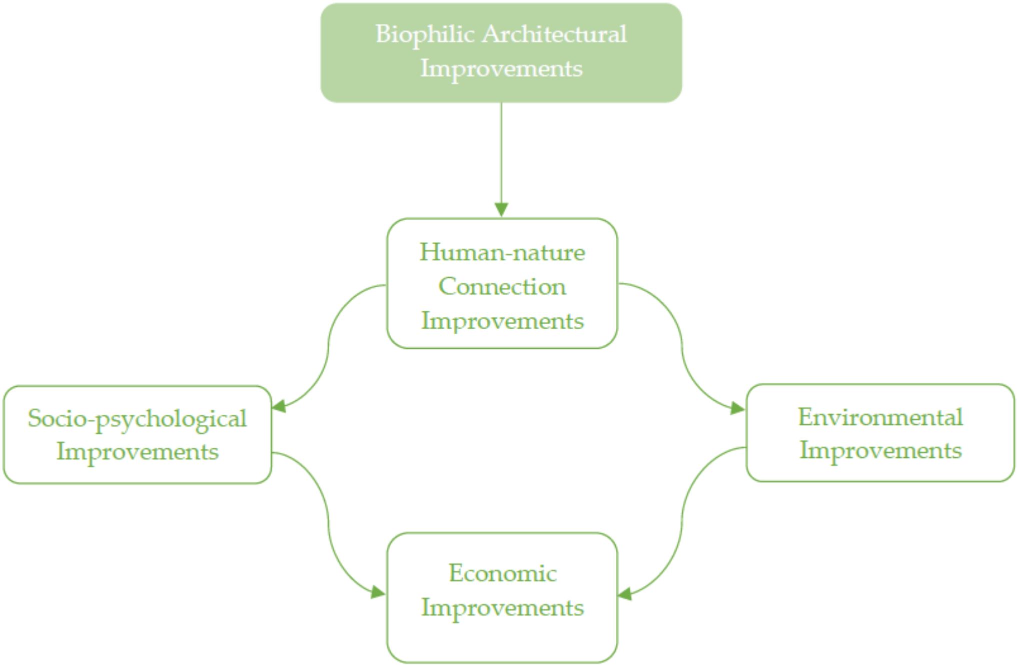
Biophilic architecture is based on the idea that humans have an inherent relation to nature that particularly in cities should be reflected in their daily lives. The recent focus on biophilic design (Figure 3.1) among architects and designers recognizes nature's influence. Even so, in an expanding urban world, more attention must be paid to urban scales, preparing for and moving toward what are known as "biophilic cities". Biophilic cities are those that not only have near and frequent communication with nature but also strive to cultivate an understanding of and concern for it.

Figure 3.1: Diagram Simply Representing the Theory of Biophilic Design.



There are pieces of evidence for how landscaping between buildings affects the human connection with nature, and Figure 3.2 depicts the inherent human-nature connection, which should illustrate indirect measures of human and nature interactions, as well as how cities function in environmental measurements, and how these two should contribute to economic improvements [1]. The biophilic architecture demonstrated how landscaping buildings utilization green roofs, green walls, indoor plants, as well as features, for instance, fractal patterns in materials, are establishing novel human-nature connections. Faced with climate change, natural disasters, economic instability, and various other shocks that cities will encounter in the future, achieving the requirements of a biophilic city will go a long way toward fostering social and landscape resilience.

Figure 3.2: Benefit flow of biophilic architecture.



Biophilia was coined for the first time in 1964 by the psychoanalyst Fromm in his investigation of the "Essence of Man," which defines humanity [2]. According to biophilic design, good design at the building, site, city, and regional scales must include nature and natural elements. It is based, in particular, on the idea of biophilia, which was popularized by Harvard myrmecologist and sociobiologist E. O. Wilson in 1984. He concludes that humans co-evolved with nature and that we bear our ancient brains as well as our need to interact with and associate with nature in order to be happy and healthy. Biophilia is also described by him as "human beings' innate emotional attachment to other living organism's innate means inherited, and therefore a part of one's ultimate human existence". He defines biophilia as a set of learning rules that developed over thousands of generations and social interaction [3]–[5].

Nowadays an increasing body of evidence linking greenery and green elements such as vertical gardens in living and workplaces to improve physical and mental health. At the building scale, research shows that the availability of natural daylight, fresh air, and greenery has a clear positive relationship with increased workplace satisfaction and productivity [6]. At the neighborhood and community levels, evidence of the influence of green qualities and features is also emerging. Stress reduction and improved physical and mental wellbeing have been linked to green neighborhoods such as green façades and more sustainable living environments [7]–[11].

A significant study published and concluded that communities exposed to more green space have lower mortality rates and that green space whether vertical greenery or horizontal greenery exposure will help reduce health disparities [12]. Besides that, the influence of vertical greenery systems as nature elements in cities has been linked to changes in a positive mood, cognitive ability, and even innovation [13] which discussed in section 3.5.2.2.2. Psychological aspect of vertical gardens in visual comfort.

An empirical study utilizing portable electroencephalography (EEG) caps shows the value of nature in minimizing mental fatigue [14]. By using greenery in the building and urban scale as bringing natural environment in the build environment can achieve immense power to restore, cure, and fascinating. Researchers suggested that while it's important to integrate green and natural elements into the design of buildings, it's important to get people out of buildings and to think about nature and the conditions in the wide urban areas in which these buildings are located more holistically. "We need a daily dose of nature," as researchers put it, which means that nature must be integrated into all aspects of our buildings and life, rather than separating people in buildings from people in nature [15].

Furthermore, biophilic architects have elaborated biophilic design principles, discovering validity via experience, intuitive understanding, and examples throughout history [16][17][18]. Researchers identified the biophilic design characteristics to the following fourteen patterns within three categories which are mentioned in Table 3.1, among them green walls are in nature in the space category [19].

Table 3.1: 14 Patterns of biophilic design [19], (adopted from [20])

1. Nature in the space:	2. Natural analogues:	3. Nature of the space:
incorporation of plants, water, and animals into the built environment, especially with movement.	one degree of separation away from true nature; patterns and materials that evoke nature.	the way humans respond psychologically and physiologically to different spatial configurations.

1. Visual connection with nature plants inside and out, green roofs, and living walls, water, nature artwork.	8. Biomorphic forms and patterns—organic building forms, structural systems (savannah effect).	11. Prospect—views, balconies, 6 m and above focal lengths, open floor plans.
2. Non-visual connection with nature—sun patches, textured materials, bird sounds, weather, nature scents.	9. Material connection with nature—organic building forms, structural systems (savannah effect).	12. Refuge—protected spaces, overhead canopies or lowered ceilings, places providing concealment.
3. Non-rhythmic sensory stimuli—clouds, shadows, nature sounds, water reflections.	10. Complexity and order—fractal patterns, sky lines, plant selection, and variety, material textures, and colors.	13. Mystery—winding paths, obscured features, flowing forms.
4. Access to thermal and airflow variability—shade, radiant heat, seasonal vegetation.		14. Risk/peril—floor to ceiling windows, water walks, high walkways.
5.Presence of water—rivers, fountains, water walls, ponds, daylighted streams.		
6. Dynamic and diffuse light—light from different angles, ambient diffuse lighting, circadian lighting.		
7. Connection with natural systems—seasonal patterning, wildlife habitats, diurnal patterns.		

Urban areas include a range of ecological and green possessions, ranging from parks to trees to rivers and riparian ecosystems, and efforts are gradually being made to improve the green characteristics and principles of these living and working environments. Daylighting urban streams (returning them to the surface from underground pipes), constructing trails, planting new trees and parks, community gardens, and installing vertical greenery systems such as green façades and living walls are only a few of the many ways cities and urban environments would become greener and overall, environmentally sustainable. Biophilic urbanism must occur at various scales, and Table 3.2 demonstrated some potential biophilic design interventions.

Table 3.2: Elements of biophilic city design at various scales [21][15].

Scale	Biophilic design elements
Building	Green rooftops Sky gardens and green atria Rooftop garden Green walls Daylight interior spaces

Block	Green courtyards Clustered housing around green areas Native species yards and spaces
Street	Green streets Urban trees Low-impact development (LID) Vegetated Swales and skinny streets Edible landscaping The high degree of permeability
Neighborhood	Stream daylighting, stream restoration Urban forests Ecology parks Community gardens Neighborhood parks/pocket parks Greening grey fields and brownfields
Community	Urban creeks and riparian areas Urban ecological networks Green schools City tree canopy Community forest/community orchards Greening utility corridors
Region	River systems/floodplains Riparian systems Regional greenspace systems Greening major transport corridors

A biophilic city is one where people regularly participate in nature experiences. Moreover, people of biophilic cities have many opportunities to participate in environmental restoration and protection. Table 3.3 provides a more detailed list of the main qualities, other than physical design, that can be used to characterize or define a biophilic city [15] and regarding this table, green walls (green façades and living walls) are among the green design features of biophilic cities' conditions and infrastructure.

It is important to understand that biophilic cities are more than just green cities. The existence of abundant nature is vital, but not enough, and the "philic" is as essential as the bio. Residents in biophilic cities are specifically and actively involved in learning about, embracing, and responsible for the surrounding nature, and have formed significant emotional connections with it.

Table 3.3: Some critical aspects of biophilic cities [15].

Biophilic Conditions and Infrastructure
• The proportion of the population that lives within some few hundred feet or meters of a park or green space. • The percentage of a city's land area that is covered by trees or other vegetation. • The number of green design features (e.g., green walls such as green façades and living walls, green roofs). • The extent to which natural images, shapes, and forms are used in architecture and can be seen in the city. • The extent of the city's flora and fauna (e.g., species).
Biophilic Behaviors, Patterns, Practices, Lifestyles
• The majority of the day is spent outside. • Rates of visitation to city parks. • Walking trips account for a certain percentage of all trips. • The extent to which members and participants of local nature clubs and organizations are involved.
Biophilic Attitudes and Knowledge
• Percentage of residents who show concern and respect for nature. • The percentage of residents who can recognize common flora and fauna.
Biophilic Institutions and Governance
• Local government prioritizes nature conservation; a percentage of municipal budget is allocated to biophilic projects. • Existence of design and planning guidelines that foster biophilic conditions (e.g., mandatory green rooftop requirement, bird-friendly building design guidelines). • The presence and significance of organizations that promote environmental education and understanding, ranging from aquaria to natural history museums. • The number and/or extent of educational activities aimed at teaching about nature in local schools. • There are numerous nature organizations and clubs of different types in the area, ranging from advocacy to social groups.

The main finding of this research is that there is an important link between vertical greenery systems such as green façades and living walls, and biophilia or biophilic cities. Making cities more green, natural, and biophilic would also help them to be more resilient. From biophilic architecture and urban biophilia, there are several paths to urban resilience, numerous ways in which the conditions of green and biophilic cities can also help to make a community more sustainable in the long run, ecologically, economically, and socially. Some of these biophilic paths are direct: promotions in green infrastructure (for example, restoring wetlands or planting drought-tolerant vegetation in cities) and

produce resilience advantages and results (e.g., reduced summer temperatures, reduced flooding from coastal storms). Other paths are more indirect: as green elements such as vertical gardens help to promote or reinforce beneficial and health-inducing activities, this improves individuals' and families' resistance to potential stresses.
The biophilia hypothesis, on the other hand, suggests that a break in human interaction with nature will result in substantial reductions in health, well-being, and efficiency. Researchers discovered that occupants are more satisfied with their overall work environment when they have physical and visual access to plants in their offices and break-out spaces [22].

3.3. Philosophical Notion of Vertical Greenery

Philosophy could assist in better understanding the human-nature/greenery relationship in order to protect the earth from climate change and progress toward sustainable development. Furthermore, philosophy is responsible for the creation of critical, reflective, and logical thought from an ethical and moral perspective, and thus provides us with opportunities to better grasp the world we are currently experiencing.

The vertical garden (greenery) as a component of green buildings (also known as green construction or sustainable building) and natural environment results from a design philosophy that focuses on increasing resource efficiency —water, energy, and materials — whereas lowering building effects on human health and the environment over the course of the building's life-cycle, through better siting, construction, design, operation, maintenance, and removal. Though the term "green building" is used in a variety of contexts, the general consensus is that it should be designed and operated in order to reduce the overall impact of the built environment on human health and the natural environment by (a) Efficiently using energy, water, and other resources, (b) Protecting occupant health and improving employee productivity, and (c) Reducing waste, pollution, and environmental dilution.

3.4. Nature-Based Solution for Workplaces

Nature-based solutions refer to measures influenced or supported by nature which are described as effective and adaptive methods that can solve various environmental issues while also providing economic/social/environmental benefits [23]. The rationale for the verification of nature-based solutions for workplaces in this dissertation is as follows:

a) greenery improves people's mental and physical health as well as their well-being, and they have a significant impact on improving the healing capacity that helps in recovery from psychological distress, such as anxiety [24][25],

b) nature-based solutions can provide economic, social, and environmental affairs by enriching people's lives through human welfare development, emotional well-being, new business opportunities, and other means, as well as by addressing a variety of social issues [23].

In particular, extremely beneficial impact of exposure to nature-friendly workplace environments on employees' mental health, as well as the controlling relationship between employee satisfaction and job performance that through this effect is very limited. Furthermore, reducing mental stress and emotional distress is a universal public concern due to human welfare [26][27]. Obtaining mental health and emotional well-being through green environments has recently become a significant lifestyle concept, and these factors can help in enhancing results through employee satisfaction, as well as efficiency gains and long-term profits for companies.

3.4.1. Vertical Gardens as a Nature-Based Solution:

Modern society is confronted with numerous concerns, including unsustainable urbanization, health issues, natural resource declines and losses, habitat degradation (e.g., water, air, and soil pollution), climate change, and increased natural disaster risks. As society seeks various solutions to existing challenges, nature-based solutions are gaining traction as a means to achieve desired outcomes, such as reduced disaster risk, improved human welfare, and green development [28]. Natural-based solutions have the potential to lead to green development, a future-oriented society, improved human health, new business opportunities, and long-term solutions to a variety of social problems [23]. Ecosystem regeneration, greening of grey surfaces (e.g., green rooftops, greened brownfields, and green walls such as green façades and living walls), integrated broad-scale climate change mitigation, and adaptation initiatives are examples of natural-based solutions (e.g., afforestation, constructed wetlands, and natural flood control) [23][28]. Recent studies on nature-based solutions can be broadly classified into three categories: i) nature-based solutions concerning green infrastructure [29]–[31]; ii) nature-based solutions for climate change mitigation and adaptation [32]; iii) nature-based solutions that are linked to ecosystem services [33]–[35]. Vertical greenery systems can perfectly cooperate in all three categories of nature-based solutions, as green walls are one of the green infrastructure systems [36][37], and many studies have shown that vertical greenery systems can significantly assist in urban heat island mitigation [38]–[40] and ecosystem improvement [41]–[45].

3.4.2. Greenery Cities as a Natural Environment and their Mental Health Benefits:

Many research in the fields of economics, sociology, psychology, and environmental sciences have recently increased interest in the natural/green environment in search of strategies to enhance people's mental health and recovery capacity [46]. Much research on the impact of urban green environments and plant diversity on psychological well-being has been performed in the last ten years. These findings indicate that when there are more plants and water in the natural world such as cities, mental health improves [47], both urban and rural green environment are important resources for physical and mental health, and they have a positive impact on people's well-being [26]. Natural environments have been shown to have a major effect on recovery and ability; in particular, exposure to natural environments tends to have very strong impacts on recovery from mental symptoms, including psychological distress, depression, and anxiety [24][25].

3.4.3. Stress Recovery Theory through Natural-based Solutions:

Negative environmental changes have many negative and harmful consequences, including chronic stress, and long-term exposure to an urban environment does have a negative mental and physical effect [48][49]. Exposure to an urban environment as a result of industrial development has been associated with obesity, high blood pressure, and diabetes [49], and a rise in stress as a result of traffic sound noise negatively affects health and is linked to a psychological state [48]. With regard to the world health organization (WHO) studies, one of the key contributing factors to premature death in modern society is a rise in stress [50]. As a result, stress has a significant effect on the health and well-being of the majority of people.

Because of the negative effect that stress has on people, researchers have been looking at different ways to alleviate or recover from stress. Existing research emphasizes approaches to green environments such as green facades, parks, and green roofs, implying the need for initiatives to become more in tune with nature [51]. The fact that natural environments can aid in stress recovery is well illustrated by stress recovery theory (SRT). Natural environments, according to SRT, are very critical for people's functional elements and can help them recover from stress. As a consequence, SRT can mitigate the negative effects of long-term urban exposure by green landscaping, vertical greenery systems, green interior design, green therapy, and other methods [52]. The biophilia hypothesis backs up these optimistic aspects of SRT. According to this hypothesis, humans engage with nature and have an innate desire to become part of nature [53]. The functional changes that arise in people's physical and mental exhaustion are evidence of the relationship between humans and nature. Researchers revealed that nature enhances people's survival potential by allowing them to recover from mental or physical exhaustion and other sources of stress, and this ability to recover encourages the solving of complex problems, which is an important ability for humankind's progressive growth, as well as the maintenance and growth of cognitive abilities like creativity [54]. SRT has shown that the natural environment, such as vertical greenery systems and landscape in urban scale and green facade, interior greenery, and roof garden as a building scale, has a significant impact on human cognitive capacity and emotional recovery. As a result, the natural environment is critical for people to heal and recover from physical and mental exhaustion, and this value should be emphasized more.

3.4.4. Green Environment of workplace:

According to studies, the physical working environment has a huge impact on employees' stress levels [55][56]. The impact of the workplace outdoor environment on employee stress has largely been overlooked, despite the fact that a large body of empirical evidence supports the relationship between access to green outdoor environments (such as green balconies, green yards, and green façades) and human stress in other contexts [9][57][58]. Many studies have been conducted to investigate the possible advantages of having access to a green indoor and outdoor environment at work for employees, companies, and societies. They have found that access to such green environments during the working day, whether visual or physical, is associated with improved wellness [59], well-being [59]–[61], job satisfaction [59][61]–[63], and performance [62][64], as well as lower perceived levels of stress [63][64]. Green indoor and outdoor environments in the workplace are health-promoting investments, and increased access to such environments for employees can contribute to lower levels of stress. Besides that, green environments are expected to be linked to a favorable attitude toward the workplace.

In workplaces that employees are in direct contact with the customer, the physical environment is the setting in which a service is provided to customers and where customer-employee interactions take place. This environment influences the mindset of the employee who serves the customer, and it is regarded as an artificial environment that the organization can monitor [65]. It is well understood that physical environments have a strong influence on the reactions and attitudes of consumers and employees [66]. Furthermore, several researchers believe that environmental factors and atmospherics trigger reactions in consumers and employees [65][67]. Many researchers identify surrounding environments that involve elements of the five senses, such as smell and sound, as intangible environmental factors that trigger unconscious sensory experiences, reactions, and behaviors in recent studies [67][68][69].

As nature-friendly environments enhance the health and comfort of indoor residents, there is a growing emphasis on indoor environmental quality [70]. The term "indoor environmental quality" refers to the indoor environment's qualitative requirements (e.g., temperature, air quality, smell, indoor interior design, decorations, specially designed green places, space layout, and the existing natural environment). Nature-friendly environments are particularly appealing in the workplace, which can be broadly classified into two categories: (1) specially designed places (e.g., lobbies, offices, conference rooms, and green façades on the office buildings façades), and (2) the existing natural environment (e.g., mountains, rivers, seas, lakes, and parks surrounding the workplace). Nature-friendly environments are also used to increase a company's economic profits and work efficiency through measures such as increased employee productivity, decreased absenteeism, lower health care costs, and lower compensation costs [71][72]. Furthermore, nature-friendly (green) environments in office buildings aim to increase air quality, make the air less dry and minimize high temperatures [73].

Previous research has found that green environments have many beneficial effects on employees and workplaces. Green natural environments produce satisfaction and value because of the emotional bond that people create with the natural world [74]. People experience mental pleasure and find an escape from different social interactions when they come into contact with the natural world [46]. Furthermore, green environments were shown to have clear benefits in terms of offering essential elements of mental health, such as the healing process from stress or psychological problems [75]. Based on these findings, can conclude that nature-friendly environments (e.g., specially built places such as green walls and actual natural environments) have a major impact on the prevention and recovery from emotional stress.

3.4.5. Effects of green environment on Job Satisfaction and Job Performance:

Job satisfaction is characterized as a pleasant and positive emotional state associated with an organization and the job as viewed by a member of that organization. It is an emotional reaction to the job that expresses itself through a contrast of real and anticipated outcomes [76]. As work experience and satisfaction are converted to personal life satisfaction, it has a large impact on the improvement of a company based on an individual's perceived satisfaction with life and enhanced job efficiency [77]. Furthermore, work satisfaction is defined by the personal emotions experienced by an individual when performing their job [78]. A positive emotional state in an organization member improves productivity levels, promotes good physical and psychological health, and boosts morale. These positive outcomes of job satisfaction can lead to favorable attitudes toward the company (e.g., reduced turnover intent, increased self-efficacy, voluntary activities, and the creation of relationships among organization members) and improve company efficiency. As a result, the work satisfaction of association members is critical to achieving a company's financial and non-financial goals.

Prior research reveals that studies emphasize the direct involvement of employees in job performance and seek strategies to improve job performance [79][80]. To be more specific, in order to enhance job competency, organizational members' confidence and job satisfaction must be increased, as well as employee education from a psychological standpoint (e.g., job skill improvement programs to increase voluntary motivation, education programs to help in the rapid recovery from work stress and mental exhaustion, etc.) and improvements to the work environment (e.g., Providing the employee with the human or material support they need, as well as securing green space for mental healing, etc.) are required [81]. When it comes to the value of job performance, combining these two approaches in a complementary manner will greatly help in enhancing job performance [82].

Nowadays, new building design developments include "the use of fresh air, daylight, plants, and window scenery, as well as other design elements, to increase employee perceptions of their job and employee efficiency" [83]. Previous research discovered that "good working conditions" contained open and airy building architecture and design, bright colors and artwork, plants and windows, and that these variables ranked fifth out of ten motivating factors for employees [84]. A study found that employees who worked in offices with plants and windows felt better about their jobs and the work they did. Additionally, this study showed that employees who worked in offices with plants (green façades, living walls or plants potted inside the workplace) or windows (with a view of green spaces such as parks) had higher overall quality-of-life ratings [85]. Other studies have shown that understanding the factors that lead to employee work satisfaction could help reduce dissatisfaction, low morale, and reduced productivity [86]–[88].

3.5. Vertical Gardens as a Green façade Retrofit Solution of existing Office Buildings

Green building development opens up numerous chances to achieve the United Nations Sustainable Development Goals (SDGs) which implementing vertical greenery systems such as green façades and living walls on the building façade as green retrofits are one of those opportunities. Green retrofitting of building façades is one of the most effective passive design solutions which is discussed in section 3.6. Energy saving performance of vertical gardens, allowing for long-term benefits in terms of building energy performance, cost savings, and beneficial environmental impacts [89]. The integration of vegetation on buildings with green façades provide for an increase in the efficiency, ecological, and environmental benefits of the building. Greening the building envelope has a variety of environmental benefits that act at various sizes [90]. The benefits related to the larger scale (neighborhood or city) mainly regard the improvement of air quality, urban wildlife (biodiversity), the mitigation of urban heat island effect, and the stormwater management [91][92][93][94], the ones addressing the building scale are concerned with the performance of the building envelope as well as the Indoor and outdoor comfort [94][95][96][97].

Green buildings, sustainability, and vertical greenery systems in dense cities have become dominating strategies in modern construction in response to environmental deterioration caused by urbanization. In practically every region, much effort has been devoted to the development of green buildings and the incorporation of nature into cities. Vertical green layers can improve building envelope performance by producing an extra stagnant air layer that acts as an insulator [97], in the Mediterranean climate, by applying vertical gardens on existing buildings it reduces the energy required for air conditioning by up to 40%–60% [98][99]. Nonetheless, the present phenomenon demonstrates that green buildings are largely new constructions rather than retrofits of existing building stocks. Actually, existing buildings, especially non-residential buildings such as office buildings, produce considerable volumes of greenhouse gases, which have serious environmental consequences.

Building retrofitting is predicted to dominate the construction sector since it saves resources by avoiding demolition and rebuilding, which generate enormous amounts of trash [100]. Researchers revealed that the cost of retrofitting is only about 30% to 50% of the cost of demolition and reconstruction [101]. These current cost savings are projected to increase when more advanced retrofit solutions entering the construction industry. The most recent green solutions for building envelopes, particularly for building façades, exhibit more consistent energy and cost savings, however, some of these solutions require a longer payback period. A diverse selection of green façade technologies (GFTs) is easily available, requiring less investment and shorter installation time while providing comparable energy efficiency to newly constructed green buildings.

Addressing energy inefficiency issues in existing buildings should be a top priority for energy savings goals, especially in non-residential buildings, which are at risk of poor thermal performance and excessive energy use. In reality, the peak electrical usage for cooling reasons in existing buildings in urban locations can be up to triple that of new construction [102]. Moreover, building envelopes have shown tremendous contributions as energy-saving measures across all building types based on a set of globally adopted retrofit measures, compared to other building mechanical systems such as smart heating, ventilating, and air conditioning (HVAC), renewable energy, metering, and sensors [103]. Building retrofitting, rather than destruction and reconstruction, would be a greener solution to these existing buildings' energy inefficiency issues. Existing building retrofitting is the best solution for ensuring environmental, social, and economic sustainability. On the environmental pillar, this solution not only protects lands but also has the potential to cut site waste and carbon emissions.

External walls and windows on the building's façades are the largest surfaces exposed to solar radiation and typically contribute the most to a building's cooling load. As a result of its stable system, façade retrofit is undoubtedly one of the most effective passive design solutions, allowing for definite, long-term benefits. Façade modifications can directly improve building energy performance, deliver immediate cost savings on electricity bills and maintenance, and contribute to favorable environmental outcomes.

The field of façade retrofitting by vertical greenery systems is critical in the goal of providing additional green places to cities in order to enhance environmental conditions [104]. Green façade retrofitting attempts an energy-efficient solution that provides indoor comfort, productive lighting, and an acceptable acoustic environment by lowering the usage of mechanical and electrical systems for lighting, ventilation, etc. According to the researchers, the costs and long-term nature of façade retrofitting are strategic, while the façade design such as green façade might be sophisticated and multidisciplinary [105]. By implementing well-proven technology solutions in building retrofits, primary energy demand and associated emissions can be decreased by 40% to 50% [106]. Previous research has shown that even 50% coverage of green façade on a glazed office building can drastically reduce energy consumption and increase thermal comfort [107] and of course, must be taken into account the building orientation, the type of plants as well as the weather condition [108]. Researchers reported that wall insulation provided the most energy savings [103]; nonetheless, some studies revealed that sun shading was the most energy-efficient approach [109].

3.6. Interaction between Vertical Garden and Workplace

A building's façade is an inseparable component of a building. Façades play an important role in reducing energy waste in buildings; however, the majority of them are built to provide static design solutions, consuming vast quantities of energy to retain indoor comfort. Furthermore, its position is affected by a variety of factors and perceptions, which can either reinforce or weaken its function as a climatic and environmental moderator. And by applying a layer of plants to the building's façade, the function of the façade is improved in a variety of ways. Green façades as layers of plants provide the opportunity to learn from traditional architecture, with the earliest type of vertical gardens dating back 2000 years in the Mediterranean region, while also incorporating new materials and other technologies to encourage sustainable building functions [41]. It is an excellent demonstration of integrating nature and buildings (linking various functions) to resolve environmental problems in dense urban environments [110], since urban centers are currently looking for places to plant vegetation due to a lack of space, in order to turn the carbon dioxide emitted by traffic and heating into carbon hydrates and oxygen.

The green façade is an integral part of construction design in the course of this investigation, which reduces building energy consumption and increases health and satisfaction of occupants. In order to understand how the green façade affects the conditions of the indoor, the climate, environment, and psychology moderators, and how their performance in turn affected and is influenced by the psychological demands of occupants, the role of the green façade is addressed. Environmental psychology theories underpin the relationship between occupants and their working environment. The goal of this part is to evaluate the effect of the green façade on the workplace and relate this to relevant theories of environmental psychology. This relationship serves as a particular strategy for aligning the proposed green façade with the workplace in terms of improving workplace conditions at the building scale.

3.6.1. Vertical Garden as a Psychological Tool

The green façade has many functions in manipulating psychological responses to its configuration. The building's exterior appearance represents symbolic messages, while its interior configuration influences how occupants interact with the elements.

3.6.1.1. Vertical Garden as a Symbolic Message

First, vertical gardens are made up of one layer of plants that are implemented on the façades of buildings by a structure which matches the form of vertical greenery, that each element (façade, plants) in this procedure send its own signal to people and environments.

The first element of green façades as vertical greenery systems discussed in this part is the façade which façade configuration itself gives symbolic messages to passers-by while also affecting the occupier's view of the indoor space and the individual's influence over the indoor environment. Human needs and perceptions of the façade are ingrained in the subconscious; they are the result of a collection of experiences dating back to the earliest buildings in human history. However, it has been argued that historical buildings, whether public or private, had better thermal efficiency and performances than modern buildings due to the availability of heavy thermal mass used in façades (for structural reasons) as compared to increased glazed areas in modern buildings' façades. This claim ignores the fact that historically, building façades were reacting to a shifting cultural agenda, which was reflected in the physical properties of the façade.

The symbolism of façades took on a new significance throughout modernism when the similarity between the façade and a narrative text was attacked as a "Romantic Fallacy." The growth of modern architecture façade and a technique to seek the truth condemned neoclassicism and other architectural trends as being "an architecture of coatings," a piling up of materials; now it is the outcome of assemblages. The cultural message of façades became the transparent skin aesthetics of the glazed office façade in modernity, a puritanical flavor that irons out all flaws and makes no compromise to the senses, clean and sparkling and casting no shadows, implying that technology will make the future living absolutely untroubled and pleasant. A well-designed structure can lead to a sense of pride and place [111].

A building could only be considered successful if it combines aesthetic aspirations with a well-thought-out performance agenda. Examining the works of modernist masters reveals a very basic perspective of environmental physical variables, proving the dualism between climate and architecture. The iconographic characteristics of buildings dominate the façades [112].

The second element is plants that are often interpreted for their decorative and symbolic roles in architecture, but several studies have shown that plants have numerous benefits for the building envelope such as preventing excessive solar radiation, wind, enhancing the thermal performance of façade, and lowering energy use, as well as the health and well-being of its residents. Indeed, the use of symbols in the past century architecture is clear, although at times cryptic [113]. The symbolic purpose, such as the symbolic role of plants, i.e. a link with the transcendent meanings of the object of representation itself, was prevalent in ancient times [114]–[120], in the Middle Ages [121]–[130][131]–[135], and in the Renaissance and up to the Age of Enlightenment [123]–[132] [136]–[139]. This connection was made possible by magical–religious beliefs in plants as expressions of the gods or divine will, which can be found in classical texts [140] and sacred iconology [141]. The advent of modern pharmacological research applied to medicine from the eighteenth century onwards eventually led to the loss of symbolism's transcendental context in the twentieth century [123]–[132]. However, plants are always a symbol of the flow of life.

Undoubtedly, the decorative and symbolic role of embellishment or the harmonious balance of the work itself is often present in works of art and architecture, especially in the depiction of flora on the building's façade and interior ornaments. Plants are important elements in contextualizing a landscape, whether horizontally or vertically [142], so a strictly descriptive purpose is also possible. Following that, a strictly naturalistic-scientific feature of a faithful portrayal of species diversity of plants in nature is also evident from the Renaissance onwards [143]. As a result, three principles guide artists, architects, and designers in their depiction and use of plants: the real, the ideal, and the symbolic, without excluding any combined and interrelated intent [144].

The use of façade and plants as vertical gardens was prevalent in ancient architecture [145]. Grapevines were planted on the exterior of buildings in ancient Greece and were utilized for both beauty and food. Vertical gardens were employed as a garden design element in many countries, depending on the demand and kind of architecture, and were usually seen in palaces and expensive buildings. Architects and garden designers employed a layer of plants on building façades to create a form of integration and harmony between the building and the green space of the garden, which was extremely valuable in terms of both beauty and pleasure, and tranquility for residents. Plants were used extensively because of their decorative and symbolic qualities [131].

Building façades are constantly subjected to environmental influences such as sunlight and acid rain, that age and eventually destroy them, which covering façade with plants could protect them from these issues. Therefore, covering the façade with plants can be a solution to protect the façade from these environmental challenges. A look back in time reveals that green façades are not a new technology, but they can provide numerous benefits as a component of current urban design. Since the 1980s, the purpose of the green façade has shifting from decorative and symbolic to practical and technical, and many studies have been conducted on issues such as the insulating effects of plants on façades, the ability of plants to control dust, the evaporative cooling benefits of plants, and the provision of habitat for urban animals such as birds, spiders, and beetles [41].

3.6.1.2. Vertical Garden as a behavioral manipulator

Since the early 1970s, environmental psychology has taken a holistic approach to the person-in-environment as a system [146]. Environmental psychology is defined as "the study of the interrelationships between the physical environment and human behavior" [147]. Environmental psychology is the study of interactions between humans and their physical surroundings [148]. Transactional relationships are those that exist between a person and their surroundings. This method is often regarded as the primary theoretical foundation for environmental psychology. Both definitions emphasize the fact that the process is mutual between the person and the environment. In other terms, the environment influences the individual, but the individual also influences the environment. Both concepts are based on the famous equation devised [149]:

$$B = f\ (P, E)$$

Where B stands for behavior, P is for the person, and E stands for the environment. The equation asserts that behavior is a function of the person, the environment, and their interaction, and it is known as a person-in-context approach to explaining behavior. In exploring causes for behavior, the basic viewpoints in psychology tend to focus on one or the other side of the equation, either in the individual or in the environment. A basic principle of environmental psychology is the interactional view.

However, in describing environmental psychology, both concepts focus solely on the physical world. This mostly reflects the field's origins, which had a very narrow focus on the impacts of building design on behavior. In fact, the field was originally known as "architectural psychology." The following is the major feature of this approach [150]:

- The unit of analysis is the person-in-environment.
- As components of a cohesive whole, both the person and the environment dynamically define and modify each other through time.
- Stability and change coexist indefinitely.
- The direction of change is emergent rather than pre-determined.
- Changes at one level have an effect on the other levels, resulting in the new person-in-environment configuration.

The fundamental idea is that the complexity of human functioning in real-life conditions must be considered holistically. It recognizes the person context as well as the environmental context, and also the interrelationships between them. The level of integration between the person and the environment is determined by this comprehensive systems-oriented approach. The notion assumes that the individual is made up of mutually defining physical/biological, psychological, and Scio-cultural characteristics, whereas the environment is made up of mutually defining physical (natural and built), interpersonal (e.g., spouse and friends), and Scio-cultural aspects (rules of home and community and culture). The system of the person-in-environment, the comprehensive approach, assumes that the person-in-environment system produces objects of perception and thinking, thereby actively participating in the cognitive process. According to this viewpoint, the reality is related to the individual's interpretations. As a result, the comprehensive approach evaluates the surroundings in both subjective and objective dimensions. The objective physical world and its qualities have implications for a person's behavior and experience fairly often without his awareness [151]. Under these conditions, the individual is unable to detect or express these impacts, and it is only via objective examination of the 'external observer' that the impact of the physical environment on the person's behavior and experience can be identified.

According to studies of the setting of office buildings in research context, climate conditions and culture in each region have a significant influence on façade design ideology in these areas. Building façades have altered and become more efficient as diverse architectural styles and technology have emerged. For instance, the Crystal Palace in Hyde Park, England, was the first large-scale glass construction, beginning in 1850 [152] (Figure 3.3). This building was 992,000 square-foot and designed to hold The Great Exhibition of 1851. The glazed façade was frequently utilized in office and commercial buildings due to environmental psychology, as well as its extensive use of sunshine and visual link to the outside space [153][154].

Occupant control is an important environmental psychology feature that is closely related to façade layouts [155]. Green façades, as a type of façade technology, have received a lot of attention since the 1980s because of numerous favorable characteristics in terms of psychology, biology, and energy-saving; consequently, green façades can modify the behavior of the building [156]–[161][41]. Furthermore, scientists discovered that green façades as natural features in cities can lower stress, increase quality of life, and reduce mortality [12].

Figure 3.3: The Crystal Palace was the first large-scale glass construction.

3.6.2. Indoor Environment Quality and Occupants' Comfort

Indoor environment quality is the overall environmental quality of a building, particularly as it relates to the health and comfort of its users. It considers a variety of factors, such as thermal comfort, and indoor air quality, and etc. Due to the fact that humans spend a substantial amount of time indoors, particularly at the workplace for up to 12 hours each day, the indoor environment quality of the office has a big impact on one's general well-being, health, and productivity. In terms of indoor air quality, high levels of carbon dioxide (CO2), particulate matter (PM), and humidity can cause headaches, allergies, and asthma attacks in severe situations.

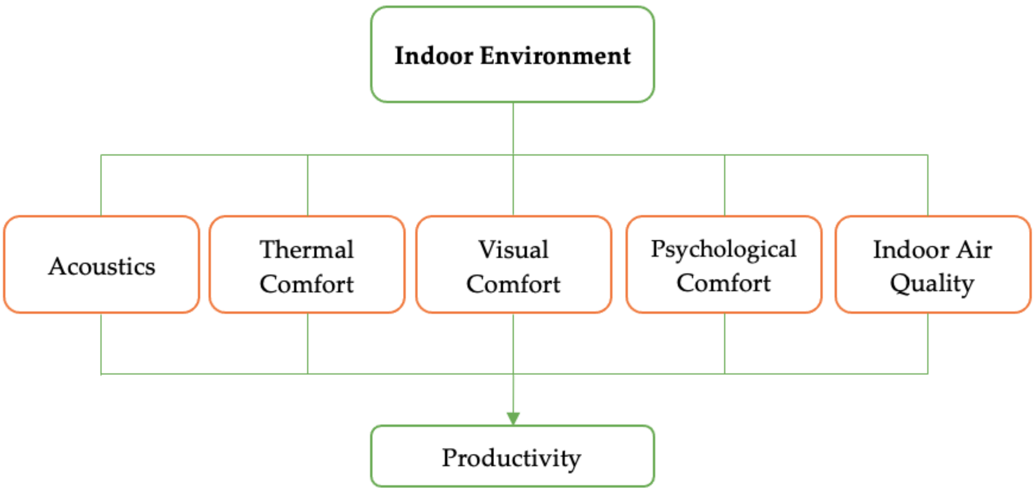
Numerous workplace research has found that improved indoor environment quality reduces sick building syndrome and promotes user comfort, which in turn increases individual work productivity [162][163], for these reasons, several studies of aspect of using green façades in office buildings that they revealed, vegetation layer on the façade can improve significantly indoor and outdoor environment quality in office buildings [164][165]. Boosting work productivity offers numerous economic benefits for companies. Green façade technologies, which are one of the features of green buildings, have a much greater percentage of user satisfaction in terms of indoor environmental quality and allow for a reduction in energy usage [166]. Due to a lot of energy is usually required to overcome office buildings, which most of the time causes discomfort to the user [167]. By applying green façades to office buildings can improve greatly the quality of the indoor environment which this improvement can save wasteful energy expenses while improving thermal comfort, which boosts workplace productivity [168][169].

Indoor thermal comfort and the technologies that support it are regarded as one of modern civilization's greatest achievements. Throughout history, tolerating cold and heat discomfort has been the norm, providing a motivation for the development of micro-control systems. Building façades and roofs (building envelope) act as a barrier between the indoor and external spaces, as well as providing protection from the climate and privacy from intruders. The building envelope is viewed as a climate moderator and people's expectations response. By applying green façade to the exterior surface of a building, building behavior can modify, allowing green façade performance to respond to people's expectations as well as climatic change.

However, the degree to which occupants perceive their indoor environmental condition as comfortable is reliant on a variety of variables via green façade that can be classified into green façade dependent variables and green façade independent variables.

Green façade dependent variables are those variables that affect the indoor environment adjacent to the green façade configuration. Thermal and visual comfort, acoustics, and indoor air quality are examples of these variables (Figure 3.4).

Figure 3.4: Indoor environmental criteria.



Climate responsive design is centred on how the form and structure of a building moderates the indoor climate to ensure the comfort of its occupants. Science and climatic characteristics are the practical and physical laws related with this area of architectural design [170].

The independent variables for green façades are those connected to job stress and satisfaction which is further explained in the previous section 3.3.1. Vertical garden as a nature-based solution, that affect the occupants' impression of the workplace in an indirect way.

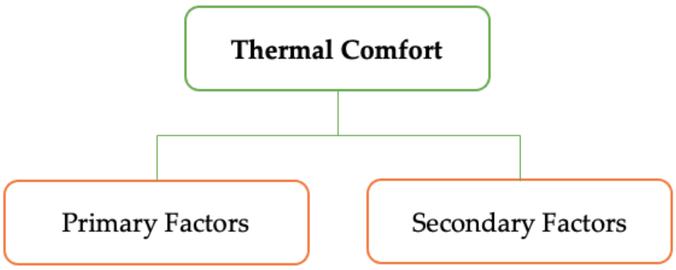
3.6.2.1. Thermal Comfort

Thermal comfort is the "condition of mind" that expresses satisfaction with the thermal environment [171]. As there are large physiological and psychological variations between people, it is hard to satisfy everyone in a space. The environmental conditions required for comfort differ from person to person. In this section, thermal environmental conditions determinations in green façades that are required to achieve acceptance by a specified percentage of that space's occupants in workplaces are expressed. The wide majority of thermal comfort data available is based on sedentary or near-sedentary levels of physical activity typical of office work.

3.6.2.1.1. Conditions for Thermal Comfort

The most important factor in the perception of comfort is thermal sensation. According to the researchers, "air is the primary transport mechanism for thermal comfort, and airspeed and turbulence influence the sensation of cooling and heating. High infiltration or unnecessary air change rates result in the loss of conditioned air and may prevent the achievement of comfort conditions" [172]. Thermal comfort is divided into two categories: primary and secondary factors (Figure 3.5).

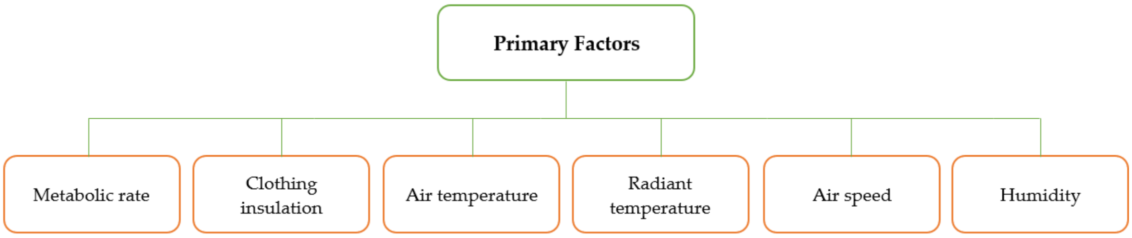
Figure 3.5: Thermal comfort categories.



- ***Primary Factors***

When defining thermal comfort conditions, six primary factors must be considered (Figure 3.6). In some cases, a number of other secondary factors influence comfort. Complete descriptions of these factors are presented in the following section 3.5.2.1.2. Thermal environmental variables. All six of these factors can change over time. As a consequence, people entering a space that meets the requirements of these factors may not find the conditions immediately comfortable if they have recently experienced different environmental conditions.

Figure 3.6: Primary factors of thermal comfort.[171]

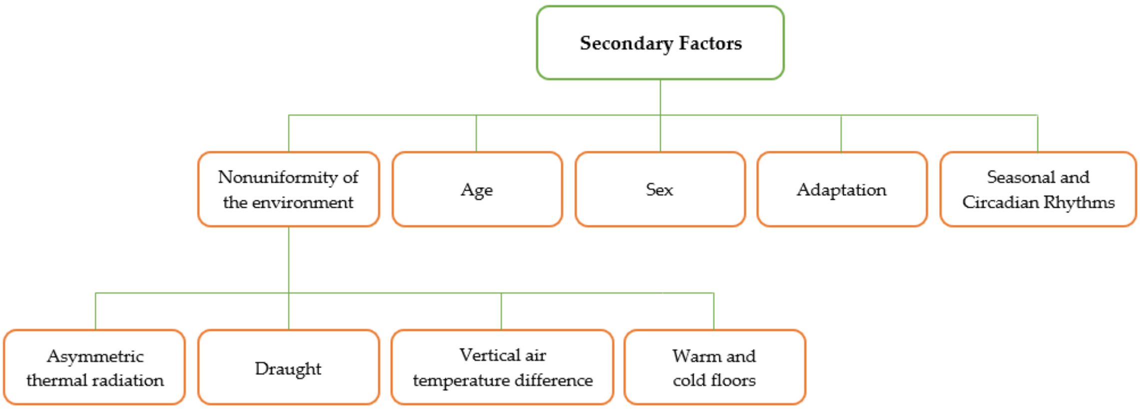


Clothing insulation, radiant temperature, air temperature, air speed, and humidity may be nonuniform over an occupant's body, and this nonuniformity may be an important factor in determining thermal comfort.

- *Secondary Factors*

Besides these six primary factors, many secondary factors, such as our age, gender, personal thermal adaptation, and thermal history, including climatological origin, can be considered [173]. These factors of thermal comfort, apart from asymmetric thermal radiation (directed operative temperature). Figure 3.7 depicted secondary variables.

Figure 3.7: Secondary factors of thermal comfort. [173]



Also, there are psychological factors, such as individual expectations, that can influence thermal comfort. When we are uncomfortable, we may attribute our feelings to a single factor, such as air temperature or humidity, when they are actually the result of a combination of many factors.

3.6.2.1.2. Thermal Environmental Variables

Description of the environmental variables has provided to understand their use in primary factors section. The thermal environment is expressed with regard to the occupant.

1. ***Air temperature:*** The average temperature of the air surrounding an occupant is referred to as air temperature. The average is based on location and time. The spatial average is, at a minimum, the numerical average of the air temperature at the ankle, waist, and head levels. For seated occupants, these levels are 0.1, 0.6, and 1.1 m (4, 24, and 43 in.), respectively, and 0.1, 1.1, and 1.7 m (4, 43, and 67 in.) for standing occupants. The average may also include intermediate, equally spaced locations. When the occupant is in a directed airflow, the upstream air temperature must be used. The temporal average must be a three-minute average of at least 18 equally spaced points in time. However, if necessary, the period can be extended to 15 minutes to average cyclic fluctuations. The spatial average is applied to all locations in the temporal average.

2. ***Local air temperature:*** The definition of local air temperature is the same as that of air temperature, except that it refers to a single level (e.g., head level). At this level, at least one location is required. To obtain a more accurate average, multiple locations around the body may be included.

3. ***Mean radiant temperature (MTR):*** The temperature of a uniform, black enclosure that exchanges the same amount of thermal radiation with the occupant as the actual enclosure is defined as the mean radiant temperature. It is a single value for the entire body and can be thought of as a spatial average of the temperature of surfaces surrounding the occupant weighted by their view factors in relation to the occupant. The mean radiant temperature is a time-averaged value as well. The temporal average must be at least three minutes long and contain at least 18 equally spaced points in time. Researchers revealed that a green wall that implementing vertical greenery can lower the mean radiant temperature of its surroundings [174].

4. ***Operative temperature:*** The operative temperature (T_o) (formerly known as resultant temperature or dry resultant temperature, but renamed to conform to ASHRAE and ISO standards) is the average of the air temperature and the mean radiant temperature, weighted by the convective heat transfer coefficient and the linearized radiant heat transfer coefficient. For occupants involved in near-sedentary physical activity (metabolic rates ranging from 1.0 to 1.3 met), not in direct sunlight, and not exposed to air velocities greater than 0.20 m/s (40 fpm), the relationship can be approximated with acceptable accuracy by:

$$T_o = (T_a + T_r) / 2$$

Where:
T_o = operative temperature,
T_a = air temperature,
T_r = mean radiant temperature

5. ***Radiant asymmetry:*** The difference between the plane radiant temperature in opposite direction is defined as radiant asymmetry. The plane radiant temperature is defined in the same way as the radiant temperature, except that it is with respect to a small planar surface element exposed to thermal radiation from surfaces on one side of the plane. Vertical radiant asymmetry occurs when there are plane radiant temperatures in both the upward and downward directions. The maximum difference between opposite plane radiant temperatures in all horizontal directions is defined as horizontal radiant asymmetry. Radiant asymmetry is measured at the waist—0.6 m (24 in.) for a seated occupant and 1.1 m (43 in.) for a standing occupant. The time averaging for radiant asymmetry is the same as the time averaging for mean radiant temperature.

6. ***Floor temperature:*** Surface temperature of the floor is the floor temperature (T_f) when it is in contact with the occupants' shoes. Because floor temperatures seldom change rapidly, time averaging does not require to be considered.

7. ***Mean monthly outdoor temperature:*** The arithmetic average of the mean daily minimum and mean daily maximum outdoor (dry-bulb) temperatures for the month is the mean monthly outdoor temperature.

8. ***Air speed:*** The average speed of the air that the body is exposed is referred to as air speed. The average is based on location and time. The time and spatial averaging methods are the same as for air temperature. However, the time-averaging period is only three minutes long. Variations that last more than three minutes must be treated as multiple different air speeds.

9. ***Turbulence intensity:*** The ratio of the standard deviation of the airspeed with respect to time and the time-averaged airspeed is used to calculate the intensity of the turbulence. The turbulence intensity is primarily for the head/shoulder portions of the body, with seated occupants experiencing 1.1 m (43 in.) and standing occupants experiencing 1.7 m (67 in.) If the ankle/lower leg areas are not covered by clothing, it may also apply—the 0.1 m (4 in.) level for both standing and seated occupants.

10. ***Humidity:*** The moisture content of the air is referred to as humidity. It can be expressed in terms of a number of thermodynamic variables, such as vapor pressure, dew point temperature, and humidity ratio. It is averaged spatially and temporally in the same way that air temperature is.

3.6.2.1.3. Method for Determining Acceptable Thermal Conditions in Occupied Spaces

To determine the requirements for thermal comfort, all subsections including Operative Temperature, Humidity Limits, Elevated Air Speed, Local Thermal Discomfort, and Temperature Variations with Time must be met. The ASHRAE standard 55 [171] recommends a specific percentage of occupants as acceptable and values of the thermal environment associated with this percentage.

1- Operative Temperature

A comfort zone can be calculated for given values of humidity, air speed, metabolic rate, and clothing insulation. The comfort zone is defined as a range of operative temperatures that provide acceptable thermal environmental conditions, or as combinations of air temperature and mean radiant temperature that people find thermally tolerable. This part explains methods for determining temperature limits for the comfort zone.

The operational temperature is included two methods: i) Graphical method for typical indoor environments and ii) Computer model method for general indoor application. The results of the two methods are consistent for a given set of conditions, and either method would be used as long as the criteria defined in the respective area are met.

i) ***Graphical Method for Typical Indoor Environments:*** This part employs a simplified graphical method for determining the comfort zone, which can be applied to a wide range of common applications. The method can be used in spaces where the occupants' activity levels result in metabolic rates ranging from 1.0 met to 1.3 met and where clothing provides between 0.5 clo and 1.0 clo of thermal insulation. The operative temperature range shown in Figure 1 is for occupant acceptability of 80%. This is based on a 10% dissatisfaction criterion for general (whole body) thermal comfort based on the PMV-PPD index, plus an extra 10% dissatisfaction criterion for local (partial body) thermal discomfort that may occur on average.

Figure 3.8: Spaces with an acceptable operative temperature and humidity range. [171]

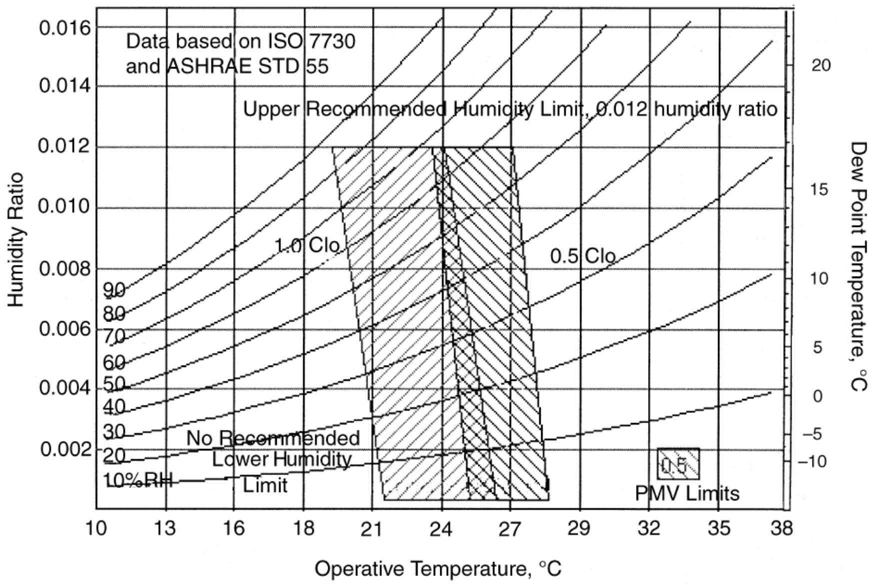


Figure 3.8 depicts the comfort zone for environments which meet the above criteria and have air speeds of less than 0.20 m/s (40 ft/min). There are two zones depicted: one for 0.5 clo of clothing insulation and another for 1.0 clo of insulation. These insulation amounts are common of clothing worn in warm and cool outdoor environments, respectively. The operative temperature range for intermediate values of clothing insulation can be calculated using linear interpolation between the limits for 0.5 clo and 1.0 clo, as shown below:

$$T_{min,\ Icl} = \left[(I_{cl} - 0.5\ col)\ T_{min} + (1.0\ col - I_{cl}) T_{min,\ 0.5\ col} \right] / \ 0.5\ col$$
$$T_{max,\ Icl} = \left[(I_{cl} - 0.5\ col)\ T_{max} + (1.0\ col - I_{cl}) T_{max,\ 0.5\ col} \right] / \ 0.5\ col$$

Where:

$T_{max,\ Icl}$ = upper operative temperature limit for clothing insulation I_{cl}
$T_{mix,\ Icl}$ = lower operative temperature limit for clothing insulation I_{cl}
I_{cl} = thermal insulation of the clothing in question (clo).

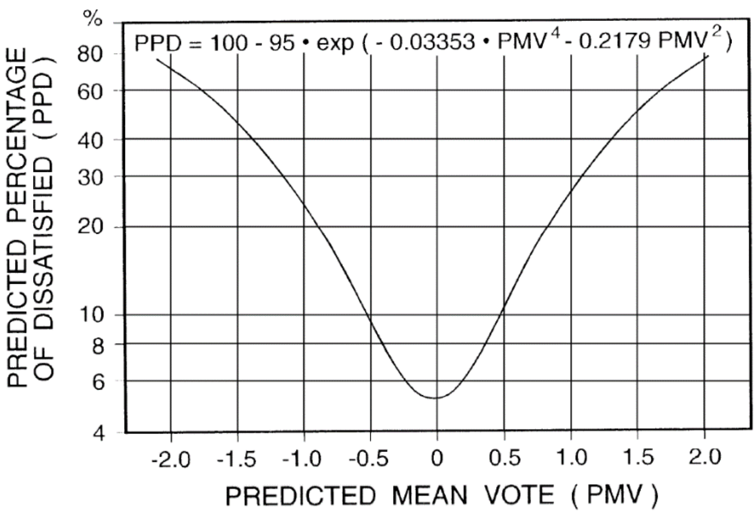
In some cases, air speeds greater than 0.20 m/s (40 ft/min) can be used to raise the upper operative temperature limit for the comfort zone.

ii) Computer Model Method for General Indoor Application: This part provided the comfort zone for a broader range of applications using a computer program based on a heat balance model. The method can be used in spaces where the occupants' activity levels result in average metabolic rates ranging from 1.0 met to 2.0 met and where clothing with a thermal insulation rating of 1.5 clo or less is worn. The ASHRAE thermal sensation scale, which was created to quantify people's thermal sensation, is as follows:

+3 Hot
+2 Warm
+1 Slightly warm
0 Neutral
-1 Slightly cool
-2 Cool
-3 Cold

The predicted mean vote (PMV) method utilizes heat balance principles to relate the six primary thermal comfort factors mentioned previously to the average response of people on the above scale. As shown in Figure 3.9, the PPD (predicted percentage of dissatisfaction) index is related to the PMV. It is predicated on the assumption that people who vote +2, +3, –2, or –3 on the thermal sensation level are dissatisfied, as well as the simplification that PPD is symmetric around a neutral PMV.

Figure 3.9: Spaces with an acceptable operative temperature and humidity range. [171]



The PPD and PMV ranges recommended for typical applications are shown in Table 3.4. This is the foundation for the section on graphical methods for typical indoor environments.

Table 3.4: Thermal environment sufficient for general comfort. [171]

PPD	PMV Range
< 10	- 0.5 < PMV < + 0.5

The comfort zone is defined by the air temperature and mean radiant temperature combinations, for which the PMV falls within the prescribed range in Table 1. The PMV model considers the air temperature and mean radiant temperature, as well as the metabolic rate, garment insulation, airspeed, and humidity. The conditions are in the comfort zone if the models resulting PMV value falls within the suggested range.

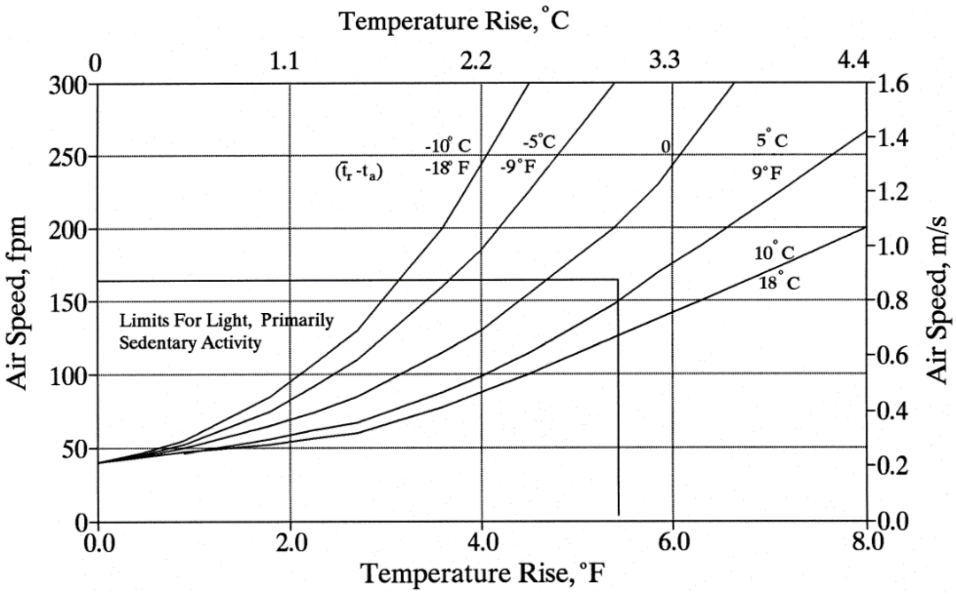
2- *Humidity limits*

Humidity-controlling systems must be able to maintain a humidity ratio of 0.012 or less, which equates to a water vapor pressure of 1.910 kPa (0.277 psi) at standard pressure or a dew-point temperature of 16.8°C (62.2°F) at standard pressure. ASHRAE standard 55 does not determine a minimum humidity level, therefore no lower humidity limitations for thermal comfort have been established. Non-thermal comfort variables like skin drying, mucous membrane irritation, eye dryness, and static electricity generation, on the other hand, may limit the acceptance of very low humidity conditions.

3- *Elevated air speed*

There are no precise connections between increased air speed and better comfort. However, ASHRAE standard allows for increased air speed to boost the maximum temperature for acceptability if the affected occupants are able to control the airspeed. Figure 3.10 depicts the amount by which the temperature can be raised. The lines in this diagram represent the combinations of air speed and temperature that result in the same heat loss from the skin. The upper temperature limit of the comfort zone (PMV = +0.5) and airspeed of 0.20 m/s (40 fpm) serve as the reference points for these curves. This figure applies to a person who is lightly clothed (with clothing insulation between 0.5 and 0.7 clo) and engaged in near sedentary physical activity (with metabolic rates between 1.0 met and 1.3 met).

Figure 3.10: Airspeed required to offset increased temperature. [171]



The indicated temperature increase applies to both the mean radiant temperature and the air temperature. That is, both temperatures rise by the same portion in comparison to their starting points. When the mean radiant temperature is low and the air temperature is high, increasing the airspeed has a lower effect on heat loss. When the mean radiant temperature is high and the air temperature is low, increased air speed is more effective at increasing heat loss. As a result, the curve in Figure 3.10 must be used, which corresponds to the relative difference between air temperature and mean radiant temperature. For intermediate differences, it is acceptable to interpolate between curves.

Elevated air speed can be used to offset a raising in air temperature and mean radiant temperature, but not by over 3.0°C (5.4°F) above the values for the comfort zone when no elevated air speed is present. The required air speed cannot exceed 0.8 m/s (160 fpm). People's preferred air speed varies greatly. As a result, the increased airspeed must be under the direct control of the impacted occupants and adjustable in increments of only 0.15 m/s (30 fpm). The advantages of increasing air speed are dependent on clothing and activity. The effect of increased speed is greater with elevated activity than with sedentary activity due to increases in skin wetness. With lighter clothing, the effect of increased air speed is magnified due to the increased amount of exposed skin. As a result, Figure 3 is conservative for activity levels greater than 1.3 met and/or clothing insulation less than 0.5 clo and may be used in these cases. With higher levels of clothing insulation, the effect of increased air speed is reduced due to increased body coverage.

4- Local thermal discomfort

Local thermal discomfort reasoned by a vertical air temperature difference between the feet and the head caused by an asymmetric radiant field, local convective cooling (draft), or contact with a hot or cold floor must be considered when determining acceptable thermal comfort conditions. Requirements for these factors are included, radiant temperature asymmetry, draft, vertical air temperature, and floor surface temperature.

The requirements in this section apply to a person who is lightly clothed (with clothing insulation between 0.5 and 0.7 clo) and engaged in near sedentary physical activity (with metabolic rates between 1.0 met and 1.3 met). People who have higher metabolic rates and/or more clothing insulation are less thermally sensitive and, as a result, the risk of local discomfort is lower. As a result, the requirements of this part can be used for metabolic rates greater than 1.3 met and clothing insulation greater than 0.7 clo, but they will be conservative. When the whole-body temperature is cooler than neutral, people are more sensitive to local discomfort; when the whole-body temperature is warmer than neutral, people are less sensitive to local discomfort. This part's requirements are based on environmental temperatures near the center of the comfort zone. These requirements apply to the rest comfort zone, but they'd be conservative for conditions near the comfort zone's upper temperature limits and may underestimate acceptability at the comfort zone's lower temperature limits.

Table 3.5: Percentage of Dissatisfied Due to various Local Discomfort Caused by Draft (DR) or Other Sources (PD). [171]

DR Due to Draft	PD Due to Vertical Air Temperature Difference	PD Due to Warm or Cool Floors	PD Due to Radiant Asymmetry
< 20%	< 5%	< 10%	< 5%

The expected percent dissatisfied (PD) for each source of local thermal discomfort described in this section is given in Table 3.5. To meet the requirements of ASHRAE standard 55, the criteria for all sources of local thermal discomfort must be met simultaneously at the levels specified.

5- Temperature Variations with Time

Alteration in air temperature and/or mean radiant temperature can have an impact on occupants' thermal comfort. Variations under the direct control of the individual occupant have no negative impact on thermal comfort, and the requirements of this part do not apply to them. Variability caused by factors beyond the individual occupant's direct control (e.g., cycling from thermostatic control) may have a negative impact on comfort, and the requirements of this part apply to these fluctuations. Variances that occupants experience as a result of moving between locations with various environmental conditions are permitted as long as the conditions at these places are within the moving occupants' comfort zone. This fluctuating temperature with time is included two factors, cycling variations and drift or ramps. Cyclic variations are defined as situations in which the operative temperature rises and falls consistently over a period of no more than 15 minutes. Temperature drifts and ramps are steady, noncyclic changes in operative temperature, and the requirements of this part also apply to cyclic variations lasting more than 15 minutes. Drifts are passive temperature changes of the enclosed space, whereas ramps are actively controlled temperature changes.

3.6.2.2. Visual Comfort

The visual comfort of the occupants should be considered while designing a green façade for an office building. Although the electricity savings from daylighting may not be as significant as those from heating or cooling, proper light distribution can help to create a more pleasant indoor environment, which can improve occupants' mood and productivity. According to the Sustainable Building Technical Manual, "daylighting creates healthier and more stimulating work environments than artificial lighting systems and can increase productivity by up to 15%." Daylighting also gives variations in light intensity, color, and perspective, all of which aid worker productivity.” According to surveys [173], 90% of occupants prefer to work near a window with a view of the outside.

The significance of the luminous environment originates from the assumption that 80% of the information we collect comes from our eyes and is thus visual in nature, combining the active information searching process (images focused on the eye retina) as well as interpretation (brain), which would be a highly advanced combination of detection and image processing [175]. Comfortable visual environments are determined by vision, perception, and what occupants want to see in various room configurations and for various activities. When optimizing the visual properties of an indoor environment, the primary goal is to eliminate the sensation of physiological pain, irritation, or distraction.

Natural light and lighting are important in the human perception of space from a psychological perspective. Many studies show that exposure to natural light in the workplace has a significant impact on the health (psychologically and physically), and productivity of office workers [59][176]–[178]. All daylighting strategies rely on luminance from the sun, the sky, the ground, and light reflected from other buildings. Natural daylight availability is determined by the latitude of the building site and its surroundings, as well as climatic conditions, particularly the duration of sunshine. The performance of daylight into a room is determined by the light that falls on the building envelope, window geometry, and the indoor properties of the space.

Furthermore, from the psychological standpoint of the green façade as a plant layer that is directly related to the visual comfort of employees in office buildings (Figure 3.11), researchers suggested that the plants' visibility can be a major factor in providing psychological benefits and that if there were more and better visibility of plants (Figure 3.12), immediate and long-term significant influences on the employees' psychophysiological states and performance would have been apparent [179]–[182].

Figure 3.11: Visual comfort of green façade in Consorcio Santiago office building.

The following visual function parameters determine good visibility and pleasant indoor environments:

- Illuminance, luminance, and daylight factor (are all terms used to describe the brightness of a light source.)
- Light Distribution - Uniformity of light across a surface
- Glare
- Direction

The interaction between the façade, green façade as a double-skin that applied on the main façade, and the occupants in providing the appropriate luminous environment in terms of visual comfort is divided into two categories: physical and psychological. All environments interact to create the final perception of comfort within a particular luminous environment. Because of the psychological demands on their performance, the luminous environment recommendations on which strategy to use for a specific façade design are not as clear cut as in the thermal environments. Since the luminous environment influences energy consumption in buildings, the purpose of this section is to review these physical and psychological aspects in an effort to understand their impact on green façade configuration choices, as well as to investigate the relationship between green façade performance in terms of visual comfort and the luminous environment that must be considered in green façade design and façade refurbishment.

Figure 3.12: Psychological benefits of increased plant visibility as visual comfort, as well as shading advantages from using vertical greenery systems on the Solaris office buildings façades.

3.6.2.2.1. The Physical Environment

The precise relationship between visual performance and illuminance is determined by a variety of factors that vary depending on the task, individual, and environment. The availability of daylight is influenced by the configuration of the green façade with its plant ratios and structure, the glazing type of the back wall, and the depth of the plan behind the façade. Ordinary window lighting can efficiently daylight the perimeter area to a depth of 1.5 times the window's head height [183]. While this description specifies the lowest possible actual area in a floor plan where daylight could be used, this should be noted that daylight also has a psychological effect in a building that outweighs its physical performance.

In a study by Wells [184], occupants underestimated the proportion of daylight in overall interior illumination beyond 6 meters from the window. He also conducted interviews with office workers on two floors of a UK-based open, deep-plan office building with glass curtain walls to determine the link between actual physical conditions and people's beliefs and attitudes toward windows, daylighting, and artificial lighting. In his study, a survey of 2500 employees revealed a strong preference for daylighting and an outdoor view: 89% of the subjects thought that having a view out was very important, and 69% thought that working by daylight was better for their eyes than working by electric light.

The author concluded that people's perceptions of how much daylight and view out they require are unaffected by the physical environment or the presence of daylight as an illuminant.

An inappropriate percentage of plants and improper cavity depth as a distance between vegetation layer and back wall in green facades can block the daylight; as a result, in green facade design, the physical performance of daylight must be taken into consideration. Altogether, the physical performance of daylight is viewed as an opportunity for lowering dependence on electrical lighting and, as a result, lowering energy consumption in buildings.

Lighting must serve a purpose in three major areas of the workplace [185]: i) to allow the occupant to work and move around safely, ii) to allow tasks to be completed properly and at the appropriate pace, and iii) to give the indoor space a pleasing appearance.

The luminous environment uses energy (natural or generated) in three distinct ways, depending on the availability of daylight:

a) Daylighting strategies: The Illuminating Engineering Society of North America (IESNA) describes light as a visually assessed radiant energy, or, to put it another way, a type of energy that allows us to see [186]. Physically, visible light is thought to encompass a small portion of the total electromagnetic spectrum, which also includes radio waves, infrared light, ultraviolet light, and X-rays. The physical property of their wavelength distinguishes the spectrum rays. As a result, allowing daylight in has additional thermal implications that are exacerbated in arid and semi-arid climates. In daylight-oriented buildings, the demand for heating and cooling is primarily determined by external environmental changes, resulting in widely fluctuating heating and cooling demands. The influence of the external environment can be reduced to such a level in buildings designed for permanent Supplementary artificial lighting for interiors (PSALI) or permanent Artificial lighting (PAL) that it becomes a minor effect. Daylight illumination from windows is determined by the combination of skylight and sunlight.

b) Electrical lighting strategies, and daylight assisted (by electrical lighting): Electric lighting is required for illuminating interiors subsequently daylight hours or in areas that are completely dark because of the depth of plans or underground areas in buildings. Electric lighting in areas adjacent to façades where daylight is available and associated with energy waste. Although research findings have shown that occupants prefer to work by daylight, complete reliance on electrical light during daylight hours cannot be ruled out. According to the interior lighting CIBSE code [187]: Offices lighting suggests that the design maintained illuminance over task area in any workplace containing Display System Equipment (DSE) be in the 300-500 Lux range. In accordance with the ASHRAE standard [188], lighting levels should be supplied by no more than 14 W/m^2 for open-plan workplaces and 17 W/m^2 for enclosed offices.

c) Hybrid strategies: Electric lighting, as mentioned in the preceding part, is required in non-residential buildings to create a comfortable and productive working environment. However lighting is a significant contributing factor to electricity consumption in buildings, the use of automated systems to turn it off and make use of daylight has been suggested in several studies to supplement other energy-saving measures in newly constructed or refurbished buildings [189]. Nonresidential indoor lighting controls that are required include the following:

i. Controls' area manually. Each area's lighting is controlled separately by manual on/off controls.
ii. Multi-level controls. Allowing occupants to use all the light in a space, some of the light, or none of the light in a space.
iii. Shut-off controls. When the space is vacant, the lighting is automatically turned off or has its light output reduced.
iv. Controls' daylighting automatically. Controlling general lighting in the day-lit area separately based on the amount of daylight in the space.
v. Lighting controls that respond to demand. Installing controls that can receive and respond to a demand response signal automatically.

3.6.2.2.2. Psychological Aspect

The literature on the psychological aspects of lighting, whether or not a green façade is used, is divided into three categories:

1) perception of the outdoor environment: Windows play an important role in providing visual amenities to occupants by connecting them to the outside environment. The following are four general psychological benefits associated with a window: i) providing access to environmental information, ii) improving access to the outside world, iii) restorative and rehabilitative services, and iv) having access to sensory change.

2) perception of indoor spaces: The amount and quality of light available, as well as the characteristics of the space, all influence visual comfort in indoor spaces [190]. Indoor space perception can be explained as the perceived modeling of contents, brightness, and spaciousness. Light entering through facade configurations and interior colors used on walls and partitions have been linked to these perceptions.

3) the influence of light on physiological state, mood, and cognition: Mood and cognition are intertwined. After reviewing a large body of literature, researchers concluded that there is a link between mood and human cognition [191][192]. Researchers also discovered a link between light and the decision-making process resulting from autonomic physiological state and mood [193][61]. The information received by the brain from the illuminated environment is crucial in defining our moods, interactions, and psychological well-being [194]. Other research has linked the availability of daylight and the color of surfaces to alterations in muscle function, breathing, heartbeat, and pressure of blood [190].

3.7. Energy Saving Performance of Vertical Gardens

Practices of sustainable building could significantly cut down the building's environmental impact on energy consumption. With green vegetation covering a building envelope, such as green walls as vertical greenery systems and green roofs, is taking into consideration as a sustainable construction practice, because green vegetation layers have a positive energy-saving performance. These plant layers can reduce heat flux and solar reflectivity, produce evaporative cooling, improves the thermal performance of the building envelope, and decrease the wind effect on the building.

Buildings consume 20-40% of total energy consumption in developed countries [195]. For example, the United States Department of Energy estimated that buildings in the US accounted for 73.6 percent of the overall electricity expenditures and 40 percent of total carbon emissions [196]. Furthermore, the built environment in the UK accounts for >50% of total carbon emissions [197], which all have significant economic and climate change consequences [198]. The concept of sustainability has been introduced to the building construction sector in order to address the identified environmental concerns. The goal of green buildings in which vertical greenery is included, is to develop environmentally friendly construction attributes that lead to energy savings, emission reductions, and material recycling and reuse [199].

Green walls are becoming increasingly popular in sustainable buildings due to their numerous environmental and social benefits, which include improved air quality, mitigation of the urban heat island effect, lower energy costs for heating and cooling, reduction and delay of stormwater runoff, reduction of noise pollution, improvement of human health and well-being, increased energy efficiency, and urban biodiversity increment and production of urban food [200]–[204]. The main benefit that could offset the initial capital cost of green vegetation in buildings is energy savings.

According to recent research on the use of vertical greenery systems (VGS) [205], there are four key factors that influence their operation as a passive system for energy savings in buildings:

- Consider the type of construction system used to place plants on building facades (classification of VGS). Concerning the classification of these systems, it is critical to consider the significant differences between construction systems, particularly between green walls and green facades, which may influence the final thermal behavior of the building. Therefore, it is necessary to provide data specific to each system and to avoid data comparison across systems.
- The climatic effect, not only on the thermal behavior of the building but also on the selection of plant species and how the climate affects their growth.
- The type of plant species that used (deciduous or evergreen, shrubs or climbing plants, etc.).
- The final key factor is associated with various mechanisms that allow these systems to behave as passive energy-saving tools in buildings.

In terms of operation, vertical greenery systems work primarily through four mechanisms: the shadow cast by the vegetation, the insulation provided by the vegetation and substrate, evaporative cooling via evapotranspiration, finally, the wind barrier effect [206]. According to previous research, the shadow effect has the greatest impact on lowering the temperature of the building walls and, as a result, on lowering energy consumption [205].

Tables 3.6, 3.7, and 3.8 are shown to organize and summarize all the key factors found in the literature that influence vertical greenery systems when used as passive energy savings systems. In general, significant reductions in the surface exterior temperature of the building can be seen, though the obtained results vary greatly, ranging from 1 °C to 31.9 °C. Furthermore, the foliage thickness and facade orientation are the most influential parameters (especially South and West).

Table 3.6: Previous research on the use of vertical greenery systems as a passive tool for energy savings in buildings. (Green façades in the traditional way)

Ref. & Date	Location	Köppen Class.	Period	Plant species	Orientation	Foliage thickness (cm)	External wall surface temp. reduction (°C)
[207] 1988	Tokyo, Japan	Cfa	Summer	Parthenocissus tricuspidate	West	--	13
[41] 2008	Berlin, Germany	Cfb	Summer/Winter	Parthenocissus tricuspidate	--	--	3 (summer) 3 (winter)
[208] 2009	Thessaloniki, Greece	Cfb	Summer	Parthenocissus tricuspidate	East	25	5.7
[209] 2011	(Byland Abbey, Ramsey, Oxford, Nailsea, Dover), England	Cfb	All year	Ivy (Hedera helix)	West South	10 to 45	1.7 – 9.7 (summer)

[97] 2011	Delft, Netherland	Cfb	Autumn	Ivy (Hedera helix)	North West	20	1.2
[210] 2014	Reading, UK	Cfb	Summer	Ivy (Hedera helix), Stachys byzantine	North South	--	7 – 7.3
[211] 2014	Manchester, UK	Cfb	Winter	Ivy (Hedera helix)	North	--	+ 0.5 (winter)
[212] 2014	Chicago, USA	Dfa	Summer	Parthenocissus tricuspidate	East South West North	20	12.6
[213] 2014	Al Ain City, UAE	BWh	Summer	--	--	--	

Table 3.7: Previous research on the use of vertical greenery systems as a passive tool for energy savings in buildings. (Green facades as a double skin)

Ref. & Date	Location	Köppen Class.	Period	Plant species	Orientation	Foliage thickness (cm) or (%)	Air layer (cm)	External wall surface temp. reduction (°C)
[207] 1988	Kyushu, Japan	Cfa	Summer	Dishcloth gourd	South West	55%	--	1 to 3
[214] 2013	Chikusa, Japan	Cfa	Summer	Bitter melon, Morning glory, Sword bean, Kudzu, Apios	South	54-52-29-52-15%	--	4.1 - 11.3 - 7.9 6.6 - 3.7
[215] 2009	Pill Nitz, Dresden, Germany	Cfb	--	Ivy (Hedera helix)	North South West East	--	--	--
[216] 2010	Brighton, England	Cfb	--	Parthenocissus quinquefolia	West, East South West	--	--	--
[97] 2011	Rotterdam, Netherland	Cfb	Autumn	Ivy (Hedera helix), Vitis, Clematis, Jasminum, Pyracantha	--	10 cm	20	2.7
[217] 2013	Ljubljana, Slovenia	Cfa/Cfb	Summer	Phaseolus vulgaris “Anellino verde”	--	--	--	4
[206] 2011	Lleida, Spain	Csa	All year	Wisteria sinensis	South East	20 cm	50 - 70	15.18 (summer)
[218] 2011	Lleida, Spain	Csa	Summer	Parthenocissus tricuspidate, Lonicera japonica, Clematis sp, Ivy (Hedera helix)	South	--	--	--

[219] 2010	Singapore, Singapore	Af	Winter	Climber plants	--	--	--	4.36
[220] 2015	Hong Kong, China	Cwa	Summer day (a)Sunny (b)Cloudy (c)Rainy	Ficus pumila, Campsis, grandiflora, Bauhinia, corymbose, Pyrostegia venusta	East, South West, North	--	--	(a) 5 (b) 1 to 2 (c) 1 to 2
[221] 2016	Puigverd de Lleida, Spain	Csa	(a)Summer (b)Winter	a deciduous plant, Boston Ivy "Parthenocissus tricuspidate"	East South West	--	25	(a) East: 13.8 South: 10.7 West: 13.9 (b) East: -0.2 South: 0.7 West: -0.3

Table 3.8: Previous research on the use of vertical greenery systems as passive energy-saving tools in buildings. (Living walls)

Ref. & Date	Location	Köppen Class.	Period	Plant species	Orientation	Substrate type/thickness (cm)	Foliage thickness (cm)	Air layer (cm)	External wall surface temp. reduction (°C)
[200] 2010	Wuhan, China	Cfa	Summer	Six different sps	West	Light substrate / 10 cm	--	3-60	20.8
[97] 2011	Benthuizen, Netherland	Cfb	Autumn	Evergreen sp	West	Soli / 22 cm	10	4	5
[222] 2014	Colmenar Viejo, Spain	Csa	Summer	Sedum sp	South	8cm substrate + 7cm extruded polystyrene	--	--	15.1 – 31.9
[223] 2013	(A) Lonigo, (B)Venezia, Italy	Cfa	Summer	Several, shrub, herbaceous, and climber species	South – West	Felt / 1 cm	--	(A) 5 (B) 3	Day: (A)12-20; (B)16 Night: (A)2-3; (B)6
	(C)Pisa, Italy	Csb	Autumn	Several, shrub, herbaceous, and climber species	East	Soil / 5 cm	--	5	Day: 12 Night: 3
[219] 2010	Singapore, Singapore	Af	--	N3: Hemigraphis repanda, N6: Phyllanthus myrtifolius, Tradescantia spathacea, N1, N4, N5, N7: Moses	--	Several – Soil substrate – Inorganic substrate – Green roof substrate	--	--	Day: 1 to 10.94 Night: 2 to 9 (Depending on the system)
[221] 2016	Puigverd de Lleida, Spain	Csa	Summer Winter	Two different evergreen shrubs	East South West	Coconut fiber substrate / 8cm	--	--	(a) East: 17.0 South: 21.5 West: 20.1 (b) East: 4.5 South: 16.5 West: 6.5

3.7.1. Governing factors of energy savings through Vertical Gardens

The energy performance of buildings with exterior green vegetation such as green facades as vertical gardens are determined by a number of governing factors. This section discusses the factors that influenced energy savings through vertical gardens, such as heat flux and solar reflectivity reduction, evaporative cooling performance, improvement of thermal performance of the building envelope, and effect of wind on the building.

3.7.1.1. Heat flux and solar reflectivity reduction

The building's surface temperature is regarded as a primary indicator of the urban heat island, and the contribution to this temperature can be estimated using entering solar radiation and surface reflectance of the roof and walls [224]. Vertical gardens can lower the temperature by absorbing latent heat and increasing the reflectivity of solar radiation incidents.

The magnitude of the heat flux reduction effect in green facades is determined by the foliage density. The species with the greatest cooling effect in the traditional green facade is “ivy,” and the difference in indoor temperature can reach up to 3 ° C [41][225]. The temperature of the interior in a double-skin facade is generally lower if plants are used instead of blind double-skin facades. Implementation of plants in a double skin facade as a kind of green facade configuration can decrease the energy use of the air conditioning system by over 20% [107][108][225].

3.7.1.2. Evaporative cooling performance

Plant evapotranspiration requires the use of energy. This physical process results in what is known as "evaporative cooling." The evaporative cooling of the leaves is affected by the type of plant and the amount of sunlight. Climate conditions also have an impact. Plants' evapotranspiration can be increased by dry environments or the effect of wind [206]. It was observed that evapotranspiration cooling of a green wall can significantly reduce peak temperatures of a building, with daily temperature fluctuations reduced by up to 50% [94]. Large amounts of solar radiation can be converted into latent heat through evapotranspiration, which does not cause temperature rise. Depending on the amount and type of plants, a building facade completely covered a vegetation layer can reflect or absorb 40–80% of the received radiation [226]. Vertical greenery systems could significantly reduce incoming solar energy into the indoor environment, saving cooling energy through shading and heat flow reduction via evaporative cooling [107][227].

3.7.1.3. Improvement of thermal performance of the building envelope

Green facades can improve the building's insulation properties, hence lowering annual energy consumption [228]. Green facades not only reduce heat loss in the winter and heat gain in the summer, but they also add thermal mass to stabilize internal temperatures throughout the year [228]–[231]. The temperature and humidity of the space between the green screen and the building wall are altered by green walls. The insulation properties of green facades are influenced by the renewal of the air in this space, the density of the foliage, and the design of the facade openings. The thickness of the substrate is another factor that influences the insulating capacity of living walls [206]. Heat transfer through a concrete wall is significantly reduced when it is covered with green vegetation on the outside. According to the researchers, a living wall can reduce energy transfer into a building wall by 0.24 KWh/m^2 [207].

3.7.1.4. Effect of wind on the building

Cold wind plays an important role in lowering the temperature inside buildings during the winter. Blocking cold wind is one method of increasing a building's energy efficiency. A building's green facade system acts as a wind barrier, reducing the effect of wind on the building's facade. This effect is determined by the density and penetrability of the foliage, as well as the facade's orientation and the direction and velocity of the wind. The thermal transmittance of a building is also affected by the wind blowing across its surface. Green facades could alter wind velocity on the underlying exterior of building materials because plant leaves of plants mostly create a stagnant layer of air or reduce wind strength [208]. Researchers also revealed that shielding a building from cold winds with vegetation (green walls and green roofs) decreases heating demand by 25% [232].

Researchers simulated the influence of vegetation on irradiance and wind reduction in similar residences in four different climates [233]. Nevertheless, when taking into consideration the use of vegetation as a modifier of the effect of wind on buildings, one must be cautious not to disrupt ventilation in the summer or favoring air circulation in the winter [206][234].

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Chapter Four: Simulation Method

4.1. Introduction

The dissertation's goal is to assess the performance of vertical gardens as a vegetation layer on office building façades in semi-arid regions as a façade refurbishment option for lowering energy consumption and improving thermal comfort while maintaining user comfort. The dissertation's generalizability applies to all areas around the world with a similar semi-arid climate, including both hot and cold semi-arid regions such as the Great Plains of North America, portions of the Northwest Territories, as well as large areas of Mongolia in China and Kazakhstan and most of the Australian outback, and also parts of southern Africa and a wide region of land on the southern edge of the Sahara Desert.

The simulation method was reviewed in this chapter to verify and quantify the relationship between vertical gardens as a vegetation layer on the façade for refurbishment and influence on energy consumption and occupancies comfort inside the workplace by modifying building behavior. The IES VE software has utilized for this purpose as a simulation tool which discussed in this chapter.

4.2. Research Methodology Development of Energy Consumption and Thermal Comfort in Relation to the Vertical Gardens

For understanding the energy and thermal performance of vertical gardens, there are two types of methodology which normally used in this context: i) Experimental, ii) Numerical, which both methodologies aimed at explaining and developing hypotheses on how and why energy is used in buildings in relation to green façade configuration were identified through a review of the literature. In this context, it's helpful to know how methodologies for studying vertical garden performance as a vegetation layer have evolved in order to determine the methodology that was used in this analysis.

Urban investigations of such organisms in Berlin 1987 [1] and in Cologne 2002 [2] focused on trapping in the leaves of airborne particles and on the effect of greenery on building surface temperatures, which was with the experimental methodology.

Research in 1993 indicated that an additional vegetation layer has greater relative insulation advantages than a well-insulated new building if the building has low isolation values [3]. The possible performance of façade greenery is determined by vegetation mass and thickness, and English ivy is usually the best climber with positive effects all year round.

The research project "Paul Lincke Ufer" (Figure 4.1) was Berlin's first urban research project, where vegetation façade was monitored, after 2 years and 5 years, before greening was added. Climbing plants were planted in planting pots on the façades and on the garden level during this research project. Projects began in 1984; the year 2005 was illustrated in Figure 4.1 and after about 10 years, the façades were replaced with plants. In the center of the backyard and on the façades on various levels, the backyard temperature was taken. Five years later about 1997, further testing was carried out [4]. As a result, an increase in isolation value for the building shows the effects of greenery in a closed environment in a four-walled yard. However, the greenery in the façade has no effect on the air quality when the backyard is totally enclosed. Positive changes in air quality were noted in an open environment (with the back wall opening). Additionally, the ground-based climber species entered the gutter at the end of the roofs during this survey over a period of 10 years and was generally more competitive than that of the plant species on the façade boxes.

Figure 4.1: In the course of a restructuring of a 100-year-old apartment block, the project "Paul Lincke Ufer" green façade in Berlin, started in 1984. Hanging planting boxes and ivy from Boston were planted in the small inner courtyard to transport much of the vegetation.

The macro and micro-nutrient distribution on and in vegetation façade was investigated in Düsseldorf's city center, Germany in 2002 [2] and was the target of air pollution. The automotive exhaust was the main cause of such pollution. Different toxic components were tested from the fine dust generated by car brakes, pipes, and fuel exhausts. Measures and simulation allowed for a reasonable dust distribution on the climber's blocks on the streets downtown [5].

Researches in 2005 show that when the leaves are dry and no direct sun or wind is present, the temperature differential between the façade and the plant structures is demonstrated by a thermal camera device. The results of an infrared thermal insulation measurement of the English ivy effect on the old mill in Figure 4.4 are shown in Figures 4.2 and 4.3. The ivy of Boston covers the whole house on a four-story house with a layer of a plant structure of about 30 cm. This works like winter thermal isolation. These values was vary by around 3°C during a freezing windless night [6].

Figure 4.2: Detail measurement of infrared temperature on a green façade with English Ivy (dark blue outside ivy leaves on the surface in the early morning hours in February 2005).

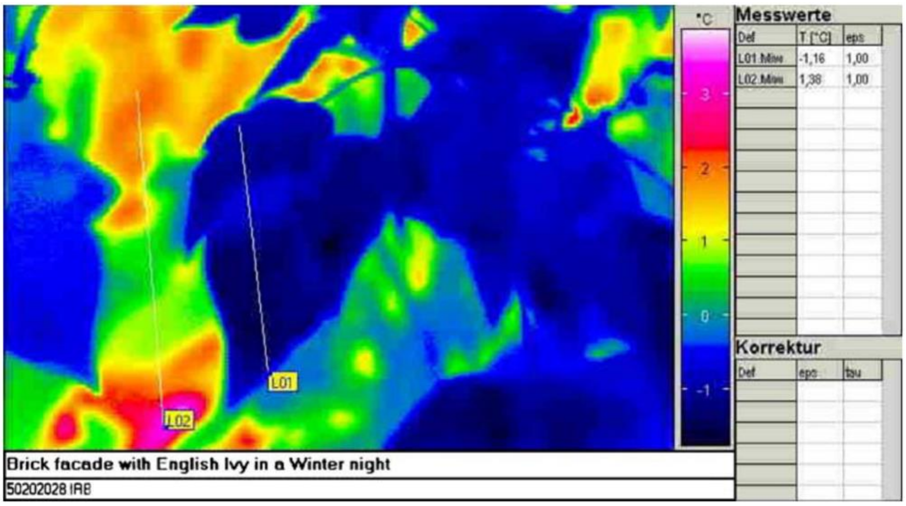


Figure 4.3: The upper blue line shows the surface temperature (degrees Celsius) of a brick facade below the ivy. The other red line is the true temperature of the outer leaf Ivy's leaf temperature from Figure 4.2: At around 3 °C this early winter morning, the temperature buffer caused by the Ivy cover. Depending on the insulation values of the total wall design, the absolute temperature effect of this temperature difference can be determined.

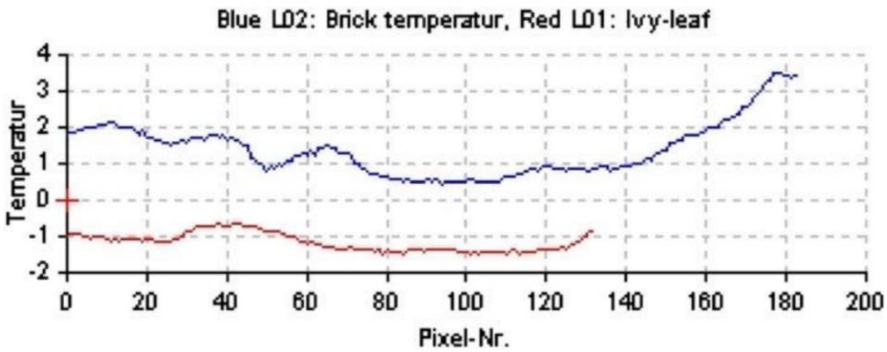


Figure 4.4: English ivy, approximately a century old. In Germany, vegetation on the façades of mills is an ancient practice and acts as a further isolation layer to cool the machinery inside.

Considering existing research, the surface temperature reduction between bare walls and vegetation layer is the most calculated parameter. These can be linked to the potential for urban heat island (UHI) mitigation due to the spectral characteristics of plants that determine heatwave selective absorption and rehabilitation, but also to the cooling impact of urban space and reduced building energy consumption during the summer. Typically, this surface temperature is determined with an infrared camera or surface temperature sensors.

There is a need to emphasize that many studies compare the temperature monitored on the bare wall and the values at the same time if the wall is covered in vegetation layers and the temperature measurement is therefore not on the substrate or on the leaves. In reality, it can also provide information about energy saving if the contribution of the vegetation mechanism and the air gap (usually present) effects can often not be distinguished. For example, the two Mediterranean studies have been carried out [7][8]; accordingly, during sunny days, the difference of surface temperature between the bare wall and the covered wall varies from 9°C (Pandorea jasminoides variegated and Rhyncospermum jasminoides) to 20°C (threefold felt layer with evergreen or seasonal plants).

Table 4.1 summarizes just the results of the previous investigations that evaluated and takes account of the difference in temperature between the bare surface and the substrate/foliage layer. The following nomenclature shall be introduced in particular: Exp

= test and Num = numeric. Continual observation times, species of plants and the form of the vertical Green system such as green façade and living wall as well as orientation, and the average or maximum value of external surface temperature reduction are other considered parameters according to Köppen-Geiger climate classification. Appendix F detailed the Köppen climate classification.

Table 4.1: Surface temperature reduction results by covering with a vegetation layer as a green façade or living walls (please note that when two separate GST are examined, GF is a green façade, LW a live wall, N stands for configuration of 1. and 2. are used).

Type & Ref.	Location	Köppen Climate class.	Period	Plant Species	GST	Orientation	External Surface Temperature Reduction
Exp. [9]	Phitsanulok, Thailand	Aw or As	December 2015 May 2016	False Heather, Princess Flower, Chinese Croton	LW	South	**Average values:** o Summer: Day: 1.6°C, Night: 0.73 °C o Winter: Day: 2.6 °C, Night:1.15 °C
Exp. [10]	Shanghai, China	Cfa	August 2015 December 2015	Greater periwinkle (Vinca major)	LW		**Maximum values:** o Summer: Day: 28 °C, Night: −2 °C o Winter: Day: 10 °C, Night−10 °C
Num. [11]	Thessaloniki, Greece	Cfa	June - August	Boston ivy (Parthenocissus tricuspidata)	GF	North East South West	**Average values:** o North: ≈ 2.73 °C o East: ≈ 11.53 °C o South. ≈ 7.46 °C o West: ≈ 17.85 °C
Exp. [12]	Covilha, Portugal	Csb	February - March	Sedum species and Thymus species	LW	South	**Maximum value:** 15 °C
Exp. [13]	Lleida, Spain	Csa	June – July December - February	1. GF: Boston Ivy - Parthenocissus tricuspidata 2. LW: Rosmarinus officinalis and Helichrysum thianschanicum	GF LW	East South West	**Average values in Summer:** o East: LW 17.0 °C; GF 13.8 °C o South: LW 21.5 °C; GF 10.7 °C o West: LW 20.1 °C; GF 13.9 °C **Average values in Winter:** o East: LW 4.5 °C; GF -0.2 °C o South: LW 16.5 °C; GF 0.7 °C o West: LW 6.5 °C; GF -0.3 °C
Exp. [14]	Nottingham, UK	Cfb	3 weeks	Hedera helix	GF		**Maximum value:** o 6.1 °C on sunny days o 4.0 °C on cloudy days

Exp. [15]	Reading, UK	Cfb	19 August	Cherry laurel (Prunus laurocerasus)	GF	South	**Average value:** 6.3 °C
Exp. [16]	Singapore	Af	24 February 2008 28 April 2008 21 June 2008	N3: LW Hemigraphis repanda N6: LW Phyllanthus myrtifolius	N1: LW N2: GF N3: LW N4: LW N5: LW N6: LW N7: LW N7a: LW N8: LW		**Maximum value:** o 24/02: N1:5.23 °C, N2: 2.45 °C, N3: 4.92 °C, N4: 5.30 °C, N5: 4.48 °C, N6: 3.25 °C, N7: 4.25 °C, N8: 3.72 °C o 28/04: N1: 7.93 °C, N2: 7.32 °C, N3: 9.21 °C, N4: 8.95 °C, N5: 8.48 °C, N6: 6.11 °C, N7a:6.12 °C, N8: 7.84 °C o 21/06: N1: 5.33 °C, N2: 6.35 °C, N3: 5.69 °C, N4: 6.34 °C, N5: 6.53 °C, N6: 4.04 °C, N7a: 4.97 °C, N8: 6.61 °C
Exp. [17]	Thessaloniki, Greece	Cfa	July – August 2006	Boston ivy (Parthenocissus tricuspidata)	GF	East	**Average value:** 5.7 °C **Maximum value:** < 8.10 °C
Exp. [18]	Mawson Lakes, Australia	Csb	December 2014 July 2015	Goodenia pinnatifida, Brachyscome ciliaris, Poa labillardie, Enneapogon nigricans, Kennedia prostrata, Atriplex semibaccata, Ixiolaena leptolepis, Ptilotus nobilis, Hardenbergia violacae	LW	West	**Average values:** o Warm days: Day:3.4 °C *, Night: 1.9 °C o Cold days: Day 0.22 °C *, Night−0.05 °C **Maximum values:** o Warm days: 14.90 °C o Cold days: −5.88 °C
Num. [19]	Hong Kong, Wuhan, China	Cfa	One hottest summer day	1. Peperomia claviformis 2. Plant not specified	LW	1. Exposure not 2. Specified West	**Hong Kong maximum values:** Hottest summer day: 24.2 °C Coldest winter day:16.9 °C **Wuhan maximum values:** Hottest summer day 26.2 °C Coldest winter day: 18.4 °C
Exp. [20]	Geneva, Italy	Cfb	May (1 week)	--	LW	South	**Maximum value:** 13 °C
Exp. [21]	Santiago, Chile	Csb	January (12 days)	Highly dense sedum, medium dense sedum	LW	North	**Maximum value:** 30 °C

4.3. *Research Methodology*

The literature review identifies the scientific approach and naturalistic approach for research in the field of energy efficiency in buildings through the implementation of vertical greenery systems (green facade and living wall). A third approach is the synthesis of the two approaches and is called 'integrated method' or 'mixed method' in literature.

➢ ***The Scientific Approach***

In the scientific process, conjectures are made, the predictions are derived as logical consequences, then experiments or empirical observations are conducted based on those predictions. A hypothesis is a conjecture based on information gathered when looking for answers to a question (Figure 4.5).

By using the scientific method, all scientific disciplines are united. The scientific approach provides an empirical methodology for scientific experimentation that leads to unbiased world interpretations and enhances knowledge. Researchers proposed the scientific method for the first time, which enables the logical and rational solution of problems to be found in many scientific domains [22]. Verifiability, predictability, falsifiability and fairness are the main precepts of the system in all scientific disciplines.

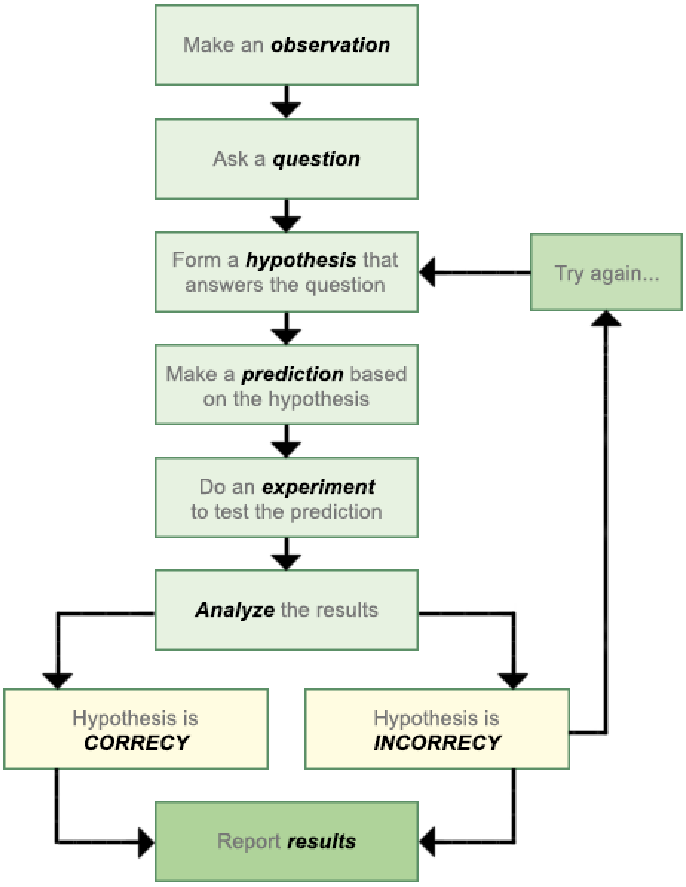
A method of knowledge achievement through a controlled systemic process is a scientific approach. It is when science is recognized to generate, replenishing, and correct knowledge not only as a body of knowledge but also as a logic of research [23].

Following the logic of scientific inquiry, the scientific approach is based on falsifiable assumptions. Falsifiability is the philosophy of robust research in which scientists do not attempt to validate the hypothesis when they overlook or ignore the events and findings which may disprove the theory [24]. Knowledge is acquired through hypothesis-based experiments. The experiments are related to the systematic sampling method, the identification of variables, the eradication, and control of variables [25].

Precision and control are the key strengths of the experiments. The systematic regulation of variables contributes to explanations, of course, in which a particular cause is related to a direct effect of another variable. Thus, control allows the scientist to define an event, why the event takes place, and under what circumstances the event takes place.

The quantitative information resulting allows statistical analysis and therefore confirms or rejects the hypothesis to be tested. If the prediction of the hypothesis is validated, the prediction is consistent with what actually happens, however; it does not prove the hypothesis is correct.

Figure 4.5: The scientific method: a procedure for collecting and analyzing data is the scientific method. It offers well-defined steps to standardize the collection of science using a logical, reasonable method of problem resolution. This diagram shows the science's phases.



The scientific method has its limitations, like any research method. This method is not immune to subjectivity bias when it comes to identifying an issue for investigation, causal explanation, assimilation of evidence, and intentionally or unintentionally ignoring explanations of unexpected or unfavorable experimental results. These shortcomings should be considered and reduced by action to ensure the reliability of the data and analysis collected.

The scientific method has limitations when testing hypotheses that deal with humans being. Researchers in education and behavioral science face enormous challenges because humans are much more complex than the inert matter examined in physical sciences. This is due to the fact that humans are not only affected by various environmental factors, but also experience, interpret, and respond to them in a variety of ways. Given this limitation, no assumptions about the facts or that all people are the same at all times should be made [24].

Inquiry-based research is performed, relying on facts, experience and data, concepts and constructs, hypotheses and conjectures, and principles and laws. Table 4.2 shows how these research concepts from a symbolic and rational method of inquiry fit together [26].

Table 4.2: Basic elements of scientific research methodology.

Law	➢ Verified hypotheses; may be empirical or theoretical to assertive a predictable relationship between variables.
Principles	➢ A principle is a law or a general truth that guides thinking or action.
Hypotheses	➢ While untested, formal propositions are subjected to testing and are generally articulated in causal terms.
Conjectures	➢ Informal propositions are not made or understood or even explicitly implied in a testable form.
Concepts and Constructs	➢ Concepts are human mind inventions that provide a way to organize and explain observations; they fulfill certain functions and all shape logical and structured relationships between data.
Facts	➢ There is something, a genuine phenomenon, or something that is commonly considered true.
Data	➢ The collection of facts through direct observations or records; observation is the process by which facts become information.

➢ ***The Naturalistic Approach***

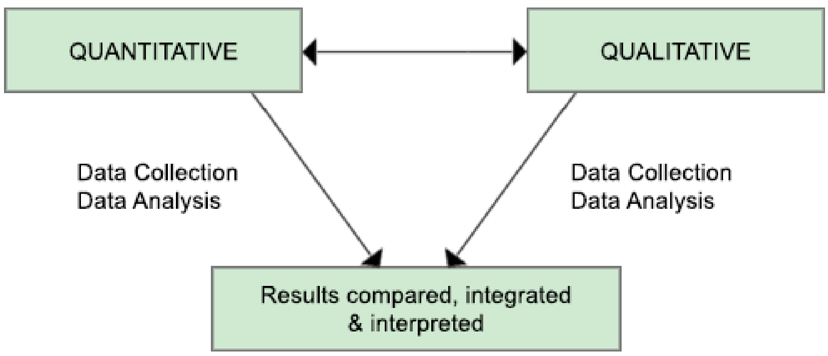
The naturalistic approach, also known as the non-experimental approach, employs observational methods for data collection that include less direct manipulation of conditions and subjects [27]. Data are generally collected through analysis previous researches, observations, and/or questionnaires. The method is based on an opposition to epistemology which supports scientific methods and those experimental assumptions which result in the generalization of results, irrespective of their context or their variables. Scientific approaches, according to proponents of this approach, are being pushed away from understanding complex human nature and toward arriving at conclusions based on experiments conducted in controlled environments with rigid environmental regulation [28].

Naturalistic approaches are also known as qualitative research methods, which seek to capture people's aspirations and behavior, whilst ensuring that human responses to their environments are complex and variable. Social science has established qualitative research methods that allow researchers to analyze social and cultural phenomena. For instance, action analysis, case study investigations, and ethnography are qualitative approaches. Qualitative data sources include observation (fieldwork), interviews and questionnaires, documents, texts, observations, and reactions of the researcher [29]. The motivation for qualitative research, as opposed to quantitative research, stems from the observation that our capacity to talk is one of the few things that separates humans from the natural world. Qualitative research approaches are intended to aid researchers in better understanding people and their social and cultural backgrounds. As textual data is quantified, researchers argue, the purpose of interpreting a phenomenon from the perspective of the participants and its specific social and institutional context is largely lost [30]. While the majority of researchers conduct a quantitative or qualitative analysis, some have proposed integrating one or more research approaches in a single study (called triangulation) [31].

- ***The Mixed Approach***

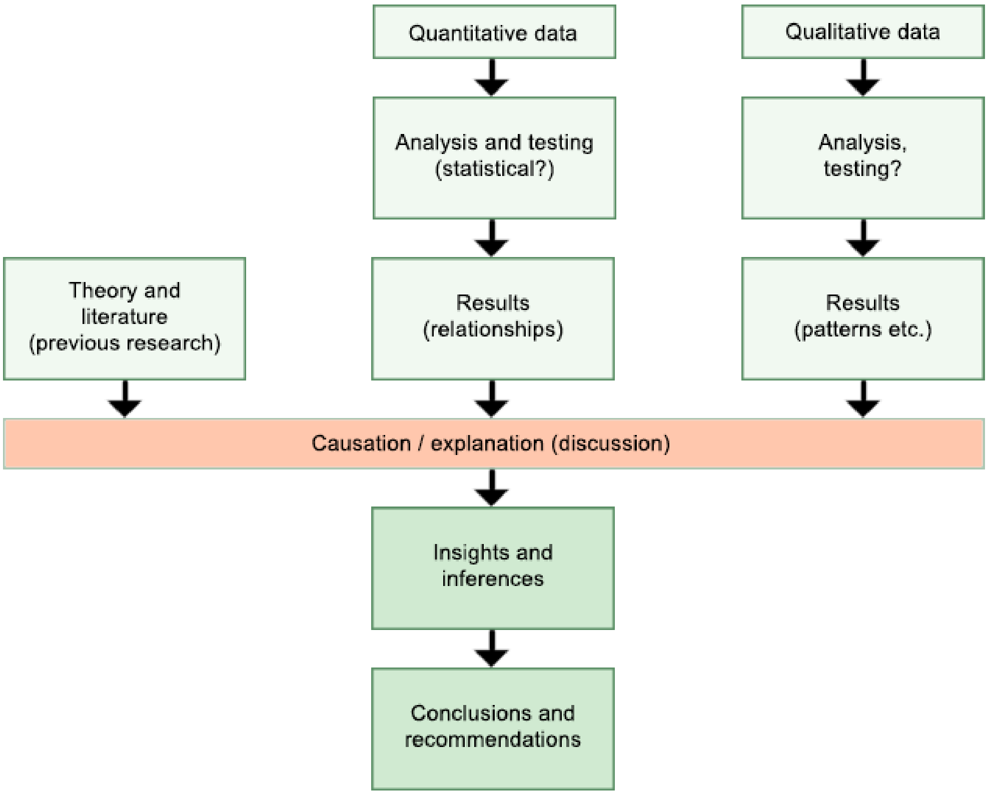
Within the research community, there is a rational belief that quantitative and qualitative research are better viewed as complementary and should therefore be combined in a variety of research. With the increasing attention on "triangulation" in science, this emphasis has grown [32]. Figure 4.6, shows the diagram of the mixed methods which in a notation system for mixed methods strategies, capitalization means that the priority of both approaches is equal.

Figure 4.6: A Visual Diagram of the Mixed-Methods Concurrent Triangulation Strategy.



The combination of methodologies in the analysis of the same phenomenon is referred to as triangulation. The efficacy of triangulation is based on the presumption that the shortcomings of each strategy would be offset by the counter-balancing strengths of another. This term is used interchangeably to describe research techniques that use a mixture of quantitative and qualitative research methods in the research of the same phenomenon. It is sometimes used to refer to a broad approach that incorporates "multiple observers, theoretical perspectives, and methodologies." It generally denotes a reference to a combination of research methods – thus the use of qualitative and quantitative techniques together to study the topic – which is very powerful for gaining insights and results, and for assisting in making inferences and in drawing conclusions, as illustrated in Figure 4.7 [33].

Figure.4.7: Triangulation of qualitative data.



4.4. Proposed Methodology

The hypothesis is analyzed and refuted using a scientific method in this dissertation. The hypotheses are based on the theory that vertical gardens can be used as a vegetation layer on façade architectural technologies to develop physical and psychological features of buildings which these enhancements can cause to reduce energy consumption, improve thermal efficiency, and increase user comfort in glazed office buildings. The semi-arid regions have been selected as the research context. The nature of the semi-arid climate has been broadcasted around the world, but patterns of energy consumption and façade configurations are based on specific socio-cultural aspects in each region and weather conditions aspects underpinning the evolution of office building façades in these regions.

A triangulated data collection approach is used to establish a comprehensive understanding of the energy consumption of office buildings in semi-arid regions. Triangulated data is information gathered from multiple sources to fill gaps in information collected in order to create a comprehensive view that supports the research hypothesis. The base case is developed from previous literature and a cross-sectional historical survey of office buildings in semi-arid regions, thus forming the unit of measurement. To provide façade thermal efficiency indicators, the physical variables from the research are mapped onto the base case façades.

Green façades are presented as a vegetation façade (vertical garden) technology that improves the environmental control of buildings. The green façade configuration is proposed as an option for refurbishing existing office building façades which described in chapter 3. Within this context, it is proposed as a potential architectural solution to reduce direct solar radiation into occupied spaces, therefore reducing cooling loads.

Dynamic software (IESVE) is used as the experimentation method to produce data for statistical analysis in order to measure the effect of using green façade configurations on building cooling loads experimentally. Section 4.4 of this chapter discusses further about the selection of IESVE software as a simulation tool. Simulation software, as a method for experimentation, provides constant boundary conditions during experimentation. In the context of the thesis, simulation replaces laboratory testing to improve the accuracy, repeatability, and reproducibility of results. However, the challenge of evaluating the truth level in the simulation results is obvious as a limitation of experimental work since simulations provide only an approximation of the real world.

To boost confidence in simulation performance, a limited reliability test is performed. Researchers suggested a way to increase reliability of simulation efficiency by calibrating input data [34][35], in which the energy models of buildings are complex and consist of several input data. The precision of building modeling in a simulation program depends in particular on the user's ability to enter the parameters (input data) which lead to a good model for the actual use of building energy [36]. Provided the many parameters involved, a detailed energy model calibrating process is a highly undefined problem that leads to a solution that is nonunique [37][38].

In this research, this methodology is employed to calibrate and verify simulation performance reliability. A simulation of a conceptual model in Denver, Colorado, which located in a semi-arid region is performed. The following parts of this chapter address evaluating factors influencing bare and green façades.

Vertical gardens tend to save a significant amount of energy as compared to traditional insulation standards, but energy savings from a second façade layer would be restricted for buildings built to low-energy standards. As a result, the empirical approach to simulation results aims to convert general assumptions and intuitions about the performance of a green façade (hypothesis) as an architectural technology in a semi-arid region into the foundations of research-based understanding of its performance.

However, based on the scientific approach adopted, the realistic progression to identifying the appropriate green façade technologies for refurbishment with the lowest amount of energy consumption could result in a devaluation of individual needs from a building façade.

4.4.1. The Measurement Tool

Different measurement tools (Rhino, grasshopper and Green building studio, and IESVE) were tested in order to select a reliable tool capable of predicting green façade performance in terms of thermal efficiency and energy consumption in a semi-arid context. The focus of this research is on methods for predicting and assessing the performance of green façades.

A dynamic tool (IESVE) was chosen to simulate energy building which describe completely in section 4.4. This study seeks to imitate reality by constructing a conceptual model, then attaching simultaneous and interactive activities to different variables in order to affect different paths to the occupied office space through heat and mass transfers.

4.4.2. The Unit of Measurement

In relation to green façade configurations and green façade technologies used for renovations, the study calculated reductions in energy consumption. The analytical unit here is the energy consumption per a standard square meter of a base case. Based on US department of energy (DOE) information and ASHRAE standard on the office buildings in Denver, Colorado, and available literature, the basic case study is structured in detail by mapping the physical and organizational profiles on the simulation model. Appendix A detailed the case study in this research.

In terms of thermal efficiency and energy consumption studies, the development of a base case simulation model is considered the spine of green façade performance. A simulation model is defined as a representation of reality [39][40]. It identifies some aspects of the real world as important to study, makes clear the meaningful connections between the aspects, and makes it possible to formulate proposals empirically testable as to the essence of these relations. This description considers the model as an empirical phenomenon that shows the relationship between variables in logical arrangements. In order to simplify complex reality relations between variables, the essence of constructing a model is to abstract reality into a representation of the basic characters of a reality.

4.4.3. Variables (Dependent and Independent Variables)

The variables that influence the vertical gardens simulation are classified as independent and dependent variables. Variables are an empirical concept; this relationship is expressed as: 'Research problems are communicated using a collection of concepts.' Empirical phenomena are synonyms for concepts. Concepts are transformed into variables in order to progress from the conceptual to the empirical level. Our definitions will ultimately appear as variables in the hypothesis to be evaluated [41], [42].' The variables expected to describe the modification of the dependent variable are called independent variables. The exploratory variable that induces changes in the values of the dependent variables is known as the independent variable.

Independent variables within the scope of this study are included in three sets, the climatic profile, building morphology, and structure operational profile. These variables are derived from a study of an office building in Denver and are not only dependent on literature (explained in section 3.6).

Under the dissertation’s hypothesis, the dependent variables are concerned with alterations to the physical properties and development of green façades as vegetation layers that would impact cooling/heating loads in office buildings in a semi-arid region.

The building façade configuration is the dependent variable, with the aim of converting existing façade configurations to green façades on a conceptual model to evaluate green façades performance.

4.5. Denver as a Case Study

The primary reason for selecting Denver as a semi-arid context for this investigation is because of the city's climatic characteristics, which include both cold weathers (below zero degrees) and hot weather throughout the year, and the efficiency of the green façade on the office building can be better understood. Additionally, in consequence, various influences on the context can be probed and analyzed substantially.

Case studies are useful as preliminaries to more extensive investigations because they generate rich data that highlights various phenomena, processes, and linkages that demand further research in their own right [43].

A case study is described as an empirical investigation that analyzes a current phenomenon within its real-life environment; when the boundaries between phenomena and context are not readily visible; and when many sources of evidence are utilized [44][45]. Applying this description to Denver, the presence of office buildings in the built environment is a relatively recent development; yet, as with any building type, the boundaries between the office building and the influence of many contextual influences on its shaping are difficult to distinguish.

When relevant behaviors cannot be manipulated, the case study methodology is preferred [43][45][46]. Likewise, buildings' energy consumption and thermal comfort as a phenomenon lack a clear relationship and distinction between both the building as a unit and the behavior of influencing factors on the building's energy usage, such as urban settings, façade configuration, building services, and occupancy levels in a particular context.

Case studies have long been criticized as a research approach since providing little basis for scientific generalization. Furthermore, case studies, like experiments, can only be generalized to theoretical concepts, not populations or universes and also like an experiment, does not represent a sample, and the investigator's purpose is to develop and generalize ideas (analytic generalizations), not to enumerate frequencies or statistical generalizations [46]. Some researchers advocated for the idea of 'fittingness' to be used instead of 'generalization,' with an emphasis on examining the degree to which the circumstance investigated matches other scenarios [27]. This technique involves a grasp of the context, which is a logical result of the emphasis on providing a considerable quantity of information on the thing being examined and the location in which it is situated [47]. Since a case study is valuable in and of itself, it is also worth documenting and evaluating. The performance of a green façade in a Denver office building would be considered a 'fitting' of a green façade performance in any similar semi-arid climate.

Office buildings, like other buildings, have the potential to have a significant impact on the environment and energy bills, both negatively and positively, depending on how they are designed and planned on-site. Their contribution to greenhouse gas emission reduction is directly tied to how they are constructed with respect to the local climate, site-specific factors, and the embodied energy of the entire construction process. Creating an energy-efficient built environment entails reducing resource waste while optimizing the use of renewable sources of energy and passive building design alternatives.

The goal of applying green façades on office buildings, which have been achieved in this research by implementing a vegetation layer, is to improve the quality of work in terms of environmental psychology while also respecting nature by lowering the use of renewable energy sources. An environmentally friendly building might save up to 70%

of energy while providing visual and thermal comfort. As a result, vertical greenery systems such as green façades and living walls should consider each of the following environmental variables: temperature, solar radiation, relative humidity, rainfall, and wind.

This dissertation demonstrates how green façades as vertical gardens can be designed to adapt to semi-arid climates, particularly to the local climate of Denver, and provide indoor comfort while encouraging sustainable office building and environmental stability.

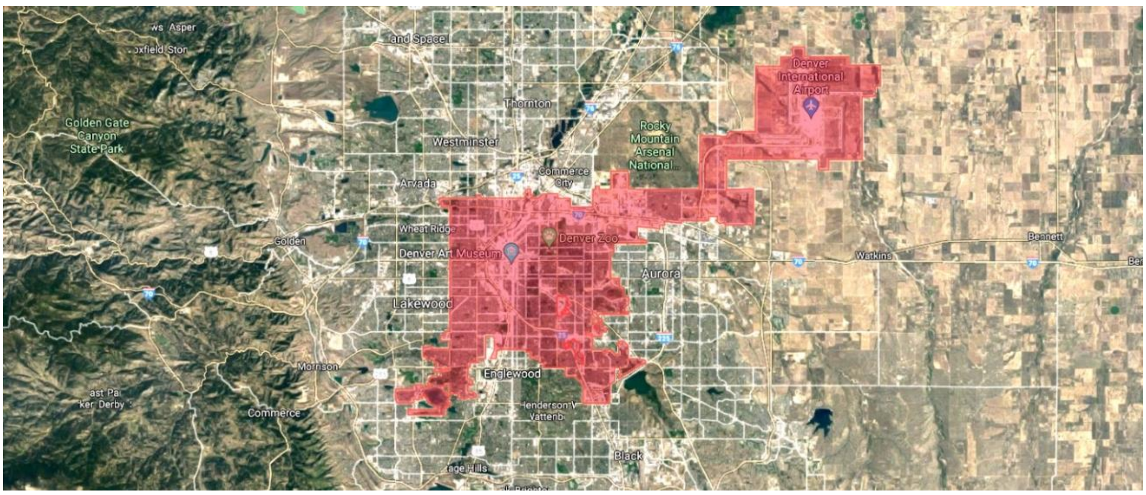
4.5.1. Overview of Denver

- ***Geographical Data of City and County of Denver***

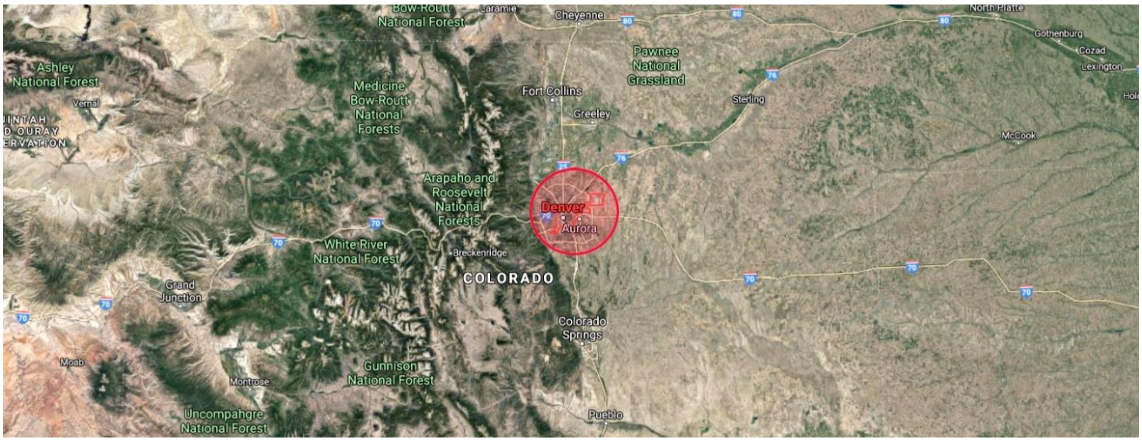
Denver, formally the city and county of Denver, is the capital and populated city in the United States state of Colorado. Denver is located in the Front Range Urban Corridor, which connects the Rocky Mountains to the west and the High Plains to the east (Figure 4.8 a, b). The topography of Denver is composed of plains near the city center and hilly areas to the north, west, and south. The city has a total area of 155 square miles (401 km2), of which 153 square miles (396 km2) is land and 1.6 square miles (4.1 km2) (1.1%) is water, according to the United States Census Bureau [48] (Figure 4.9).

Although Denver is known as the "Mile-High City" because its official elevation is one mile above sea level, as measured by a milestone on the steps of the State Capitol building, the city's elevation fluctuates from 5,130 to 5,690 feet (1,560 to 1,730 m). The city's elevation is 5,278 feet (1,609 m) according to Geographic Names Information System (GNIS) and the National Elevation Dataset, which is represented on many websites such as the National Weather Service [49].

Figure 4.8: a) Location of Denver, Colorado. b) Denver located between great plain and Colorado mountains.

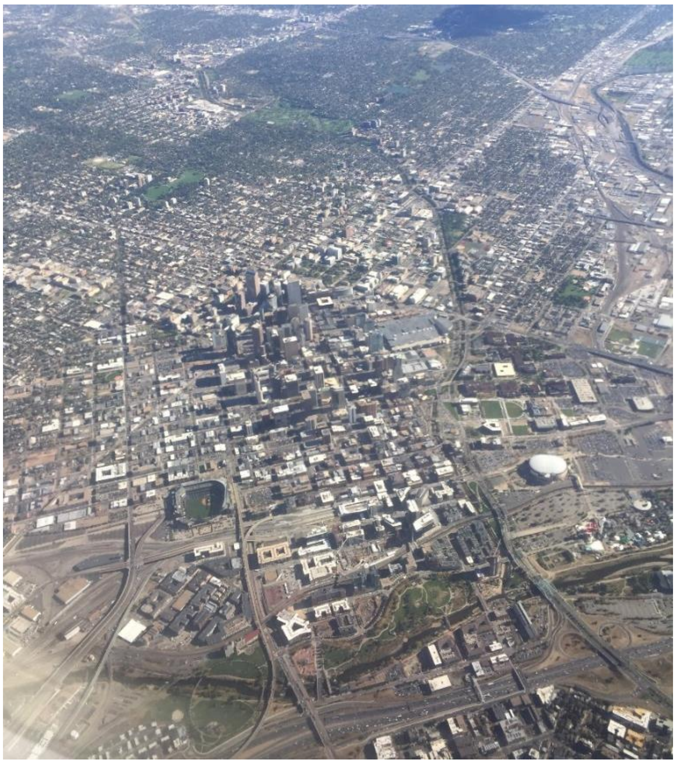


a)



b)

Figure 4.9: Aerial photograph of Denver from the northwest. Many large office buildings are located in the central city.



- ***Demographic and Culture***

Denver has a population of around 705.576 people, according to the 2019 Population and Housing Census (United States Census Bureau. 2010. Retrieved December 6, 2019). The population is made up of various racial communities, including: 68.9% White, 10.2% Black or African American, 3.4% Asian, 1.4% American Indian or Native Alaskan, 0.1% Pacific Islander or Native Hawaiian, and 4.1% two or more races, with 31.8% of Hispanic or Latino origin [50].

4.5.2. Climatic Data Analysis of Denver, Colorado

Climate is defined as the condition of the weather or average course in a location, usually over a long period of time, as manifested by temperature, wind velocity, precipitation, and humidity. It is a crucial factor in architectural design and has a significant impact on a building's performance and energy usage.

Colorado is astride the Continental Divide's tallest peaks. Its north and south borders are the 41° and 37° N. parallels, respectively, while its east and west limits are the 102° and 109° W. meridians. With an area of more than 104,000 square miles, it is the eighth-largest of the 50 states. Although it is famed for its mountains, the eastern high plains cover roughly 40% of its land area.

The combination of high elevation and mid-latitude interior continent terrain produces a chilly, dry, but energizing environment. Temperature variations from season to season, as well as day to night fluctuations, are significant. Summer days on the plains might be hot, although they are frequently eased by afternoon thundershowers. Mountains are almost usually cool. The humidity level is often rather low, which promotes quick evaporation and a rather cool feeling even on hot days. The thin atmosphere allows more solar radiation to penetrate, resulting in pleasant daytime conditions even in the winter. Outdoor labor and pleasure can typically be done in relative comfort all year, but sunburn and skin cancer are issues due to the powerful high-altitude sunshine. Temperatures drop swiftly at night, and freezing temperatures are conceivable in some alpine places throughout the year (Figure 4.10, 4.11).

Figure 4.10: The Great Plains of North America.

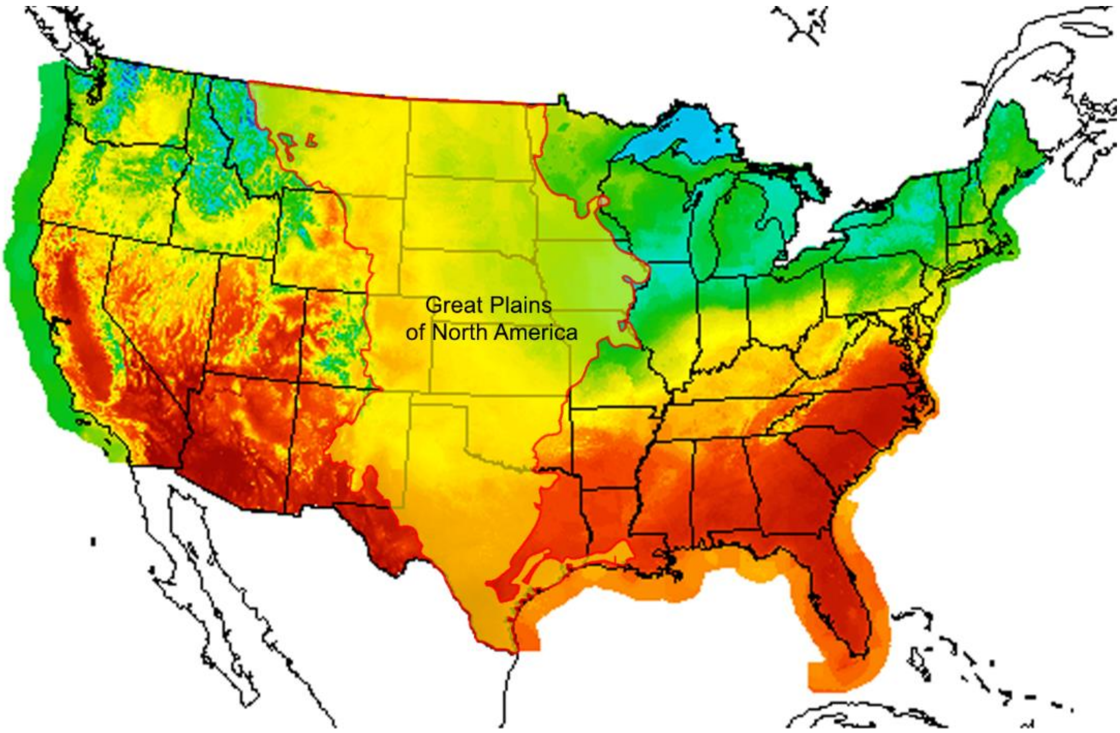
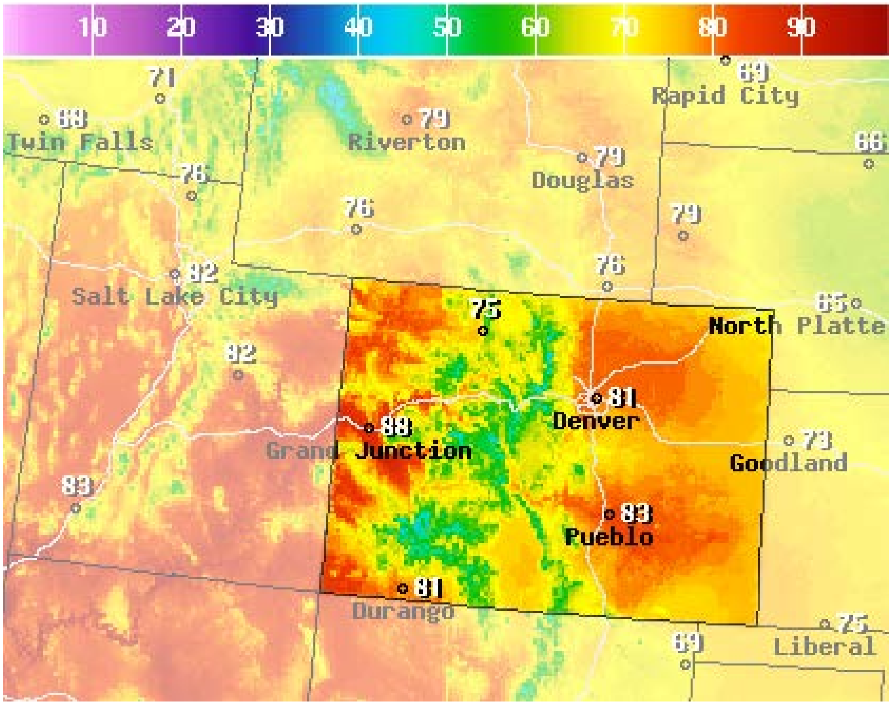


Figure 4.11: Colorado, a western U.S. state, has a diverse landscape of arid desert, river canyons, and the snow-covered Rocky Mountains.



Denver is located in a part of Colorado which is within the Great Plain of North America, which has a semi-arid climate (Köppen climatic classification BSk), with very low humidity and approximately 3,100 hours of sunlight per year. The presence of the Rocky Mountains to the west influences the weather in the city and surrounding area.

- *Air Temperature*

Geographic factors (latitude, hydrography, and topography), surface texture, solar radiation, wind, and location all have a significant impact on air temperature, which is a measure of how hot or cold the air is (i.e., rural vs urban setting). Daily and monthly temperature ranges allow for the forecast of heat loss/gain in buildings, allowing the designer to make appropriate design solutions to create indoor thermal comfort.

Denver has high maximum temperatures and low minimum temperatures, with large temperature variations throughout year (Table 4.3). The hot season lasts 3.2 months, from June 7 to September 14, with daily high temperatures averaging more than 27°C. July 10 is the hottest day of the year, with an average high of 31°C and a low of 17°C. The cold season lasts 3.5 months, from November 19 to March 2, with daily high temperatures averaging less than 12°C. December 30 is the coldest day of the year, with an average low of -6°C and a high of 7°C (Figure 4.12).

Table 4.3: Average temperatures table for Denver, Colorado.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max Temperature °C	6.2	8.1	11.2	16.6	21.6	27.4	31.2	29.9	24.9	19.1	11.4	6.9	17.9
Average Temperature °C	-1.3	0.8	3.9	9	14	19.4	23.1	21.9	16.8	10.8	3.9	-0.6	10.1
Average Min Temperature °C	-8.8	-6.6	-3.4	1.4	6.4	11.3	14.8	13.8	8.7	2.4	-3.7	-8.1	2.4

This temperature variation is one of the significant elements for climate-responsive architecture in Denver, as the primary goal is to use the green facade for both temperature extremes. One of the research strategies is to implement a green façade as a second skin on the façade that minimizes heat gain during the hot months and reduces heat loss during the cold months.

Figure 4.12: The average high and low temperature in Denver. The daily average high (red line) and low (blue line) temperatures, with bands spanning the 25th to 75th and 10th to 90th percentiles, respectively. The narrow-dotted lines represent the average felt temperatures.

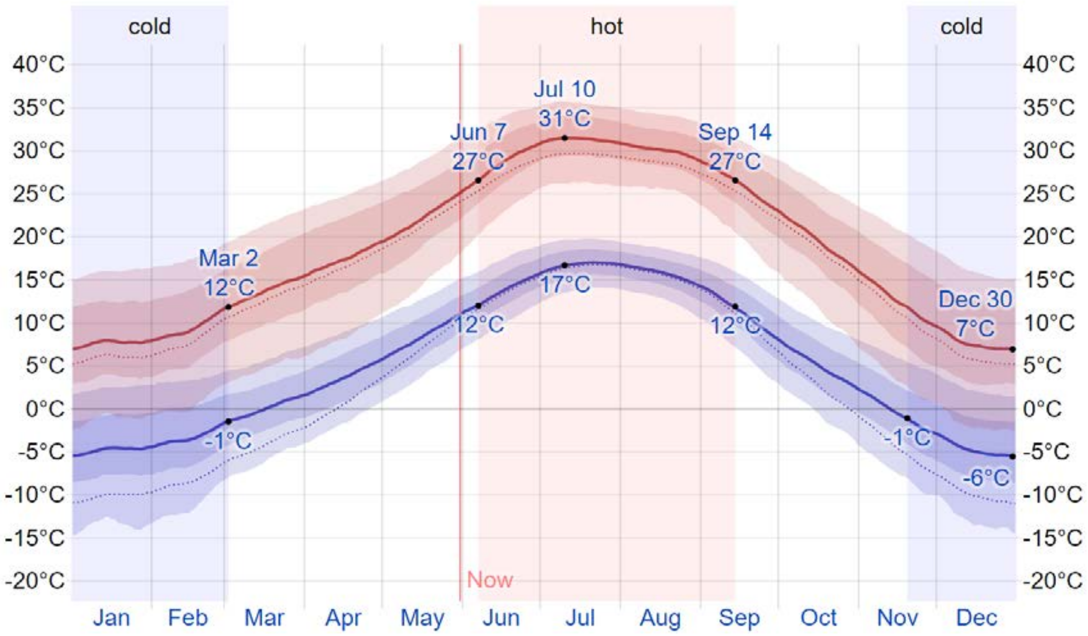
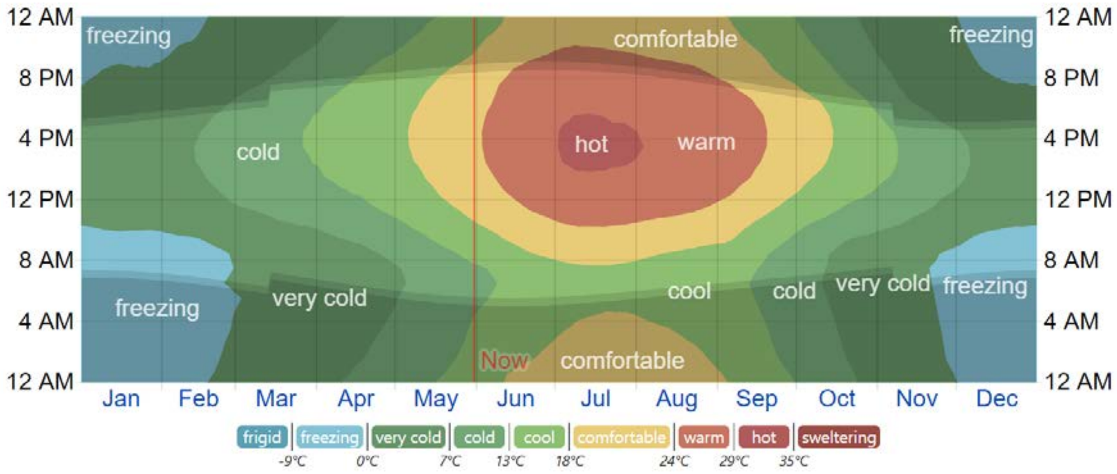


Figure 4.13 gives a concise representation of the full year's hourly average temperatures. The horizontal axis represents the calendar day, the vertical axis represents the hour of the day, and the color represents the average temperature for that hour and day.

Figure 4.13: The hourly average temperature in Denver, color-coded into bands. Night and civil twilight are shown by the shaded overlays.



- ***Precipitation***

A wet day is defined as having at least 0.04 inches of liquid or liquid-equivalent precipitation. The likelihood of rainy days in Denver fluctuates throughout the year. The wetter season lasts 5.2 months, from April 1 to September 7, with a greater than 18% probability of precipitation on any given day. The chances of rainy-day peaks at 31% on July 22.

From September 7 to April 1, the drier season lasts 6.8 months. On December 19, the chance of precipitation is only 6%. Regarding the weather information of Denver, they define rainy days based on whether they are rain-only, snow-only, or a combination of the two. According to this classification, the most prevalent type of precipitation in Denver varies throughout the year. Rain is the most prevalent occurrence for 9.1 months, from February 17 to November 21. On July 22, the probability of a single day of rain is 31% (Figure 4.14, Table 4.4). Snow is the most prevalent precipitation for 2.9 months, from November 21 to February 17. On January 6, the possibility of a snow-only day is 4%.

Figure 4.14: Precipitation in Denver on a daily basis. The percentage of days with various types of precipitation, omitting trace amounts: rain alone, snow alone, and mixed (both rain and snow fell in the same day).

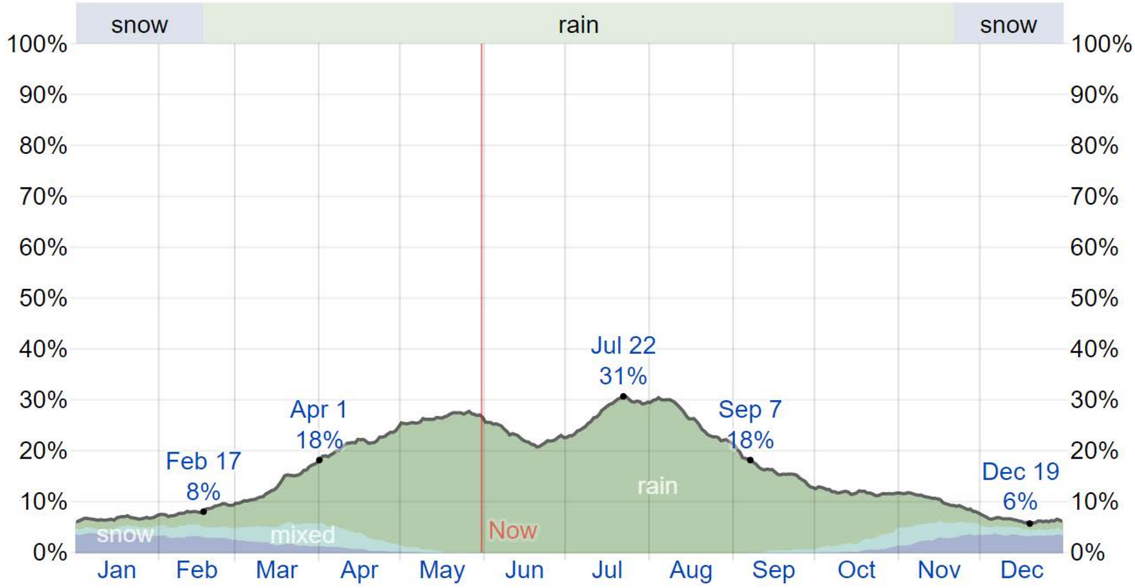


Table 4.4: Precipitation Table of Denver.

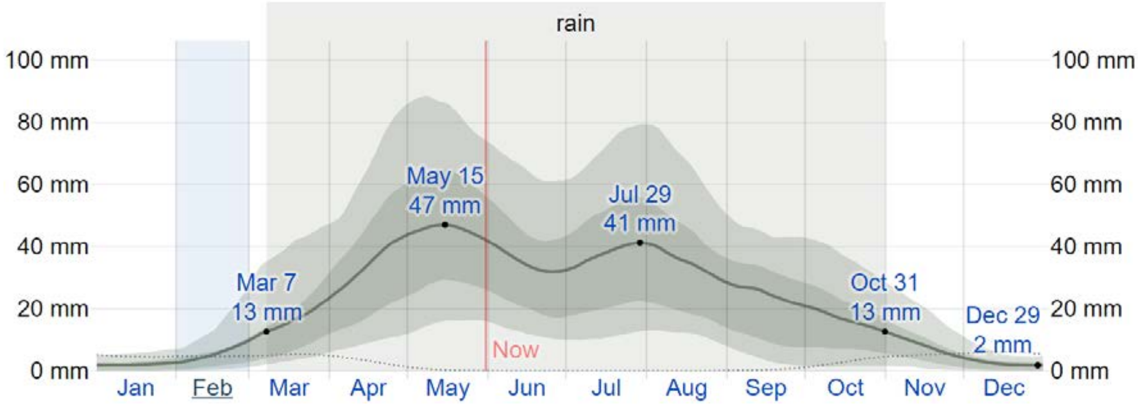
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Precipitation mm (in)	12.7 (0.5)	14.5 (0.6)	32.5 (1.3)	43.4 (1.7)	61 (2.4)	45.5 (1.8)	48.5 (1.9)	38.4 (1.5)	31.5 (1.2)	24.9 (1)	22.1 (0.9)	16.3 (0.6)	391.3 (15.4)
Precipitation Liters/m² (Gallons/ft²)	12.7 (0.31)	14.5 (0.36)	32.5 (0.8)	43.4 (1.06)	61 (1.5)	45.5 (1.12)	48.5 (1.19)	38.4 (0.94)	31.5 (0.77)	24.9 (0.61)	22.1 (0.54)	16.3 (0.4)	391.3 (6.9)
Number of Wet Days (probability of rain on a day)	5 (16%)	6 (21%)	9 (29%)	9 (30%)	11 (35%)	8 (27%)	9 (29%)	8 (26%)	5 (17%)	5 (16%)	5 (17%)	4 (13%)	84 (23%)
Percentage of Sunny (Cloudy) Daylight Hours	71 (29)	65 (35)	70 (30)	62 (38)	64 (36)	73 (27)	72 (28)	75 (25)	76 (24)	75 (25)	64 (36)	70 (30)	71 (29)

- ***Rainfall***

The rainfall data of Denver show the rainfall gathered over a sliding 31-day period centered on each day of the year to demonstrate variance between the months rather than just the monthly totals. Monthly rainfall in Denver varies according to the season (Figure 4.15). From March 7 to October 31, the rainy season lasts 7.7 months, with a typical 31-day rainfall of at least 13 millimeters. The most rain falls over the 31 days surrounding May 15, with a total amount of 47 millimeters. The rainless season lasts 4.3 months, from

October 31 to March 7. The least amount of rain falls around December 29, with a total accumulation of 2 millimeters.

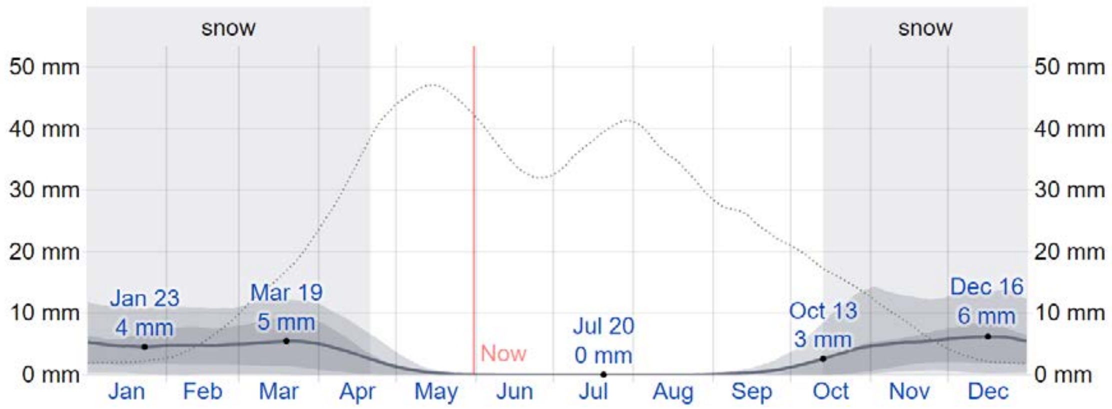
Figure 4.15: The average rainfall (solid line) in Denver gathered during a sliding 31-day period centered on the day in question, with bands ranging from the 25th to the 75th and 10th to the 90th percentiles. The typical liquid-equivalent snowfall is represented by the thin dotted line.



- ***Snowfall***

The sliding 31-day liquid-equivalent amount of snowfall in Denver does not change considerably during the year, remaining within 3 millimeters of 3 millimeters (Figure 4.16).

Figure 4.16: The average liquid-equivalent snowfall (solid line) in Denver accumulated during a sliding 31-day period centered on the day in question, with bands ranging from the 25th to the 75th and 10th to the 90th percentiles. The average rainfall is represented by the thin dotted line.



- ***Relative Humidity***

The behavior of green facades, as well as their back-wall materials, is influenced by relative humidity. High relative humidity accelerates metal corrosion and slows evaporation from wet surfaces, which also can cause warping and crack in certain materials such as timber. It also influences evaporation from the human body, which has an immediate impact on thermal sensation and comfort.

The average annual relative humidity in Denver is 36.8%, with monthly averages ranging from 31% in July to 43% in February (Table 4.5).

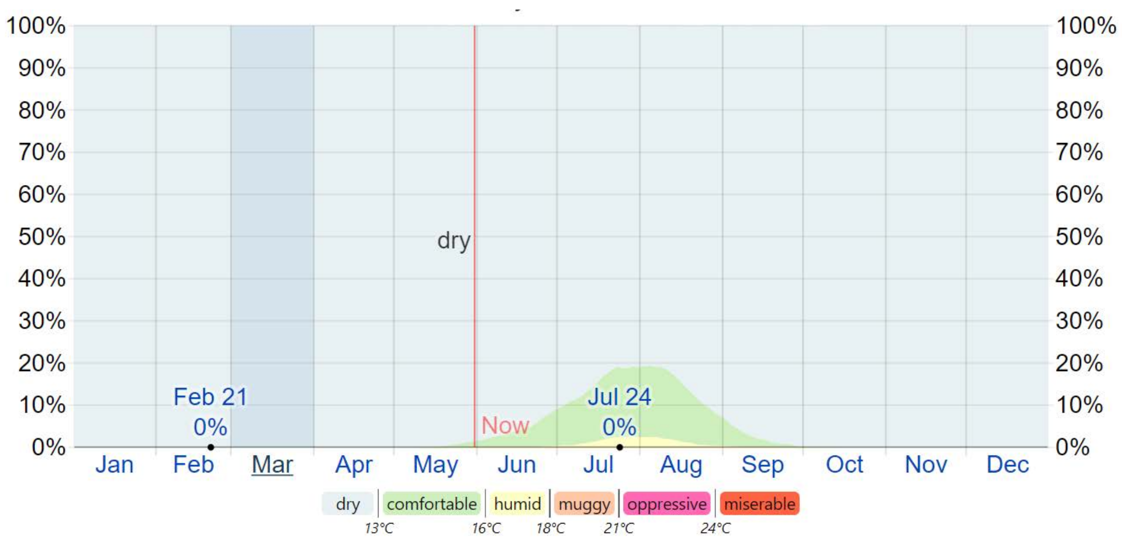
Table 4.5: Relative humidity in Denver, Colorado, USA.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Relative Humidity (%)	42	43	40	38	38	33	31	32	32	34	38	40	36.8
Average Dew Point Temperature (°C)	-11.3	-9.2	-7.5	-4	-0.1	2.7	5.1	4.5	0	-3.9	-8.1	-11.2	-3.6

The dew point determines whether perspiration evaporates from the skin and so cools the body, thus base the humidity comfort level on it. Lower dew points make you feel drier, whereas higher dew points make you feel more humid. In contrast to temperature, which often varies dramatically between night and day, dew point tends to change more slowly, so though the temperature may decrease at night, a muggy day is usually followed by a muggy night.

The perceived humidity level in Denver, as defined by the proportion of time when the humidity comfort level is muggy, oppressive, or terrible, does not change greatly throughout the year, maintaining nearly constant at 0% (Figure 4.17).

Figure 4.17: Humidity Comfort Levels in Denver during the course of a year. The percentage of time spent at various levels of humidity comfort, classified by dew point.



- ***Solar Radiation***

Radiant energy (solar radiation) is emitted by the sun in the form of electromagnetic waves, infrared radiation, ultraviolet radiation, and visible light. It influences the majority of climatic occurrences because it is the source of practically all the earth's energy [51]. This section covers the total daily incident shortwave solar radiation reaching the ground's surface over a large area, taking into consideration seasonal fluctuations in the length of the day, the Sun's height over the horizon, and absorption by clouds and other atmospheric elements. Visible light and ultraviolet radiation are examples of shortwave radiation. Over the course of the year, the average daily incident shortwave solar energy shows substantial seasonal variation.

The brighter period of the year lasts 2.8 months, from May 9 to August 3, with an average daily incident shortwave energy per square meter of more than 6.8 kWh. June 21 is the brightest day of the year, with an average of 7.9 kWh. From November 3 to February 10, the year's darkest phase lasts 3.2 months, with an average daily incident shortwave energy per square meter of less than 3.5 kWh. December 21 is the darkest day of the year, with an average of 2.4 kWh (Figure 4.18).

Figure 4.18: Denver's average daily incident shortwave solar radiation. The average daily shortwave solar radiation reaching the ground per square meter (orange line), with bands ranging from the 25th to the 75th and 10th to the 90th percentiles.

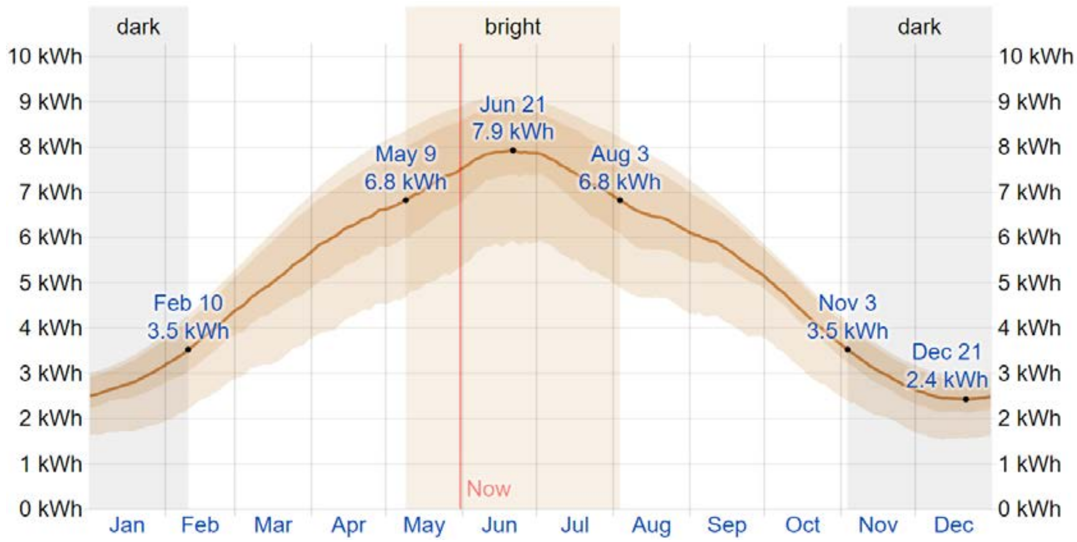


Table 4.6 presents the sunshine and daylight hours in Denver, and the data is provided below:

- According to the data, the hours of sunlight in Denver, Colorado range from 6:27 each day in November to 11:06 each day in June.

- The longest day of the year lasts 14:49 minutes while the shortest day lasts 9:10 minutes.
- The longest day lasts 5:38 more than the shortest.
- There are 3115 hours of sunlight each year on average (out of a potential 4383), with an average of 8:31 hours of sunlight every day.
- It is sunny 71.1% of the daily hours. The remaining 28.9% of daytime hours are likely to be cloudy, with shade, haze, or low sun intensity.
- In Denver, Colorado, the sun is 50.6° above the horizon on average during midday.

Table 4.6: Sunshine and daylight hours in Denver, Colorado, USA.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Sunlight Hours/ Day	06:48	07:30	08:09	08:20	09:07	11:06	10:25	10:07	09:36	08:09	06:30	06:27	08:31
Average Daylight Hours & Minutes/ Day	09:41	10:37	11:52	13:12	14:20	15:55	14:39	13:41	12:24	11:03	09:56	09:23	12:00
Sunny & (Cloudy) Daylight Hours (%)	71 (29)	72 (28)	70 (30)	64 (36)	64 (36)	75 (25)	72 (28)	75 (25)	78 (22)	75 (25)	66 (34)	70 (30)	71 (29)
Sun altitude at solar noon on the 21st day (°)	30.4	39.8	50.6	62.3	70.5	73.7	70.6	62.2	50.7	39.3	30.2	26.8	50.6

Implementing a green façade in Denver should maximize solar radiation absorption during cold seasons and minimize it during hot seasons to provide indoor thermal comfort as well as energy savings related to heating and cooling the structure. This is achieved by utilizing proper green façade typologies, choosing appropriate plants, and building orientation.

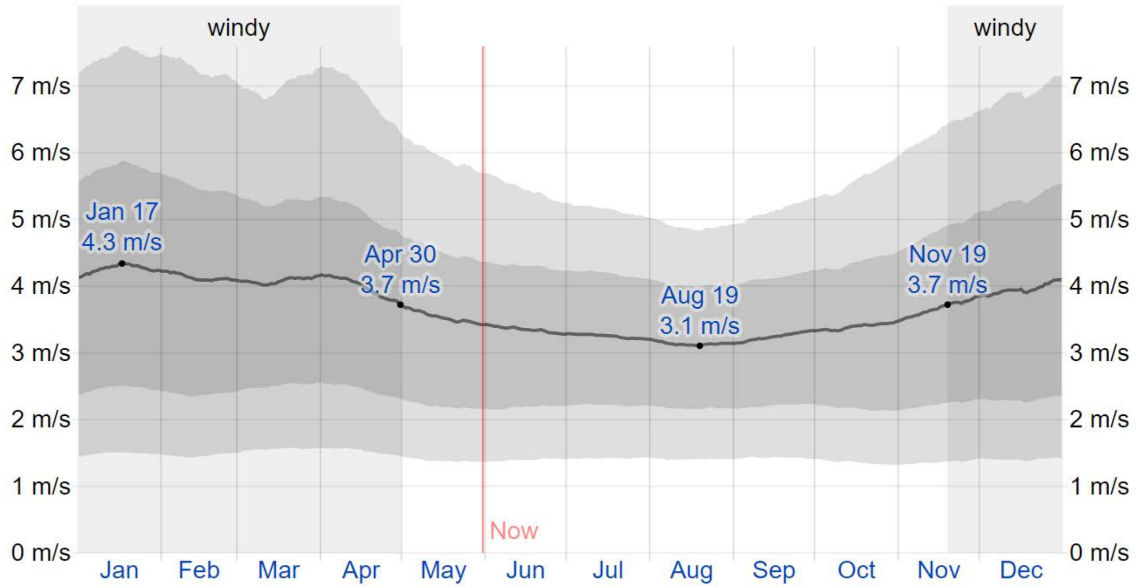
- ***Windspeed and Direction***

Wind is the movement of air masses induced by temperature gradients and pressure differences in the atmosphere. Natural air movement allows for natural ventilation, which is useful in the following ways: it maintains the quality of air in buildings beyond a specific minimum level by replacing contaminated indoor air with fresh air from outside; it cools the building's structure and encourages heat loss from the body, providing thermal comfort [52].

The hourly average wind vector (speed and direction) at 10 meters above the ground is indicated, although the wind experienced at any given site is strongly dependent on local topography and other factors, and immediate wind speed and direction vary more considerably than hourly averages.

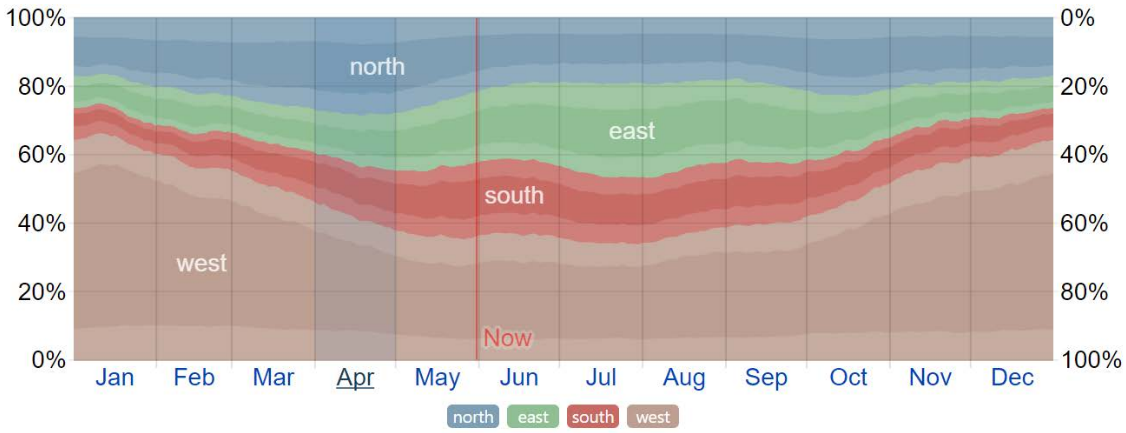
Over the course of the year, the average hourly wind speed in Denver displays modest seasonal change. From November 19 to April 30, the windier season lasts 5.4 months, with average wind speeds of over 3.7 meters per second. January 17 is the windiest day of the year, with an average hourly wind speed of 4.3 meters per second. April 30 to November 19 are the calmer season that lasts 6.6 months. August 19 is the coolest day of the year, with an average hourly wind speed of 3.1 meters per second (Figure 4.19).

Figure 4.19: Average wind speed in Denver. The average means hourly wind speeds (dark gray line), with bands ranging from the 25th to the 75th and from the 10th to the 90th percentiles.



The proportion of hours where the mean wind direction is from one of the four cardinal wind directions, omitting hours when the mean wind speed is less than 0.4 m/s. The percentage of hours spent in the implied intermediate directions is represented by the pale shaded patches at the border (northeast, southeast, southwest, and northwest) (Figure 4.20). Throughout the year, the major average hourly wind direction in Denver is west.

Figure 4.20: Wind Direction in Denver.



- ***Bioclimatic Chart***

Passive building design strategies are derived from climatic conditions since the gap between these and comfort conditions creates the need to take appropriate measures to reduce it as much as feasible without using any artificial heating or cooling systems. Passive design solutions have the ability to significantly cut energy consumption in buildings.

Givoni's bioclimatic chart (Figure 4.21) is a basic tool for understanding a specific location's climate. It compares air temperature (shown by vertical lines) to relative humidity (represented by curved lines) and can be used to communicate human thermal comfort, design methods, and energy requirements for those methods. A point on the chart can be located using these two factors. The conditions are comfortable if it is within the comfort zone. Corrective procedures are required for any point that falls outside of this zone in order to restore the sensation of ease. As a result, a bioclimatic chart can provide information on the requirements for comfort at a specific period. Design decisions can then be made in accordance with this.

This chart provides architectural solutions for adapting the architecture of a building to the prevailing environment based on six zones outlined on the chart, as seen in Figure 4.21. These zones are as follows:

1- *Comfort zone:*

This is the range in which residents are content with their surroundings. Thermal comfort is felt when the ambient temperature ranges between 20 and 26°C and the relative humidity are between 20 and 80%.

2- *Zone of natural ventilation:*

Natural ventilation can increase thermal comfort when the ambient temperature exceeds 26 °C or the relative humidity is quite high (over 50%). This increases thermal comfort up to a maximum external air temperature of 32 °C. Night cooling, on the other hand, would be preferable to day ventilation in conditions where the temperature reaches 26 °C and the relative humidity is less than 50%.

3- Zone of evaporative cooling:

When the air temperature is above 26 °C and the relative humidity is less than 20%, water vapor can be employed to prolong the thermal comfort zone of a place by lowering the air temperature and increasing the relative humidity.

4- Zone of high thermal mass:

In a building, high thermal mass can be employed to reduce variance under internal temperature compared to the outdoor temperature, as well as peaks in conditions of strong diurnal temperature fluctuation. This solution can be utilized successfully in locations where the relative humidity ranges between 10% and 50% and the air temperature ranges between 26 and 35 °C.

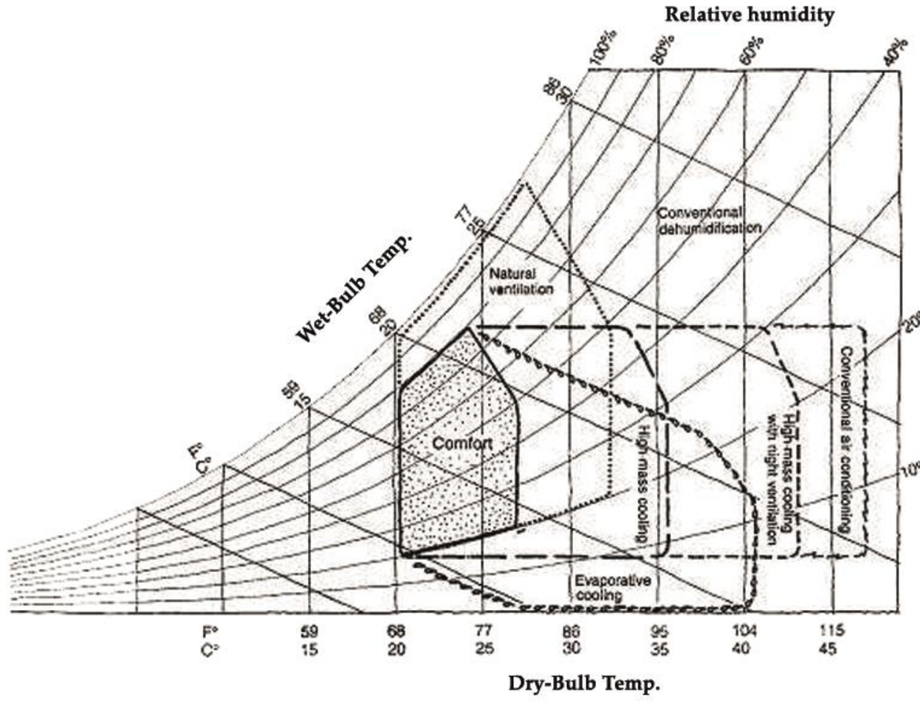
5- Zone of passive heating:

Passive solar heating is appropriate for extending the thermal comfort zone where the air temperature is less than 20 °C. Insulation is one of the other options.

6- Zone of high thermal mass and night ventilation:

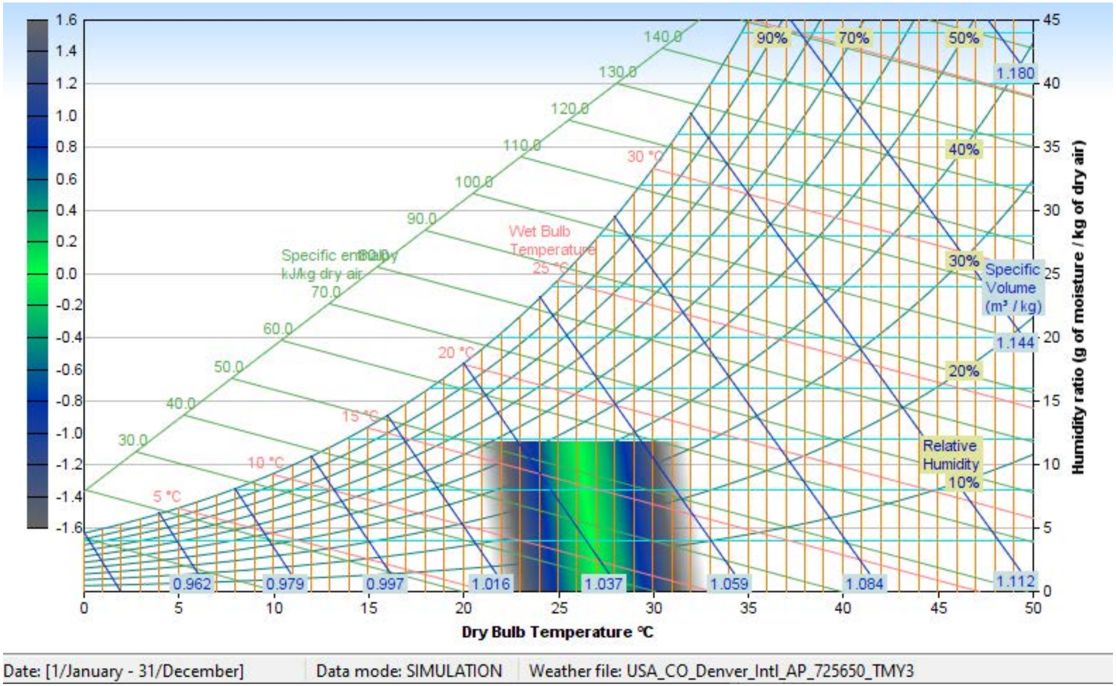
Thermal mass combined with night ventilation can be employed to provide cooling when the diurnal temperature swing is large and the nighttime temperature falls below 20 °C.

Figure 4.21: Givoni's bioclimatic chart showing recommended design strategies based on hourly data points for dry bulb temperature and relative humidity.



In the case of Denver (Figure 4.22), the psychrometric chart created using the meteorological data file obtained from the IESVE software demonstrates that the majority of the hourly points of outside dry bulb temperature and relative humidity are inside the comfort zone.

Figure 4.22: Psychrometric chart of Denver. Temperature and humidity comfort regions displayed by Comfort ASHRAE 55.



However, as seen in Figure 4.22, a significant fraction falls below the comfort zone, implying the necessity for space heating to achieve indoor thermal comfort. Passive heating via thermal mass is advised. Throughout the day, the heat stored in the building fabric is released to the indoor space during the night/when inside temperatures fall below outdoor levels. Direct solar heat gain can also be used for passive heating (especially during the cold period). Additionally, internal heat gains from occupants, lights, and equipment aid in extending thermal comfort and lowering heating demand.

Outdoor dry bulb temperatures and relative humidity might rise above the comfort level at times of the year. Daytime ventilation is not acceptable in these settings since it would warm up the building. The best technique is to minimize ventilation during the day to minimize the flow of hot air flowing in and to use nighttime ventilation to cool the indoor space by utilizing colder air.

Passive cooling can also be achieved by combining high thermal mass with night ventilation. During the night, outside air is pumped through the structure, cooling the cloth. The cooling stored in the building fabric is thus accessible the next day to counter heat increases and bring temperatures closer to comfortable levels. Thermal mass and nocturnal ventilation can be employed to reduce or eliminate the need for mechanical cooling.

4.5.3. Vertical Garden performance in Denver

Greater urban density is being widely regarded as a requirement for more sustainable lifestyle patterns that minimize energy use and thereby prevent climate change. The concentration of people in denser cities - sharing space, infrastructure, and facilities - provides considerably more energy-efficient than the expanding horizontal metropolis, which requires more land and more energy investment in infrastructure and mobility. Nevertheless, the full repercussions of this push for more density, particularly vertical density, are unknown, and cities all over the world are dealing with how to move towards larger heights and densities.

There are design ideas and technology available that can significantly lower office building energy usage in a considerably more significant way than implementing plants to a building's skin. The secret to green walls, however, is that they can provide major benefits to both the building and the surrounding urban environment at the same time. Many of these advantages are already well known and have been used in vernacular buildings in some geographic areas for literally centuries.

On a smaller scale, these green wall benefits include lowering building operating energy for heating/cooling by either insulting or shading the façade, increasing occupant satisfaction and even productivity by connecting the resident directly to elements of nature, filtering pollution for improved internal air quality, potentially providing agriculture, and reducing urban noise pollution, and the increasing value of the building. On an urban scale, the benefits include reduced urban heat island effect, improved urban air quality, carbon sequestration from the atmosphere, noise absorption, visual improvement, and enhanced biodiversity.

Green walls require increased resources (mainly water and energy), and there are concerns about the ability of the plants to withstand larger environmental pressures at height (mainly wind, particularly vortex shedding) as well as varied climates such as semi-arid climes.

The local climate conditions of Denver are among the most important variables influencing green wall design choices. The viability of green wall types and plant species is affected by air temperature, relative humidity, wind speed, solar radiation, cloud cover, and monthly precipitation. Although the majority of green wall installations are in year-round warm climates, past empirical studies on green walls [53] that include more than

18 case studies reveal conclusively that warm, tropical climates are not the only locations that can support external green walls. Green walls can thrive in a variety of climates if the right plants, façade orientation [54], and irrigation technique are used.

Colorado is divided into five distinct regions that reflect various growing conditions and life zones. The plains/prairie, southeastern Colorado, the Front Range/foothills, mountains above 7,500 feet, and the lower elevation Western Slope are all included. Denver is located in Colorado's plains/prairie region.

As previously stated, Denver has a semi-arid climate (Köppen climatic classification BSk) with very low humidity and approximately 3,100 hours of sunlight per year. In these climate conditions, plants native to the project must be chosen for use as green walls since they are naturally tolerant of local weather conditions and are more resistant to local pests and diseases.

The use of adapted non-native plants does not preclude the use of native plants. Many non-native plants are adapted to Colorado's climate and can be used in a native landscape as long as their moisture, light, and soil requirements are similar. Even though a site has a non-native landscape that requires additional inputs (such as an irrigated plain landscape), dry-land native plants could be used in non-irrigated pockets within the non-native landscape. These native "pocket gardens" can be found in places like median strips and next to hardscapes that are difficult to irrigate. It should be noted that in years with less than average rainfall, non-irrigated landscapes may suffer in appearance if not supplemented with water [55].

- *Data gathering*

In terms of size, location, façade design components, and building services systems, the commercial building stock in Denver is diverse, and some of them have a "green rating." The decision to employ a case study methodology in Denver, Colorado originated from the need to investigate how is the performance of green façade in office buildings in a semi-arid context. These performances could be measured in terms of energy usage, thermal comfort, as well as psychological and aesthetically.

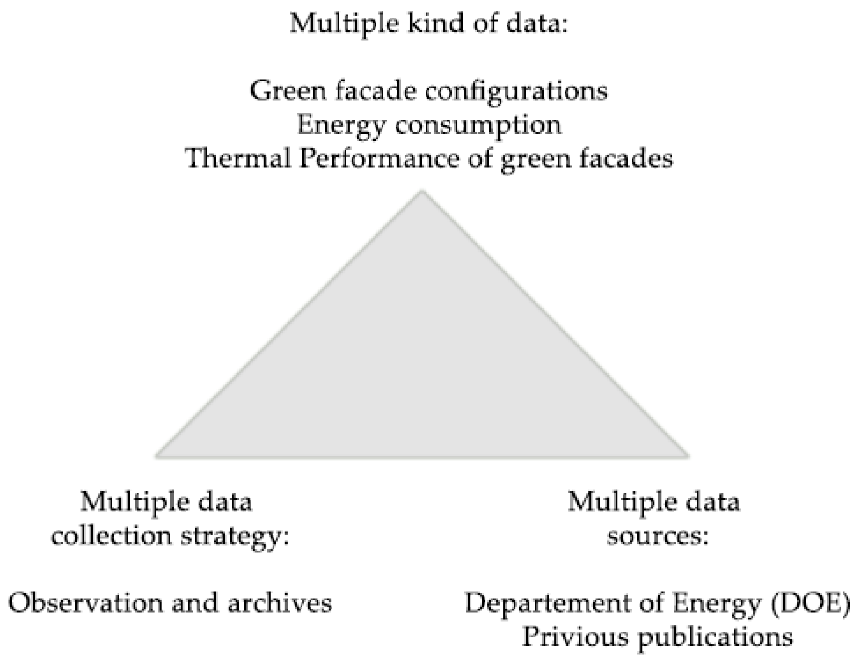
This section's goal is to understand the existing façade configurations of Denver office buildings and reduce variables characterizing the existing green façade configurations and then induce these variables into the construction of a conceptual base case façade to be used as a measurement unit.

1- *Data gathering with Triangulated approach*

The utilization of numerous data sources with comparable focuses to gain varied views through a range of data on the issue is known as triangulation in data collection.

According to researchers that promote the concept of triangulation, "no single approach ever adequately answers the dilemma of rival casual elements... because each technique shows different parts of empirical reality" [58]. Within the analysis, data triangulation is performed to give confirmation and accuracy. It is not simply the combining of many types of data, but the attempt to connect them in order to reduce the hazards to validity in each data collection method. Using triangulation is an attempt to capture a more comprehensive, integrative, and contextual representation of changes in office building behavior by implementing a green façade as a phenomenon. The data triangulation approach used for the analysis is depicted in Figure 4.23.

Figure 4.23: Data triangulation.



Data triangulation is utilized in this context to understand the prevailing constructs of green facades in their real-world environment. This concept seeks to identify components relevant to the formation of plant layers as a green façade, so establishing boundaries on which to base rules for selecting a representational building façade.

Prior to the analysis, multiple information sources on office building numbers and locations were identified (Figure 4.23), including the Department of Energy (DOE), and previous publications. Three strategies for improving information gathered were suggested: direct observations utilizing pictures of office building façades, employing Google Earth Pro for the site analyzing, and emailing building management to demonstrate any modifications that may have occurred in the building's façade.

The building technologies program of the U.S. Department of Energy (DOE) has set strong goals for improving building energy efficiency. This goal will necessitate coordination between DOE laboratories and the building industry. DOE produced 16 reference building types that represent the majority of commercial buildings (Table 4.7) across 16 locations according to ASHRAE climate zone (Table 4.8) that represent all climate zones in the United States [59]. In this classification, Office buildings are under the category of commercial activities which are divided into three groups of large, medium, and small office spaces. By using the data on DOE standard reference buildings, this research attempted to understand green façade performance in office buildings in semi-arid regions.

Table 4.7: Commercial buildings classification according to DOE standard.

Building Type Name	Floor Area (Ft^2)	Number of Floors
Large Office	498,588	12
Medium Office	53,628	3
Small Office	5,500	1
Warehouse	52,045	1
Stand-alone Retail	24,962	1
Strip Mall	22,500	1
Primary School	73,960	1
Secondary School	210,887	2
Supermarket	45,000	1
Quick Service Restaurant	2,500	1
Full Service Restaurant	5,500	1
Hospital	241,351	5
Outpatient Health Care	40,946	3
Small Hotel	43,200	4
Large Hotel	122,120	6
Midrise Apartment	33,740	4

Denver is classified as a dry location with "a wide range of temperature and a low moisture content in the air" by the ASHRAE Climate Zone 5B (table 4.8).

Table 4.8: The 16 climate zones (ASHRAE Climate Zone) used to create the reference buildings.

Climate Zone	Representative City
1A	Miami, Florida
2A	Houston, Texas

2B	Phoenix, Arizona
3A	Atlanta, Georgia
3B-Coast	Los Angeles, California
3B	Las Vegas, Nevada
3C	San Francisco, California
4A	Baltimore, Maryland
4B	Albuquerque, New Mexico
4C	Seattle, Washington
5A	Chicago, Illinois
5B	Denver, Colorado
6A	Minneapolis, Minnesota
6B	Helena, Montana
7	Duluth, Minnesota
8	Fairbanks, Alaska

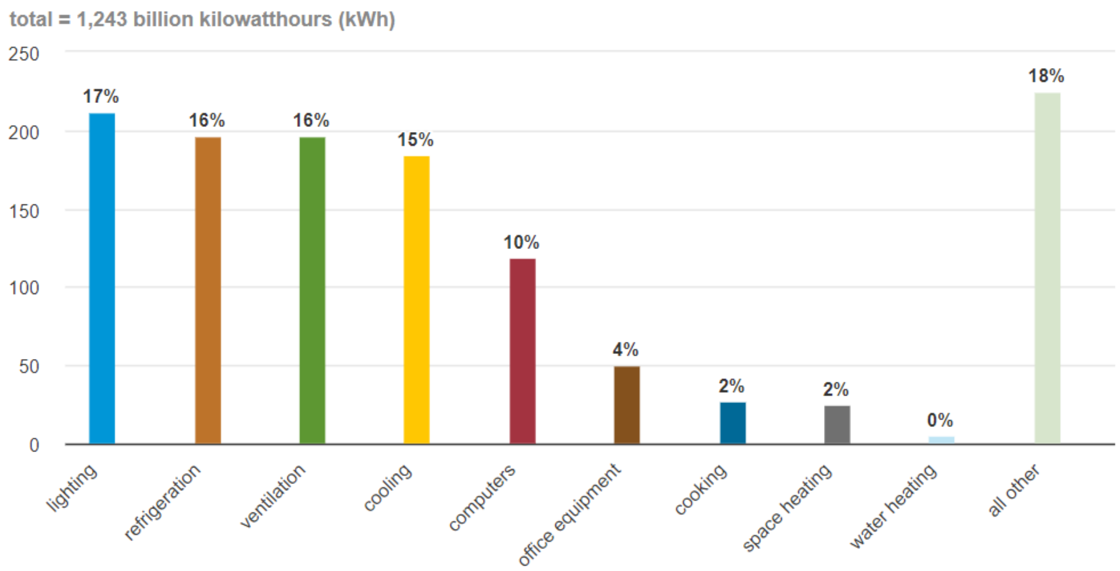
Earlier publications have been evaluated in Denver and the entire U.S. for inspection of office buildings stock [60][61]. This research aggregated the buildings, analyzed, and supplied the foundation for a list of buildings to be included in this thesis in the sample frame.

Researchers calculated the heating and cooling loads in existing commercial buildings, as well as the efficiency of the equipment employed to meet those loads [62]. They employed 120 model buildings representing 12 different styles of old and new construction. In 2005, researchers proposed a common set of assumptions for commercial building energy evaluations [63]. They classify buildings into seven categories: large office, small office, retail, education, apartment, small hotel, and hospital. These are designed to resemble typical commercial buildings; nevertheless, the types chosen have little justification. The energy-related characteristics are in accordance with ASHRAE Standards 90.1-2001 (ASHRAE 2001 [64]) and 62.1-1999. (ASHRAE 1999 [65]). These models could be used to assess the energy performance of the seven different building types in any climate.

Electricity and natural gas, which are the most prevalent energy sources, are also prevalent types of energy utilized in commercial buildings. Figure 4.24 illustrates the use of electricity in U.S. commercial buildings. Most of the commercial buildings have their own systems for heating and cooling. However, district energy systems provide heating and cooling to groups of commercial buildings. District energy systems may generate electricity in addition to heating and cooling energy. Likewise, district energy systems are often powered by fossil fuels (coal, natural gas, or fuel oil), although some are powered by renewable energy sources (biomass, geothermal, solar, and wind energy).

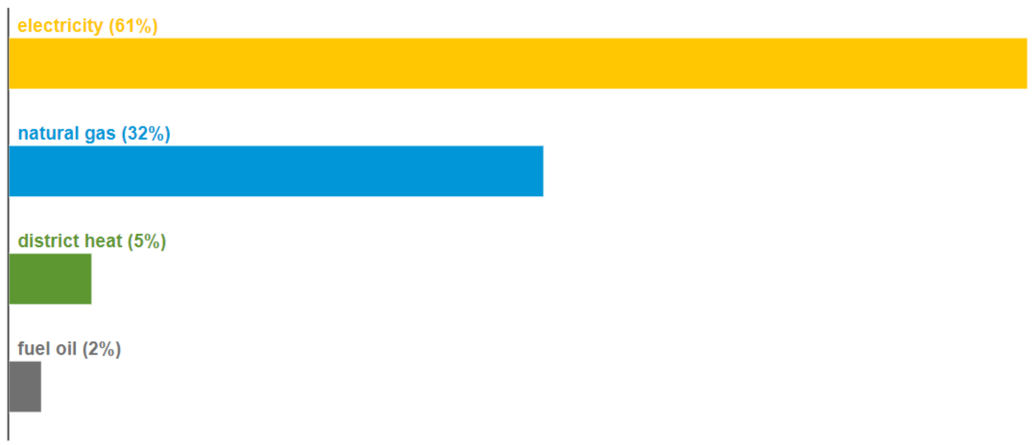
Figure 4.25 shows that electricity and natural gas respectively are major energy used in commercial buildings.

Figure 4.24: Electricity use in U.S. commercial buildings by major end uses, 2012. *U.S. Energy Information Administration, 2012 Commercial Building Energy Consumption Survey, Consumption and Expenditures, Table E5, May 2016.*



Note: All other includes motors, pumps, air compressors, process equipment, backup electricity generation, and miscellaneous appliances and plug-loads.

Figure 4.25: Share of major energy sources used in commercial building, 2012. *U.S. Energy Information Administration, 2012 Commercial Building Energy Consumption Survey: Energy Usage Summary, Table 1, May 2016.*



The reference buildings demonstrate about 70% of the commercial buildings that have realistic HVAC operation schedules and building envelope/fenestration conditions. About half the energy utilized by all commercial buildings in 2012 was used in the top five energy-consuming building categories and included the following types of buildings [66]:

1- Mercantile and service (15% of total energy consumed by commercial buildings)
2- Office (14% of consumption)
3- Education (10% of consumption)
4- Health care (8% of consumption)
5- Lodging (6% of consumption)

Among the five most energy-consuming buildings, one reference building type was chosen to research the performance of green façades as a layer of vegetation, which is a large office between three types of offices.

- ***Case study selecting***

To select samples, office buildings have been chosen that included glazed facades. These buildings are in the "large office" group of DOE standard reference buildings. Due to data collection constraints, all office buildings found confirming the thesis definition were combined as a sample frame. Triangulation of data from several sources, including prior publications, photos, and knowledge of the environment, resulted in a random yet diversified selection of an existing office building.

Among all office buildings in Denver, the Triangle office building has been selected because of the different shape of the building with other office buildings and also having 45 degrees angles. The reason is that in previous research, green facade performance in an office building in Barcelona with a Mediterranean climate which was a high-rise office building with unique design as well as having 45 degrees angles had been analyzed and results of that will be compared with the result of this case study which is in a semi-arid climate, at the end of this chapter.

- ***Morphology of the Base Case***

Two primary approaches are used in the literature to build a base case morphology. The definition of a base case is divided into two parts by the two methodologies: existent basis case and conceptual basis case.

The first methodology is based on simulating alternative measures to improve a building's thermal comfort performance and reducing energy consumption by applying a green facade. The existing entity of the building is used as a model base case in this methodology.

The Triangle Building office space is an existing base case which built-in 2015. This ten-story with 140 ft (43 m) tall and 227,631 square foot (21,150 m^2) mesmerizing building was constructed with LEED design elements and high-end energy efficient materials to maximize comfort and minimize waste in lower downtown Denver (LoDo), Colorado, USA (Figure 4.26, 4.27, 4.28). The whole façade of the building is made of glass.

Figure 4.26: The Triangle Building office space, Denver, Colorado.

Figure 4.27: The Triangle Building office space site plan.

Figure 4.28: The southern view of Triangle Building office space.

The second methodology is to create a conceptual basis case. A prototype building in this context is defined as a synthetic building constructed from statistical data of building analysis and/or results from previous research. A conceptual base case, according to its definition, is a hypothetical structure with size, shell construction, window area, HVAC systems, operating and occupied schedules based on the mean or prevalent circumstances across surveyed building samples [62]. To investigate green facade configurations, the morphology is optimized and controlled as a simulation variable. The conceptual basis case is used to investigate green facades performance for enhancing building energy performance and many other beneficial, with the results extended and extrapolated to a broader built environment in a specific climatic context [67]–[69]. Hypothetical building models are often used to test emerging technologies or building fabric options that would have been costly to create and time-consuming to test otherwise [70]. This methodology is utilized to build the conceptual basis case that will be used as the initial and main step throughout the simulation method in this dissertation.

The level of model conceptualization, estimates place of floor plate, conditioned to non-conditioned space connected directly to the green facade, and number of floors with considering standard of DOE for large office building in the model are all considered while constructing the three-dimensional characteristics of a basis case morphology.

Table 4.9 gives a quick summary of the prototype chosen. The ASHRAE Standard 90.1-2010 Energy and Cost Saving Analysis gives additional details. Figure 4.29 illustrated the morphology of conceptual basis case in this part. Appendix A contains the selected prototype profiles printed on the ASHRAE standard 90.1-2010 Energy and Cost Saving Analysis. Included in this profile were the ASHRAE Standard 90.1-2010 Goal energy and cost saving analysis.

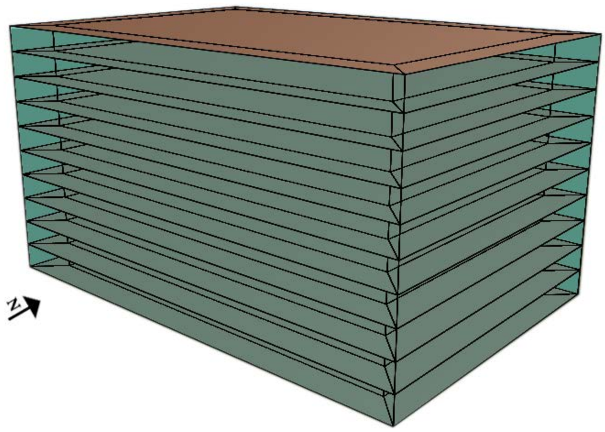
Table 4.9: Overview of the selected prototype.

Building Prototype		Large Office
Floor area (ft^2)		498,640
Number of Floors		12
Window to Wall Ratio (WWR)		40%
Floor-to-Floor Height (ft)		13
Roof		Insulation above deck
Exterior Wall		Mass
Occupancy (people/W/ft^2)		5.0
Plug Loads (W/ft^2)		0.73
Interior Lighting	2007 (W/ft^2)	1.00
	2010 (W/ft^2)	0.93

Exterior Lighting	2007 (kW)	60.2
	2010 (kW)	53.7

Note: These buildings also include a basement which is not included in the number of floors.

Figure 4.29: The conceptual case study.



- ***Construction profiles and Façades***

According to the U.S. Department of energy (DOE) commercial reference building model and the national stock, for each building type has three variants of the reference building models:

1- New construction: The new construction models meet the basic standards of ANSI/ASHRAE/IESNA Standard 90.1-2004. (ASHRAE 2004a).
2- Post-1980 construction: Models produced after 1980 fulfil the basic standards of Standard 90.1-1989. (ASHRAE 1989).
3- Pre-1980 construction: The pre-1980 versions are built in accordance with a set of specifications derived from prior standards and other construction practice studies.

All have the same building shape and size, as well as the same operating schedules. Insulation values, illumination levels, and HVAC equipment varieties and efficiency all reflected the differences. Figure 4.30 depicts the relationship between context-specific influences and the evolution of office building facades. This information aided in the preparation of a stratified sample based on the age category of the office buildings, as well as providing insights into its evolution in an actual context.

Figure 4.30: Evaluation in façade design in new construction, post-1980 construction, and pre-1980 construction, a) Daniels & Fisher Tower Office Building, 1910; b) AT&T Office Building, 1929; c) 621 17th Street Office Building, 1957; d) The 410 Office Building, 1977; e) 555 Office Building, 1978; f) Regus North Tower Office Building, 1981; g) 1801 California Office Building, 1983; h) Wells Fargo Office Building, 1983; i) Republic Plaza Office Building, 1984; j) Stanford Place III Office Building, 1986; k) Wellington E. Webb

Municipal Office Building, 2002; l) The Triangle Office Building, 2015; n) 1144 15th street Office Building, 2017; m) 50 FIFTY DTC Office Building, 2018.

a) Daniels & Fisher Tower Office Building
Building Reference: Pre-1980 Construction
Year Built: 1910 – Renovated in 2006
Building Height: 20 Stories
Façade Materials: Brickwork, Metalwork, Terracotta tiles, Glass

b) AT&T Office Building
Building Reference: Pre-1980 Construction
Year Built: 1929
Building Height: 24 Stories
Façade Materials: Terracotta tiles, Granite, Steel, Glass

c) 621 17th Street Office Building
Building Reference: Pre-1980 Construction
Year Built: 1957
Building Height: 28 Stories
Façade Materials: Stone, Glass

d) The 410 Office Building
Building Reference: Pre-1980 Construction
Year Built: 1977
Building Height: 24 Stories
Façade Materials: Stone, Glass

e) 555 Office Building
Building Reference: Pre-1980 Construction
Year Built: 1978
Building Height: 40 Stories
Façade Materials: Glass

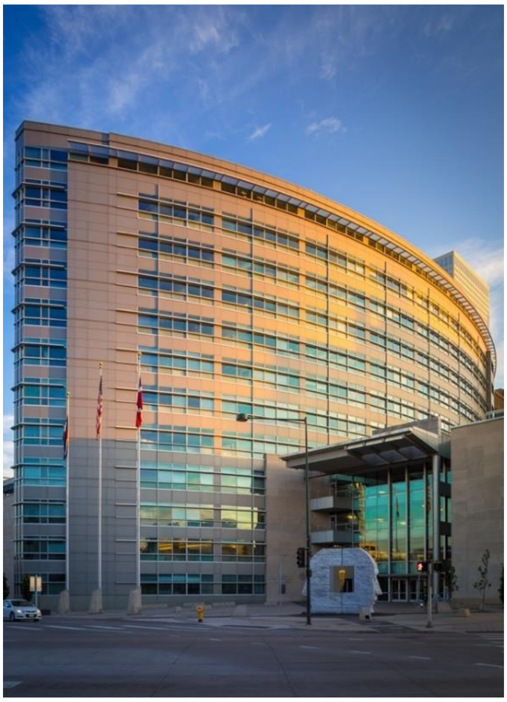
f) Regus North Tower Office Building
Building Reference: Post-1980 Construction
Year Built: 1981
Building Height: 23 Stories
Façade Materials: Glass, Stone

g) 1801 California Office Building
Building Reference: Post-1980 Construction
Year Built: 1983
Building Height: 53 Stories
Façade Materials: Brown precast concrete, Curtain walling

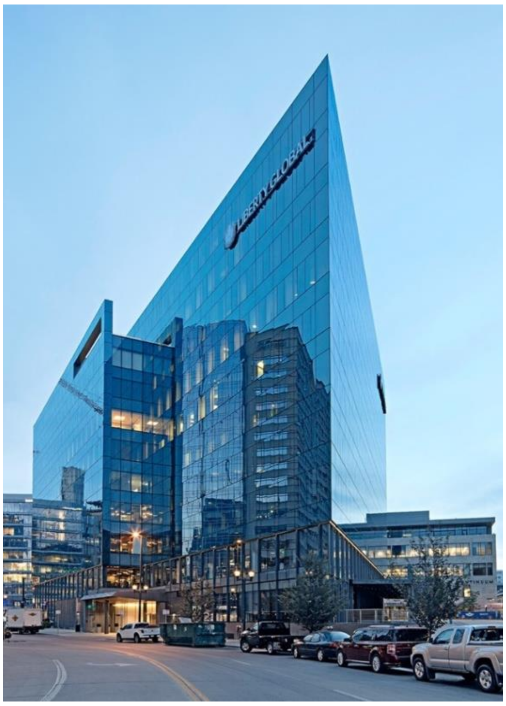
h) Wells Fargo Office Building
Building Reference: Post-1980 Construction
Year Built: 1983
Building Height: 52 Stories
Façade Materials: Red granite, Glass façade

i) Republic Plaza Office Building
Building Reference: Post-1980 Construction
Year Built: 1984 – Renovated in 2016
Building Height: 56 Stories
Façade Materials: Sardinian granite, Windows are flush-mounted with the aluminum grid

j) Stanford Place III Office Building
Building Reference: Post-1980 Construction
Year Built: 1986 – Renovated in 2017
Building Height: 17 Stories
Façade Materials: Brick, Glass

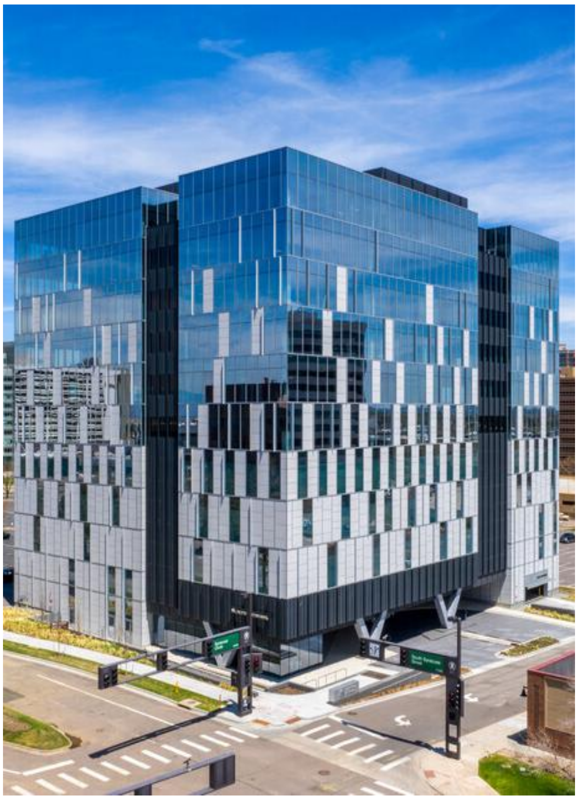


k) Wellington E. Municipal Office Building
Building Reference: New Construction
Year Built: 2002
Building Height: 12 Stories
Façade Materials: Glass, Stone



l) The Triangle Office Building
Building Reference: New Construction
Year Built: 2015
Building Height: 10 Stories
Façade Materials: Glass Walls

m) 1144 15th street Office Building
Building Reference: New Construction
Year Built: 2017
Building Height: 40 Stories
Façade Materials: Curtain Wall



n) 50 FIFTY DTC Office Building
Building Reference: New Construction
Year Built: 2018
Building Height: 12 Stories
Façade Materials: Curtain Wall, Sierra White Granite

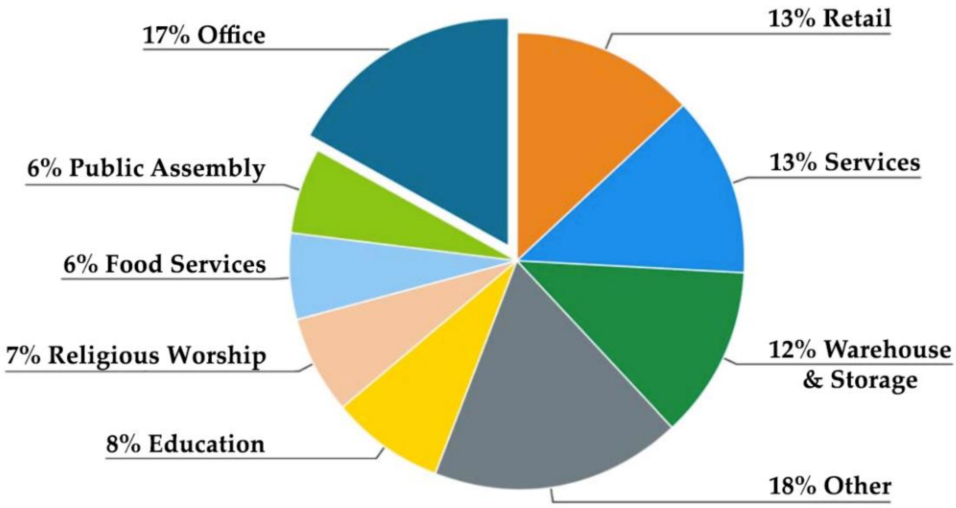
Moreover, Figure 4.30 depicts an increase in Window to Wall Ratio (WWR), which is between 20-40% in pre-1980 construction office buildings and growing to 40-60% in post-1980 construction office buildings, with WWR averaging between 90-100% in new construction office buildings.

In the absence of previous research to classify the office building stock from the perspective of green façade performance, an explanation building method was used in conjunction with a time analysis method (division of buildings based on construction year) to understand the evolution and prevalent use of building materials, construction methods, and wall configurations for facades. The purpose of this evaluation is that finding suitable office building configurations to analysis green facade performance in Denver as a context of this research.

- ***Energy Consumption in Office Buildings***

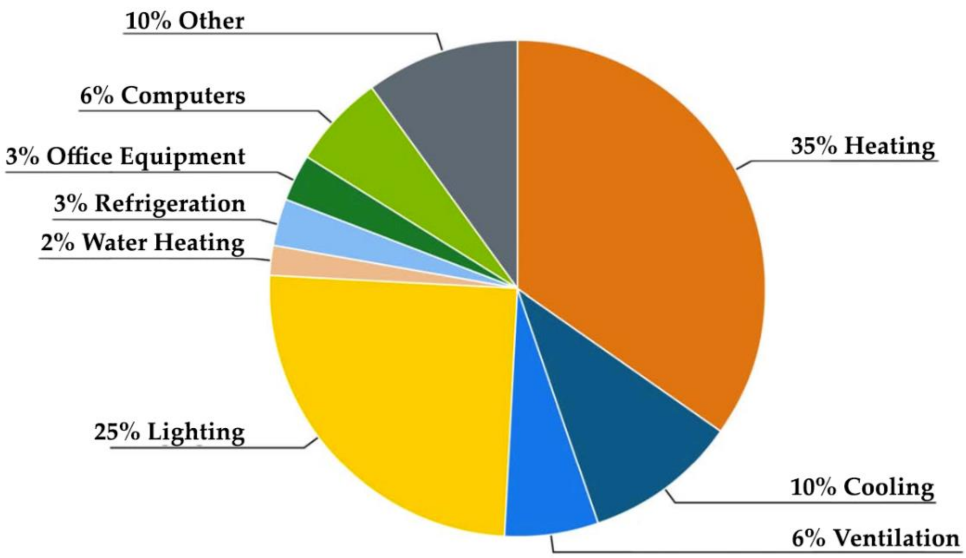
This section addresses the energy consumption of office buildings, which account for approximately 17% of all commercial building energy use in the United States (Figure 4.31). Office buildings consume the most energy of any building type in U.S. [71]. Furthermore, with over 60% of current office buildings constructed before 1980 (pre-1980 construction), many are overdue for updates to old building equipment, systems, and assemblies.

Figure 4.31: Distribution of Commercial Building Energy Use. (U.S. Energy Information Administration, 2018)



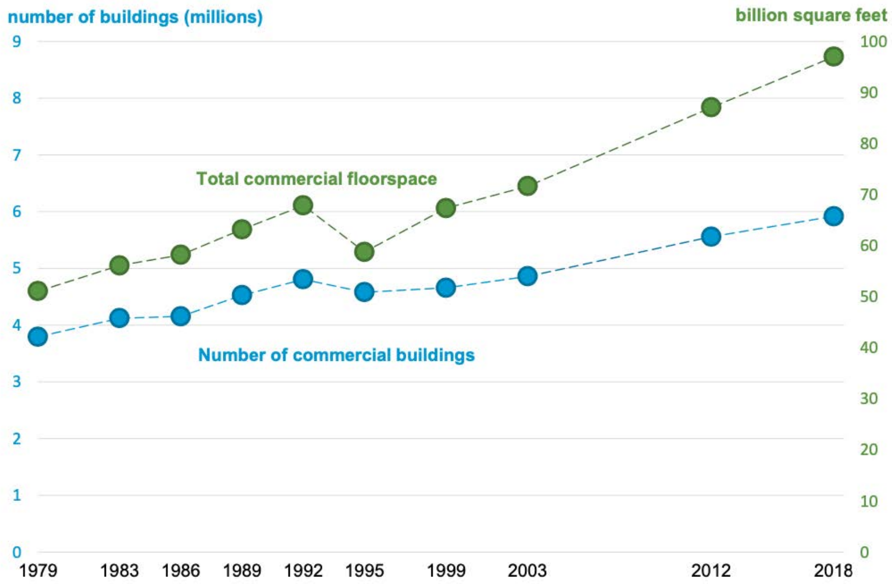
Before entering into how green facades could increase energy efficiency, it's important to know how energy consumption is distributed among building systems in a regular office building. Figure 4.32 shows the percentage breakdown of energy usage by end-use for office buildings in the U.S. As seen in this Figure, end-uses related to the HVAC system (heating, cooling, and ventilation) account for 51% of total energy use, while lighting accounts for 25% [71]. Because these two end-uses often account for three-quarters of an office building's energy consumption, it's usually recommended to prioritize energy retrofits linked to these end-uses first.

Figure 4.32: Percent Energy Use by Building System. (U.S. Energy Information Administration, 2018)



According to the commercial buildings energy consumption survey (CBECS), the total number of buildings grew by 6% between 2012 and 2018, while total floor space rose by 11%. Between the initial CBECS in 1979 and the 2018 CBECS, the number of buildings expanded from 3.8 million to 5.9 million (55%), and commercial floor space expanded from 51 billion square feet to 97 billion square feet (90%). (Figure 4.33)

Figure 4.33: Number of commercial building and floor space. (U.S. Energy Information Administration, 2018)



Note: Number of building (millions) and billion square feet.

A building's size, vintage, geographic region, and primary activity are among the important characteristics that determine its energy consumption. According to CBECS, the demand for energy has increased as the floor space of commercial buildings has expanded throughout the years.

4.5.4. Tested Variables (Dependent and Independent Variables)

Variables were identified as an empirical concept by the researchers, and this relationship was presented as follows: “A set of concepts is used to communicate research challenges. Concepts are expressions for empirical phenomena. Concepts are turned into variables in order to progress from the conceptual to the empirical level. Our concepts will eventually appear as variables in hypothesis to be evaluated.” [72]

The description of the case study model is based on three aspects that are hard to characterize. These aspects are as follows:

i) The physical attributes (such as window to wall ratios, façade layers such as green façade, and shading systems, number of floors, and plan area). These physical properties are static, observable, and generally simple to record.

ii) Building occupation patterns are difficult to characterize since they are dependent on the actual area assigned to residents, their habits of occupying the space, their requirement for electrical lighting, and zoning within a building.

iii) The heating, ventilation, and air conditioning (HVAC) systems are the most difficult to define since they are the technology of indoor and vehicular environmental comfort, and their objective is to offer thermal comfort and appropriate indoor air quality. Although the fundamental system configuration types for the sample buildings were analysed, actual electricity use is difficult to calculate because these systems are affected by their control, operation, efficiency, and maintenance. It is nearly impossible to establish a correlation between the use of air-conditioning equipment in inhabited and vacant places. As a result, engineering judgment is required to evaluate these variables for prototypal construction.

This part describes the test variables, which are classified as dependent and independent variables. Changes in energy consumption will be measured using the dependent variables. The building facade such as green façade and bare façade is the independent variable, with changes to existing façade configurations on bare or green façade considered.

4.5.4.1. Dependent Variables

The operating profile of the building and the climate profile are the dependent variables regulated for simulation. The operating profile within the simulations is based on optimal design guide suggestions. The weather varies depending on where you are. In the literature, there is a strong emphasis on relating climate characteristics to power use at regional scales. The findings of these investigations demonstrate that different types of electricity use are sensitive to local weather. Because of the distinctive feature of this variable, the simulation's results are only generalizable to identical meteorological conditions [73].

1- Operational profile

Operational Profiles provide quantitively information about how the simulation tool will be utilized, allowing for the identification of software components that are more vulnerable to dependability based on their profile utilization. As the primary interest in this research is the room dynamics, the specification of the green façade as a vertical greenery system is idealized and simply conceptual. In this situation, cooling and heating are supplied and removed entirely from the air within a building inside borders. The 'optimal' green façade performance is defined as the ability to adjust the indoor temperature without the need of system inertia or time-dependent characteristics (such as delays in startup, or time needed by the system to provide the control system).

Operational profile in this research is included thermal comfort, occupancy, and lighting and office equipment which these identified as follows:

i) ***Thermal Comfort:*** The primary goal of using air-conditioning systems in buildings is thermal comfort. The third chapter explored difficulties underlying the range of thermal comfort temperatures that are controlled within the workplace environment to give thermal comfort to occupants, with the goal of increasing productivity. These variables were determined using accepted criteria [74].
   - In workplaces, the minimum outdoor air demand for sedentary occupants is 8 liters/s per person [75].
   - In the summer, the resultant indoor air temperature (operative temperature) in office buildings should be between 22 and 24°C (± 1.5) [76][77].
   - Relative humidity levels in office buildings are typically between 40 and 60 percent. This protects against excessively low or extremely high air moisture content [78].
   - Infiltration is computed at 0.5 ac/hr., with recent air tightness values achieving 0.25 ac/hr. The larger value utilized in simulations due to the age of office goods and previous experience with workmanship standards [79][80].

ii) Occupancy: Information on office space occupancy is included in CBECS. Based on the number of workers on the main shift from the 1999 CBECS [81], office building occupancy ranged from 334 ft2/person to 300,000 ft2/person (31 m2/person to 27,871 m2/person), with a mean of more than 25,000 ft2/person (2,323 m2/person). Table 4.10 shows the occupancy rates of office buildings by space type, either as the total number of occupants per space or as occupant density. In Appendix B, large office buildings model's occupancy is listed per zone.

Table 4.10: Occupancy by space type.

Space Type	Occupancy per Space	Occupancy		Data Source
		Ft^2 / person	M^2 / person	
Lobby (office building)	-	100	9.3	ASHRAE 2004 [82]
Office	-	200	18.6	ASHRAE 2004 [82]
Office (apartment)	2.0	-	-	Gowri et al. 2007 [83]
Office (school)	-	215	20	Pless et al. 2007 [84]
Office (warehouse)	5.0	-	-	Liu et al. 2007 [85]

Following a recommendation by the ASHRAE 90.1 Simulation Working Group, the occupancy rates for the reference building models were derived from the advanced energy design guides (AEDG) studies for the appropriate building types and from the default occupancy rates in standard 62.1-2004 [82][86][87].

Traditional American business hours are 9:00 a.m. to 5:00 p.m., Monday through Friday, for a workweek of five eight-hour days totaling 40 hours. These are the origins of the phrase "9-to-5," which refers to a routine and possibly unpleasant employment [88]. In the late nineteenth century, the average work week in the United States was believed to be more than 60 hours a week [89]. Nowadays, the average number of hours worked in the U.S. is roughly 33 [90], with the average man working full-time for 8.4 hours per day and the average woman working full time for 7.9 hours per day [91]. The universal occupancy pattern from 9 a.m. to 5 p.m. is assumed in this research. The occupancy reasonable gains are 90 W/person, with one person occupying 18.6 m^2.

iii) lighting and Office equipment: According to DOE, each building type has three versions of the reference building models: new construction, post-1980 construction, and pre-1980 construction. All have the same building shape and size, as well as the same operating schedules and the insulation values, lighting levels, and HVAC equipment kinds and efficiency all varied [59].

Interior and exterior lighting, HVAC, service water heating (SWH) equipment, are all included in the equipment category of office buildings [59]. In interior lighting to determine maximum lighting power densities (LPDs) for new construction models, the building area approach or the space-by-space approach from standard 90.1-2004 was used, and Standard 90.1-1989 was utilized for existing building models. LPDs for large office buildings zone are listed in Appendix B.

Prescriptive parameters and system performance criteria approaches are provided in Standard 90.1-1989 for establishing the allowable lighting power. These criteria approach provides LPDs at the building level. The approach based on system performance requirements produces space-level LPDs as well as an area factor (AF) multiplier. The LPD for large office buildings with variant space types was calculated by multiplying the allowable unit power density from ASHRAE (1989). The AF is defined as follows:

$$AF = 0.2 + 0.8\ (1/0.9^{n})$$

$$n = \frac{10.21\ (CH - 2.5)}{\sqrt{A_r}} - 1$$

Where:
AF = area factor
A_r = room area (ft^2)
CH = ceiling height (ft)

Exterior lighting in large office buildings is included following the values shown in Table 4.11 and Table 4.12. All exterior lighting is controlled by an astronomical clock, which turns the lights on when the sun goes down and off when the sun comes up. Exterior façade lighting is featured in all buildings around the perimeter of the building per area of the first floor outside walls plus the first-floor plenum exterior walls, as well as the main entryway doors and other exterior doors in large office models.

Table 4.11: Assumptions Regarding Exterior Lighting.

Area	Existing Large Office Models (90.1 - 1989)	New Construction Large Office Models (90.1 - 2004)
Façade	0.25 W/ft² (2.69 W/m²)	0.2 W/ft² (2.15 W/m²)
Main entry doors	30 W/ft (98.4 W/m)	30 W/ft (98.4 W/m)
Other doors	25 W/ft (82.0 W/m)	20 W/ft (65.6 W/m)
Canopy (heavy traffic)	10 W/ft² (108 W/m²)	1.25 W/ft² (13.5 W/m²)
Canopy (light traffic)	4 W/ft² (43 W/m²)	1.25 W/ft² (13.5 W/m²)
Drive through	-	400 W
Parking lot	0.18 W/ft² (1.9 W/m²)	0.15 W/ft² (1.6 W/m²)

Table 4.12: Lighting Levels of office buildings Parking Lot.

Building Type	Parking Lot Area	Total Parking Lot Lighting Level	
		Existing Office Buildings	New Construction Office Buildings
Small Office	8,910 ft² (828 m²)	1,604 W	1,337 W
Medium Office	86,832 ft² (8,067 m²)	15,630 W	13,025 W
Large Office	325,087 ft² (30,201 m²)	58,516 W	48,763 W

HVAC equipment for baseline office buildings was standardized by ASHRAE (2004) [82][92][93]. This data is used to develop reference buildings. Appendix D is a list of HVAC systems for office buildings.

2- *Weather profile*

Locations were chosen to represent important segments of the current building stock as well as all temperature zones in the United States. In five of the 15 climate zones in U.S., about 78% of the population is situated. To demonstrate all U.S. climate zones, DOE selected the most populous cities in each climate zone which is included Denver, Colorado state. Briggs et al. in 2003 [94] established a climate zone classification system based on SAMSON [95] weather data for DOE and ASHRAE Standard 90.1-2004, as shown in Figure 4.34. The fact that these climate zones tend to run in east–west bands across the country is an essential feature; subdivisions for moist, dry, and marine divide these bands. Table 4.13 displays a selection of locations chosen to balance the climate's representativeness in each climate zone.

Figure 4.34: Climate zone classification. [94][96]

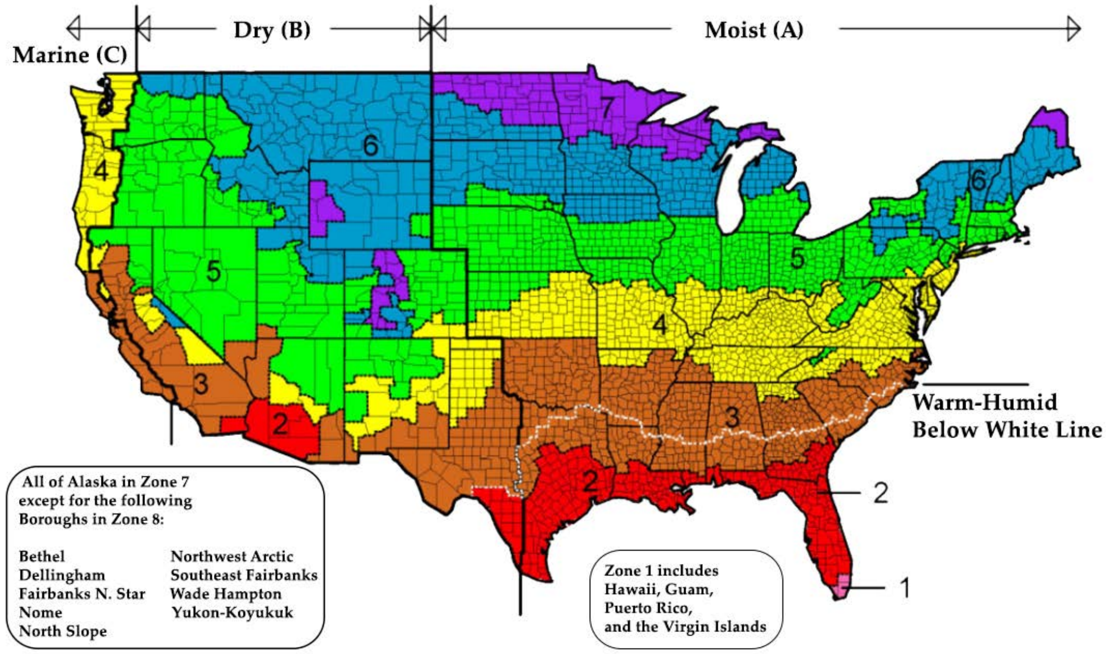


Table 4.13: Selected commercial building reference model locations.

Number	Climate Zone	Climate Zone Type	Representative City	TMY2 Weather file location	Included in analysis
1	1A	Very Hot, Humid	Miami, Florida	Miami, Florida	No
2	2A	Hot Humid	Houston, Texas	Houston, Texas	No
3	2B	Hot, Dry	Phoenix, Arizona	Phoenix, Arizona	No
4	3A	Hot, Humid	Atlanta, Georgia	Atlanta, Georgia	No
5	3B-CA	Hot, Dry	Los Angeles, California	Los Angeles, California	No

6	3B-other	Hot, Dry	Las Vegas, Nevada	Las Vegas, Nevada	No
7	3C	Marine	San Francisco, California	San Francisco, California	No
8	4A	Mild, Humid	Baltimore, Maryland	Baltimore, Maryland	No
9	4B	Mild, Dry	Albuquerque, New Mexico	Albuquerque, New Mexico	No
10	4C	Marine	Seattle, Washington	Seattle, Washington	No
11	5A	Cold, Humid	Chicago, Illinois	Chicago-O'Hare, Illinois	No
12	5B	Cold, Dry	Denver, Colorado	Boulder, Colorado	Yes
13	6A	Cold, Humid	Minneapolis, Minnesota	Minneapolis, Minnesota	No
14	6B	Cold, Dry	Helena, Montana	Helena, Montana	No
15	7	Very Cold	Duluth, Minnesota	Duluth, Minnesota	No
16	8	Extremely Cold	Fairbanks, Alaska	Fairbanks, Alaska	No

A most representative location and associated typical meteorological year (TMY) weather file are found for 230 locations in the USA plus four locations in Cuba, Marshall Islands, Palau, and Puerto Rico, derived from a 1948-1980 period of record. A TMY weather file is data sets of hourly solar radiation and meteorological data for a specific geographical place that includes data values for a one-year period. The data are drawn from hourly data collected over a longer period of time (normally 10 years or more). Their intended application is for computer simulations of solar energy conversion systems and building systems to allow for performance comparisons of various system types, configurations, and locations throughout the United States and its territories.

Climate will undoubtedly play a significant effect on the performance of any building, so it is critical to employ suitable geographical settings for any investigation. For the purpose of this dissertation, a simulation weather file (such as TMY weather file) of Denver, Colorado is required for Apache dynamic simulations in IESVE. For each hour of the year, the Denver weather file provides data for factors such as dry bulb and wet bulb temperature, wind speed and direction, solar altitude and azimuth, cloud cover, and etc.

4.5.4.2. Independent Variables

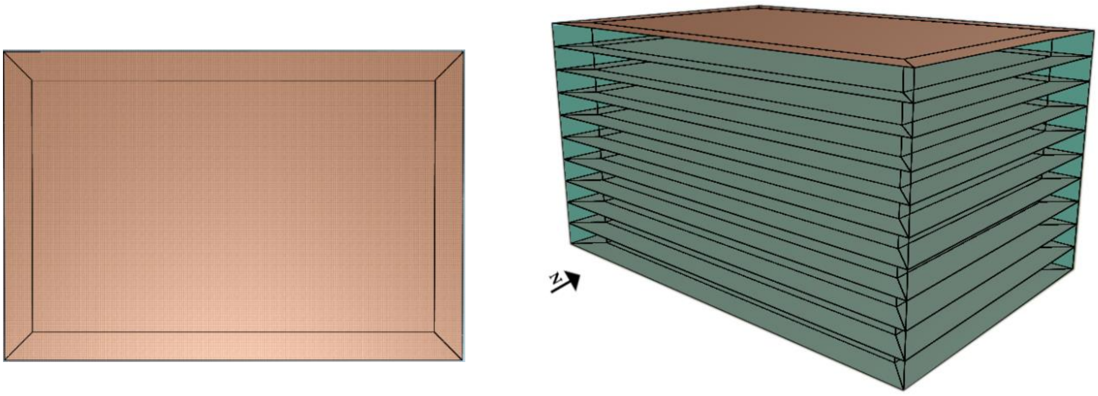
There are two sets of independent variables in this research. The bare façade (glazed) independent variable, and the green façade independent variable as a vegetation layer.

The results from both sets are utilized the performance of green façade in semi-arid regions.

- ***Bare façade configuration***

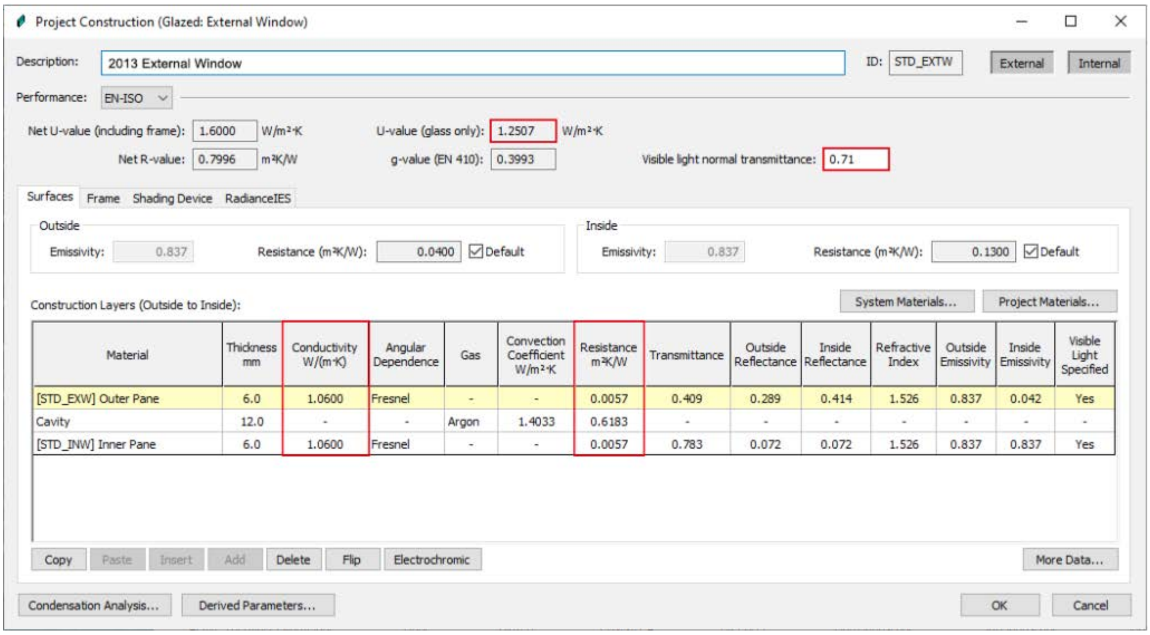
According to reference building models, window fraction (Window-to-Wall Ratio) is 40% of above-grade gross walls (37.5% of gross walls including the below-grade walls). Appendix A listed more information about large office building model. Figure 4.35 illustrates standard large office building and isometric configuration of the model as a bare façade and Figure 4.36 shows the glazed façade specification (U-value, R-value, Conductivity and etc.) in IESVE simulation software which are used in the following section 4.4. Analysis and discussion.

Figure 4.35: office building shape as a conceptual case study and isometric configuration.



Researchers on hot seasons in arid and semi-arid climates have consistently advocated for the use of smaller WWR to decrease cooling loads, but today, researchers presented that there is a significant and growing interest in the use of highly glazed facades in office buildings due to the many benefits of large WWR for office building envelope. Large portions of the façade, or even the entire façade, are glazed with reasonably high transmittance glazing systems and, in most cases, some type of sun control. The movement of using fully glazed façade began in Europe and is now spreading to other regions, including the United States [97]. Glass is an extraordinary material, but its performance is greatly boosted when it is processed or altered to provide additional intrinsic characteristics. When glass elements of a structure are built to be part of a full façade system, their overall performance can be improved. Finally, the façade system performs greatest in office buildings when it is an essential component of a completely integrated building design.

Figure 4.36: Glazed (bare) façade specification in IES VE simulation software.

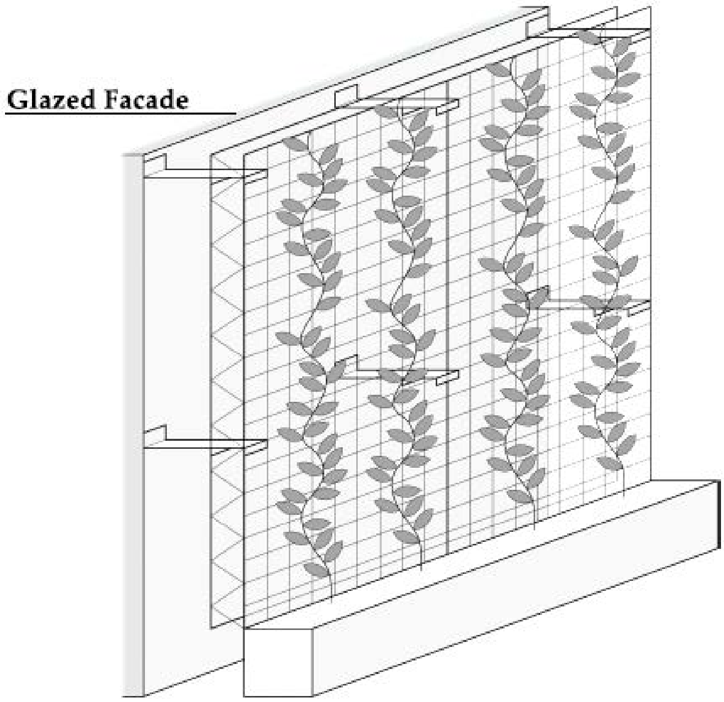


- *Green façade configuration*

The performance of green façades related to many factors such as material of back walls, building orientation, the density and type of plants, green façade typologies which explained in chapter 2, and material of green façade structure. Furthermore, building orientation has been one of the primary considerations within the construction of green façades which can affect substantial on green façade performances [54][98]–[100].

According to last research, thermal comfort is one of the most important features of green façades that efficiently decrease exterior surface temperatures of façades, lowering indoors daily temperature, and overall reduce heat transmission through the exterior wall, especially on days with significant insolation [101]. The configuration of green façades employed in this research is based on studies on the cavity depth size of green façades, glazed back walls configuration, and density of vegetation layers (Figure 4.37). The cavity thermodynamics in green façade as double skin façade are related to the air temperature and airspeed of the cavity. To improve the performance of green facades, various aspects related to the climatic context and the economics of its configuration must be considered.

Figure 4.37: Three-dimensional green façade system.



4.6. Method for Examining the Performance of Green Façade

To select an appropriate methodology to investigate the research hypothesis and measuring method to quantify the influence of alternative refurbishment configurations of office building facade on green façade performance is identified. A methodological literature review was conducted. In this context, a 'methods literature review' [102] is defined as a literature review focusing on methods and definitions used in previous studies and obtained from both primary which are articles and secondary which are books sources, and limited to studies relevant to the specific issue of green facade efficiency. These reviews give summaries of previous research as well as an evaluation of the approach utilized to investigate the topic under study's strengths and weaknesses.

The literature research revealed two distinct methodologies for evaluating the performance of green facades. Although these methods are commonly used to analyze the performances of all various green facade configurations, the focus of this context is on methodologies used to predict and analyze the performance of green facades as a type of vertical greenery.

The two methods are:

1. Numerical method [101][19]
2. Experimental method [103][104]

Performance of vertical gardens had been investigated in terms of thermal and energy performance, thermal comfort, environmental noise reduction, sustainability, psychological and astatically in building and urban scale during the last 20 years, approximately 100 studies have been conducted according to numerical and experimental criteria [105].

All strategies were discovered to have a place. Although each approach has implicit limitations, these limitations have not generated a compelling cause to dismiss any of the preceding study methodologies. The scope and limitation of each method will be discussed and the rationale behind choosing simulation method for this study is explained. This section examines these strategies in order to comprehend their scope. The previously reported results in the literature produced by employing these different methodologies are used to assess and develop the matrix of green facade independent and dependent factors that are relevant to simulate in order to achieve the dissertation's objective.

4.6.1. Numerical method

A numerical method is a mathematical tool designed to solve numerical problems. The differing functioning procedures of the human brain and computers result in numerical method. While the human brain seeks relationships that explain occurrences in reality and allows human to replicate them, computers can only do simple logic operations at enormous speed. Thus, using appropriate algorithms, humans could construct the relationships that their brains to think of, deconstructing them into simple operations that a computer can accomplish [106].

Building simulation could be considered numerical methods. Building simulation programs such as TRNSYS, EnergyPlus, IESVE, and computational fluid dynamics (CFD) can be employed as simulation tools [107]. Researchers provided a mathematical model of building exterior walls with climbing plant for vertical greenery systems [108]. Several additional researchers investigated the thermal balance of the vegetation and heat transfer through the substrate layer of the vertical greenery system, and they used models in building simulation programs such as TRNSYS and EnergyPlus [19][109][110]. Table 4.14 depicted some investigations that used numerical method to analyze vertical gardens (green facades and living walls) performance. Appendix E contains governing equations and a schematic of the energy balance and a very brief description for completeness and to aid comprehension of the overview of the mathematical model.

Table 4.14: Some research that by using numerical method could analyze vertical gardens performance (please, note that GF is Green Façade, LW is Living Wall, and GST is Green System Technology).

Ref.	Location	Köppen Climate class.	Period	Plant Species	GST	Orientation
[11]	Thessaloniki	Cfa	June - August	Parthenocissus tricuspidate	GF	North, East, South, West
[19]	Hong Kong and Wuhan	Cfa	One hottest summer day, One coldest winter day	1.Peperomia claviformis 2.Plant not specified	LW	West
[111]	Siena	Csa	One year	Plants embedded in the felt layers, without substrate, with mass of 20 kg/m².	LW	South
[112]	Hong Kong	Cwa	Cooling period	Divided creeper: deciduous	GF	Whole building
[113]	Kelowna	Dfb	One year	Plant not specified	LW	Whole building
[114]	Genoa	Csa	June - September	20 species both climbing plants and shrubs.	GF	South
[115]	Singapore	Af	Cooling period	Turfing	LW	Whole building
In publishing process	Barcelona	Csa	One year	Plant not specified.	GF	South
[54]	Barcelona	Csa	One year	Plant not specified.	GF	North, East, South, West
[101]	Barcelona	Csa	One year	Ivy	GF	Whole building

4.6.2. Experimental method

The experimental method entails altering one variable to see if changes in one variable cause changes in another. To test a hypothesis, this method employs controlled methods, random assignment, and variable manipulation. The reported experimental work on green facades has primarily concentrated on specific features (thermal efficiency, noise reduction, improving indoor and outdoor air quality, and etc.) of green façade performance as a vertical greenery.

Researchers revealed that by analyzing a living wall on the southern façade of a building in Thailand's Phitsanulok city with tropical wet and dry climate from December 2015 to May 2016, they were able to accomplish considerable temperature decrease [9]. Researchers installed green façades and living walls in the east, south, and west façades of buildings in Puigverd de Lleida, Spain, with Mediterranean hot summer climates (Csa), and they reported that by analyzing them from June to July (summer) and December to February (winter), they revealed high thermal performance of green façades and living walls [13]. Another study from the city of Lleida found that by implementing indirect green façades and analyzing them over the course of one week in August 2015, it was possible to save 34% of the energy [116]. Table 4.15 demonstrated some researches that used experimental method to examine vertical gardens (green facades and living walls) performance.

Table 4.15: researches that by using experimental method studied vertical gardens performance (please, note that GF is Green Façade, LW is Living Wall, and GST is Green System Technology).

Ref.	Location	Köppen Climate class.	Period	Plant Species	GST	Orientation
[9]	Phitsanulok	Aw or As	December 2015 May 2016	False heather, Princess Flower, Chinese croton	LW	South
[10]	Shanghai	Cfa	August 2015 December 2015	Vinca major varegata	LW	---
[12]	Covilha	Csb	February March	Sedum and Thymus species	LW	South
[13]	Lleida	Csa	June – July December February	GF: Boston Ivy – Parthenocissus tricuspidate LW: Rosmarinus officinalis, Helichrysum thinschanicum	GF LW	East South West
[14]	Nottingham	Cfb	3 weeks	Hedera helix	GF	---
[15]	Reading	Cfb	19 August	Prunus laurocerasus	GF	South
[16]	Singapore	Af	24 February 2008 24 April 2008 21 June 2008	Hemigraphis repanda, Phyllanthus myrtifolius	LW GF	---
[17]	Thessaloniki	Cfa	July – August 2006	Parthenocissus tricuspidate	GF	East
[18]	Mawson Lakes	Csb	December 2014 July 2015	Goodenia pinnatifida, Brachyscome ciliaris, Poa labillardie, Enneapogon nigricans, …	LW	West
[20]	Geneva	Cfb	May (one week)	---	LW	South
[21]	Santiago of Chile	Csb	January (12 days)	Highly dense sedum, medium dense sedum	LW	North
[117]	Wuhan	Cfa	One day of cooling period	---	LW	West
[118]	Al-Ain City	Bwh	One year	---	LW	East
[119]	Lleida	Csa	6 days of cooling period	Ivy, Honeysuckle, Boston Ivy, and Clematis	GF	South
[120]	La Rochelle	Cfa	August 2012	Six different species on Chile sphagnum of 15 cm	LW	West

Nevertheless, the inherent restrictions could not be overlooked. Testing the effect of changing one independent variable, such as glazing type or greenery system, is time-consuming and costly. The costs of conducting experimental model of green façade are often substantial and are covered by big international organizations. In order to analyze the performance of green façade configurations in this scenario, the model has to be built in the specific region or a similar semi-arid climate where the performance of the green façade is to be examined.

4.7. The Measurement Method Utilizing IESVE as a Simulation Tool

The main reason for choosing building simulation over other methods for predicting green façade performance in buildings is those real-world systems that are frequently difficult or complicated to analyse using simple manual mathematical models, experimental work, or monitoring techniques. Computer modelling and simulation are currently the most powerful techniques available for the analysis and design of complex systems such as buildings [121][122]. Modelling is the process of creating a model that accurately represents a complex system. Simulation is the process of simulating future reality by using a model to analyse and predict the behaviour of a real-world system. As a result, green facade simulation attempts to extract from the real system the elements relevant to the stated requirements while disregarding the relatively insignificant elements.

Integrated Environmental Solutions (IES) was founded in 1994. The IES Virtual Environment (VE) is a collection of applications for analysing building performance. Designers can use it to test different options, identify passive solutions, compare low-carbon and renewable technologies, and draw conclusions about energy use, CO2 emissions, and occupant comfort.

IESVE is a comprehensive suite of integrated building design and retrofit analysis tools. This software can virtually test design and refurbishment options to improve the performance of any building and deliver robust and reliable results. Integrated analysing including:

- BIM Interoperability,
- Energy Modelling,
- Daylight Modelling,
- Solar Analysis,
- Comfort Analysis,
- Low Energy Design,
- Global Building Regulations,

- Loads Analysis & HVAC.

Furthermore, the IESVE software has been approved by the US Department of Energy (DOE), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and the Chartered Institution of Building Services Engineers (CIBSE).

4.8. Plant Model for Vertical Garden Simulation

Many studies have considered the importance of using deciduous species in the regulation of solar gains throughout the year [123]. The importance of understanding the biological cycles of different species is emphasized in different climates, as these influences when leaves fall (or grow) and thus what number of solar gains could be considered for the thermal balance of the building. This is especially important during the transition seasons of Spring (when the leaves grow) and Autumn (when the leaves fall).

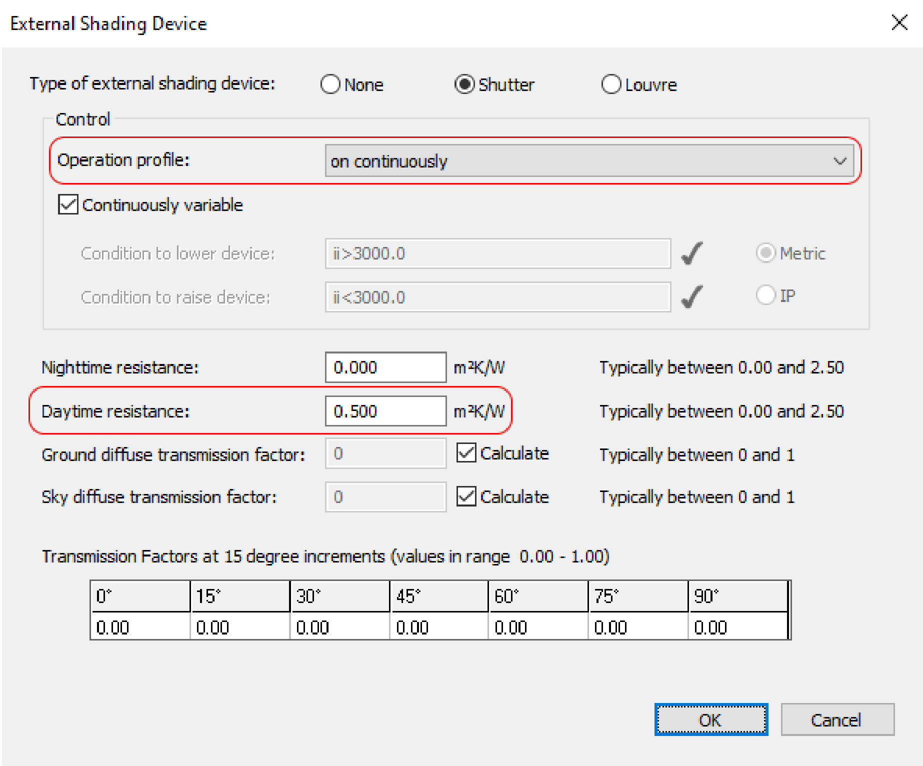
In this investigation, a vegetation layer model with Boston ivy (Parthenocissus tricuspidata) plant created by shutter structure that was used in the IESVE building simulation tool. Figure 4.38, illustrated the configuration of vegetation layer which simulated in this research by IESVE building simulation software. The leaf absorptivity coefficient and stomatal conductance values were taken from the biophysics literature and are thought to be appropriate for Boston ivy [124]–[126]. The effective plant R-values modeled in this research correspond to plant layer thermal resistance values previously discovered in other studies, which is including 0.5 m2 K/W for a 0.25 thick ivy layer [11]. Table 4.16 details the thermal properties and depth of the plant growing media, as well as substrate properties such as height and leaf area index that were used in this research.

Table 4.16: Thermal characteristics of the plant and the substrate layer.

Plant Layer (Boston ivy)					
Leaf absorptivity	Average leaf dimension	Average leaf area index	Radiation attenuation coefficient	Typical stomatal conductance	Layer thickness
0.5	0.12 m	1.8	0.4	0.2 mol/ m^2 s	25 cm
Substrate Layer					
Conductivity (W/ (m.K))	Density (kg/m^3)	Specific heat (J/ (kg. K))		Substrate thickness	
0.35	1100	1200		10 cm	

According to studies, a plant layer with the densest foliage (high leaf area index) and leaves parallel to the wall (high attenuation coefficient values) is the most effective at lowering facade surface temperatures and heat flux through the façade [108]. These findings are consistent with the findings of other experimental studies, which show reductions in facade surface temperatures of 1.6 - 19 °C [11] and 6 - 11 °C [127], as well as reductions in facade heat flux of 4 - 11 W/m² [128] for vine-covered exterior walls. With regard to previous studies, this developed model that used in this investigation can quantify the decrease in conductive heat load and its contribution to overall energy use for space conditioning in buildings with green façades [108]. The model will aid in the assessment of energy improvements in existing buildings retrofitted with green facades, as well as in the design of vertical greenery systems for maximum energy efficiency in new construction.

Figure 4.38: Green façade configuration in IES VE simulation software.



4.9. *Leaf area index (LAI)*

Plants' ability to intercept solar radiation is determined by their spatial structure, or the three-dimensional geometry of the plant canopy. This concept has previously been extensively researched and applied in the fields of agriculture, with the goal of approximating crop growth and yield, and thus the needs of water and nutrients, and also forest ecology, with the goal of estimating the amount of biomass, energy balances, and water in ecosystems, and so on [129]. The leaf area index (LAI) is described as a dimensionless quantity that characterizes canopy structures, and it has become a key measure for understanding and comparing plant canopies and also is the most commonly used methodology for characterizing the leaf mass of a plant or group of plants (LAI).

In broadleaf canopies, LAI is defined as the one-sided green leaf area per unit ground surface area (LAI = leaf area/ground area, m2/m2) using a parametric approach [130]. The LAI value varies depending on the plant type and growth phase (crop), typically ranging from 0 to 10 [116].

LAI of crops or in a forest ecosystem could be measured using either direct or indirect methods. The most reliable method for measuring LAI is to harvest all the leaves in a plot and measure the area of each leaf. In contrast, indirect methods are based on the measurement of LAI-related parameters including the amount of light transmitted or reflected by the plant canopy [131]. The photosynthetically active radiation (PAR) inversion technique is one of the most widely used indirect methods. It is based on estimating LAI using the amount of light energy transmitted by a plant canopy, with the more leaf density, the lighter absorption. This method is based on Beer's law, which is an empirical relationship that connects light absorption to the properties of the material traversed [132].

In order to study the LAI in green facades, researchers in 2009 designed an experimental double-skin green facade with a steel trellis support and Ivy plants (Hereda helix). According to these authors, in the case of vertical greenery, LAI represents the relationship between the leaf area and the square meters of facade rather than the traditional relationship between the leaf area and the square meters of floor (e.g., for green roofs application). Furthermore, it is necessary to consider the fact that the LAI value in a green facade varies with height. Although researchers do not consider the thermal benefits of green facades, because the LAI index has a direct influence on foliage density, this value can be linked to green system thermal behavior. At the end of the testing period, the LAI average measured at each exposition ranged from 7 (East) to 8.51. (South). These leaf area indexes are comparable to or even exceed those of conventional facade greenery with Hereda helix (2.6–7.7) [133].

In 2009, another group of researchers conducted an interesting simulation of the effects of vertical greenery systems on building temperature and energy consumption. To that end, the authors attempted to establish a relationship between LAI and the shading ratio (the ratio of solar radiation beneath the plant to the bare wall) using measurements taken in an experimental setup with eight different VGS compared. Even though a connection between these two parameters was discovered, it cannot be generalized and should not be considered conclusive because the measurements were few and were conducted in very different construction systems (some of them were green facades and the other ones were living walls). The overall trend was as expected: low solar radiation beneath the plant means that the plant effectively shades the wall. The authors conducted the simulations using specific data from plants, both at the building level (Urechites lutea, Ophiopogon japonicas ʻʻKyoto Dwarfʺ, and Tradescantia spathacea ʻʻcompactaʺ), with corresponding shading coefficients of 0.986 (high), 0.500 (medium), and 0.041 (low) (Nephrolepis exaltata, Boston fern, with a LAI of 6.76, even though this plant is a fern, not a climbing plant). The equipment used to measure LAI and the shading coefficient (solar radiation) is described in this study, but not the methodology or the quality of the data provided [115].

Furthermore, in 2013 researchers developed a mathematical model to characterize the thermal effects of plants on heat transfer through building facades. Leaf density, as measured by LAI, is one of the parameters used in the simulation and is one of the most influential in lowering the building facade wall surface temperature. In this investigation, LAI was calculated by measuring the area of a single typical leaf and counting the area of ivy in a photograph of a traditional green facade under consideration [108].

A study published in 2014 proposed a mathematical model for the energy performance of living walls. LAI was a crucial consideration to consider in the theoretical model once again. In this research, the two LAI values used were 3 for a living wall with a "vertical garden" made of different shrub species and 5 for a living wall that uses grass as vegetation, which was surprisingly higher than the first. These LAI values are from a previous study conducted by the authors, and were obtained by measuring LAI under shrubs placed horizontally in the nursery [134].
Based on previous research, it is possible to conclude that LAI is a key parameter for characterizing the foliar density and, as a result, the thermal behavior of VGS, particularly for green facades, due to its significant influence on the shadow effect. Having real LAI values for different plants in different climates, and linking these values to energy savings, can be useful information for dealing with design requirements during the green facade design.

4.10. Simulation Setup

For the context of this research, 6 simulation cases for the large office building type, which was simulated in this dissertation by IESVE software as a dynamic building simulation tool, were established to investigate how the exterior greenery system affects energy savings as a function of wall orientation. All six cases were simulated for post-building types.

Case 1: Bare façade (no plant);
Case 2: Whole-building green façade;
Case 3: South bare and green façade;

Case 4: West bare and green façade;
Case 5: North bare and green façade;
Case 6: East bare and green façade.

For all 6 cases, semi-arid climate conditions were considered, which is Denver, Colorado. Table 4.17 summarizes climate conditions in Denver. US climate classified into 17 zones [135] that Denver is classified as cold and dry (5B climate zone) and also according to Köppen climate classification is included in semi-arid regions (BSk) (see Appendix F for more information). The monthly and annual heating and cooling energy savings due to the vertical greenery systems on the façade were investigated for each simulation case. This research implies that cooling energy savings from vertical greenery systems on the façade vary greatly with local climate, owing to the fact that shading and evapotranspiration effects differ across climates. Shading can reduce solar radiation passing through building walls, and evapotranspiration can be converted into a cooling potential due to latent heat transfer.

Table 4.17: The climate variables of Denver, Colorado, were investigated in this study.

Denver, Colorado				
Annual average temperature (°C)	Annual Average max/min temperature (°C)	Annual average relative humidity (%)	Monthly average relative humidity (%)	Average Wind speed (m/s)
10.1	17.9 / 2.4	36.8%	July 31% February 43%	4

4.11. Analysis and Discussion

This section is divided into four subsections. The first subsection describes the monthly heating and cooling energy consumptions for a large office building's bare and green façade. The second subsection is presented the thermal comfort performance of the green façade in the glazed office building. The third subsection showed the effect of green façade in cooling loads. And the fourth subsection demonstrated energy saving in a green façade and compared it with the bare façade.

4.11.1. Monthly heating and cooling energy consumption in bare and green façades

Figures 4.39 - 4.42 show the monthly heating (boiler) and cooling (chiller) energy consumptions (kW/h) of the bare and green façades of an office building in a semi-arid region. The figures show that heating and cooling energy consumption varies depending on the type of building façade and season. By comparing heating energy consumption in the bare and green façades (Figures 4.39, 4.40), it is possible to conclude that the green façade is effective in lowering the use of energy for heating office buildings in semi-arid climates.

Figure 4.39: 3D graph of bare façade heating energy (kW/h) in one year.

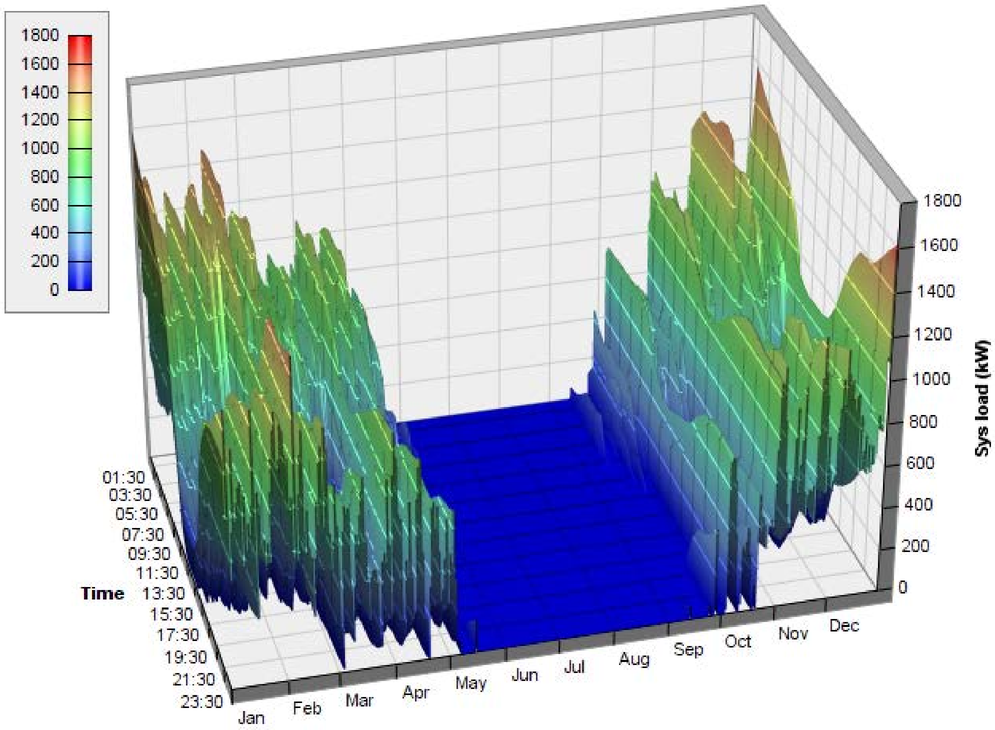
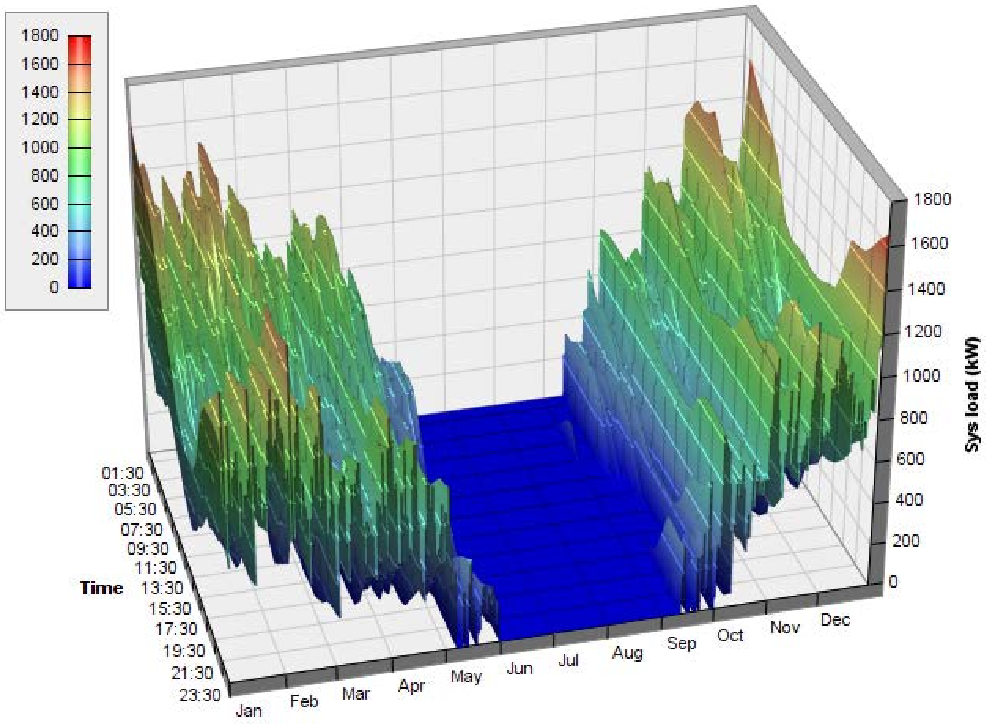


Figure 4.40: 3D graph of green façade heating energy (kW/h) in one year.



By comparing heating load in December (the coldest month of winter) (Figures 4.41, 4.42) between the bare and green façade it can be seen, by applying a green façade, boilers load increased about 43.8 kW and also room heating plant sensible load growth about 39.4 kW. One of the reasons for the increase in heating energy is the closure of the path of solar radiation by vegetation layer on the facade into the building space, which can raise the indoor temperature especially through the southern side of the building in winter. This issue can be controlled by applying the appropriate density of plants and avoiding blocking façades via plants.

Figure 4.41: The maximum heating energy (kW/h) consumption in a bare façade over the course of a year.

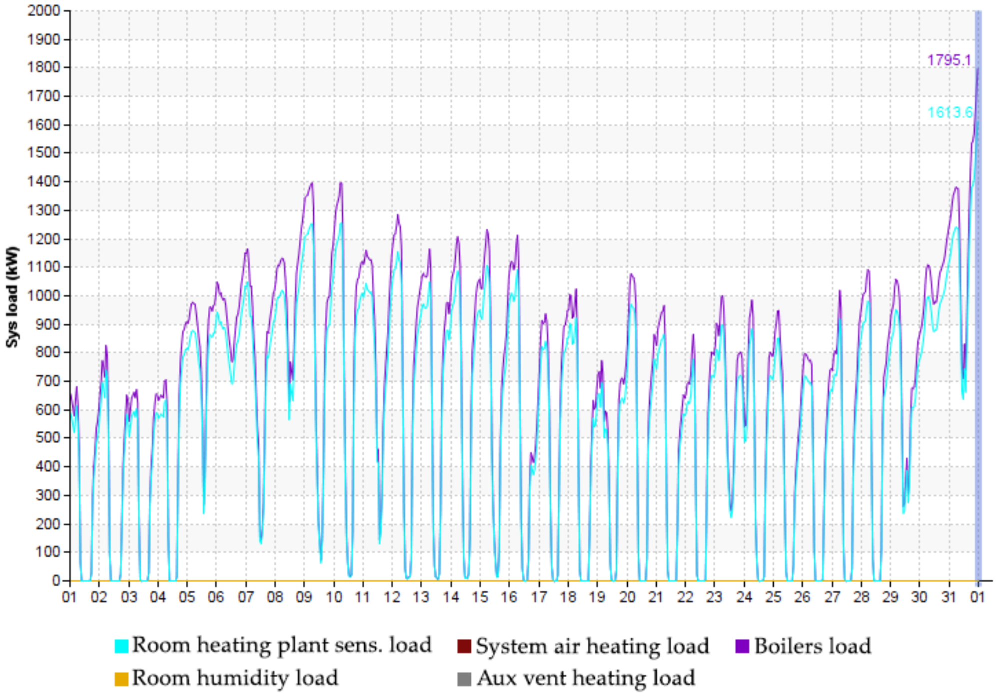


Figure 4.42: The maximum heating energy (kW/h) consumption in a green façade over the course of a year.

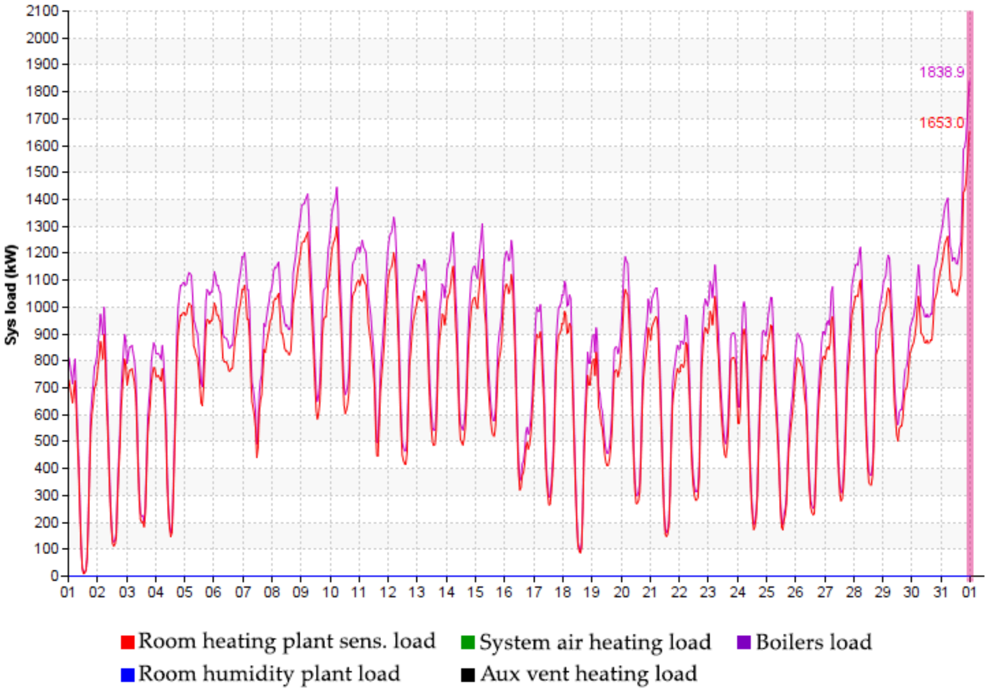


Table 4.18 depicted the maximum consumption of heating load (boilers load and room heating plant sensible load) monthly which heating load use natural gas energy. These differences show the influence of solar radiation on lowering indoor air temperature.

Table 4.18: The monthly maximum number of boilers load (kW/h) and room heating plant sensible load (kW/h) of the bare and green façade.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bare Façade	**Boilers load (kW/h)**	1760	1661.8	1166.6	1292.3	896.2	-	-	-	489.6	878.2	1695.1	1795.1
	Room heating plant (kW/h)	1580	1493.7	1048.6	1161.6	805.6	-	-	-	440.0	789.4	1523.6	1613.6
Green Façade	**Boilers load (kW/h)**	1800	1693.7	1196.9	1341.9	940	-	-	-	708.0	993.7	1725.0	1838.9
	Room heating plant (kW/h)	1620	1522.5	1075.8	1206.2	842.3	-	-	-	636.4	893.2	1550.6	1653.0

As shown in figures 4.43 and 4.44, the maximum cooling energy in the bare façade is 954.0 kW/h (Figure 4.45), but this figure has been reduced by using green façade by about 779.6 kW/h, and the maximum cooling energy use in green façade is 174.4 kW/h (Figure 4.46) in one year.

Figure 4.43: 3D graph of bare façade cooling energy (kW/h) in one year.

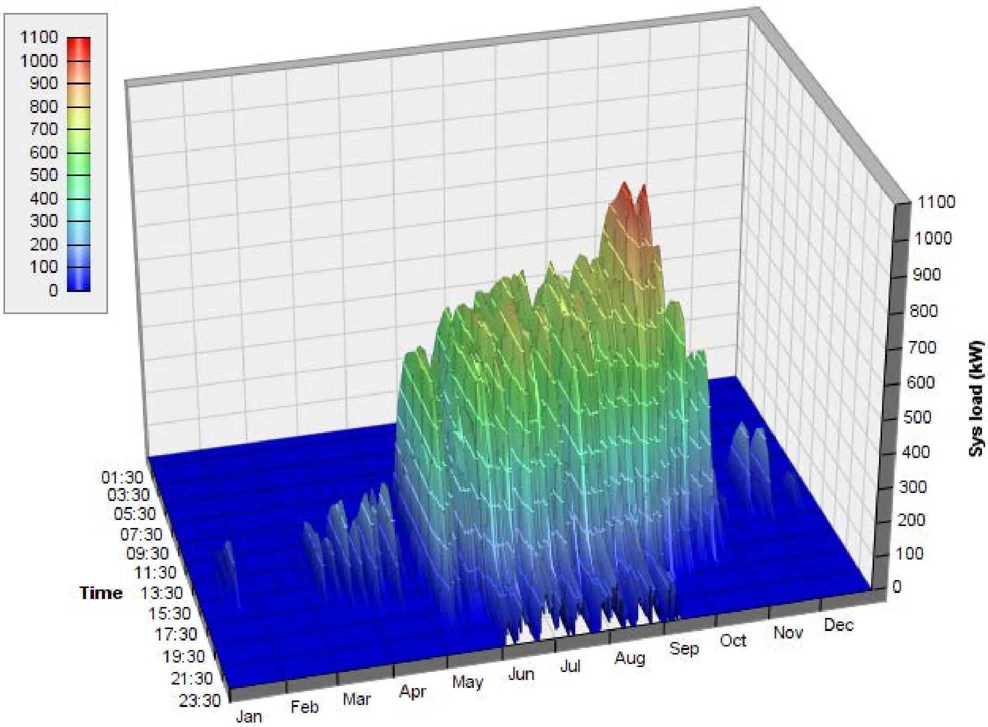
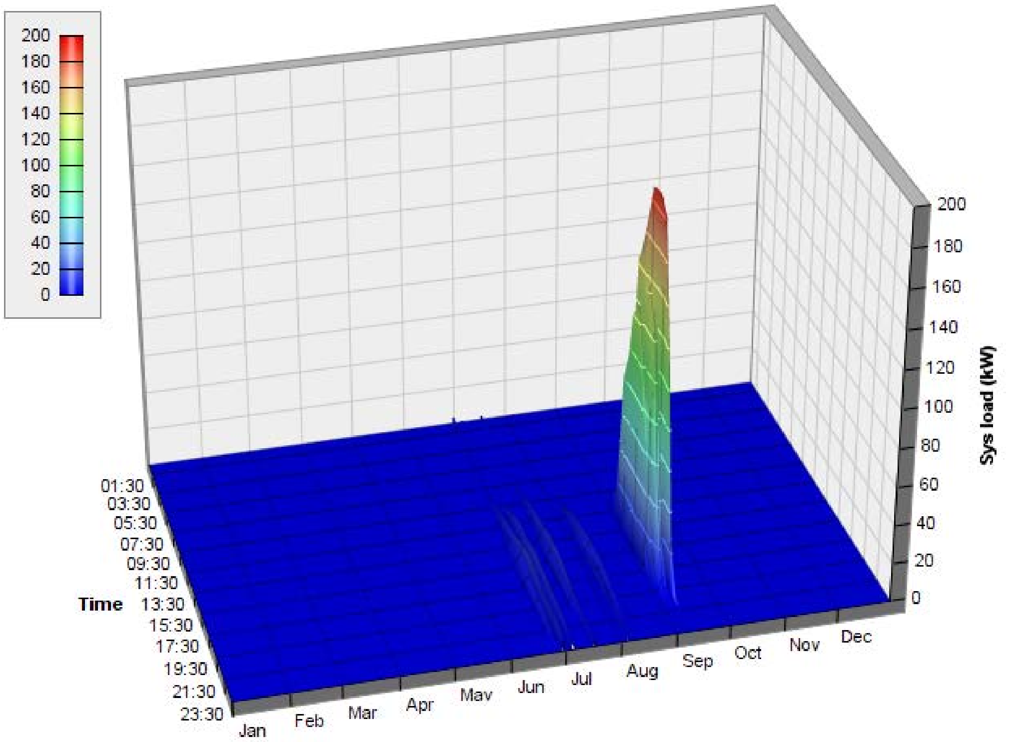


Figure 4.44: 3D graph of green façade cooling energy (kW/h) in one year.



By analyzing the cooling load in one of the hottest months of summer (June) in both bare and green façades (Figures 4.45, 4.46), we can see the effect of the green façade on reducing the cooling energy, which is a very significant reduction. According to these graphs, the maximum use of chillers load on the bare façade is 729.1 kW/h and on the green façade this figure is 12.1 kW/h during June.

Figure 4.45: The maximum cooling energy (kW/h) and room cooling plant sensible load (kW/h) in a bare façade during June.

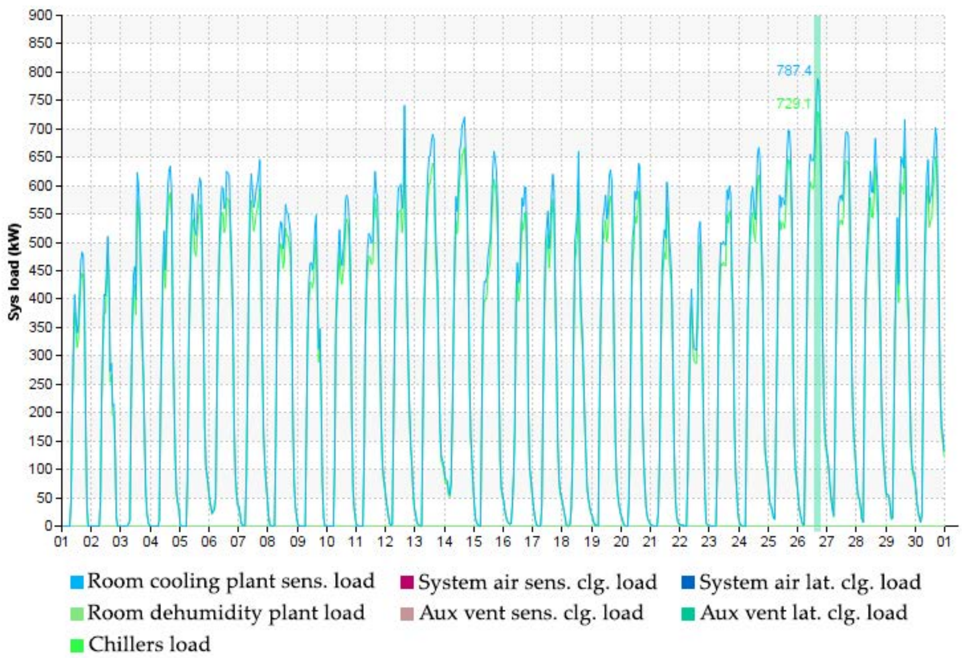


Figure 4.46: The maximum cooling energy (kW/h) and room cooling plant sensible load (kW/h) in a green façade during June.

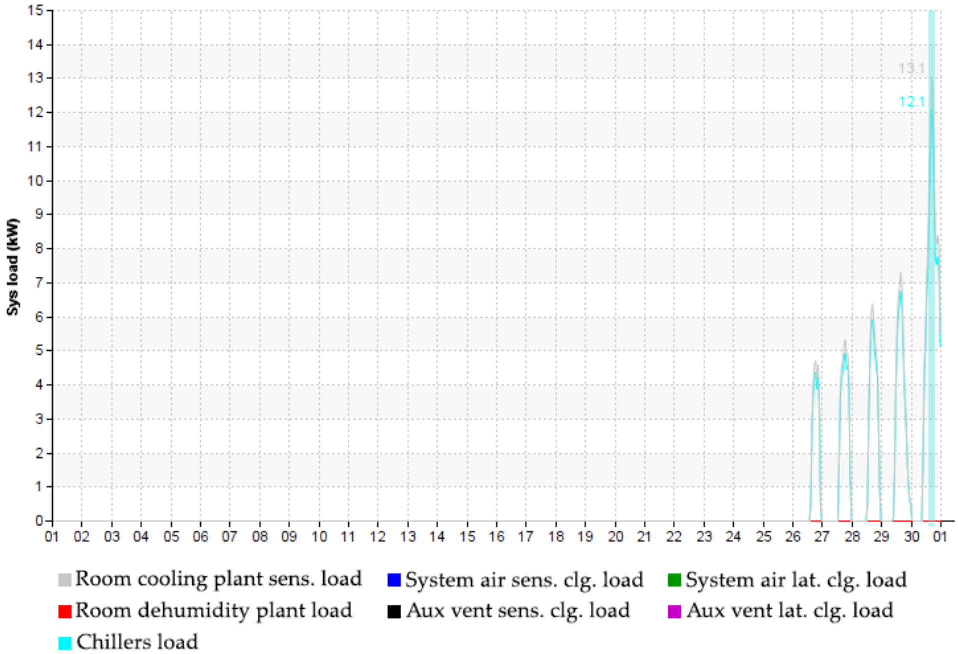


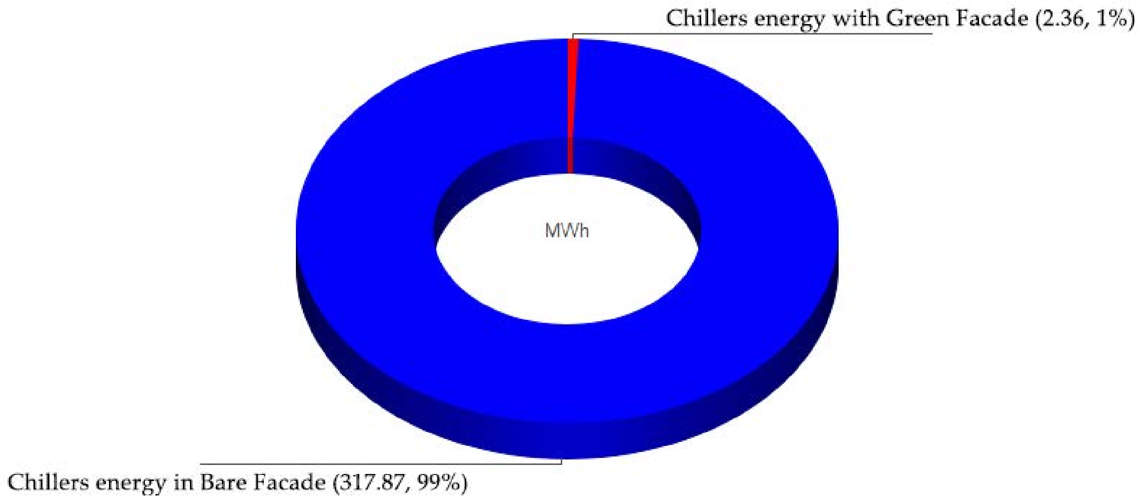
Table 4.19 demonstrates the monthly maximum number of chillers load (kW/h) and room cooling plant sensible load (kW/h) in both bare and green façades which as it can be seen during January, February, March, April, May, and also October, November, December the use of cooling load by applying a green façade is zero and just in hottest months of summer cooling energy is used but this number is very lower than bare façade.

Table 4.19: The monthly maximum number of chillers load (kW/h) and room heating plant sensible load (kW/h) of the bare and green façade.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bare Façade	Chillers load (kW/h)	126.5	9.5	229.3	246.5	597.4	729.1	682.7	717.7	954.0	636.6	200.2	205.2
	Room cooling plant (kW/h)	136.6	10.3	247.6	266.3	645.2	7874.4	734.4	775.2	103.3	687.6	216.2	221
Green Façade	Chillers load (kW/h)	-	-	-	-	-	12.1	11.1	7.6	174.4	-	-	-
	Room cooling plant (kW/h)	-	-	-	-	-	13.1	12.0	8.2	188.4	-	-	-

Previous research on evaluating the performance of a green façade office building in Barcelona with Mediterranean climate revealed that the green façade used 31% and the glazed façade used 69% chiller energy in one year [101]. This proportion is significant in a glazed office building in Denver with a semi-arid climate, with the green façade using 1% of the chiller energy and the bare façade using 99% (Figure 4.47). With making a comparison between two different regions can be understood the beneficial of green façade in various climates, which in this research are semi-arid and Mediterranean climates.

Figure 4.47: The maximum cooling (chiller) energy (kW/h) consumption in a green façade over the course of a year.



4.11.2. *Thermal comfort performance of green façades*

Thermal comfort and its conditions were thoroughly discussed in Chapter 3 (3.5.2.1. Thermal comfort), and according to previous discussion, there are environmental variables that must be addressed when defining thermal comfort conditions, which are air temperature, mean radiant temperature, operative temperature, and also predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD).

- ***Air temperature***

Green vertical systems such as green façades and living walls have been shown to reduce the temperature of a building's façade in the summer and behave as an insulator in the winter [15][136]–[139]. These systems in a densely populated urban area create a microclimate in which the space between buildings (termed a "canyon") experiences a lower temperature as a result of plant transpiration [140]–[142]. Many researches revealed that the installation of vertical greenery systems could improve the indoor air temperature, therefore, reducing energy demand for cooling and improving thermal comfort [99][19][114][115][10][143].

This section discusses the indoor air temperature of the bare and green façades, which are shown in figures 4.48 and 4.49 that air temperature reduced by applying a vegetation layer on the glazed façade.

Figure 4.48: The indoor air temperature of the bare façade.

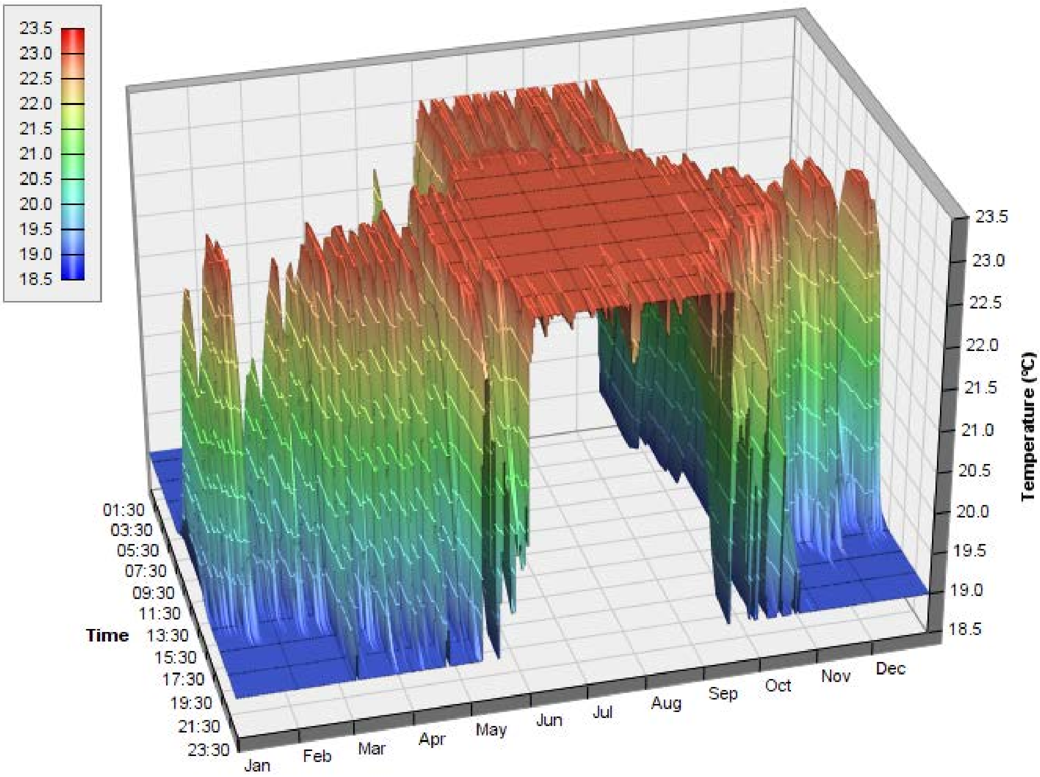
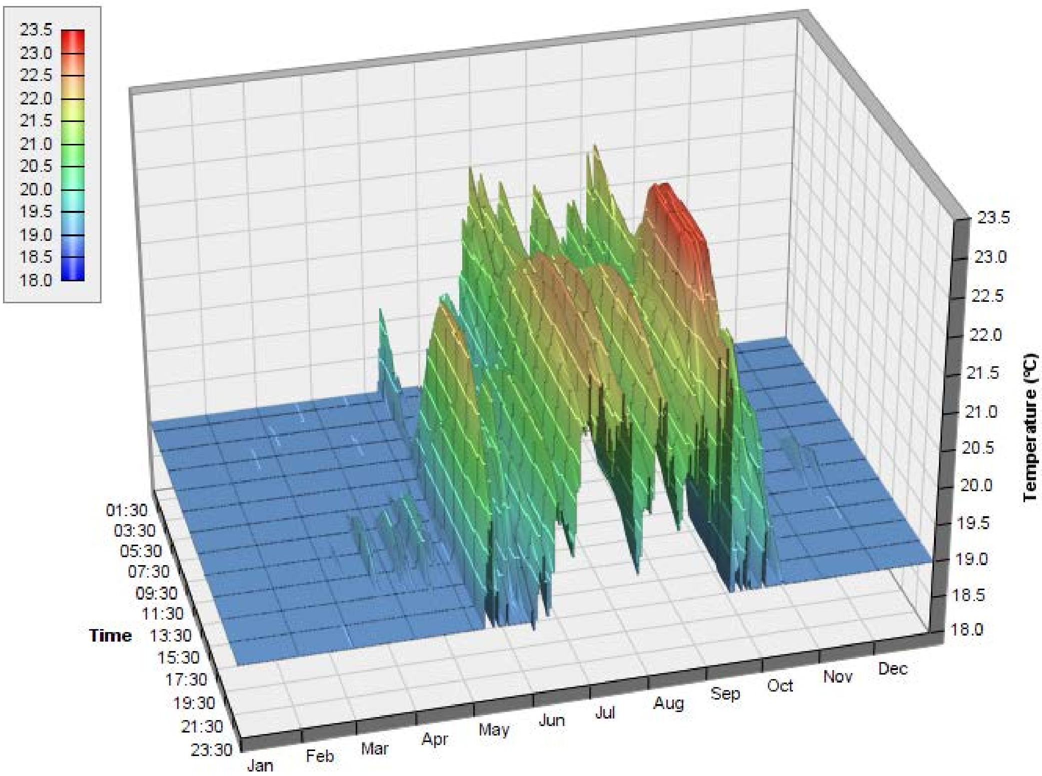


Figure 4.49: The indoor air temperature of the green façade.



As can be seen in these graphs (Figures 4.48, 4.49), the air temperature decreased over the course of a year due to the façade's protection from solar radiation and wind by a vegetation layer. Consequently, it should be noted that a vegetation layer on the façade, known as a green façade, has many advantages, including the ability to keep air temperature stable and improve building thermal comfort. The hourly changes in air temperature in both glazed and green façades can be specified by comparing two days, 21st June and 21st December (Figures 4:50 and 4:51). The air temperature in office buildings during working hours is considered, which shows that on June 21st, the air temperature was reduced in the case of green façade during working hours (9 am -5 pm).

Figure 4.50: Compared the indoor air temperature of the bare and green façades on 21 June.

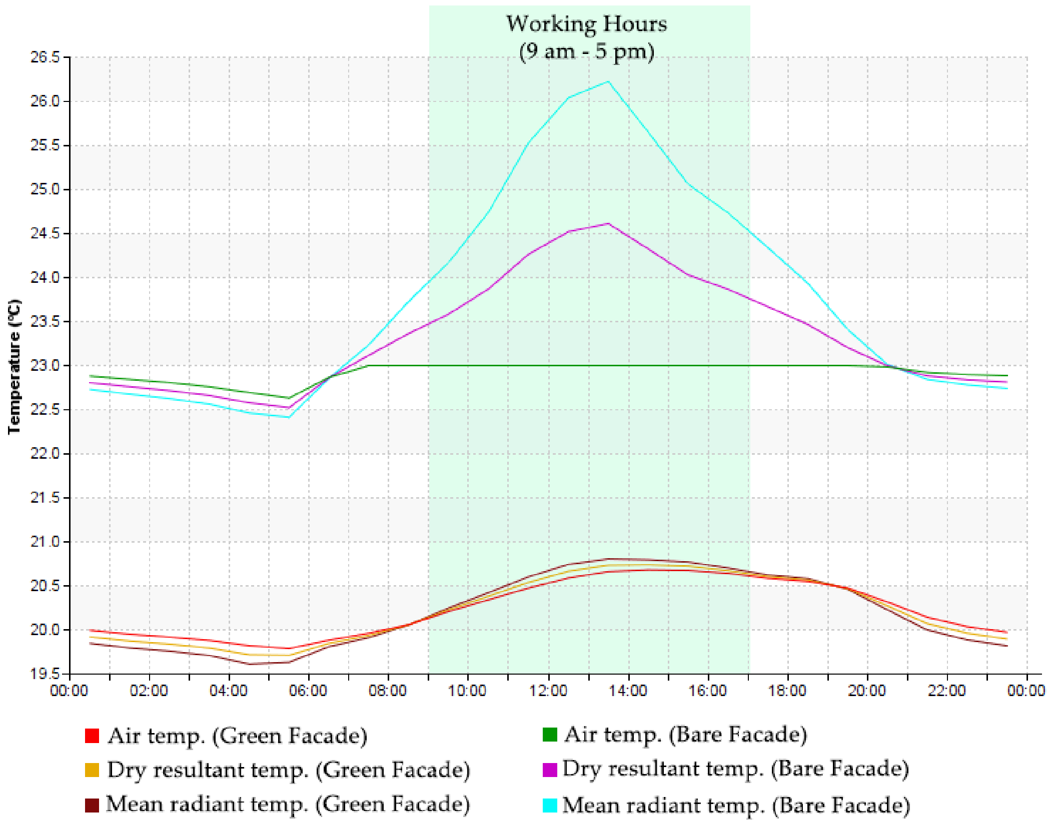
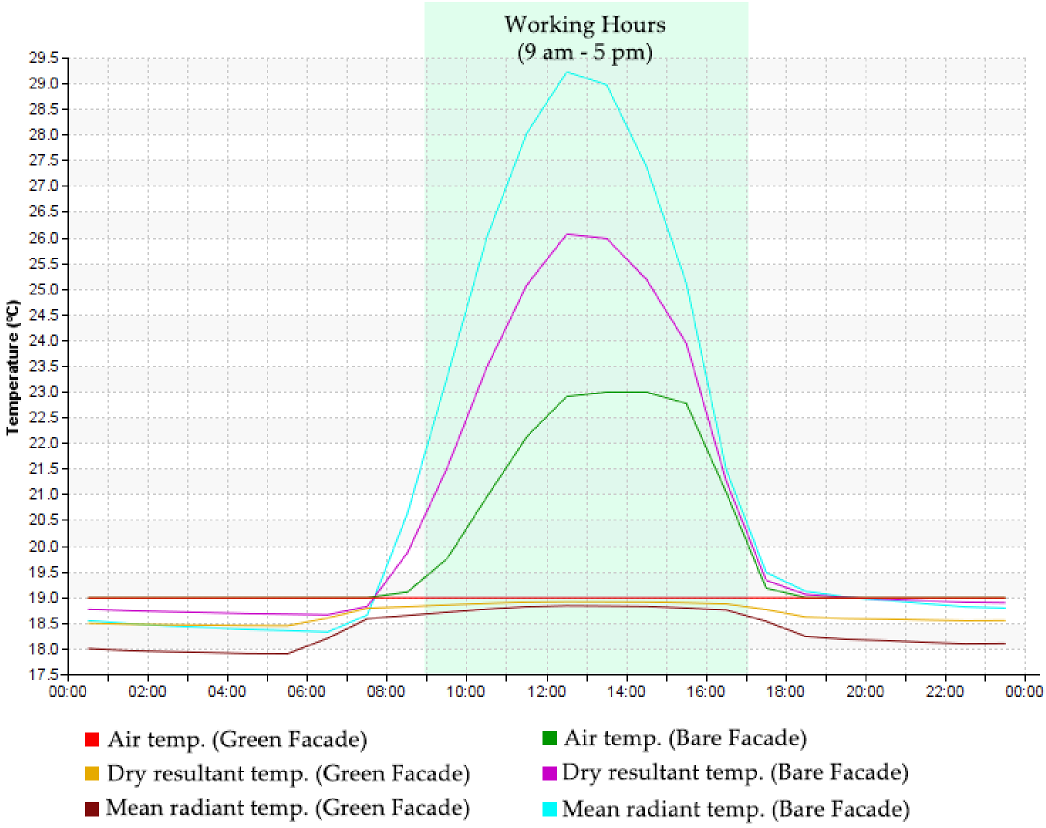


Figure 4.51 presented indoor temperature difference in bare and green façades on 21st December which is a cold day in winter. It can be seen that the air temperature stands steady by about 19 C, and indoor air temperature by applying a green facade is lower than the bare facade and the use of heating energy could be considered.

Figure 4.51: Compared the indoor air temperature of the bare and green façades on 21 December.



- *Mean radiant temperature*

The radiant temperature can be calculated by measuring the temperature of the surrounding walls and surfaces, as well as their locations in relation to an individual [144]. According to previous research, large areas of glass can cause greater differences in mean radiant temperature and air temperature [101]. To gain a better understanding of the performance of green façade on the mean radiant temperature in the context of a semi-arid climate, the mean radiant temperature of both bare and green façade in the south, west, north, and east orientations, as well as the central area of the office building during one year, is presented in this section.

Figure 4.52 and 4.53 illustrated the difference of mean radiant temperature in both green and bare façade which located on southern and western. Due to the southern part of the building is in direct contact with solar radiation, it has gained a higher figure of mean radiant temperature in the bare façade in one year, as the red color indicates that the temperature is above 25 ° C. While using a green façade in both orientations, the red color completely disappeared and was replaced by an orange color that displayed temperatures below 25 ° C for a short period in June, July, and August.

Figure 4.52: The mean radiant temperature of bare and green façade with south orientation during one year.

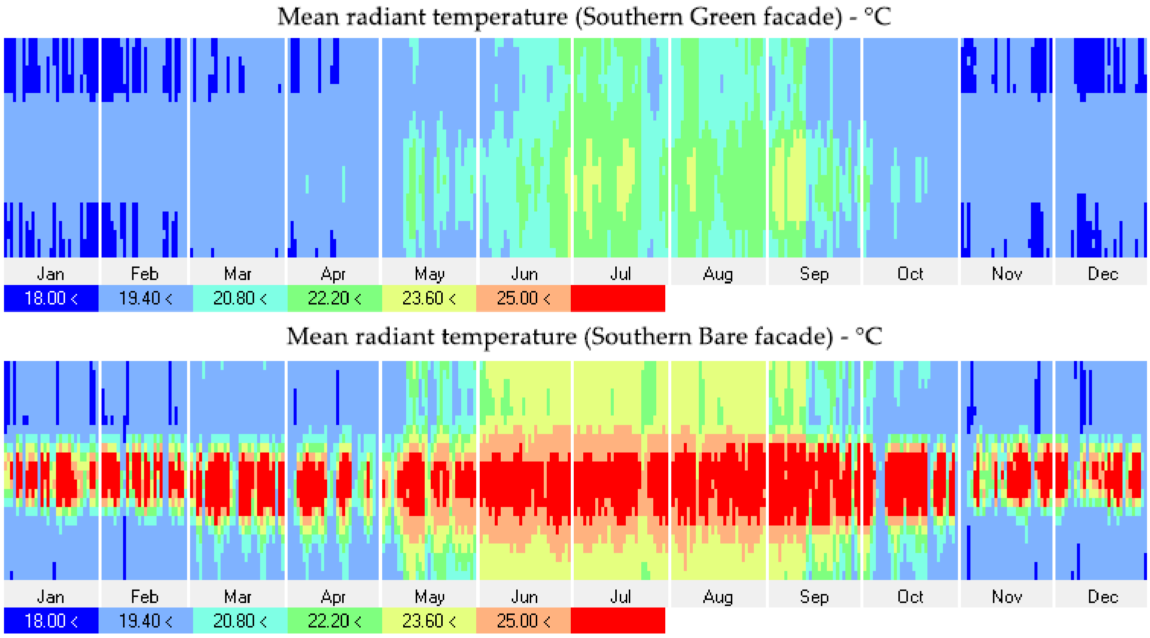
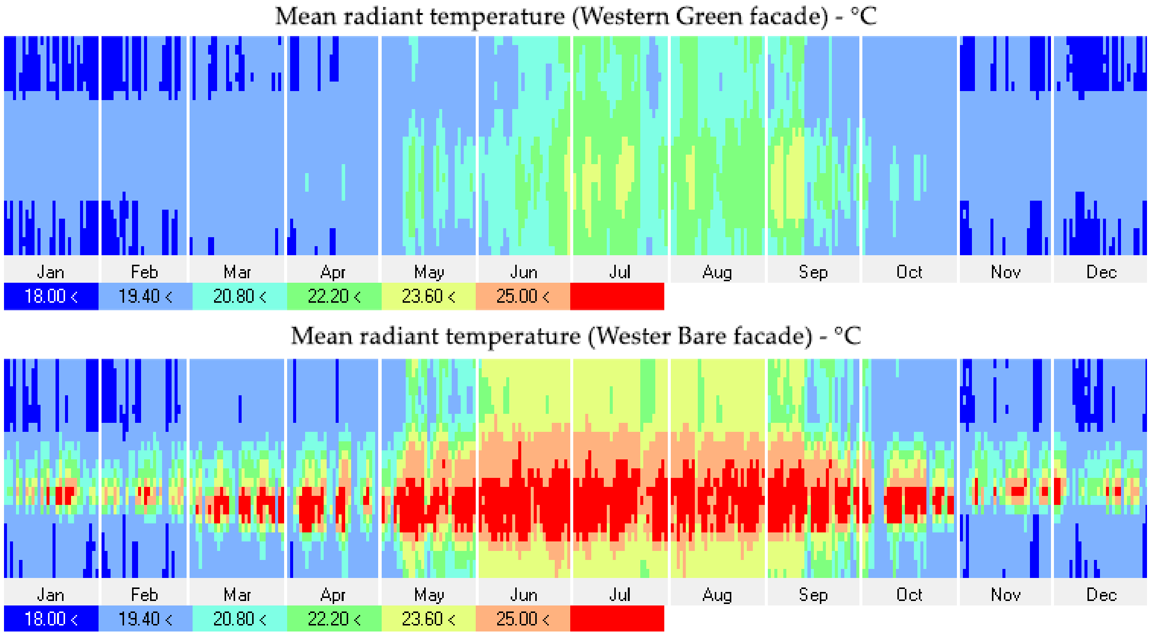


Figure 4.53: The mean radiant temperature of bare and green façade with west orientation during one year.



The north orientation results (Figure 4.54) demonstrated that the mean radiant temperature is lower in the bare façade due to the less connection of this part of the building to solar radiation and that using the green façade in this orientation could improve mean radiant temperature less than the southern and western parts of the office building. Also Figure 4.55 which is east orientation results presented the reduction of mean radiant temperature by applying a vegetation layer on the glazed office building façade.

Figure 4.54: The mean radiant temperature of bare and green façade with north orientation during one year.

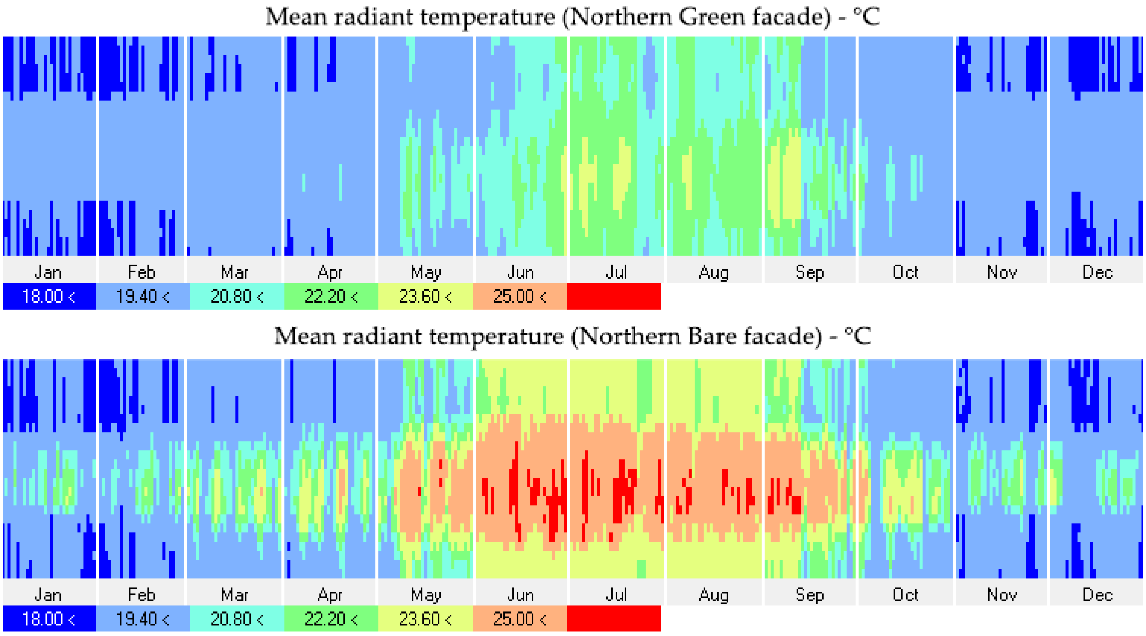
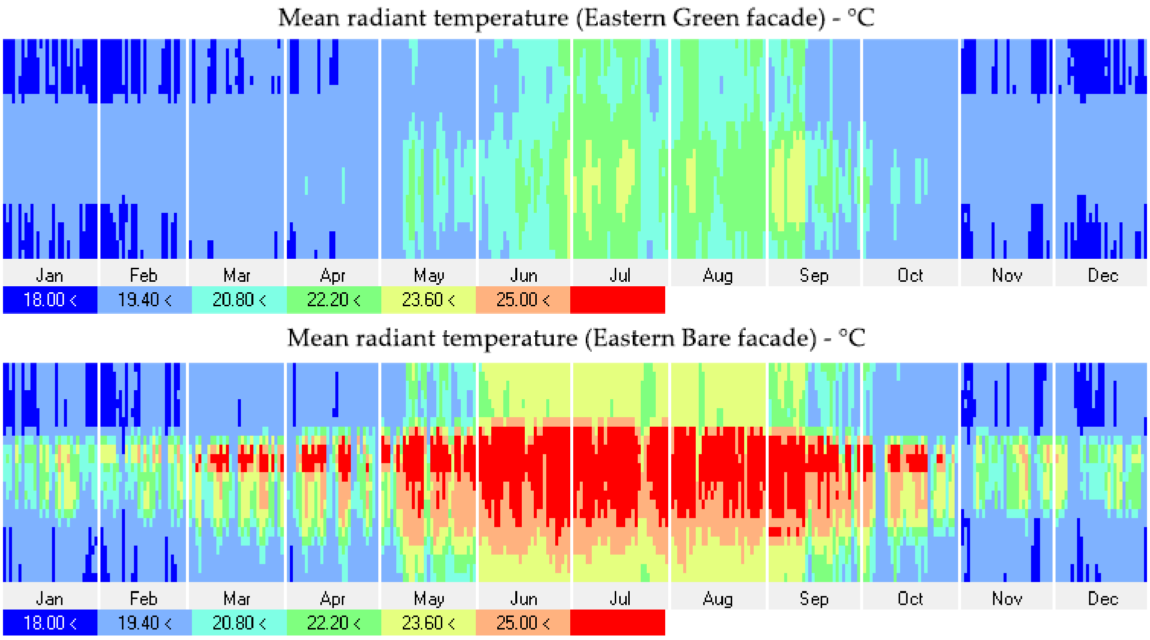
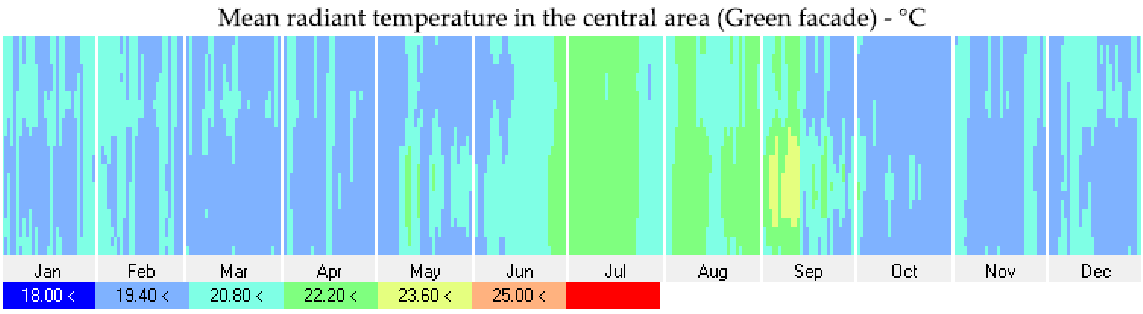


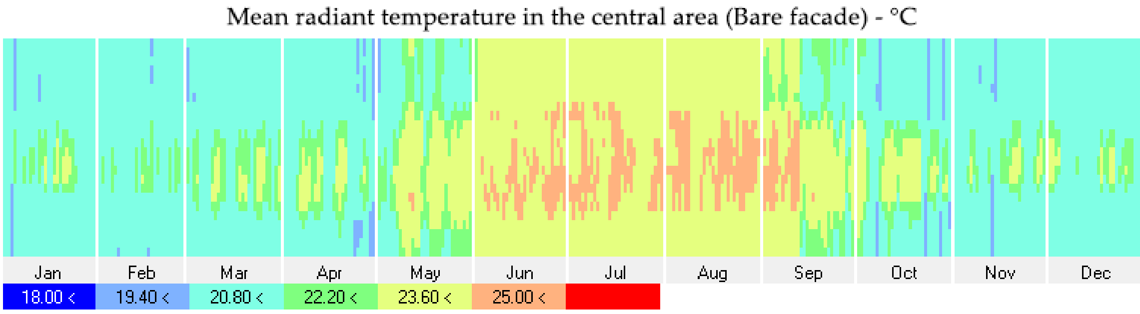
Figure 4.55: The mean radiant temperature of bare and green façade with east orientation during one year.



As shown in figure 4.56, the central area of the office building has a lower mean radiant temperature in the bare facade simulation due to its distance from the glazed façade, which in this case study is 4.50 m. Furthermore, as shown in this figure, the green façade influences the central area as well, and when compared to the results of the southern, western, northern, and eastern green façades, the mean radiant temperature in this area improved.

Figure 4.56: The mean radiant temperature of bare and green façade in the central area of workplace during one year.





- ***Operative temperature***

The operative temperature is the average of the air temperature and the mean radiant temperature, weighted by the convective heat transfer coefficient and the linearized radiant heat transfer coefficient. Figure 4.57 and 4.58 presented operative temperature of bare and green façade respectively in course of on year. In terms of operative temperature, there is a significant difference between the bare and green facades, particularly between January and June and October and January, demonstrating that the green facade has a significant influence on temperature.

Figure 4.57: Operative temperature of the bare façade during one year.

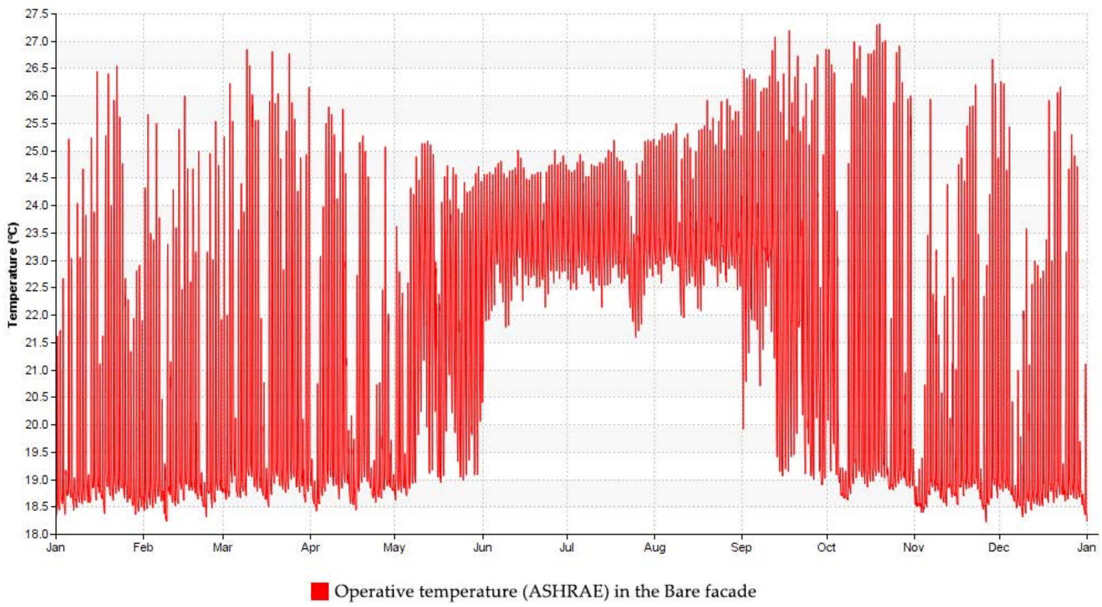
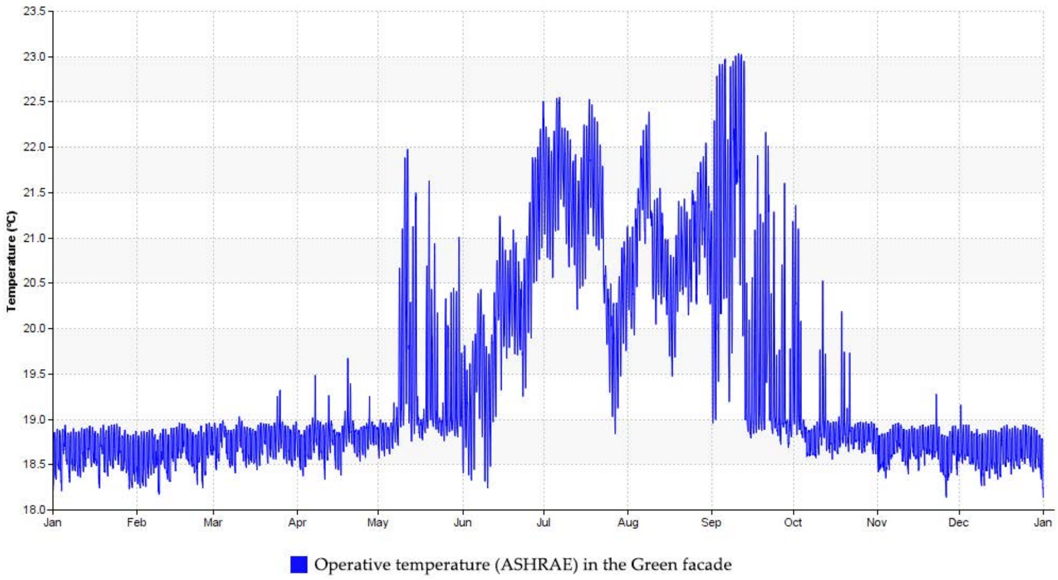


Figure 4.58: Operative temperature of the green façade during one year.



As mentioned in chapter 3, operative temperature can be approximated with acceptable accuracy by:

$$T_o = (T_a + T_r) / 2$$

Where T_o is operative temperature, T_a is air temperature, and T_r is mean radiant temperature. For proving this equation, employed IESVE software and has been chosen 21st June and 21st December (Figure 4.59 to 4.62). As can be seen operative mean radian is an average of air temperature and mean radiant temperature. These figures also show the reduction of operative temperature by using green façade in office buildings in summer.

Figure 4.59: Operative temperature of the bare façade on 21st June.

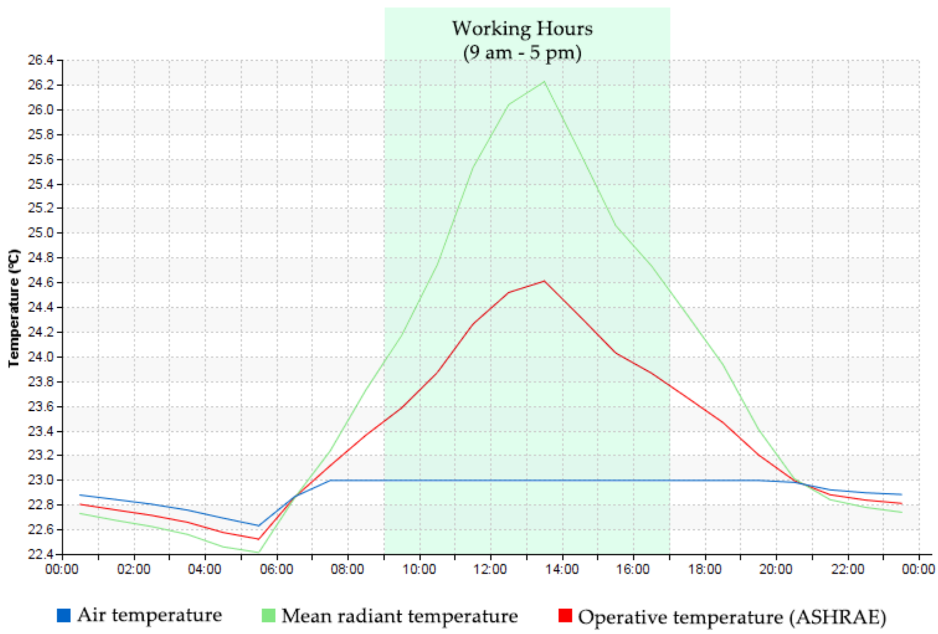
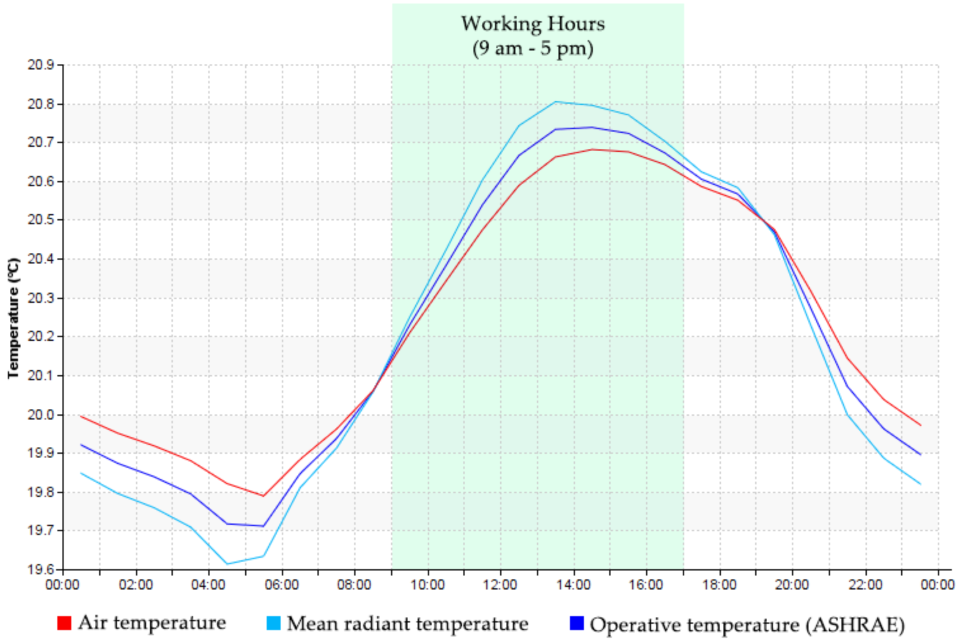


Figure 4.60: Operative temperature of the green façade on 21st June.



- ***Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD):***

The predicted mean vote (PMV) is an empirical score of the human sensation of thermal comfort. As discussed in chapter 3, PMV is a scale that ranges from -3 to +3, which 0 representing ideal thermal comfort and +3 indicating too hot and -3 indicating too cold. It assumes that people who vote +2, +3, –2, or –3 on the thermal sensation level are dissatisfied, and also the simplification that PPD is symmetric around a neutral PMV. Figures 4.61 and 4.62 shows the PMV on 21st June and 21st December in both bare and green façades. Figure 4.61 shows the value of PMV in both bare and green façade in a warm day of summer (21st June) which the green façade is closer to ideal thermal comfort (0) with the minimum value of 1.0 and maximum 1.1 of PMV. Also, by analyzing Figure 4.62, which presents the PMV in a cold day (21st December), the green façade and bare façade maximum value are very far away together. The minimum value is the same in both bare and green façades at 7 am which is not valuable because this is before working hours. During working hours (9 am – 5 pm), the green façade is again closer to ideal value of PMV.

Figure 4.61: Predicted mean vote in bare and green façade on 21st June.

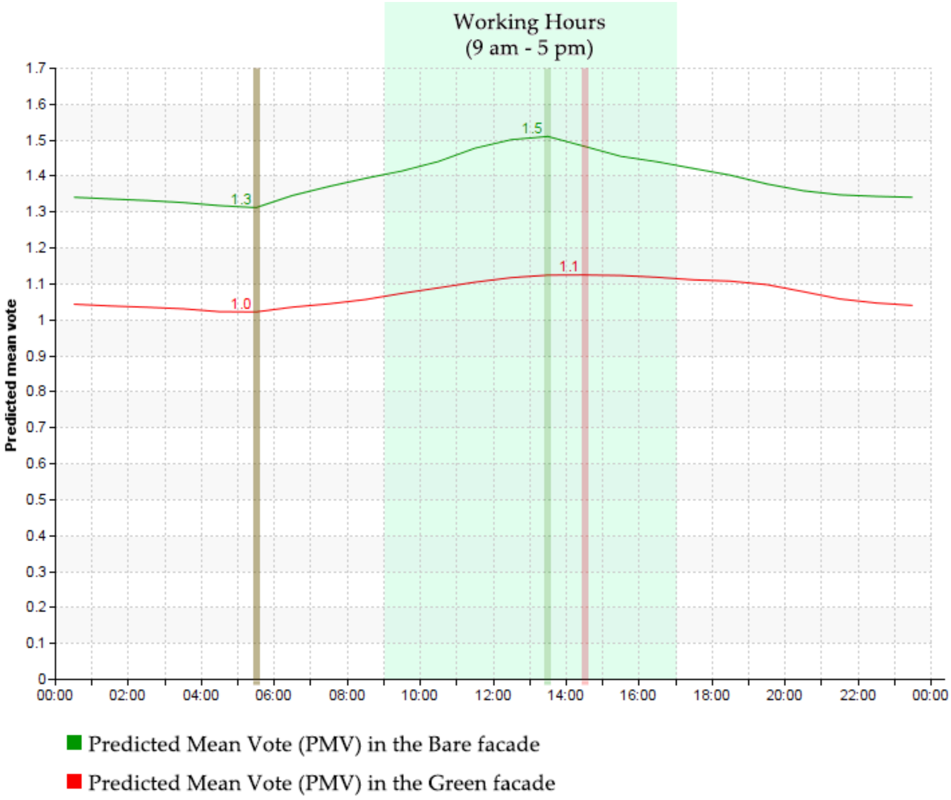
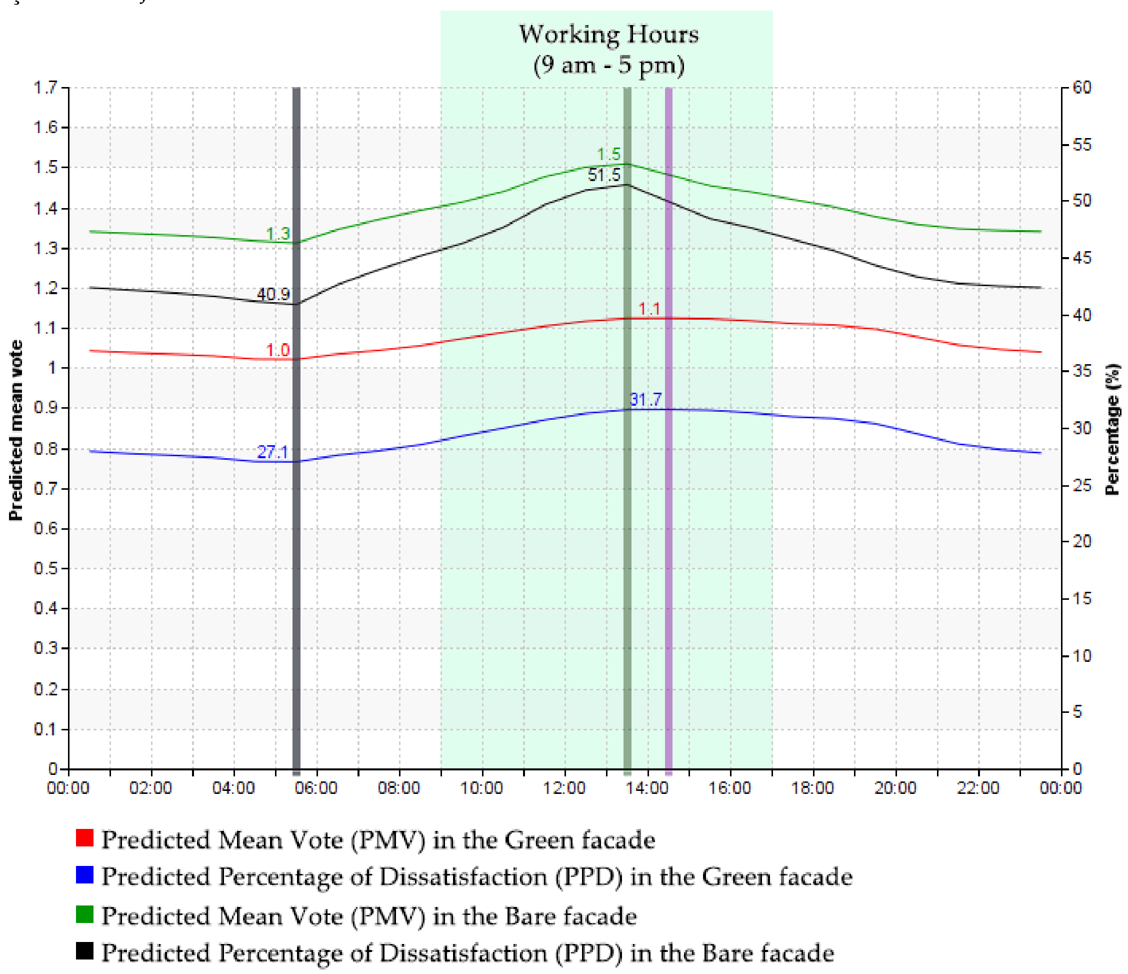


Figure 4.62: Predicted mean vote in bare and green façade on 21st December.

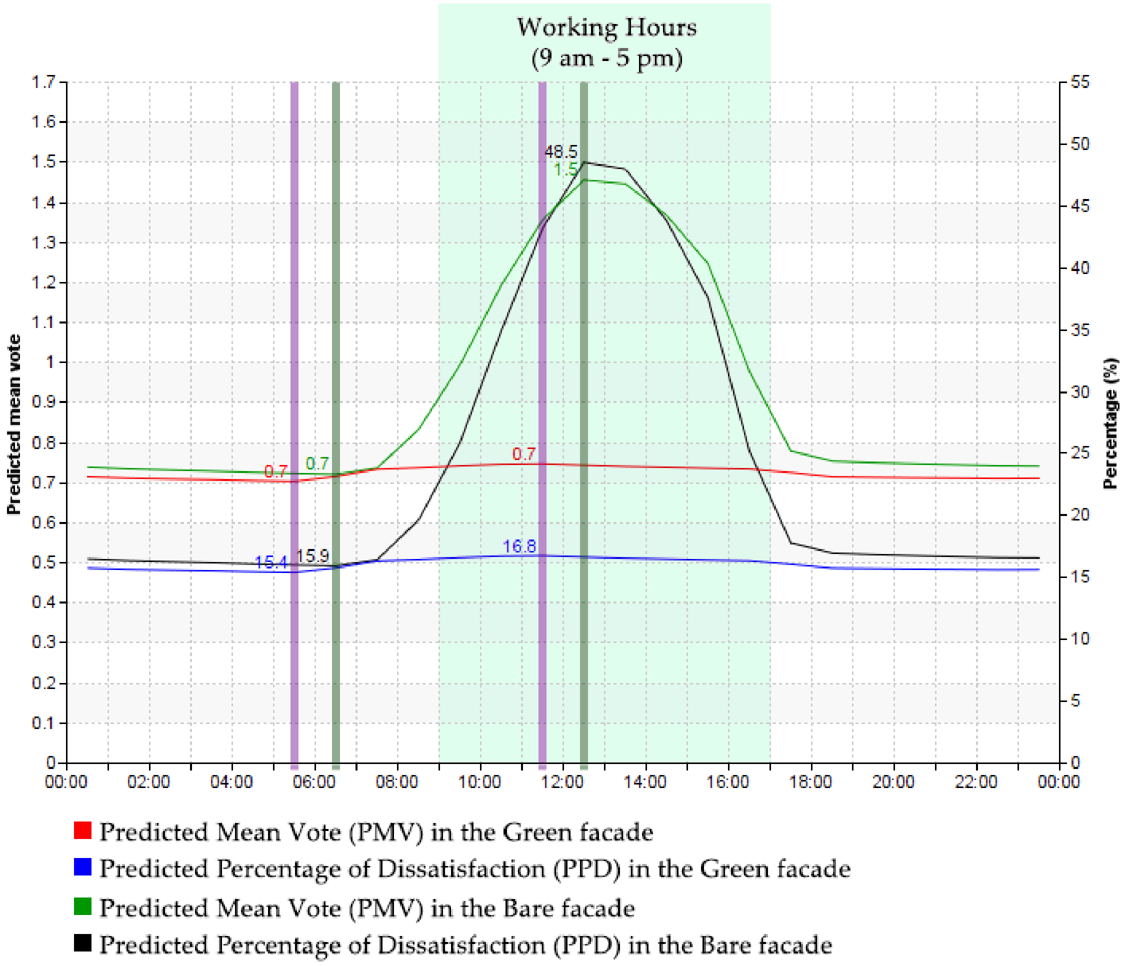
The predicted percentage of dissatisfaction (PPD), which is a function of PMV, is another factor should be considered in measuring thermal comfort [145]. Figure 4.63 presented the difference between bare and green façades in terms of PMV and PPD in 21st June, which can be seen during working hours the maximum percentage of PPD in the bare façade is 51.5% and in the green façade this percentage is 31.7% at 1:30 pm. As a result, by applying green façade the PMV value is closer to ideal (0) and also the percentage of PPD is lower than the bare façade in a warm day of summer.

Figure 4.63: Predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) in bare and green façade on 21st June.



Furthermore, PPD and PMV in a cold day of winter (Figure 4.46) demonstrated that the maximum percentage of PPD in the bare façade is 48.5% while this percentage in the green façade is 16.8% during working hours. From this difference could understand the green façade performance in terms of thermal comfort in glazed office building with a semi-arid climate.

Figure 4.64: Predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) in bare and green façade on 21st December.



4.11.3. The Effect of Green Façade in Cooling Loads

The cooling load of buildings is closely associated to the radiative, the air infiltration from the outside, conductive, and convective heat transfer from building envelopes, and the internal heat gains from lights, equipment, and people. The addition of greenery to building envelopes, also known as a "vertical greening" or "green facade", is a promising approach for lowering cooling loads of buildings [146]. Green facades, from a heat balance standpoint, can reduce overheating of the building's exterior wall due to solar exposure, thereby inhibiting heat conduction through the wall and lowering the cooling load of internal spaces. Besides shading, the vegetation and soil layers cool and humidify the surrounding air through evapotranspiration, influencing the energy demand of the building through air infiltration.

In semi-arid regions, the building's exterior walls temperatures are directly related to the diurnal and annual patterns of solar radiation and air temperatures. The increased surface temperature raises indoor air temperatures and, as a result, cooling loads [147]. While the orientation of a building's façade may be dictated by its urban setting, understanding the climatological impact on the façades aids in selecting the appropriate green façades to minimize heat gain and reduce system cooling loads. For this purpose, to test the effect of the green facade on cooling loads within Denver's weathering profile, a base case simulation was performed. Green façade configurations contribute to the sensible loads of cooling systems.

Direct solar radiation and ambient air temperature are related to sensible cooling loads of a typical base case floor to test the effect of green façades on the cooling load (4th floor of the model) [54]. The ambient dry bulb temperatures are simulated for a typical summer day, with the maximum dry bulb temperature reaching 40 °C (dry bulb temperature calculated by IESVE, from the Denver weather file).

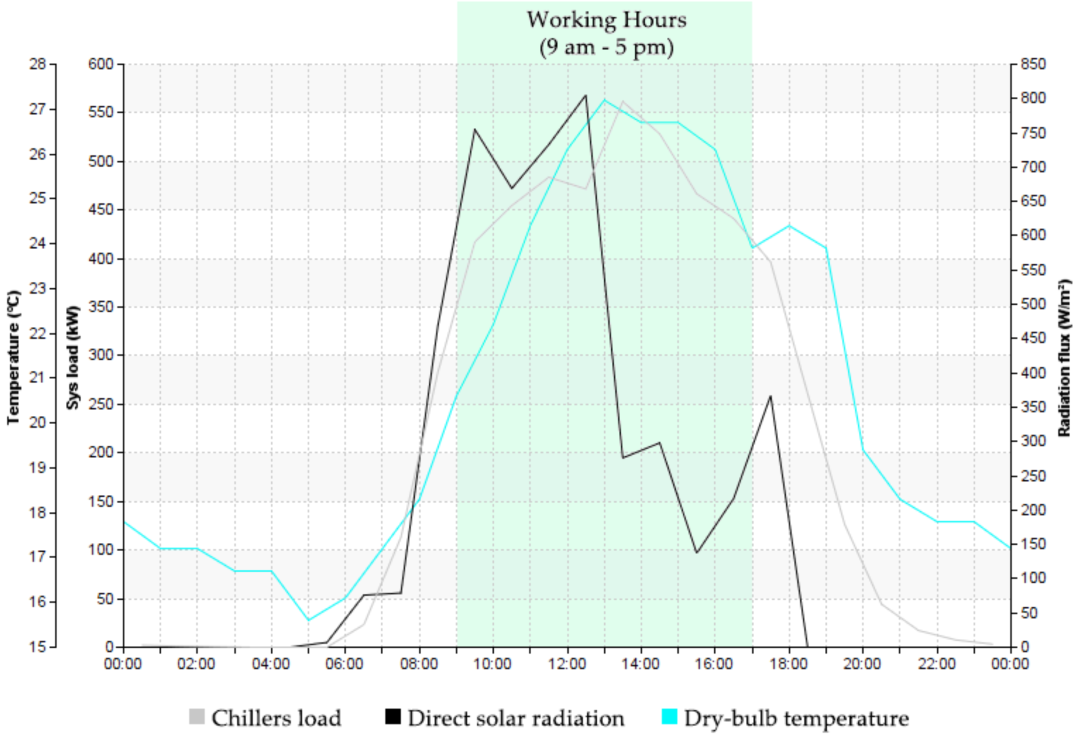
Summer is considered the most thermally stressful season of the year in semi-arid regions, and discussions in the review of the literature demonstrated the complexity of providing thermal comfort in an office building environment without air conditioning in summer. Cooling loads due to green façade performance are investigated to understand the interaction between green facades as an indoor thermal moderator in order to reduce building energy consumption. The results analysis discusses the effect of green façade on peak summer cooling loads, as well as annual cooling loads.

- ***The Influence of Green Façade on Peak Summer Cooling Loads***

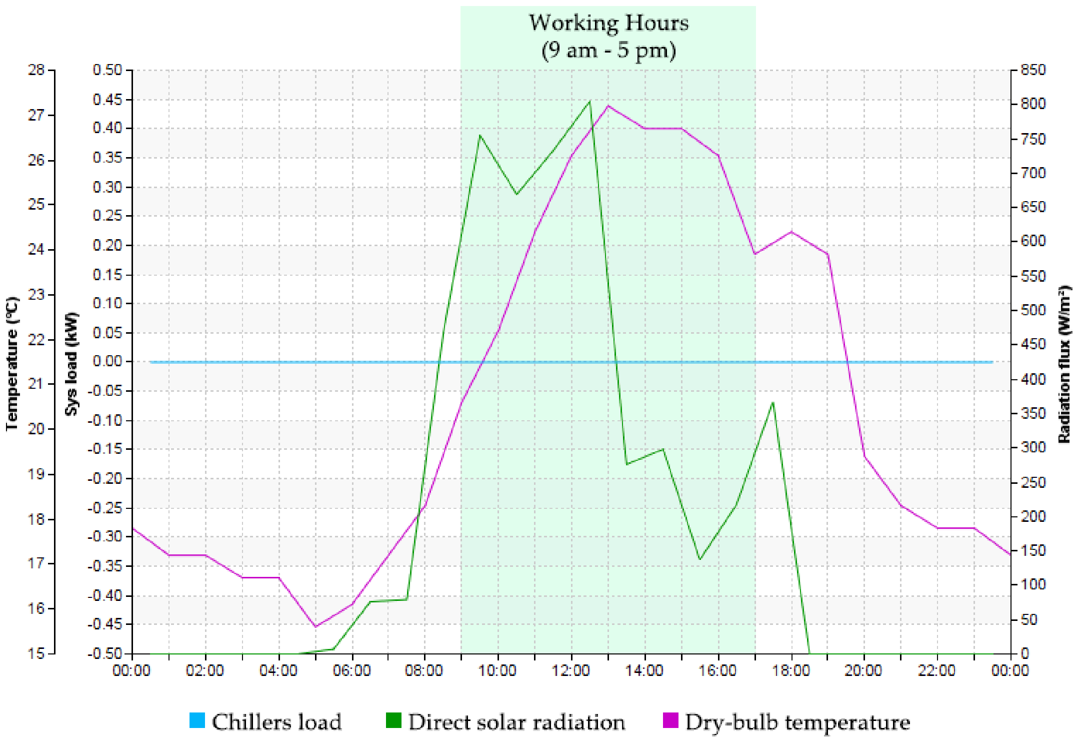
To evaluate the relationship between green façade and cooling loads, simulation results for bare and green façades were disaggregated to solar gains through façades, sensible system cooling loads, and ambient dry bulb temperatures. The three Y-axes in Figure 4.65 are, from left to right, the dry bulb temperature in °C, cooling loads in KW, and direct solar radiation in W/m2, with the X-axis displaying the time of day. The simulation results shown in figure 4.65 are based on the sensible cooling loads of the zone behind the model's bare and green façades on a typical building floor (Level 4 of the model). The rises in dry bulb temperature are directly related to conduction gains through both green and bare façades and have a similar effect in raising cooling loads on both façades.

According to the results of the simulation on 21st June, in both bare and green façades, dry-bulb temperature and direct solar radiation have the same values and the difference is in cooling load. The cooling load of the green façade is 0 kW/h, which this figure in the bare façade is about 550 kW/h. Consequently, the green façade as a vegetation layer could influence the cooling load of glazed office buildings in a semi-arid region significantly, and subsequently cooling energy use will be decreased dramatically.

Figure 4.65: Effect of green façade on sensible summer cooling loads (21st June). a) Bare façade; b) Green façade.



a) Bare façade cooling load



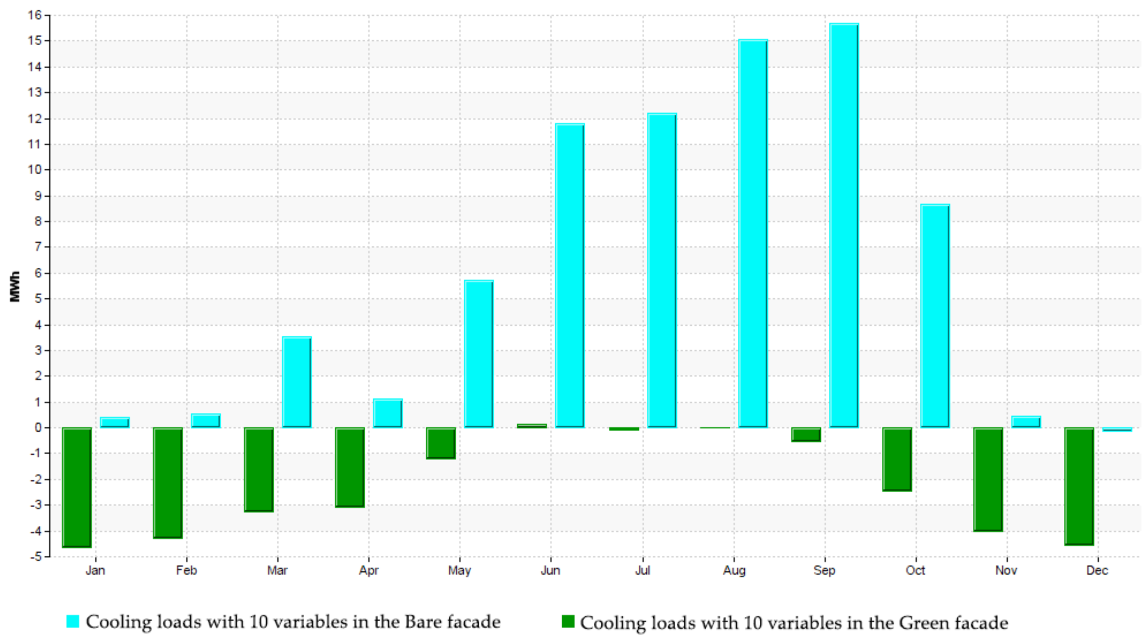
b) Green façade cooling load

- ***The Influence of Green Façade on Monthly Cooling Demand***

Denver has a semi-arid climate (BSk), which means that façades must compete not only with high amplitudes of daily temperatures in the summer but also with cold winds in the winter. The general building recommendations are to construct façades with minimal dimensions and openings to the West and East orientations and to use the South façade for winter heating [148].

Peak load calculations are used to determine the size and operation characteristics of cooling equipment. Total monthly cooling loads of both bare and green facades were calculated for the typical model floor and using dynamic weather profiles to predict annual cooling loads (Figure 4.66). Dynamic Weather is a representation of weather with the ability for variability during a simulation that estimates cloud cover, wind velocity, and dry and wet-bulb temperatures. The relationship between the predicted total cooling loads (Y-axis) and the month of the year (X-axis) is depicted in Figure 4.66. The monthly cooling loads in this simulation are calculated using ten variables: air temperature, dry resultant temperature, relative humidity, internal gain, solar gain, external conduction gain, internal conduction gain, aux ventilation gain, infiltration gain, natural ventilation gain, cooling plant sensible load, dehumidification plant load, and cooling + dehumidification plant load.

Figure 4.66: Monthly total cooling loads in bare and green façades, with considering 10 variables including: air temperature, dry resultant temperature, relative humidity, internal gain, solar gain, external conduction gain, internal conduction gain, aux ventilation gain, infiltration gain, natural ventilation gain, cooling plant sensible load, dehumidification plant load, and cooling + dehumidification plant load.



Due to Denver's climatic profile, it is clear that maintaining thermal comfort within an office environment necessitates sensible and latent load removal all year. As figure 4.66

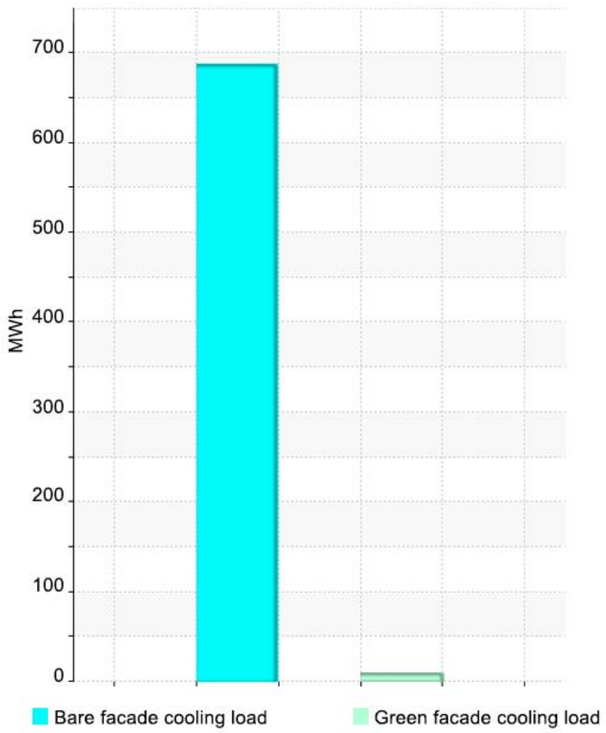
presented, green façade influenced the thermal performance of building envelopes in all seasons with protecting façade from solar radiation during summer and also wind and cold weather during winter. Using appropriate cavity depth, proper plant density, selecting structure in accordance with the main facade, and also considering the climate in the green facade design are all important for improving the green façade performance.

At this point, predicting the annual total cooling loads is critical in determining which type of façade (glazed or green façades) offers opportunities for energy savings through climatic control.

- ***The Influence of Green Façade on Annual Cooling Demand***

Summing the total monthly cooling loads of the bare and green façades which presented in Figure 4.67 indicated that the green façade has a very less annual demand for cooling loads than the bare façade. The green façade is expected to consume 1% annual total cooling loads and the bare façade 99%, which can be attributed to that the glazed layer back of the green façade is less exposed to direct solar radiation, combined with lower dry-bulb temperatures during the day.

Figure 4.67: Annual total cooling loads for bare and green façades.



4.11.4. Energy Savings in a green façade versus a bare façade

Green walls, such as green façades and living walls that incorporate plants into building envelopes, improve façade thermal performance, as discussed in section 4.7.2, and reduce building cooling loads, as discussed in section 4.7.3, and Overall energy consumption. Furthermore, green walls can be used to control the microclimate of buildings as passive energy-saving systems.

In previous research, the energy-saving properties of green façades have been evaluated based on field experiments [7][114][13][116][120][149]–[151], self-developed models [143], or professional building simulation tools [109][11][111][118]. The reported green façades energy-saving rates have a considerable range of 4.7%–65%. The wide variation in energy-saving rates can be related to climatic conditions, the size of green façades, and vegetation/soil characteristics, but it could also be associated to building size.

- *Electricity Consumption*

With simulating a green façade and bare façade as presented in Figure 4.65, 4.66, electricity consumption during one year predicted which in the bare façade electricity usage during summer is higher than another seasons and the maximum use of electricity is in September about 810.2 kW. While, electricity consumption in green façade demonstrated that higher usage of electricity is in summer but this electricity usage is reduced significantly by comparing with bare façade, and also the maximum use of electricity is during September which is about 389.2 kW. This comparison shows that during fall, winter, spring seasons green façade could perfectly reduce electricity consumption which this value is the most of the months has reached almost zero, and during summer and September this reduction is more than half of electricity consumption in the bare façade.

Figure 4.68: Total electricity consumption in bare façade during the course of one year.

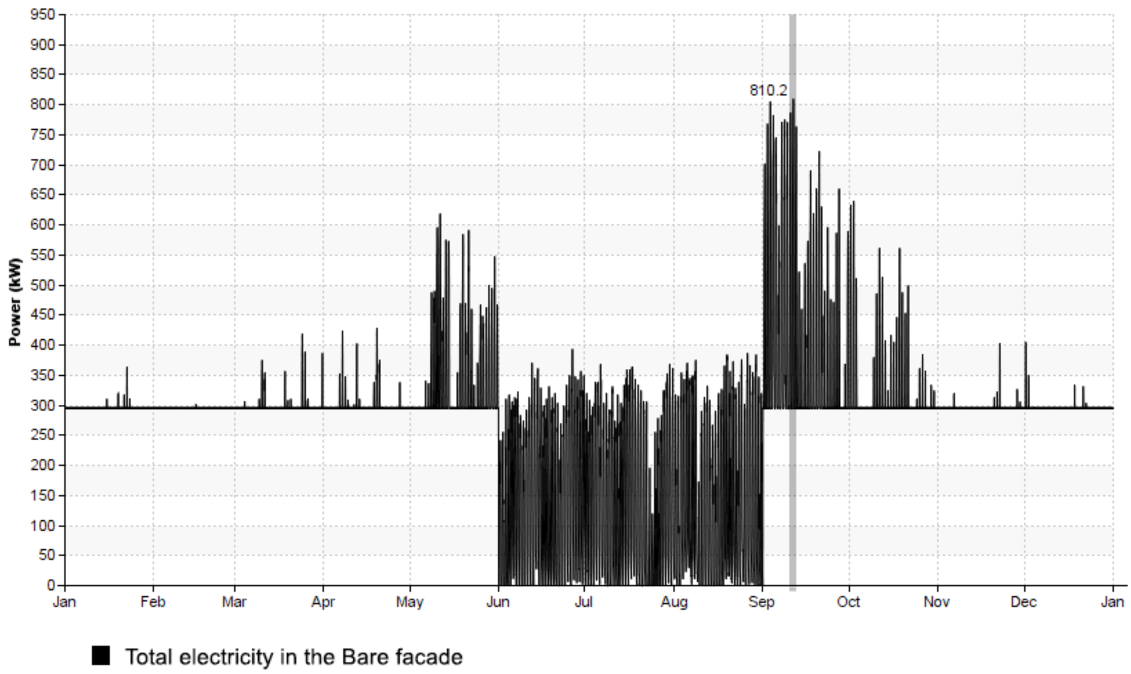
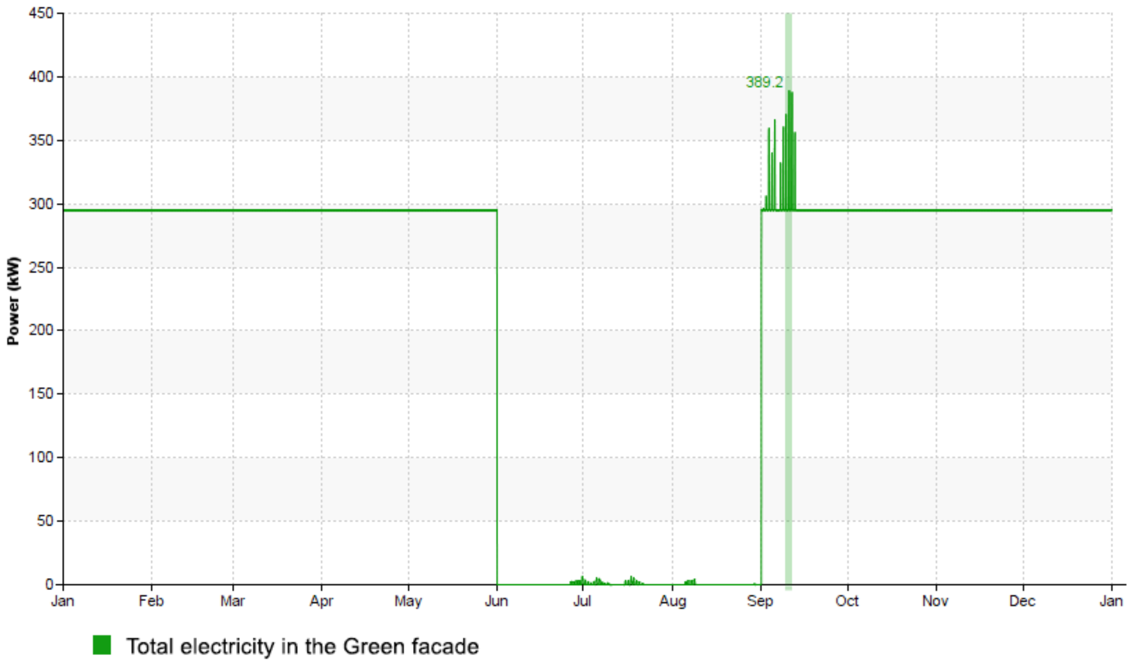


Figure 4.69: Total electricity consumption in green façade during the course of one year.



- ***Total Natural Gas Consumption***

The green façade prevents entering direct solar radiation from by covering the glazed façade; this feature is very effective in lowering electricity consumption, especially during summer. However, in winter, solar radiation can improve indoor air temperature, which green façades prevent entering solar radiation partly in building envelope. Due to this approach, many researches recommended considering the proper density of vegetation in green façade specially in southern part of buildings that this matter could improve green façade performance considerably. It should be noted that, as previously discussed, the green façade also protects building envelopes from cold winter winds. In the context of this research, the wind direction in Denver is from the west, and it is very effective applying high density of plants in west orientation of buildings to reducing energy consumption.

Results of simulation (Figure 4.70, 4.71) in terms of natural gas consumption in bare and green façades show that the green façade increased partly the amount of natural gas consumption in the building. The maximum amount of natural gas consumption in the bare façade is 2017.0 kW/h which this figure in green façade is 2066.2 kW/h.

Figure 4.70: Total natural gas consumption in bare façade during the course of one year.

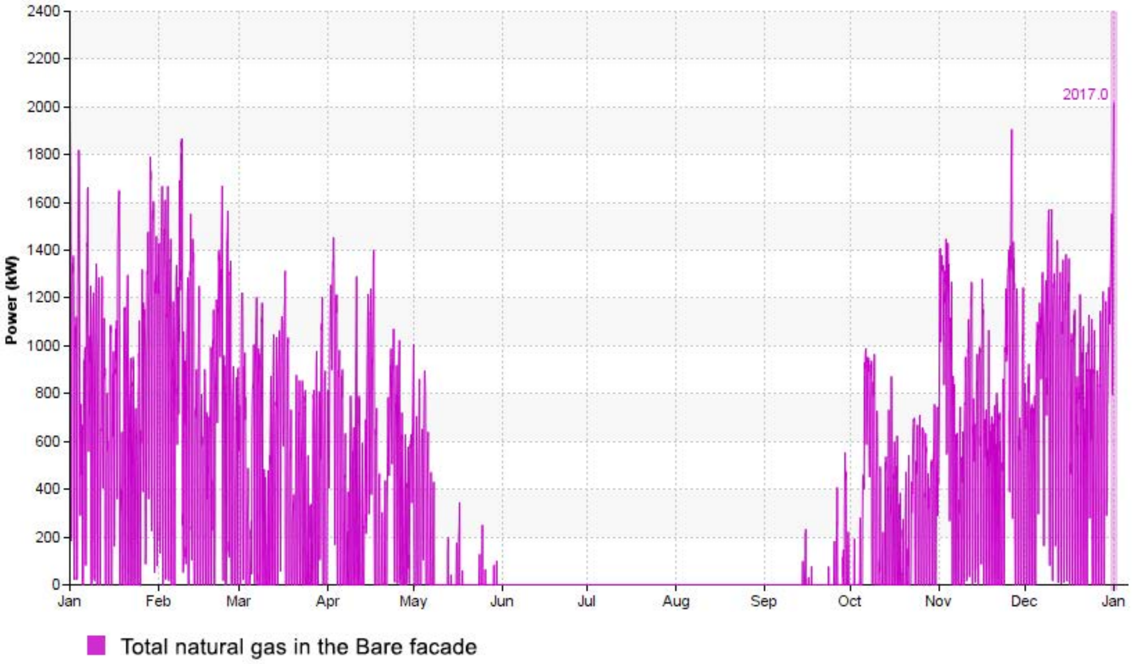
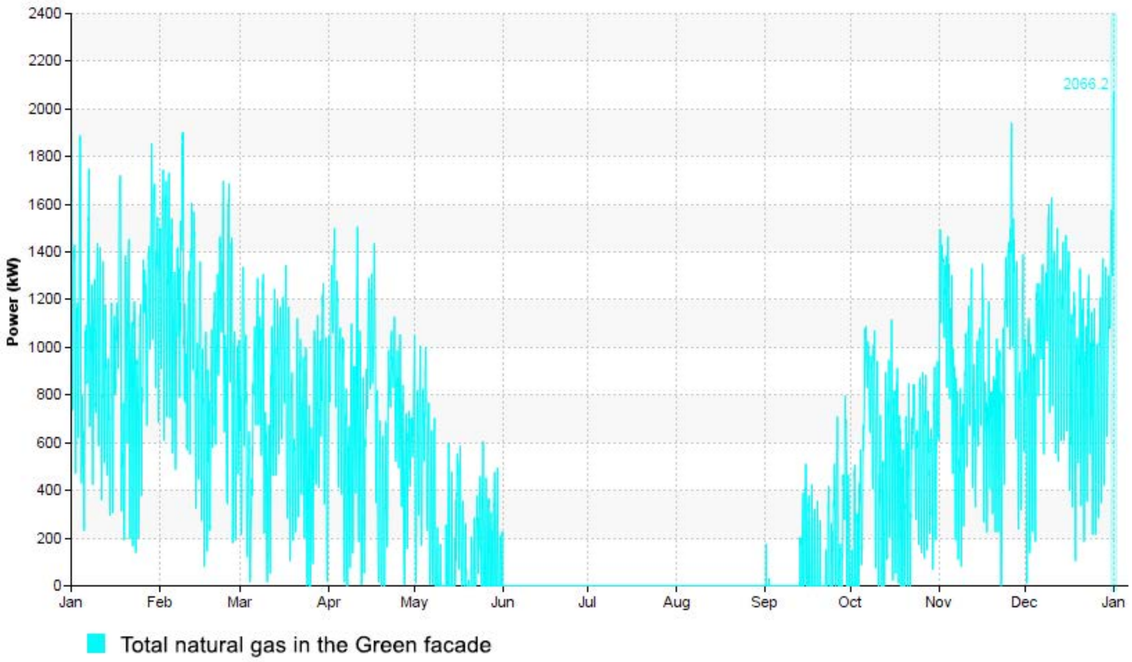


Figure 4.71: Total natural gas consumption in green façade during the course of one year.



- ***Total Energy Consumption***

More than 76 percent of all electricity used as well as over 40 percent of all energy used in the United States and associated greenhouse gas (GHG) emissions, are used to provide comfortable for residential and commercial buildings. Therefore, it is critical to reduce energy consumption in buildings in order to address national energy and environmental challenges. Heating, ventilation, and air conditioning account for 35% of total building energy consumption; lighting accounts for 11%; major appliances (water heating, refrigerators and freezers, dryers) account for 18%; and the remaining 36% is spent on miscellaneous items such as electronics [152].

Heating, cooling, ventilation, lighting, water heating, refrigeration, drying, computers and electronics, and other factors all contribute to total energy consumption in commercial buildings, which includes office buildings. Figures 4.72, 4.73 presented total energy consumption in bare and green façades during the course of one year. According to these results, total energy use in the green façade is lower than the bare façade which during summer this reduction is more expected, and during winter due to the use of natural gas energy for heating the use of total energy in the green façade is more than summer.

Figure 4.72: Total energy consumption in bare façade during the course of one year.

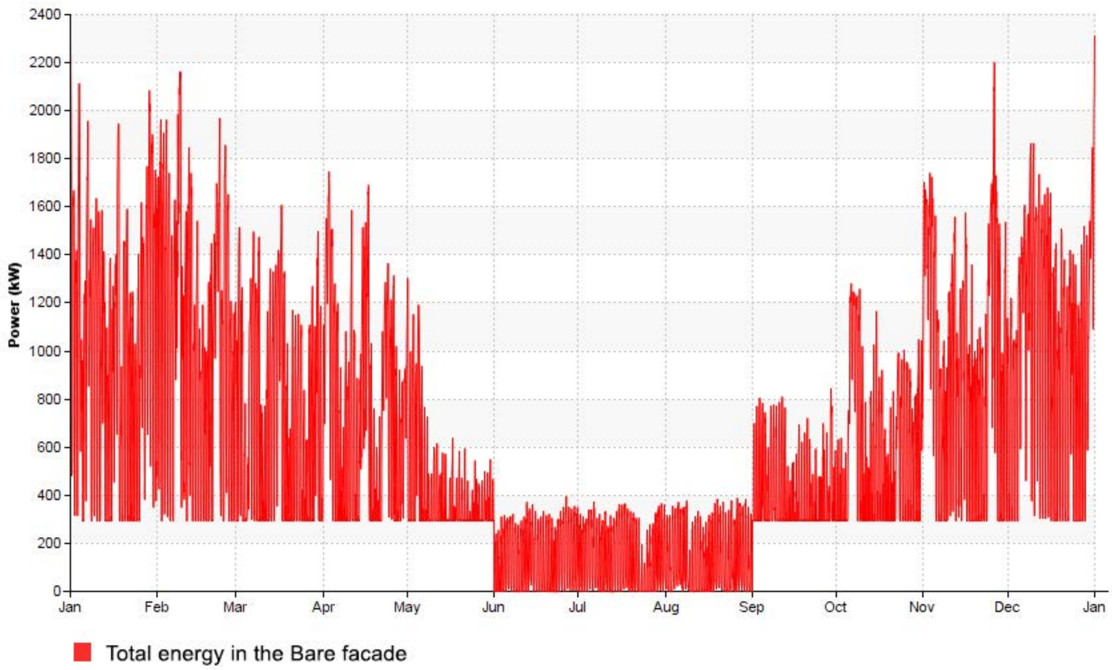
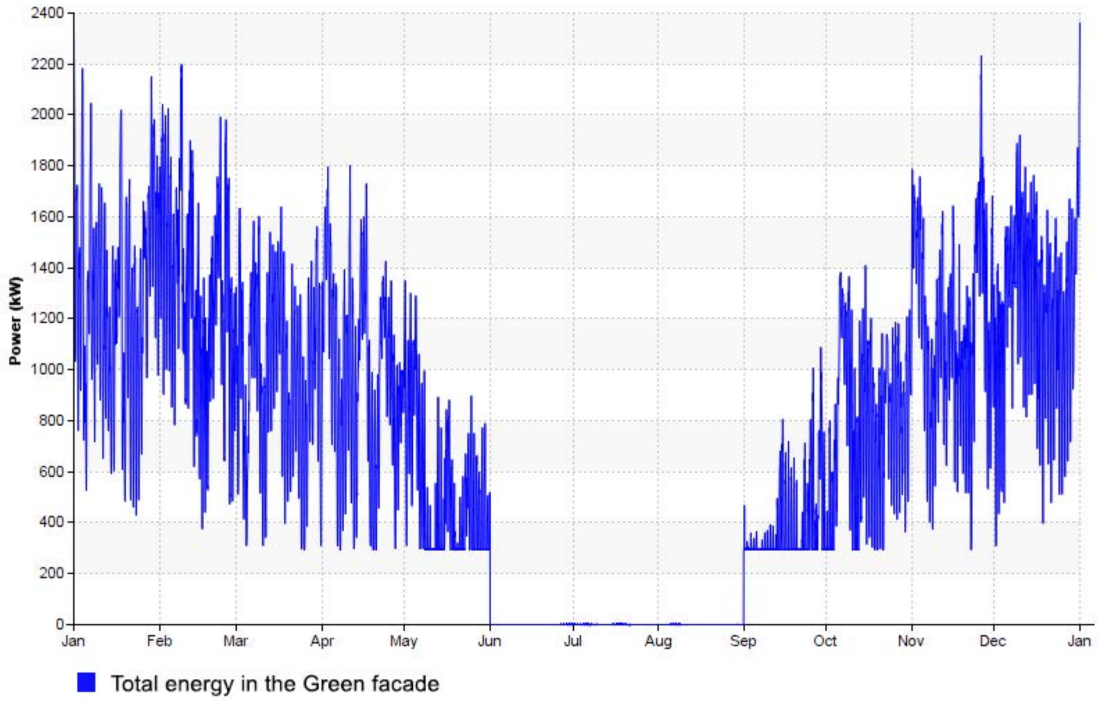


Figure 4.73: Total energy consumption in green façade during the course of one year.



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Chapter Five: Future Research (A New Concept of Vertical Gardens)

5.1. Introduction

With our world's increasing urbanization, it is becoming increasingly clear that the city will become the humanity biosphere. Attempts to integrate nature into our built environment are increasing and the biological paradigm has been permeated in our building culture. Vertical greenery systems, such as green façades and living walls, that respond to and interact with their surroundings and inhabitants, are already a part of today's bio façade scenarios.

By 2050, cities will be home to two-thirds of the world's population, as well as the source of the majority of the world's pollution. We are already dealing with metropolitan populations of nearly 40 million people. As a result, the world population is faced with resource scarcity such as clean air and water, as well as the challenges of massive waste production, and at the same time, urbanization contributes to climate change. As an example, across the American continents, newly formed semi-arid regions evolved from arid regions, where the climate became wetter [1], and this issue shows the long-term global warming and climate change trend is especially increasing in semi-arid regions [2][3]. Sustainability, renewable energy, alternative building techniques, refined materials, and interacting digital systems all play crucial roles in this situation.

Nature has long been regarded as a source of inspiration in architecture. There are numerous movements that can be merged together under the overarching concept "bio-inspired." Most refers to imitating nature by performing aesthetic forms and symbolic associations without regard for knowledge of biology or necessarily sustainable development [4]. Architects and researchers should indeed distinguish between a primarily formal inspiration of nature with an aesthetic or symbolic goal and a scientific approach of biological knowledge that attempts to bring biology and architecture closer together, referring to a new movement known as biomimetic architecture [5].

A new concept of vertical gardens takes on these challenges with the concept of living architecture, focusing on blending architecture with technology and biology that can adapt to the environment and the needs of semi-arid regions in a process of constant evolution. 3D printing as a technology in architecture has recently been widely researched, and in this chapter, a new concept of vertical gardens in architecture has been created by combining this technology as creating structures of vertical gardens with biological components which are cyanobacteria as vegetations in green façades.

5.2. Vertical Gardens and Blending Architecture with Technology and Biology

Within the development of science and technology in the past century, important discoveries have paved the way for progress in incorporating nature into the built environment which according to the "Anthropocene" that describes the story of man's impact on the planet, these discoveries can aid in reducing human impacts on nature.

Since the biological paradigm has appeared as new developments in architecture and design, have caused enter phenomena of nature into our built environment. A strategic investigation for signs of nature in the context of architecture has known the growth phenomenon as one of the still blank spots on the building scale [6]. Growth is a matter that is discussed on an urban scale and also investigated in the digital domain, but there are no individual growing buildings that exhibit the qualities connected with natural growth.

Vertical gardens (green façades and living walls), as a form of biological growth in building scale, have numerous benefits in buildings and urban scales, such as mitigating urban heat islands, reducing energy consumption, improving thermal comfort, reducing air pollution, and enhancing living conditions, all of which have been thoroughly discussed in previous chapters [7]–[12].

Biological growth appeared on varied levels. In systems of nature, it occurs at the molecular, cellular, tissue, organ, and organismal level and also the development of populations, ecosystems, and the evolution of the biosphere. In the context of biology, growth is one of life's primary characteristics. In other fields, such as sociology and economics, the term is used more broadly, referring to growth as the quantitative aspect of increase. In biology, quantitative growth is frequently characterized as reaching higher levels of complexity, introducing a qualitative alteration into the structure. Changes at the cellular level may result in different tissue quality, for instance, a phenomenon related to the design principles of hierarchical structuring and emergence. Qualitative growth concepts demonstrate strategies that vary from quantitative aspects, referring to more complex structures.

Growth in an architectural context is typically associated with construction, causing an increase in terms of material used or enclosed space. This connection could also include all stages of material processing and the logistical efforts involved, but it is most visible on building construction sites or with urban scale.

Some architects utilized merging technology and biology in architecture such as Prof. Marco Poletto, Prof. Claudia Pasquero (the Bartlett School of Architecture, UCL) and also Prof. Kyoung-Hee Kim (University of North Carolina at Charlotte) that their projects described in below.

▪ ***Micro-algae Window Project by Kyoung-Hee Kim and her research group:***

This project was three months into field application to develop a micro-algae window for retrofitting low-performing commercial façades that tested in the Storrs building which is an office building constructed before 1980. The 8' x 12' (20.32 cm x 30.48 cm) window's resin lattice is filled with water-based micro-algae fluid, which glows bright green in the sunlight (Figure 5.1, 5.2). This study has been measuring how much a micro-algae window can improve energy efficiency by shading and insulation, as well as how well it can improve indoor air quality by carbon sequestration. The results have shown that micro-algae façades have environmental benefits [13].

Figure 5.1: The micro-algae project by Kyoung-Hee Kim and her research group, the College of Arts + Architecture (UNC at Charlotte).

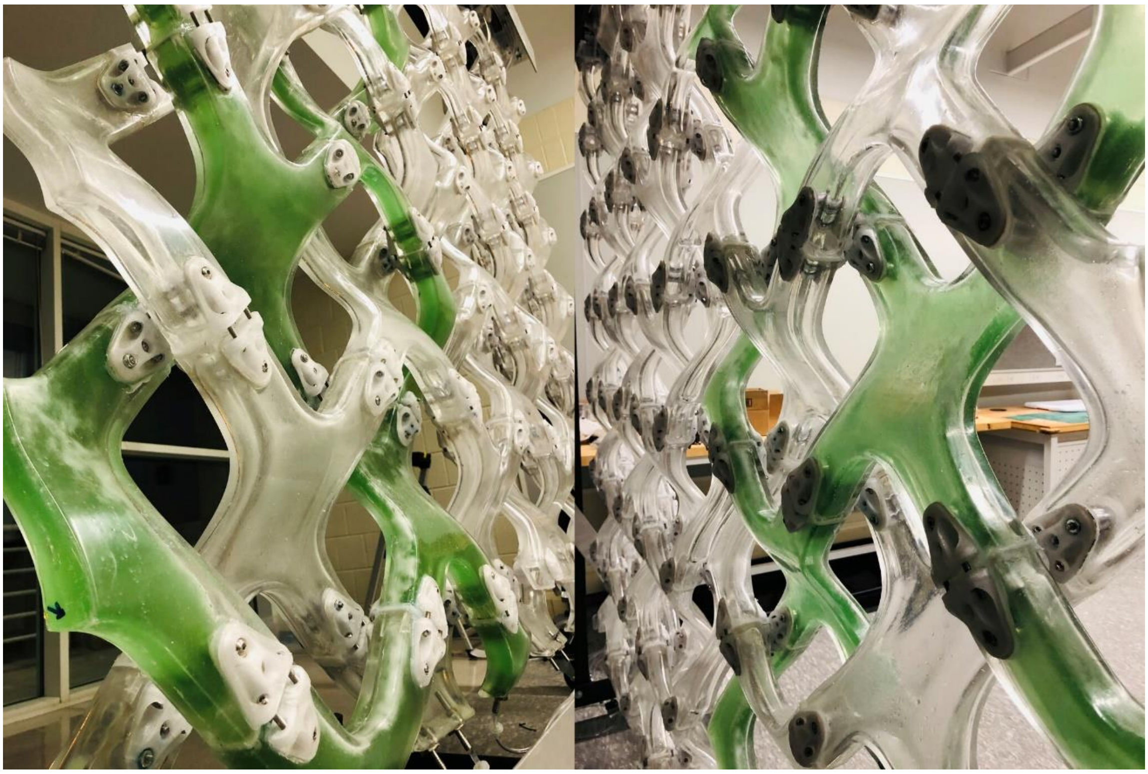
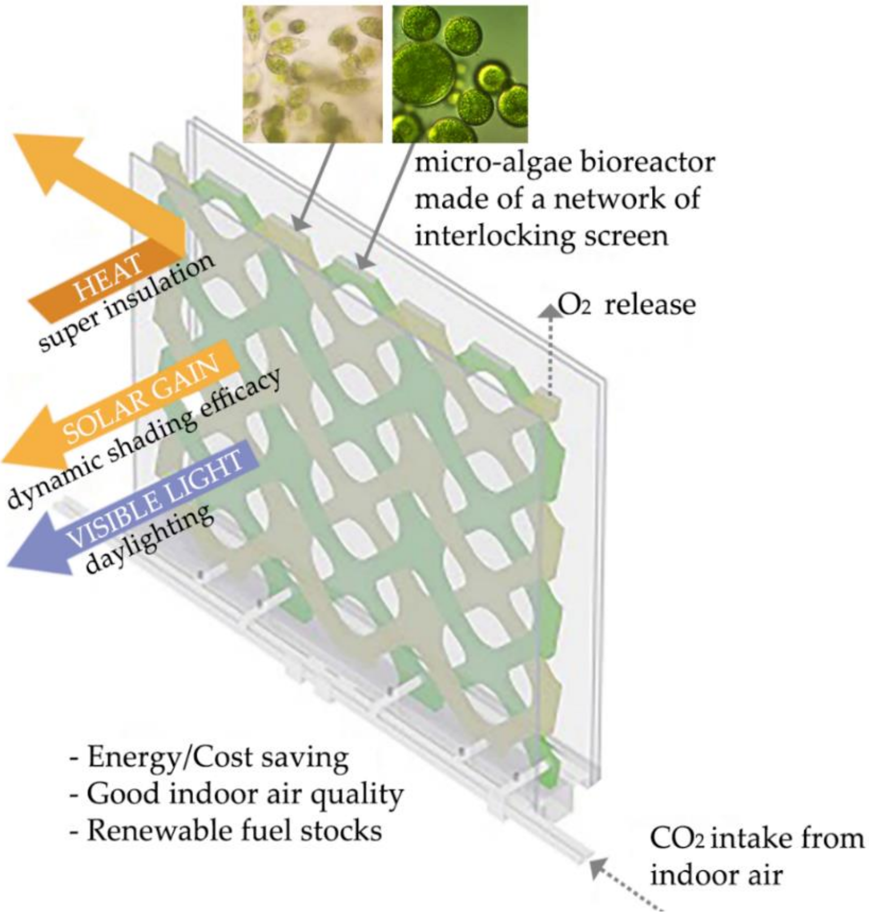


Figure 5.3 shows how divided micro-algae facades will include a network of micro-algae-filled screens that will serve multiple beneficial functions such as carbon sequestration, solar shading, and thermal insulation. Not only will this result in lower energy costs and cleaner indoor air, but algae can also be collected and transformed into biofuel, producing a renewable energy source. Indoor air quality has been shown in studies to have an impact on office workers' productivity and cognition. A 2015 study discovered that workers in "green" office environments performed significantly better in nine areas of cognitive function than workers in conventional office environments [14].

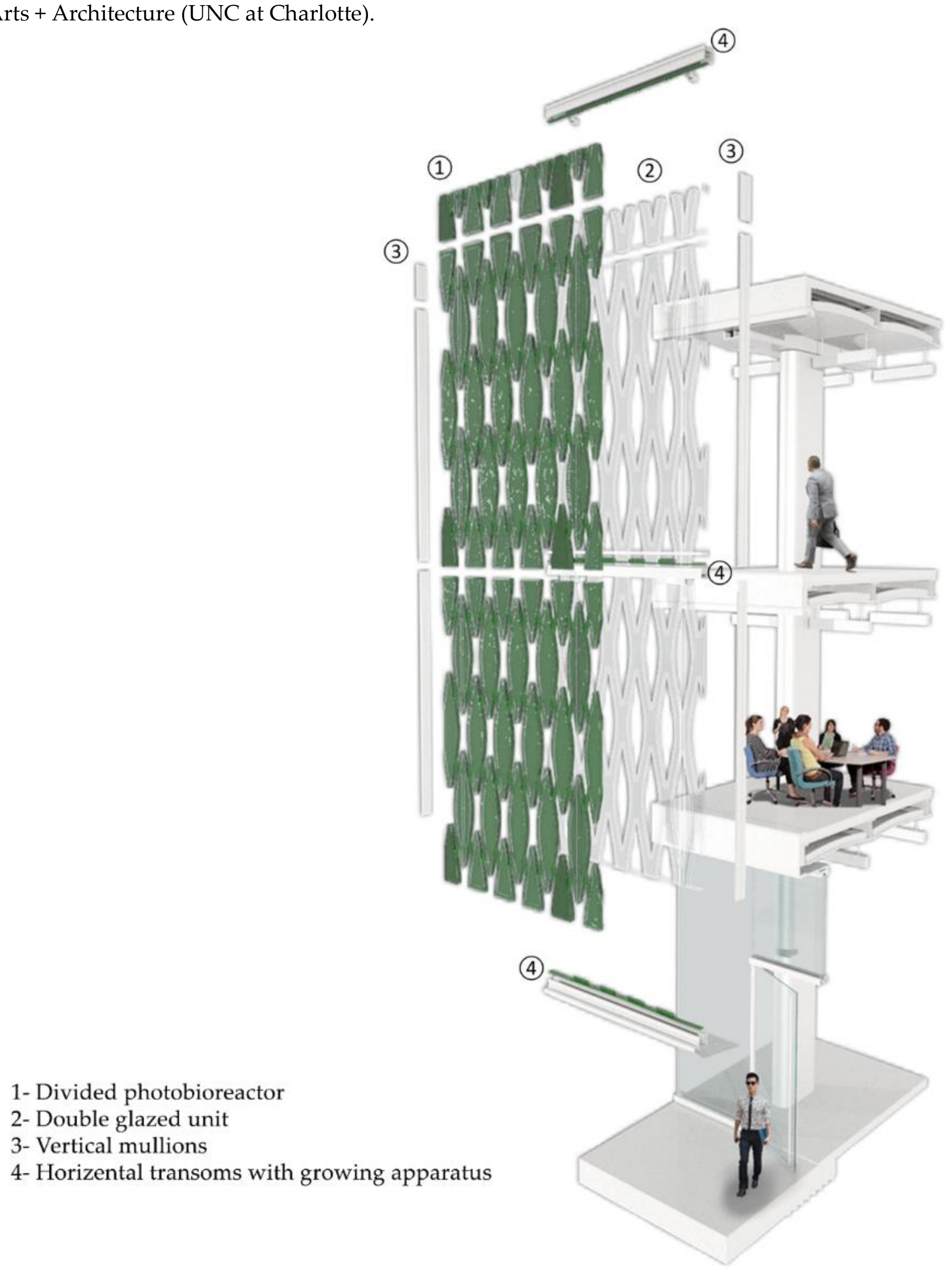
Figure 5.2: The micro-algae project testing in the Storrs building.

Figure 5.3: Showing the mechanism of micro-algae window by Kyoung-Hee Kim and her research group.



According to Young-Hee Kim [15], the "micro-algae façade is made up of two primary components: photobioreactors integrated with vision glazed panels attached to metal frames, and micro-algae growing apparatus housed in metal frames." (Figure 5.4) the micro-algae façade is designed as a factory-assembled unitized façade system for quality control and quick installation; each façade unit could be installed at the edge of the concrete slab or perimeter beam, with the micro-algae growing apparatus installed on site.

Figure 5.4: Divided micro-algae façades by Prof. Kyoung-Hee Kim and her research group, the College of Arts + Architecture (UNC at Charlotte).



- ***Photosynthetic building cladding system by M. Poletto, C. Pasquero:***

This project uses solar energy to remove CO_2 and pollutants from the atmosphere and produce a valuable food resource in the form of algae. Photosynthetic building cladding system (Figure 5.5) offers: biologically active (BIO) and digitally connected (SMART) design, capable of capturing CO_2 and evolving into a carbon-negative product over its entire life-cycle. Furthermore, it improves citizens' well-being by reducing the impact of air pollution in urban areas.

Figure 5.5: Three projects (a, b, c) of photosynthetic building cladding system by M. Poletto and C. Pasquero.

a) The Urban Algae Canopy at the 'feeding the planet' Expo in Milan, 2014

b) Urban Algae Folly, Expo in Milan, 2015

c) The Photo.Synth.Etica project, Dublin, 2018.

This new composite bio-digital technology merges the aesthetic and material properties of ethylene tetrafluoroethylene (ETFE) cladding - lightweight, robust, transparent, and chemically inert - with micro-natural algae's ability to capture solar radiation and absorb CO_2 10 times (Figure 5.6) more efficiently than trees. Buildings that are photosynthetic are converted into bio-power plants, carbon sinks, and air pollution filters. According to this research design, the same amount of CO_2 is absorbed by a mature tree in only 2 square meters of the photosynthetic building cladding system. Because of the high energy and protein value of micro-algae, the integrated bio-building approach enables local production for the urban environment while removing no land from forest and nature.

Figure 5.6: Comparison photosynthetic building cladding system and trees in terms of absorbing CO_2, Dublin, 2018.

M. Poletto and C. Pasquero explained how the photosynthetic building cladding system works as follows [16] (Figure 5.7):

1- At the bottom of the facade, unfiltered urban air is introduced. Air bubbles naturally rising through the watery medium within the ETFE cladding panels come into contact with algae microbes.
2- Photosynthetic modules are designed to maximize algal culture solar exposure and also increase the amount of surface contact they have with air molecules and particles.
3- The algae capture and store CO_2 molecules and air pollutants, allowing the algae to grow into biomass.

4- The biomass can be easily harvested and used to make bioplasmic raw material, biofuel, fertilizers, and superfoods.
5- To complete the process, freshly photosynthesized oxygen is released into the urban microclimate or the building interior from the top of each photosynthate facade unit.

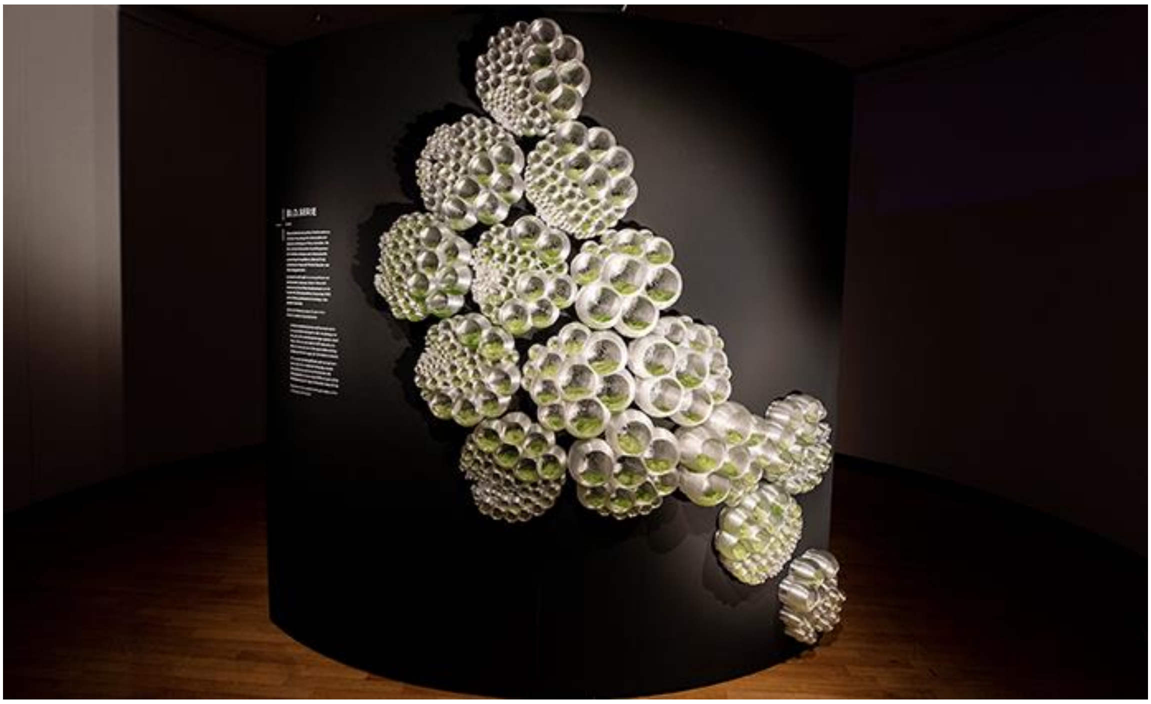
Figure 5.7: Photosynthetic building cladding system mechanism, Dublin, 2018.

The functionality of EFTE modules has been broadened beyond screening and heat retention, therefore, make them more adaptable to urban environments. The cavity within each module is transformed into a habitat for the cultivation of living cultures by this design. This project combines digital design and fabrication technologies to improve aesthetic qualities, environmental performance, and adaptability to specific urban and architectural conditions. As a result, the photosynthetic system is appropriate for both new and retrofit usage.

- ***bI.O. Serie Project by M. Poletto, C. Pasquero in the 'Back to the Future' exhibition, Frankfort – 2020:***

This project is a living 3D printed boiserie created exclusively for the 'Back to the Future' exhibition (Figure 5.8), which was conceived by ecoLogicStudio in collaboration with the Synthetic Landscape Lab at Innsbruck University and the Urban Morphogenesis Lab at the Bartlett UCL (PhotoSynthEtica Consortium 2020).

Figure 5.8: bI.O.serie project in 'Back to the Future' exhibition, Frankfort, Germany, 2020.



The bI.O.serie, which is part of the PhotoSynthetica bio-digital innovation research line, consists of porous wall mounted photo-bioreactors that mimic the life cycle of the collective green algae species known as Volvox [17] (Figure 5.9).

Figure 5.9: Close view of bI.O.serie project which showed details of substrate that consists of porous wall mounted photo-bioreactors.

According to M. Poletto and C. Pasquero, volvox is distinctive in that it manifests cellular aggregation of thousands of units in colonies with up to three generations of cells. Volvox's material resolution and morphologic distinctions were studied and algorithmically reproduced in the design of the bI.O.serie project.

The collective logic of volvox manifests itself here in the form of an assemblage of bio-digital cells containing living cultures of Spirulina growing on a jellified medium. The resolution of the 3D printed reactors, which have been designed and fabricated to allow sufficient airflow across the living active medium, is comparable to the size of the Spirulina cells. As a result, bI.O.serie will capture CO2 molecules and filtrate air pollutants from the gallery space, while generating freshly synthesized oxygen for visitors to breathe. Toxins are stored and re-metabolized by algae, resulting in reusable biomass and the activation of data, and energy.

- ***H.O.R.T.U.S. XL project by M. Poletto, C. Pasquero in Centre Pompidou, Paris - 2019:***

H.O.R.T.U.S. XL Astaxanthin.g is receptive to both human and non-human life (Figure 5.10). This project stands a large-scale, 3D printed bio-sculpture with high-resolution (Figure 5.11). Claudia Pasquero and Marco Poletto (ecoLogicStudio) conceptualized the project, which was developed in collaboration with the University of Innsbruck's Synthetic Landscape Lab.

Figure 5.10: H.O.R.T.U.S. XL Astaxanthin.g project designed by M. Poletto, C. Pasquero in 2019 and located in Centre Pompidou, Paris.

Nowadays, new interactions are emerging in the digital epoch between creativity and the fields of life science, neuroscience, and synthetic biology. This project depicts human rationality's demands with the effects of proximity to bio-artificial intelligence. It is generated through "collaboration" with living organisms [18].

Figure 5.11: H.O.R.T.U.S. XL. Project is a high-resolution 3D printed bio-sculpture.

The growth of a substratum inspired by collective coral morphology can be simulated using a digital algorithm. 3D printing machines physically deposit this in 400 microns layers, which endorsed by triangular cells of 46 mm and also divided into hexagonal blocks of 18.5 cm (Figure 5.12).

Photosynthetic cyanobacteria have been inserted on a bio-gel medium into single triangular cells, or bio-pixels, which serve as the system's biological intelligence units. Their photosynthesis-powered metabolisms transform radiation into actual oxygen and biomass. Each bio-density-value pixel's is digitally calculated in order to effectively arrange photosynthetic organisms along iso-surfaces of enhanced incoming radiation. Cyanobacteria unique biological intelligence is this gathered as part of a new type of bio-digital architecture, despite being among the oldest organisms on Earth.

Figure 5.12: H.O.R.T.U.S. XL. Project has an integrated and organic shape which inspired by collective coral morphology.

5.3. Cyanobacteria as a Plant Species in the Vertical Garden

Cyanobacteria are a diverse and ancient group of photosynthetic, gram-negative, photoautotrophic prokaryotes which are cosmopolitan in nature. They are aquatic and photosynthetic and often called "blue-green algae", which means they live in water and also can produce their own food. Since they are bacteria, they are small and usually unicellular, though they frequently grow in colonies large enough to see. They can be found in every type of habitat on the planet, from terrestrial to aquatic, from frigid to tropical regions [19][20]. Cyanobacteria are also known to survive in deserts, where they spend the majority of their time dormant [21]. They can be found in soil, on rocks, and in both fresh and saltwater [22][23]. They exist as free-living organisms and can form symbiotic relationships with a wide range of organisms, including protists, plants, animals, and fungi [24]–[27].

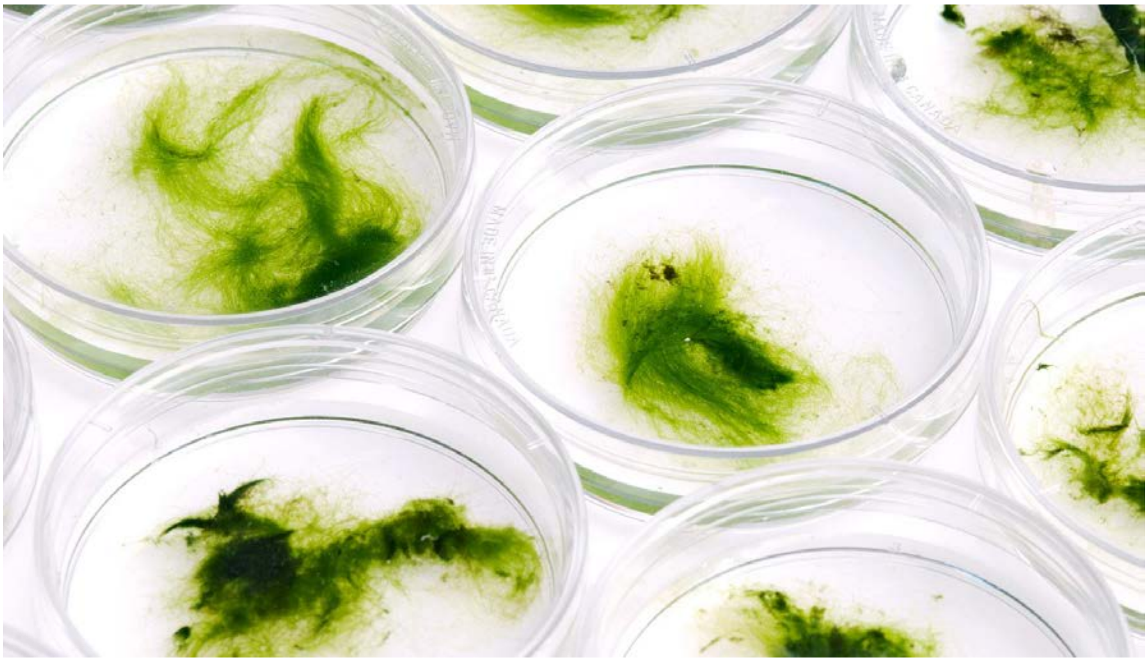
The great contribution of cyanobacteria is the origin of plants. The chloroplast, which plants using to make food, is actually a cyanobacterium that lives within the plant's cells. Moreover, cyanobacteria are a diverse and ancient group of photosynthetic, gram-negative, photoautotrophic prokaryotes which are cosmopolitan in nature.

Photosynthetic microorganisms, algae, and cyanobacteria are recognized as the primary colonizers of stone surfaces, and many cyanobacterial species can withstand climate extremes that is essential issue for selecting this species as a plant in green façades; thus, special attention is paid to this group of organisms. Cyanobacteria, which require only light and water to grow, and can withstand most types of stress [28].

Cyanobacteria are now regarded to have enormous potential in serving humanity in a variety of ways which will be investigated in the future research of this dissertation, particularly in a novel phenomenon of vertical gardens as a layer of cyanobacteria as plants on façades. Their diazotrophic[1] nature, widespread distribution, and ability to enter N2–fixing symbiosis make them appealing research subjects. Cyanobacteria have a long history of use as bio-fertilizers in agriculture [25]. In recent years, there has been a lot of interest in other potential applications of cyanobacteria in various fields of human welfare [29]–[32].

Cyanobacteria are capable of forming biofilms[2] (Figure 5.13). According to a study, based on cyanobacteria macro- and micro-morphological characteristics, the organisms forming the biofilm were identified to the species or genus level [33].

Figure 5.13: Here are some samples of cyanobacteria biofilm.



[1] Diazotrophs are bacteria and archaea that fix atmospheric nitrogen gas into a more usable form such as ammonia. A diazotroph is a microorganism that is able to grow without external sources of fixed nitrogen.

[2] A biofilm comprises any syntrophic consortium of microorganisms in which cells stick to each other and often also to a surface. These adherent cells become embedded within a slimy extracellular matrix that is composed of extracellular polymeric substances.

Since cyanobacteria have simple growth requirements and efficiently use light, CO2, and inorganic elements, the use of cyanobacteria as a kind of plant on the façade (double skin façade) is a potential system for the biosynthesis of solar energy and CO2 into such a valuable resource. As their organisms execute oxygenic photosynthesis, this photosynthesis is like that performed by higher plants [34][35].

Cyanobacteria must keep in the appropriate medium for growing such as bio-gel and BG-11 media. Photosynthetic Cyanobacteria can be applied into the structure of the green facade using a bio-gel medium, forming the system's biological intelligence units. Their photosynthesis-powered metabolisms convert radiation into biomass and actual oxygen. BG-11 Media is also ideal for the growth and maintenance of certain Cyanobacteria in this research.

5.4. 3D Printing as a Technological Tool

This century has been marked by two major concepts in architecture: the first is sustainability in architecture, which has been striving for a smaller environmental footprint in the ecosystem, and the second is digital technologies, which have driven a novel approach in all types of man-made products, including architecture [36].

3D printing or additive manufacturing (AM) as a digital technology tool in architecture is one automated process of creating three-dimensional objects obtaining all relevant information from 3D solid models that has the potential to lower carbon footprint and construction costs. This technique offers great abilities to improve labor safety and efficiency while also drastically reducing build time. In an additive process, a target is created by laying down successive layers of material until it created the entire object. Each of these layers can be seen as a thinly sliced horizontal cross-section of the ultimate object [37].

Additive manufacturing technologies can be traced back to the 1980s, which emerged as a promising method for fabrication and construction automation [38]. In the context of architecture, 3D Printing is also known by various terms such as Rapid Prototyping, Desktop Manufacturing, Automated Fabrication, Layer Fabrication, etc. [39]. According to the researchers, digital fabrication technology, which can create a physical artifact from a 3D digital file, enables the "effortless transition from digital to physical" [40].

According to the researchers, 3D printing technology is a relatively new manufacturing technology that has the potential to provide strong stimulation for "sustainable development" [41]. Many other researchers demonstrate that 3D printing is a process of industrial manufacturing with the ability to reduce resource significantly and also energy demands, as well as process-related CO2 emissions per unit of gross domestic product (GDP) [42]–[45].

In contrast to traditional manufacturing processes that are subtractive, 3D printing is an additive method of production. In this regard, 3D printers can produce a wide range of different material types that are supplied in various states (powder, filament, pellets, granules, resin, etc.). Table 5.1 depicts the various materials used in 3D printing. This includes all recyclable materials, such as glass, plastic, thermoplastic polymers (ABS), metals, ceramics, and etc. that during the printing process, they can be shaped. Furthermore, 3D printing lowers manufacturing-related resource inputs by only requiring the amount of material that ends up in the printed product without incurring too many losses [46]. Typically, support materials can be reused [47].

Nature's material systems are generally made up of graded composites grown and adapted from a single material system rather than an assembly of parts [49]. Neri Oxman, MIT Media Lab professor and leader of the Mediated Matter research group, presented a sustainable approach to additive manufacturing and digital fabrication in general, pointing to new possible directions in sustainable manufacturing [50]. She was inspired by nature and biological systems could create sustainable fabrication by utilizing 3D printer tool as additive manufacturing, one of her projects introduced below.

Table 5.1: 3D printing technology type and materials [48].

Classification	Technology	Description	Materials	Developers (country)
Binder jetting	3D printing Ink-jetting S-print M-print	Creates objects by depositing a binding agent to joint powdered material	Metal polymer, ceramic	ExOne (US) Voxljet (Germany) 3D Systems (US)
Direct energy deposition	Direct metal Deposition Laser deposition Laser consolidation Electron beam direct metaling	Builds parts by using focused thermal energy to fuse materials as they are deposited on a substrate	Metal: powder and wire	DM3D (US) NRC-IMI (Canada) Irepa Laser (France) Trumpf (Germany) Sciaky (US)
Material extrusion	Fused deposition modeling	Creates objects by dispensing material through a nozzle to build layers	Polymer	Stratasys (US) Delta Micro Factory (China) 3D Systems (US)

Material jetting	Poly jet Ink-jetting Thermo jet	Builds parts by depositing small droplets of build material, which are then cured by exposure to light	Photopolymer, wax	Stratasys (US) LUXeXcel (Netherlands) 3D Systems (US)
Powder bed fusion	Direct metal laser sintering Selective laser melting Electron beam melting Selective laser sintering	Creates objects by using thermal energy to fuse regions of a powder bed	Metal, polymer, ceramic	EOS (Germany) Renishaw (UK) Phenix Systems (France) Matsuura Machinery (Japan) AROAM (Sweden) 3D Systems (US)
Sheet lamination	Ultrasonic consolidation Laminated object manufacture	Builds parts by trimming sheets of material and binding them together in layers	Hybrids. metallic, ceramic	Fabrisonic (US) CAM-LEM (US)
VAT photopolymerization	Stereolithography Digital light processing	Builds parts by using light to selectively cure layers of material in a vat of photopolymer	Photopolymer, ceramic	3D Systems (US) EnvisionTEC (Germany) DWS Sri (Italy) Lithoz (Austria)

Biopolymer pavilion (AGUAHOJA):

The Aguahoja collection (pronounced agua-hocha) provides a material alternative to plastic by disrupting the toxic waste cycle through the development of biopolymer composites with tunable mechanical, optical, olfactory, and even gustatory properties (Figure 5.14 – 5.20). These biocompatible and renewable polymers harness the power of natural resource cycles which could be materially ‘programmed' to decay as they come back to the earth, thereby fueling new growth process [51].

Figure 5.14: AGUAHOJA Pavilion is located in SFMOMA, CA (2020).

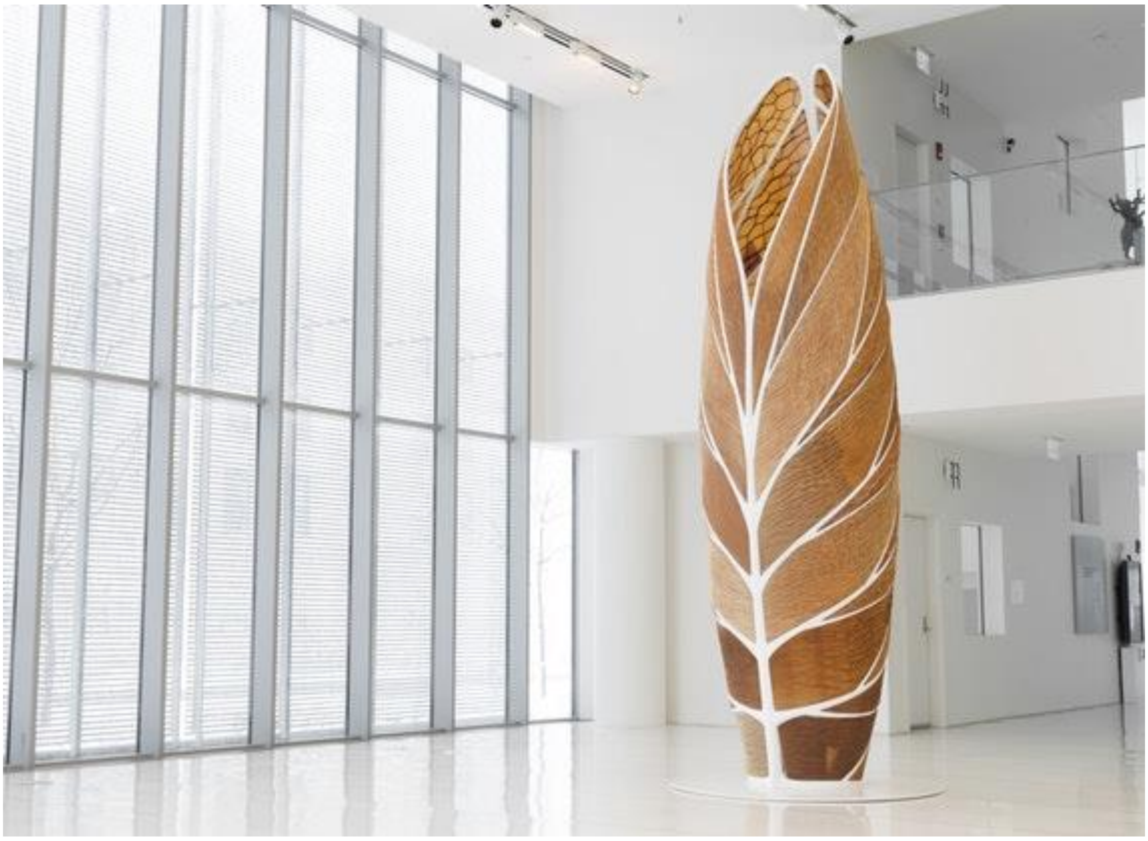


Figure 5.15: In AGUAHOJA Pavilion, the nozzle pressure and speed have been used to control the geometrical variation of structural members.

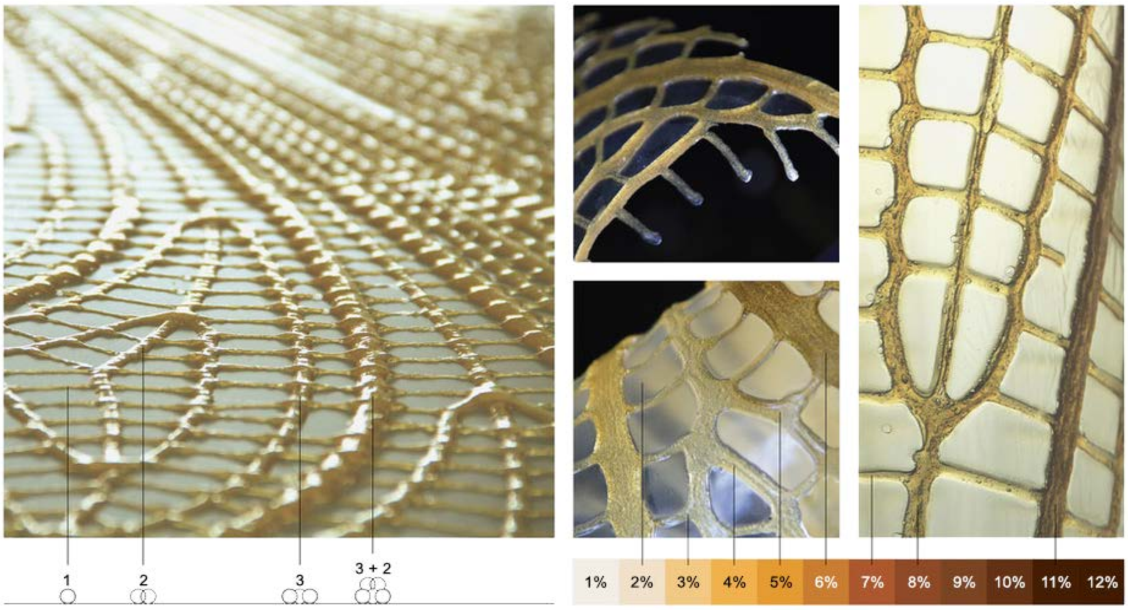


Figure 5.16: Chitosan-based textile-like network which color indicates physical property variations.

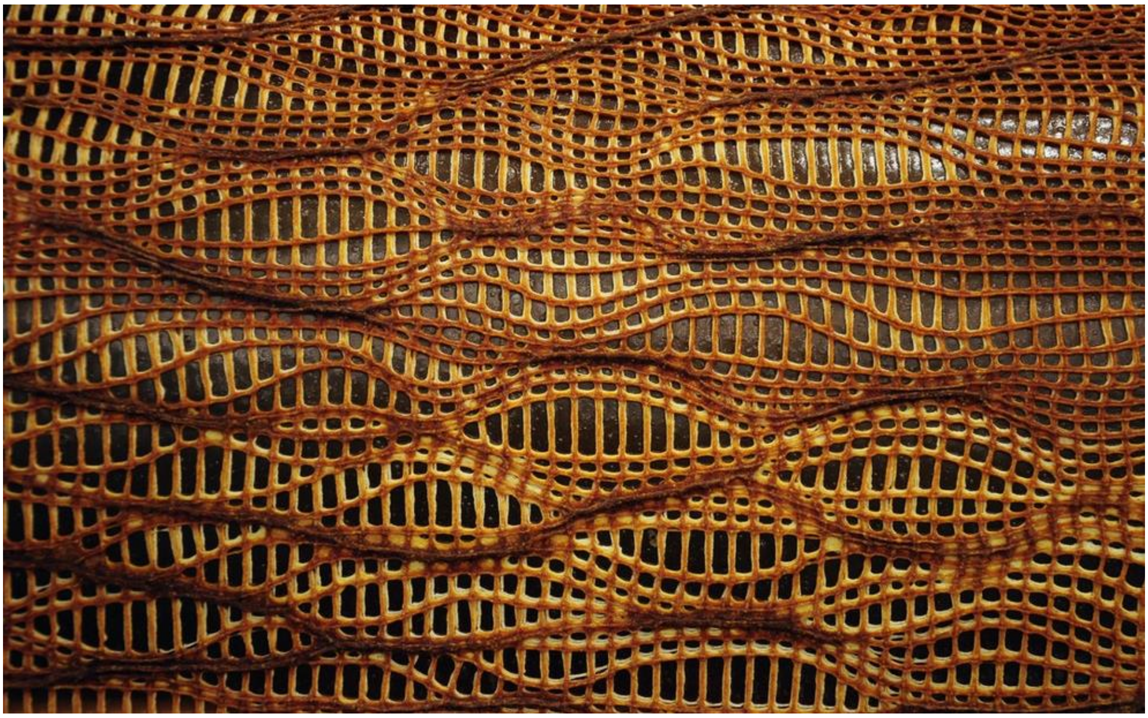


Figure 5.17: 3D printed chitosan, a shrimp shell derivative.

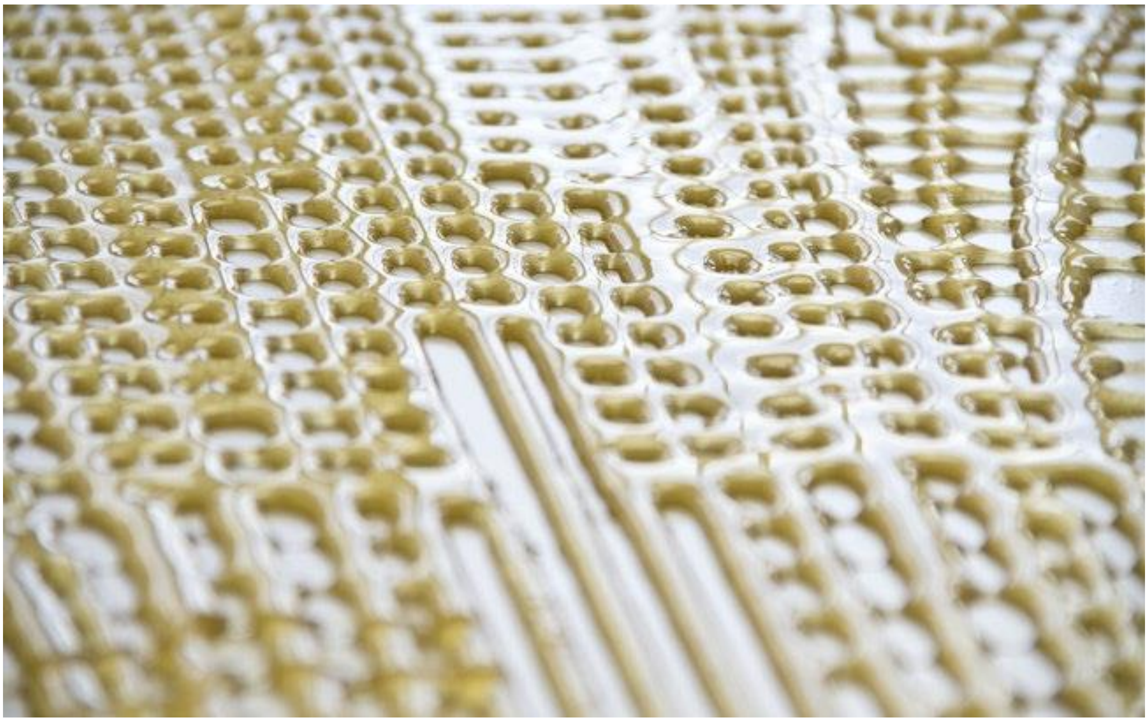


Figure 5.18: 3D printed chitosan, a plant derivative.

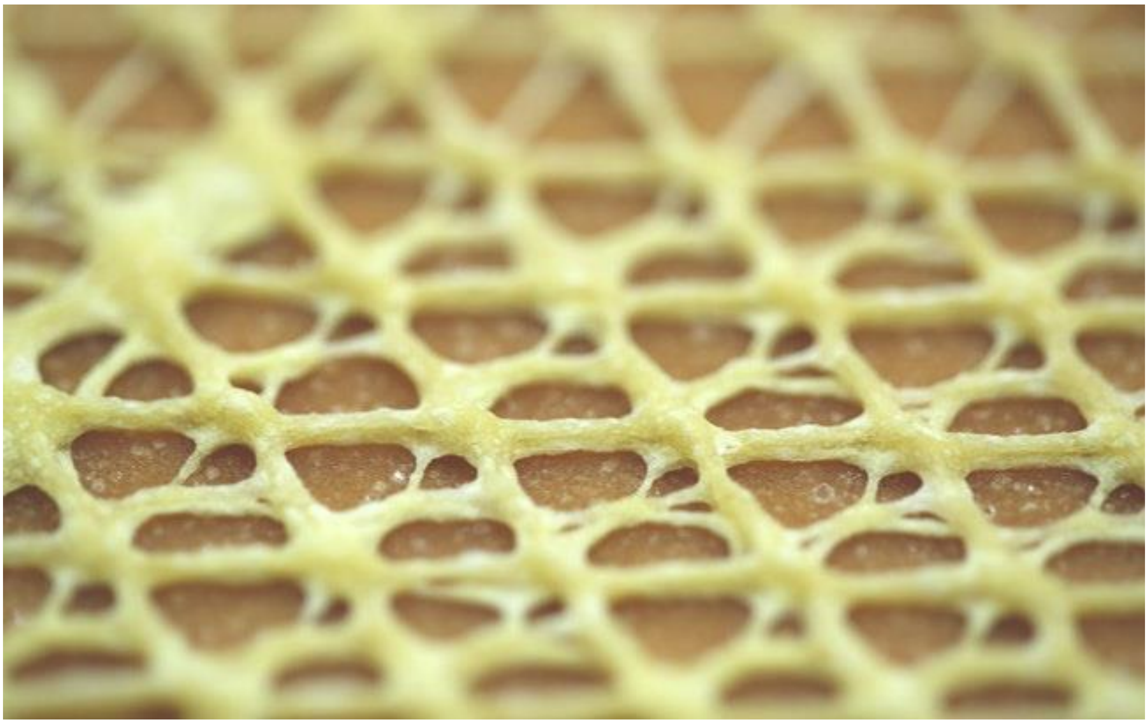


Figure 5.19: Detail of a structural member.

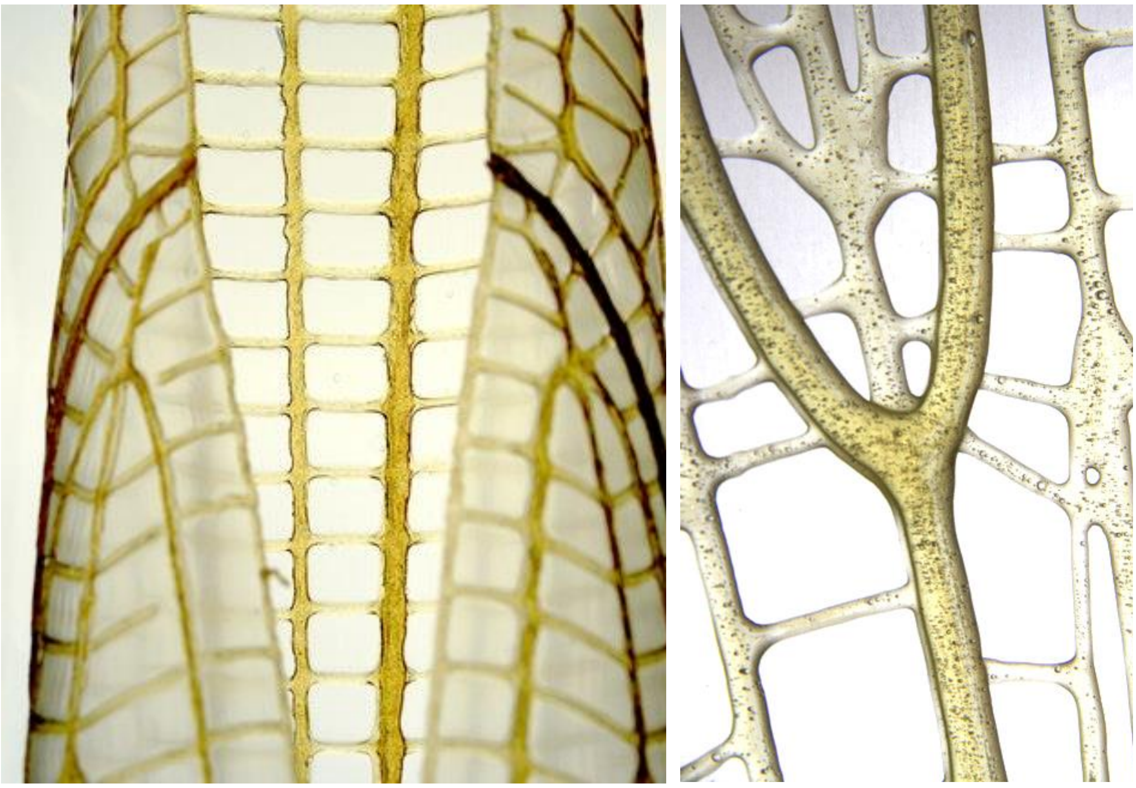


Figure 5.20: A 5-meter long structural 'structural skin' prototype.

5.5. Summary

By reviewing previous studies in this chapter, it can be achieved that it is possible to combine living matter, such as biological materials and technology, in architecture. Imagine a building as a plant system that can breathe, regenerate, grow, and shrink like a second skin, presenting an exciting and comforting future in various climates. This concept can be replaced with traditional ways of vertical greenery systems, such as green façades which have maintenance and some limitations in various regions due to weather conditions.

The incorporation of new hierarchical levels and therefore information into existing materials has resulted in lightweight and biomaterial design. Fibber structures, as well as the use of biological materials such as algae and etc., can be particularly promising as role models and in terms of technology transfer. 3D printing as technology in architecture has been brought another option for producing complex geometries at various levels.

Biological materials are typically soft and flexible during growth, allowing for transformation, but they must still be able to perform their function. The use of leaves in vertical gardens is an excellent example which small leaves can already bear self-loads and carry out photosynthesis as they grow to their actual size. In another example, in plants, during apical growth, the soft part at the tip expands, while the remaining parts continue to grow in diameter and make a distinction between functional tissues and organs. As a principle of growth, every living thing, whether human, animal, or plant cells, needs an appropriate medium for growing, for instance, plants need soil and water. For the purpose of future research, cyanobacteria as a biological material have been chosen because of many benefits that they have, such as resistance in different climates, no soil requirement, and etc. to be inoculated with bio gel or BG-11 medium to can grow. This biological component requires a substrate for implementing on that building façade as a double-skin which can be created by 3D printing with transparent and biomaterials.

This concept refers to vertical greenery systems such as green façades as photosynthetic skin on façades and urban structures that create bio habitats for cyanobacteria integrated into the built environment. Not only are cyanobacteria used as photosynthetic machines, but they are also used to absorb emissions from the built environment.

By making comparisons between vertical gardens and the new concept of vertical gardens, can be understood both of them act as a double-skin on façades, and due to their same organisms, they can be enhancing living conditions by reducing energy consumption and improved thermal comfort. Both can purify air pollutions and improve air quality, but the difference is that the new concept of vertical gardens has been predicted the ability to capture solar radiation and absorb CO_2, ten times more efficiently than trees (that in the previous section mentioned).

Green façades implementation and their maintenance have some limitations in some regions due to poor weather conditions as well as the shortage of water. On the contrary, there is no limitation on the new concept of vertical gardens and can be adapted in all regions with various climates such as the Mediterranean climate of Barcelona which vertical greenery systems have been examined by the author in previous chapters and articles, and also in Denver city with a semi-arid climate that is the context of this research.

Future research of the dissertation has attempted to help with improving living conditions in semi-arid regions by blending biology with technology in architecture. For this purpose, integrity, evolvability, and co-creation which are required for resilient systems such as the new concept of vertical gardens. Architecture can create future solutions by deeply interconnecting technology and biology into adaptable systems.

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Chapter Six: Conclusions

6.1. Summary

Over the next few years, if people continue at our current rate of energy consumption, communities will face three major challenges: an increase in energy demands, pollution, and global warming. Since buildings contribute significantly to greenhouse gas emissions and energy consumption, architects and engineers can combat these challenges by improving occupant thermal comfort in buildings and avoiding active and fossil fuel-based systems, which is a major challenge in many cities around the world.

These issues are more severe in the context of this research, which is semi-arid regions, due to weather conditions and a water shortage. However, the effects of green façades as a passive design strategy on thermal comfort, improving occupancy conditions and also their performance in semi-arid regions have received seldom studies. With the rapid population growth and the widespread use of heating and cooling systems, there is a need to educate building designers and city authorities about the possibility of implementing green façades in semi-arid areas that can achieve almost optimal conditions. Therefore, in this research, the performance of green façades as a type of vertical greenery system in glazed office buildings has been simulated and analyzed to better understand the impact of passive design parameters on thermal comfort and improving living conditions in semi-arid climates.

Energy efficiency with a sustainability approach via vertical greenery systems to the refurbishment of glazed office building façades in Denver is viewed as a viable step forward toward the sustainability agenda. The literature review indicates that a sustainability approach cannot be implemented effectively unless the entire building design team uses its expertise to generate commercially viable sustainable solutions. Furthermore, it is possible to conclude that the way forward is through an underlying relationship between reality, design creativity, and innovations in building materials and solutions to achieve a genuine commitment to low-energy green building as well as an improvement in terms of the psychological and physical well-being of occupants.

In this thesis, vertical gardens are defined as a collection of natural elements that serve multiple functions at the building and urban scales. The building energy savings, as well as the reduction of ambient temperatures and the urban heat island effect, stand out among these functions. The new plant integration technologies on buildings open up new possibilities for achieving sustainability in construction, particularly in terms of energy savings.

As previously stated, vertical greenery systems such as green façades and living walls function primarily as passive systems via four mechanisms: the shadow cast by the vegetation; the insulation provided by the vegetation and substrate; evaporative cooling via evapotranspiration; and eventually, the wind barrier effect. In chapter 4, by simulating a green façade as a double-skin façade in a glazed office building, it was proved that the vegetation layer shadow effect has the greatest impact on the building wall temperature reduction and consequently over the energy consumption reduction by lowering the indoor air temperature in semi-arid regions. Moreover, articles with the context of the Mediterranean climate in Barcelona have reached similar conclusions using simulations [1][2][3]. Furthermore, plant growth in local climatic conditions must be considered because the final results as a real project can vary greatly from one climate area to the next. For this reason, the Boston ivy plant was selected in this research because this plant is a kind of local plant in Denver, Colorado. Plants for vertical gardens with a specific climate are of particular interest to the researchers.

6.2. Conclusions

The original concept of office building façades design with a vegetation layer as a double-skin façade which is an environmental moderator by combining using shading, natural ventilation, noise insulation, evaporative cooling, and also the physical and psychological aspect of nature in workplaces in a semi-arid region. This is attributed to reduced environmental and urban stress, improved workplace conditions, increased work productivity, and better adoption of 9 a.m. to 5 p.m. working hours.

Environmental stress is defined as the emotional, cognitive, and behavioral responses to an environmental stimulus (or stressor), where the environmental stimuli are associated with an increase in traffic noise, air pollution, air temperature, and poor thermal comfort. As anticipated by environmental psychology theories (the overload theory, Environmental stress theory, or behavior constraint theory), if people are unable to control, change, or adapt to their surroundings, a sense of helplessness and lack of control appears, leading to occupant dissatisfaction, anxiety, and reduction in welfare and wellness. According to previous researches, plants can reduce stress, and a plant layer on the façade can work as sound insulation. Furthermore, plants can purify the air perfectly and improve air quality, which is critical for reducing environmental stressors.

The study of the context of semi-arid regions, especially Denver, Colorado, revealed a challenging urban and environmental setting for office buildings' façades. With current ambient environmental characteristics of semi-arid regions, the rise in office operational energy demands, and the current state of office building façades, it is reached the conclusion that integration between the physical characteristics of the building envelope and the design of the air conditioning system is required to improve indoor thermal and psychological comfort. Within these environmental constraints, green façade technologies were evaluated in search of a façade architectural technology with the potential to alleviate collectively these environmental stresses on office building occupants while causing the least disruption to building occupancy.

In terms of thermal performance, using the façade as an environmental separator resulted in heat accumulation indoors and reduced natural ventilation as an opportunity to improve thermal comfort. Vertical greenery systems, such as green façades and living walls, can be promoted as a way to improve thermal comfort and productivity. Green façades as a façade technology can result in lower electricity demands.

The conceptual hypothesis, as the state-of-the-art of the thesis in chapter two, examined the function of green façades as more than just a separating layer between indoors and outdoors. As a result, green façades are successful in fulfilling their multiple roles and are evaluated as a holistic interface that not only acts as an environmental moderator with an impact on the building's energy usage but they can also meet predicted occupants' expectations and psychological expectations.

Chapter three reviewed the foundations and validations of green façades which have been used to enhance the integration between the façade thermal performance and the building systems for delivering occupants' comfort as well as psychological comfort within a refurbishment framework. Finally, the availability and continuous improvement of green façades as one of the insulation strategies provide opportunities to lowering the operational energy of the building. Also, green façades can also be used on a single skin façade or extended to act in multilayer façades capable of integrating passively or actively to minimize the total energy. The chapters that followed evaluated green façade technologies in greater depth within a refurbishment framework, attempting to parametrically assess their effect on thermal comfort, energy consumption, and working to improve living conditions.

Chapter four presented the dissertation’s operational framework and explained the research methodology, which included simulating a conceptual model (model is according to ASHRAE standard) for testing environmental variables affecting green façades in a semi-arid region. Various test methods were discussed in order to examine the propositions intended in this research. A scientific methodology is adopted to quantify energy-saving measures predicted by simulating variables affecting the green façade thermal performance to achieve a benchmark green façade configuration. In this case, hypothesis three is put to the test. Based on information obtained from the US Department of Energy (DOE), the ASHRAE standard, and a Denver office building, a simulation base case was created. Testing the base case revealed that cooling and heating were required all year. The sum of sensible and latent cooling loads is the total cooling loads. The effect of changing glazed façade variable as part of a refurbishment scenario is simulated to show changes during peak summer (maximum cooling load) and peak winter (heating load) and on an annual basis. The simulation has been chosen as a method for calculating the influence of modifying green façade variables on the building's total cooling and heating loads.

Hypothesis three, which is stated improvement of thermal comfort and energy savings through the use of vertical gardens while making no changes to the architectural configurations that will reduce the cooling and heating loads of glazed office buildings in a semi-arid region. The simulation results showed that heating and cooling were required all year. By adding a green façade to the base case, the reduction in electrical energy consumption and improvement in thermal comfort were tested. Simulation results of the Base Case model have indicated that the effect of green façades on the annual cooling loads was 1% in the green façade and 99% through the glazed façade. This means that by applying green façades use of cooling load is almost zero. A layer of ivy with 25 cm thickness can improve the R-value of the façade by adding 0.5 m^2 K/W that caused reducing U-value. As mentioned in chapter four, this reduction of R-value is during the daytime, due to plants have resistance in the daytime and their nighttime resistance is zero.

Thermal performance of green façades is also examined in the simulation method chapter (four) which green façades by protecting the glazed façade from solar radiation can reduce indoor temperature in hot days which in the green façade maximum indoor air temperature in southern part of office building on 21st July (a hot day) between 13:00 to 14:00 is about 20 °C and this temperature fluctuates during the day by changing the angle of solar radiation while in the bare façade indoor temperature is about 23 °C. Also, during the winter and cold months, a green façade can protect the building envelope from the cold wind, which comes from the west in Denver, as well as the cold weather. According to the result of the predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD), a green façade in both hot and cold seasons is close to ideal thermal comfort.

Finally, the new concept of vertical gardens which are possible to use in all climates without limitation presented in chapter five which is also stated as future research of this dissertation. The primary objective of this chapter is by blending biology and technology in architecture can solve the issue of weather conditions and shortage of water for implementing vertical gardens in some climates such as semi-arid climates. This chapter is related to hypothesis four, which is looking for recent vertical greenery generation. The biological material in this concept is cyanobacteria (has photosynthetic microorganisms) and merging it with technology is the 3D printing method and creates a significant phenomenon in architecture. This combination is inspired by vertical gardens, which have many benefits and aspects in both building and urban scales. The importance-performance of vertical gardens and also the new concept of vertical gardens is that they can improve living conditions.

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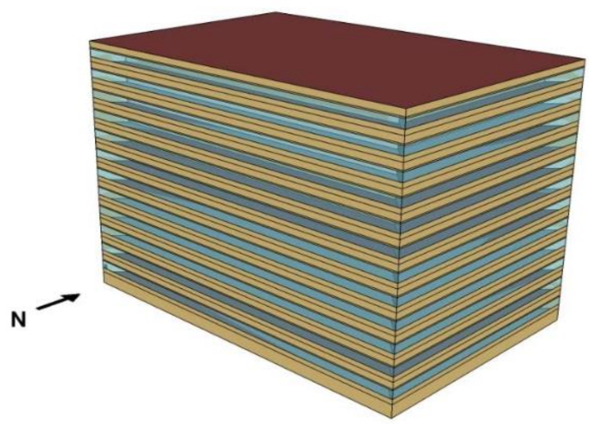
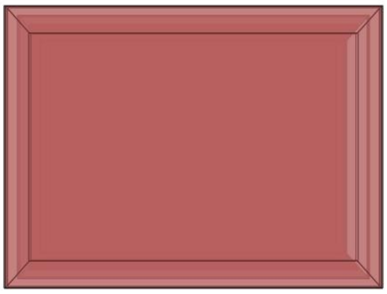
Appendix A: Energy Modeling Prototype Building Description

A.1: Large Office Modeling Specifications.

Pacific Northwest National Laboratory, updated on October 18, 2018

Item	Descriptions			Data Source
Program				
Vintage	**NEW CONSTRUCTION**			
Location (Representing 8 Climate Zones)	Zone 1A: Honolulu, Hawaii (very hot, humid) Zone 1B: New Delhi, India (very hot, dry) Zone 2A: Tampa, Florida (hot, humid) Zone 2B: Tucson, Arizona (hot, dry) Zone 3A: Atlanta, Georgia (warm, humid) Zone 3B: El Paso, Texas (warm, dry) Zone 3C: San Diego, California (warm, marine)	Zone 4A: New York, New York (mixed, humid) Zone 4B: Albuquerque, New Mexico (mixed, dry) Zone 4C: Seattle, Washington (mixed, marine) Zone 5A: Buffalo, NY (cool, humid) Zone 5B: Denver, Colorado (cool, dry) Zone 5C: Port Angeles, Washington (cool, marine)	Zone 6A: Rochester, Minnesota (cold, humid) Zone 6B: Great Falls, Montana (cold, dry) Zone 7: International Falls, Minnesota (very cold) Zone 8: Fairbanks, Alaska (subarctic	Selection of representative climates based on ASHRAE Standard 169-2013
Available fuel types	Gas, electricity			
Building Type (Principal Building Function)	**Office**			
Building Prototype	**Large Office**			
Form				
Total Floor Area (sq feet)	498,600 (240 ft x 160 ft)			Time Saver Standards; Large Office studies (ConEd, EPRI, MEOS, NEU1(1-4), NEU2, PNL) cited in Huang et al. 1991
Building shape	 			

	Aspect Ratio	1,5	
	Number of Floors	12 (plus basement)	
	Window Fraction (Window-to-Wall Ratio)	40% of above-grade gross walls 37.5% of gross walls (including the below-grade walls)	When applicable, certain codes or standards may restrict the window area to lower fractions
	Window Locations	Even distribution among all four sides	PNNL's CBECS Study
	Shading Geometry	None	
	Azimuth	Nuon-directional	
	Thermal Zoning		Time Saver Standards; Large Office studies (ConEd, EPRI, MEOS, NEU1(1-4), NEU2, PNL) cited in Huang et al. 1992
		Perimeter zone depth: 15 ft. Each floor has four perimeter zones, one core zone and one IT closet zone. Percentages of floor area: Perimeter 29%, Core 70%, IT Closet 1% The basement has a datacenter zone occupying 28% of the basement floor area.	
	Floor to floor height (feet)	13	
	Floor to ceiling height (feet)	9	
	Glazing sill height (feet)	3 ft	
Architecture			
Exterior walls			
	Construction	Mass (pre-cast concrete panel): 8 in. heavy - weight concrete + wall insulation + 0.5 in. gypsum board	Construction type: PNNL's CBECS Study
	U-factor (Btu / h * ft^2 * °F) and/or R-value (h * ft^2 * °F / Btu)	Requirements in codes or standards Nonresidential; Walls, Above - Grade, Steel - Framed	Applicable codes or standards
	Dimensions	Based on floor area and aspect ratio	
	Tilts and orientations	Vertical	
Roof			
	Construction	Built-up roof: Roof membrane + roof insulation + metal decking	Construction type: PNNL's CBECS Study Base assembly from 90.1

			Appendix A.
	U-factor (Btu / h * ft² * °F) and/or R-value (h * ft² * °F / Btu)	Requirements in codes or standards Nonresidential; insulation entirely above deck	Applicable codes or standards
	Dimensions	Based on floor area and aspect ratio	
	Tilts and orientations	Horizontal	
Window			
	Dimensions	Based on window fraction, location, glazing sill height, floor area and aspect ratio	
	Glass-Type and frame	Hypothetical window with a weighted U-factor and SHGC	
	U-factor (Btu / h * ft² * °F)	Requirements in codes or standards Nonresidential	Applicable codes or standards
	SHGC (all)		
	Visible transmittance	Same as above requirements	
	Operable area	0%	Ducker Fenestration Market Data provided by the 90.1 Envelope Subcommittee
Skylight			
	Dimensions	Not modeled	
	Glass-Type and frame	NA	
	U-factor (Btu / h * ft² * °F)		
	SHGC (all)		
	Visible transmittance		
Foundation			
	Foundation Type	Basement (conditioned)	
	Construction	8" concrete wall; 6" concrete slab, 140 lbs heavy-weight aggregate	
	Thermal properties for ground level floor U-factor (Btu / h * ft2 * °F) and/or R-value (h * ft2 * °F / Btu)	Requirements in codes or standards Nonresidential; Floors, Mass	Applicable codes or standards
	Thermal properties for basement walls	No insulation	
	Dimensions	Based on floor area and aspect ratio	
Interior Partitions			
	Construction	2 x 4 uninsulated stud wall	
	Dimensions	Based on floor plan and floor-to-floor height	
	Internal Mass	6 inches standard wood (16.6 lb/ft²)	
Air Barrier System			

	Infiltration	Peak: 0.2016 cfm/sf of above grade exterior wall surface area, adjusted by wind (when fans turn off) Off Peak: 25% of peak infiltration rate (when fans turn on)	Reference: PNNL-18898. Infiltration Modeling Guidelines for Commercial Building Energy Analysis. Modeled peak infiltration rate may be different for different codes or standards because of their continuous air barrier requirements.
HVAC			
System Type			
	Heating type	One gas-fired boiler	PNNL's CBECS Study
	Cooling type	Water-source DX cooling coil with fluid cooler for datacenter in the basement and IT closets in other floors Two water-cooled centrifugal chillers for the rest of the building	Reference: PNNL-23269 Enhancements to ASHRAE Standard 90.1 Prototype Building Models
	Distribution and terminal units	VAV terminal box with damper and hot-water reheating coil except non-datacenter portion of the basement and IT closets that are served by CAV units.	
HVAC Sizing			
	Air Conditioning	Authorized to design day	
	Heating	Authorized to design day	
HVAC Efficiency			
	Air Conditioning	Requirements in codes or standards	Applicable codes or standards
	Heating		
HVAC Control			
	Thermostat Setpoint	75°F Cooling/70°F Heating	90.1 Simulation Working Group
	Thermostat Setback	85°F Cooling/60°F Heating	
	Supply air temperature	Maximum 110F, Minimum 52F	Temperature setpoint reset may be required by codes and standards.
	Chilled water supply temperatures	44 F	
	Hot water supply temperatures	180 F	
	Economizers	Requirements in codes or standards	Applicable codes or standards
	Ventilation	ASHRAE Standard 62.1 or International Mechanical Code See under Outdoor Air	Applicable codes or standards

	Demand Control Ventilation	Requirements in codes or standards	Applicable codes or standards
	Energy Recovery	Requirements in codes or standards	Applicable codes or standards
Supply Fan			
	Fan schedules	See under Schedules	
	Supply Fan Total Efficiency (%)	Depending on the fan motor size and requirements in codes or standards	Requirements in applicable codes or standards for motor efficiency and fan power limitation
	Supply Fan Pressure Drop	Depending on the fan supply air cfm	
Pump			
	Pump Type	Primary chilled water (CHW) pumps: constant speed; secondary CHW pump: variable speed; IT closet (water loop heat pump) pump: constant speed; cooling tower pump: variable speed; service hot water (SWH): constant speed; hot water (HW) pump: variable speed	
	Rated Pump Head	Use the pump power assumptions as specified in 90.1 Appendix G, i.e., 22 W/gpm for chilled water pump, 19 W/gpm for hot water and condensing water pumps. For SWH pump, first estimated based on circulation flow and then adjusted based on modeled design flow.	If applicable, model inputs for other codes or standards may be different. PNNL 2014. Enhancements to ASHRAE Standard 90.1 Prototype Building Models
	Pump Power	Authorized	
Cooling Tower			
	Cooling Tower Type	Open cooling tower with two-speed fans; two-speed fluid-cooler for data center and IT closets	
	Cooling Tower Power	Authorized	
Service Water Heating			
	SWH type	One main water heater with storage tank	
	Fuel type	Natural gas	
	Thermal efficiency (%)	Requirements in codes or standards	Applicable codes or standards
	Tank Volume (gal)	300	Reference: PNNL-23269 Enhancements to ASHRAE Standard 90.1 Prototype
	Water temperature setpoint	140 F	

			Building Models
	Water consumption	See under Schedules	
Internal Loads & Schedules			
Lighting			
	Average power density (W/ft²)	Requirements in codes or standards See Zone Summary	Applicable codes or standards
	Schedule	See under Schedules	
	Daylighting Controls	Requirements in codes or standards	Applicable codes or standards
	Occupancy Sensors	Requirements in codes or standards	Applicable codes or standards
Plug load			
	Average power density (W/ft²)	See under Zone Summary	For data center and IT closet, see PNNL-23269 Enhancements to ASHRAE Standard 90.1 Prototype Building Models
	Schedule	See under Schedules	
Occupancy			
	Average people	See under Zone Summary	ASHRAE Standard 62.1
	Schedule	See under Schedules	
Misc.			
Elevator			
	Quantity	12	DOE Commercial Reference Building TSD (unpublished) and models (V1.3_5.0).
	Motor type	Traction	
	Peak Motor Power Watts per elevator	20370	
	Heat Gain to Building	Exterior	
	Peak Fan/lights Power Watts per elevator	161,9	90.1 Mechanical Subcommittee, Elevator Working Group

	Motor and fan/lights Schedules	See under Schedules	DOE Commercial Reference Building TSD (unpublished) and models (V1.3_5.0) and Appendix DF 2007
Exterior Lighting			
	Peak Power	Based on design assumptions for façade, parking lot, entrance, etc. and requirements in codes or standards	Applicable codes or standards
	Schedule	See under Schedules and control requirements in codes or standards	Applicable codes or standards

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Appendix B: Reference Large Office Building Internal Loads

Table B.1: Reference Building Zone Internal Loads (IP units).

Building Type/Zone	Area ft²	Vol. ft³	ft²/ person	1989 Lights Wft²	2004 Lights Wft²	Elec. Proc. W/ft²	Gas Proc. W/ft²	Vent. cfm	Exhst cfm	Infil. ACH	SWH gal/h
Large Office	**498,588**	**6,291,164**									
Basement	38,353	306,899	400.0	0.70	1.0	0.4	0.0	1917.6	0.0	0.00	0.0
Perimeter_bot_ZN_3	3,374	30,371	200.0	1.50	1.0	0.7	0.0	337.4	0.0	0.25	0.0
Perimeter_bot_ZN_2	2,174	19,572	200.0	1.50	1.0	0.7	0.0	217.4	0.0	0.26	0.0
Perimeter_bot_ZN_1	3,374	30,371	200.0	1.50	1.0	0.7	0.0	337.4	0.0	0.25	0.0
Perimeter_bot_ZN_4	2,174	19,572	200.0	1.50	1.0	0.7	0.0	217.4	0.0	0.26	0.0
Core_bottom	27,258	245,391	200.0	1.50	1.0	0.7	0.0	2725.8	0.0	0.00	21.3
Perimeter_mid_ZN_3	3,374	30,371	200.0	1.50	1.0	0.7	0.0	337.4	0.0	0.25	0.0
Perimeter_mid_ZN_2	2,174	19,572	200.0	1.50	1.0	0.7	0.0	217.4	0.0	0.26	0.0
Perimeter_mid_ZN_1	3,374	30,371	200.0	1.50	1.0	0.7	0.0	337.4	0.0	0.25	0.0
Perimeter_mid_ZN_4	2,174	19,572	200.0	1.50	1.0	0.7	0.0	217.4	0.0	0.26	0.0
Core_mid	27,258	245,391	200.0	1.50	1.0	0.7	0.0	2725.8	0.0	0.00	21.3
Perimeter_top_ZN_3	3,374	30,371	200.0	1.50	1.0	0.7	0.0	337.4	0.0	0.65	0.0
Perimeter_top_ZN_2	2,174	19,572	200.0	1.50	1.0	0.7	0.0	217.4	0.0	0.66	0.0
Perimeter_top_ZN_1	3,374	30,371	200.0	1.50	1.0	0.7	0.0	337.4	0.0	0.65	0.0
Perimeter_top_ZN_4	2,174	19,572	200.0	1.50	1.0	0.7	0.0	217.4	0.0	0.66	0.0
Core_top	27,258	245,391	200.0	1.50	1.0	0.7	0.0	2725.8	0.0	0.40	21.3
Ground floor _ plenum	38,353	153,412	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0.07	0.0
Mid floor _ plenum	38,353	153,412	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0.07	0.0
Top floor _ plenum	38,353	153,412	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.97	0.0

Table B.2: Reference Building Zone Internal Loads (SI units).

Building Type/Zone	Area m^2	Vol. m^3	m^2/ person	1989 Lights Wm^2	2004 Lights Wm^2	Elec. Proc. W/m^2	Gas Proc. W/m^2	Vent. L/s	Exhst L/s	Infil. ACH	SWH L/h
Large Office	**46,320**	**178,146**									
Basement	3,563	8,690	37.16	7.53	10.76	10.76	0.0	958.8	0.0	0.15	0.0
Perimeter_bot_ZN_3	313	860	18.58	16.14	10.76	10.76	0.0	168.7	0.0	0.30	0.0
Perimeter_bot_ZN_2	202	554	18.58	16.14	10.76	10.76	0.0	108.7	0.0	0.30	0.0
Perimeter_bot_ZN_1	313	860	18.58	16.14	10.76	10.76	0.0	168.7	0.0	0.30	0.0
Perimeter_bot_ZN_4	202	554	18.58	16.14	10.76	10.76	0.0	108.7	0.0	0.30	0.0
Core _ bottom	2,532	6,949	18.58	16.14	10.76	10.76	0.0	1362.9	0.0	0.15	80.6
Perimeter_mid_ZN_3	313	860	18.58	16.14	10.76	10.76	0.0	168.7	0.0	0.30	0.0
Perimeter_mid_ZN_2	202	554	18.58	16.14	10.76	10.76	0.0	108.7	0.0	0.30	0.0
Perimeter_mid_ZN_1	313	860	18.58	16.14	10.76	10.76	0.0	168.7	0.0	0.30	0.0
Perimeter_mid_ZN_4	202	554	18.58	16.14	10.76	10.76	0.0	108.7	0.0	0.30	0.0
Core _ mid	2,532	6,949	18.58	16.14	10.76	10.76	0.0	1362.9	0.0	0.15	80.6
Perimeter_top_ZN_3	313	860	18.58	16.14	10.76	10.76	0.0	168.7	0.0	0.30	0.0
Perimeter_top_ZN_2	202	554	18.58	16.14	10.76	10.76	0.0	108.7	0.0	0.30	0.0
Perimeter_top_ZN_1	313	860	18.58	16.14	10.76	10.76	0.0	168.7	0.0	0.30	0.0
Perimeter_top_ZN_4	202	554	18.58	16.14	10.76	10.76	0.0	108.7	0.0	0.30	0.0
Core _ top	2,532	6,949	18.58	16.14	10.76	10.76	0.0	1362.9	0.0	0.15	80.6
Ground floor _ plenum	3,563	4,344	-	-	-	-	-	-	-	0.00	0.0
Mid floor_ plenum	3,563	4,344	-	-	-	-	-	-	-	0.00	0.0
Top floor_ plenum	3,563	4,344	-	-	-	-	-	-	-	0.00	0.0

Appendix C: Schedule

Table C.1: Large Office Hourly Operation Schedules.

Schedule	Day of Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
ALWAYS_ON	All	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
BLDG_ELEVATORS	All	0.05	0.05	0.05	0.05	0.1	0.2	0.4	0.5	0.5	0.35	0.15	0.15	0.15	0.15	0.15	0.15	0.35	0.5	0.5	0.4	0.4	0.3	0.2	0.1
INFIL_QUARTER_ON_SCH	WD, Summer Design	1	1	1	1	1	1	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	1	1
	Sat, Winter Design	1	1	1	1	1	1	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	1	1	1	1	1	1
	Sun, Hol, Other	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
BLDG_OCC_SCH	Summer Design	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.05	0.05
	WD	0	0	0	0	0	0	0.1	0.2	0.95	0.95	0.95	0.95	0.5	0.95	0.95	0.95	0.95	0.7	0.4	0.4	0.1	0.1	0.05	0.05
	Sat	0	0	0	0	0	0	0.1	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1	0.1	0.1	0	0	0	0	0	0
	Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BLDG_LIGHT_SCH	WD	0.05	0.05	0.05	0.05	0.05	0.1	0.1	0.3	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.5	0.5	0.3	0.3	0.1	0.05
	Sat	0.05	0.05	0.05	0.05	0.05	0.05	0.1	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.15	0.15	0.15	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Summer Design	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Winter Design	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Other	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
BLDG_EQUIP_SCH	WD	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.8	0.6	0.6	0.5	0.5	0.4	0.4
	Sat	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.35	0.35	0.35	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Summer Design	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Winter Design	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Other	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
ACTIVITY_SCG	All	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
WORK_EFF_SCH	All	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AIR_VELO_SCH	All	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
CLOTHING_SCH	All	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	All	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	All	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
CLGSETP_SCH	WD, Summer Design	26.7	26.7	26.7	26.7	26.7	26.7	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	26.7	26.7
	Sat	26.7	26.7	26.7	26.7	26.7	26.7	24	24	24	24	24	24	24	24	24	24	24	24	26.7	26.7	26.7	26.7	26.7	26.7

	Winter Design	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7
	Other	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7
HTGSETP_SCH	WD	15.6	15.6	15.6	15.6	15.6	15.6	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	15.6	15.6
	Summer Design	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
	Sat	15.6	15.6	15.6	15.6	15.6	15.6	21	21	21	21	21	21	21	21	21	21	21	21	15.6	15.6	15.6	15.6	15.6	15.6
	Winter Design	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
	Other	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
Seasonal-Reset-Supply-Air-Temp-Sch	All	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8
MinOA_MotorizedDamper_Sched	WD, Summer Design	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
	Sat, Winter Design	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
	Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dual Zone Control Type Sched	All	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
HVAC Operation SCH	WD, Summer Design	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
	Sat, Winter Design	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
	Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CW-Loop-Temp-Schedule	All	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7
HW-Loop-Temp-Schedule	All	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2	82.2
BLDG_SWH_SCH	WD, Summer Design	0.05	0.05	0.05	0.05	0.05	0.08	0.07	0.19	0.35	0.38	0.39	0.47	0.57	0.54	0.34	0.33	0.44	0.26	0.21	0.15	0.17	0.08	0.05	0.05
	Sat, Winter Design	0.05	0.05	0.05	0.05	0.05	0.08	0.07	0.11	0.15	0.21	0.19	0.23	0.2	0.19	0.15	0.13	0.14	0.07	0.07	0.07	0.07	0.09	0.05	0.05
	Other	0.04	0.04	0.04	0.04	0.04	0.07	0.04	0.04	0.04	0.04	0.04	0.06	0.06	0.09	0.06	0.04	0.04	0.04	0.04	0.04	0.04	0.07	0.04	0.04
Water Equipment Latent fract sched	All	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Water Equipment Sensible fract sched	All	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SWHSys 1 Water Heater Ambient Temperature Schedule Name	All	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22
Water Equipment Temp Sched	All	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3
Water Equipment Hot Supply Temp Sched	All	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3
SWHSys 1 Water Heater Setpoint Temperature Schedule Name	All	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
SWHSys 1-Loop-Temp-Schedule	All	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60

Appendix D: Heating, Ventilation, and Air Conditioning (HVAC)

HVAC equipment for baseline buildings is specified by ASHRAE [1][2]. This data is used to create reference buildings and does not necessarily reflect standard construction practices. According to Winiarski et al. [3], they examined 2003 CBECS data to estimate typical HVAC system types by building type that can be used with reference buildings. They analyzed the data in two groups: All 33 buildings were built in 1980 or earlier, and the remaining buildings were built after 1980. The final equipment types chosen accounted for the majority of the floor area. Table D.1 shows the results for post-1980 and new construction, while Table D.2 shows the results for pre-1980 construction. Strip malls were excluded because they are supposed to have the same systems as the stand-alone retail model. Discussions with the ASHRAE Standard 90.1 mechanical subcommittee determined the number of chillers and type of condenser (air or water).

Table D.1: Types of HVAC equipment for Post-1980 and new construction.

Building Type	**Heating**	**Cooling**	**Air Distribution**
Small Office	Furnace	PACU (packaged air-conditioning unit)	SZ CAV (single-zone constant air volume)
Medium Office	Furnace	PACU	MZ VAV (multizone variable air volume)
Large Office	Boiler	Chiller (2) – water cooled	MZ VAV
Primary School	Boiler	PACU	CAV
Secondary School	Boiler	Chiller – air cooled	MZ VAV
Stand-Alone Retail	Furnace	PACU	SZ CAV
Strip Mall	Furnace	PACU	SZ CAV
Supermarket	Furnace	PACU	CAV
Quick Service Restaurant	Furnace	PACU	SZ CAV
Full Service Restaurant	Furnace	PACU	SZ CAV
Small Hotel	ISH (individual space heater), furnace	IRAC (individual room air conditioner), PACU	SZ CAV
Large Hotel	Boiler	Chiller (2) – air cooled	FCU (fan coil unit) and VAV
Hospital	Boiler	Chiller – water cooled	CAV and VAV
Outpatient Healthcare	Furnace	PACU	CAV and VAV
Warehouse	ISH, Furnace	PACU	SZ CAV
Midrise Apartment	Furnace	PACU-SS (split system)	SZ CAV

Table D.2: Types of HVAC equipment for Pre-1980 and new construction.

Building Type	Heating	Cooling	Air Distribution
Small Office	Furnace	PACU	SZ CAV
Medium Office	Furnace	PACU	MZ VAV
Large Office	Boiler	Chiller (2) – water cooled	MZ VAV
Primary School	Boiler	PACU	CAV
Secondary School	Boiler	PACU	CAV
Stand-Alone Retail	Furnace	PACU	SZ CAV
Strip Mall	Furnace	PACU	SZ CAV
Supermarket	Furnace	PACU	CAV
Quick Service Restaurant	Furnace	PACU	SZ CAV
Full Service Restaurant	Furnace	PACU	SZ CAV
Small Hotel	ISH	IRAC	SZ CAV
Large Hotel	Boiler	Chiller (2) – air cooled	FCU and MZ VAV
Hospital	Boiler	Chiller – water cooled	FCU, CAV and VAV
Outpatient Healthcare	Furnace	PACU	CAV and VAV
Warehouse	Furnace, ISH	PACU	SZ CAV
Midrise Apartment	Furnace	PACU-SS	SZ CAV

Equipment sizing for all reference building models is determined by EnergyPlus using a sizing factor of 1.2 from design day runs for each location. The nominal coefficient of performance (COP), energy efficiency ratio (EER), seasonal energy efficiency ratio (SEER), and boiler and furnace efficiencies are calculated using the appropriate energy standard for the equipment type and size. Using the models available in EnergyPlus, performance curves and HVAC system models are used to model how performance may vary when operating away from the nominal operating point. The operation of the economizer is determined by the cooling system size and climate zone in accordance with 90.1-2004 requirements. On the other hand, economizers are not used in any healthcare critical systems that must operate within specific humidity constraints.

Equipment efficiencies are calculated using 90.1-2004 for new construction reference building models, 90.1-1989 for post-1980 reference building models, and an analysis of historical equipment efficiencies and equipment lifetimes for pre-1980 reference building models [4]. Table D.3 shows the equipment efficiencies for pre-1980 reference building models for cooling equipment, Table D.4 shows space heating equipment, and Table D.5 through Table D.6 shows water heating equipment.

Table D.3: Unitary Cooling Equipment Efficiencies Estimated for Pre-1980 Construction.

Equipment Category	Capacity (Btu/h)	Heating Section	Equipment Subcategory	Efficiency Metric	Average Efficiency	Life (years)
Air conditioners, air cooled	0 – 65,000	Any	Single package	SEER	11.06	15
		Any	Split	SEER	11.09	15
	65,000 – 135,000	Electric or none	Split and single package	EER	9.63	15
		Other	Split and single package	EER	9.63	15
	135,000 – 240,000	Electric or none	Split and single package	EER	9.28	15
		Other	Split and single package	EER	9.28	15
	240,000 – 760,000	Electric or none	Split and single package	EER	8.92	15
		Other	Split and single package	EER	8.92	15
	>760,000	Electric or none	Split and single package	EER	8.63	15
		Other	Split and single package	EER	8.63	15
Air conditioners, water or evaporatively cooled	0 – 65,000	Any	Split and single package	EER	10.50	19
		Any	Split and single package	EER	10.50	19
	65,000 – 135,000	Electric or none	Split and single package	EER	10.75	19
		Other	Split and single package	EER	10.58	19
	135,000 – 240,000	Electric or none	Split and single package	EER	10.04	19
		Other	Split and single package	EER	9.87	19
	>240,000	Electric or none	Split and single package	EER	10.04	19
		Other	Split and single package	EER	9.87	19
Heat pumps, air cooled	0 – 65,000	Any	Single package	SEER	11.33	15
		Any	Split	SEER	11.33	15
	65,000 – 135,000	Electric or none	Split and single package	EER	9.61	15
		Other	Split and single package	EER	9.61	15
	135,000 – 240,000	Electric or none	Split and single package	EER	9.27	15
		Other	Split and single package	EER	9.27	15
	>240,000	Electric or none	Split and single package	EER	8.92	15
		Other	Split and single package	EER	8.92	15
Heat pumps, water source	0 – 17,000	All	All	EER	10.09	19

	17,000 – 65,000	All	All	EER	10.46	19
	65,000 – 135,000	All	All	EER	10.99	19
	135,000 – 240,000	All	All	EER	10.99	19
Heat pumps, ground water source	0 – 135,000	All	All	EER	14.53	19
Heat pumps, ground source	0 – 135,000	All	All	EER	11.89	19
Heat pumps, air cooled	0 – 65,000	Any	Single package	HSPF	6.93	19
		Any	Split	HSPF	7.04	19
	65,000 – 135,000	Electric or none	Split and single package	COP47	3.03	19
		Other	Split and single package	COP47	3.03	19
	135,000 – 240,000	Electric or none	Split and single package	COP47	2.94	19
		Other	Split and single package	COP47	2.94	19
	>240,000	Electric or none	Split and single package	COP47	2.94	19
		Other	Split and single package	COP47	2.94	19
Heat pumps, water source	0 – 17,000	All	All	COP68	3.88	19
	17,000 – 135,000	All	All	COP68	3.88	19
Heat pumps, ground water source	0 – 135,000	All	All	COP50	NA	19
Heat pumps, ground source	0 – 135,000	All	All	COP32	NA	19

Table D.4: Water Chilling Equipment Efficiencies Estimated for Pre-1980 Construction.

Equipment Category	Capacity (tons)	Equipment Subcategory	Efficiency Metric	Average Efficiency	Life (years)
Chiller, air cooled, electrically operated	<150	All	COP	2.70	23
	150 – 300	All	COP	2.64	23
	>300	All	COP	2.64	23
Chiller, water cooled, electrically operated	<150	Reciprocating	COP	3.98	23
	150 – 300	Reciprocating	COP	3.98	23
	>300	Reciprocating	COP	3.98	23
Chiller, water cooled, electrically operated	<150	Screw/scroll	COP	4.13	23
	150 – 300	Screw/scroll	COP	4.50	23
	>300	Screw/scroll	COP	5.11	23
	<150	Centrifugal	COP	4.53	23

Chiller, water cooled, electrically operated	150 – 300	Centrifugal	COP	4.93	23
	>300	Centrifugal	COP	5.54	23
Chiller, air cooled, absorption, single effect	All	-	COP	0.55	23
Chiller, water cooled, absorption, single effect	All	-	COP	0.69	23
Chiller, double effect, direct fired	All	-	COP	0.98	23
Chiller, double effect, indirect fired	All	-	COP	0.98	23

Table D.5: Packaged terminal cooling equipment efficiencies estimated for Pre-1980 construction.

Equipment Category	**Capacity (Btu/h)**	**Efficiency Metric**	**Average Efficiency**	**Life (years)**
PTAC	9,000	EER	9.79	10
	12,000	EER	9.22	10
PTHP	9,000	EER	9.67	10
	12,000	EER	9.09	10
PTHP - heating	9,000	COP47	2.86	10
	12,000	COP47	2.78	10
PTAC < 42 * 16 in	9,000	EER	8.82	10
	12,000	EER	8.24	10
PTHP < 42 * 16 in	9,000	EER	8.76	10
	12,000	EER	8.18	10
PTHP heating < 42 * 16 in	9,000	COP47	2.69	10
	12,000	COP47	2.60	10

COP47 heating COP at 47°F outdoor air source temperature
HSPF heating seasonal performance factor
NA analysis incomplete
PTAC packaged terminal air-conditioning
PTHP packaged terminal heat pump

Table D.6: Water Heating Equipment Efficiencies Estimated for Pre-1980 Construction.

Equipment Category	Capacity	Efficiency Metric	Average Efficiency	Life (years)
Electric storage water heater	< 12 kW	EF	NA	7
	> 12 kW	SL	NA	7
Gas storage water heater	< 75,000 Btu/h	EF	NA	7
	< 75,000, < 155,000 Btu/h	E_t	0.80	7
		SL	NA	7
	> 155,000 Btu/h	E_t	0.80	7
		SL	NA	7
Gas instantaneous water heater	50 – 200 kBtu/h	EF	NA	15
	> 200 Kbtu/h, < 10 gal	E_t	0.80	15
	> 200 Kbtu/h, > 10 gal	E_t	0.79	15
		SL	NA	15
Hot water supply boiler, gas	> 300, < 12,500 kBtu/h, < 10 gal	E_t	0.79	25
	> 300, < 12,500 kBtu/h, > 10 gal	E_t	0.78	25
		SL	NA	25

E_t thermal efficiency
EF energy factor
SL standby loss (rating to be defined either in Btu/h or in % per hour of stored water heat above ambient)
NA analysis incomplete

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Appendix E: Governing Equation

This section provided a summary of the mathematical model as well as the input parameters used in the simulations. The green façade model of Susorova et al. accounts the various heat transfer mechanisms for a vegetated wall [1], and the energy balance is defined as:

1)

$$SR_{vw} + LR_{vw} + XR + C_{vw} = Q_{vw} + S_{vw}$$

Where:
SR_{vw} = incident shortwave radiation
LR_{vw} = net long-wave radiation
XR = radiative exchange between the leaves and wall surface
C_{vw} = convective heat flux
Q_{vw} = conduction heat flux
S_{vw} = $\rho C_P L\ (dT_{vw}/dt)$ = heat storage in the façade material
ρ = density of the wall material
C_P = specific heat of the wall
L = wall thickness
t = time
T_{vw} = wall temperature.

Note that essentially, the wall temperature T_{vw} (t) is linked with the air temperature T_{air} (t), the sky temperature T_{sky} (t), the ground temperature T_{gr} (t), the indoor air temperature T_{in} (t) and the leaf temperature T_{leaf} (t). The energy balance equation of bare wall is similar to equation 1, without the XR term and the unknown bare wall temperature denoted as T_{bw}.

As a result, the energy balance equation is as follows:

2)

$$SR_{bw} + LR_{bw} + C_{bw} = Q_{bw} + S_{bw}$$

The governing ordinary differential equations (ODEs) are described as follows:

3)

$$\frac{dT_{vw}}{dt} = a_{vw} + b_{vw}(t)\,T_{vw} + c_{vw}(t)T_{vw}^4$$

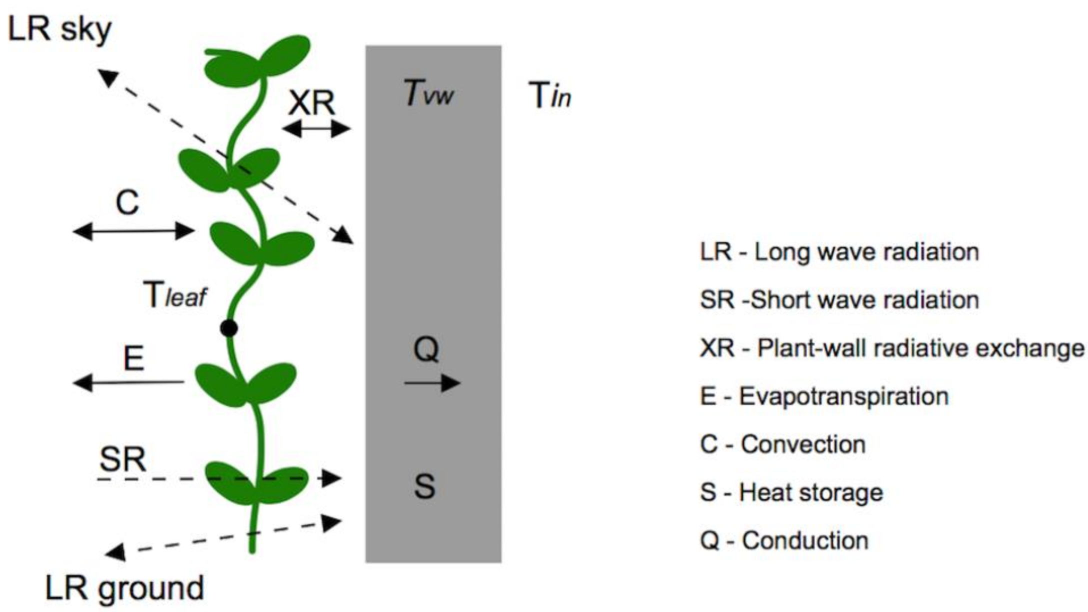
4)

$$\frac{dT_{bw}}{dt} = a_{bw} + b_{bw}(t)\,T_{bw} + c_{bw}(t)T_{bw}^4$$

Where:
The time-varying coefficients (a_{vw} , b_{vw} , c_{vw} , a_{bw} , b_{bw} , and c_{bw}) are functions of the other related temperatures and Thermo-physical parameters.

Figure 1 depicts a schematic representation of the green wall arrangement and accompanying energy transfer processes.

Figure 1: Schematic of the green wall's energy balance [1][2].



Therefore, the terms of equation 1 for green walls are as follows:

$$SR_{vw} = I_t \alpha_w \tau$$
$$LR_{vw} = \tau \varepsilon_w \, \varepsilon_{sky} \, \sigma F_{sky} \left(T_{sky}^4 - T_{vw}^4 \right) + \tau \varepsilon_w \, \varepsilon_{gr} \, \sigma F_{gr} \left(T_{gr}^4 - T_{vw}^4 \right)$$
$$XR = (1 - \tau) \frac{\varepsilon_w \, \varepsilon_{leaf} \, \sigma}{\varepsilon_w + \varepsilon_{leaf} - \varepsilon_w \, \varepsilon_{leaf}} \left(T_{vw}^4 - T_{leaf}^4 \right)$$
$$C_{vw} = h_{vw} \left(T_{air} - T_{vw} \right)$$
$$Q_{vw} = \left(T_{vw} - T_{in} \right) / R_{bw}$$
$$S_{vw} = \rho CpL(dT_{vw} / dt)$$

Furthermore, the terms of the equation 2 for bare walls are specified as follows:

$$SR_{bw} = I_t \alpha_w$$

$LR_{bw} = \tau\varepsilon_w \, \varepsilon_{sky} \, \sigma F_{sky} \left(T_{sky}^4 - T_{bw}^4 \right) + \tau\varepsilon_w \, \varepsilon_{gr} \, \sigma F_{gr} \left(T_{gr}^4 - T_{bw}^4 \right)$

$C_{bw} = h_{bw} \left(T_{air} - T_{bw} \right)$

$Q_{bw} = \left(T_{bw} - T_{in} \right) / R_{bw}$

$S_{bw} = \rho CpL(dT_{bw} / dt)$

Where it is the total solar radiation incident on the wall:
αw = wall absorptivity
τ = plant layer transmissivity of radiation,
ε_w, ε_{sky}, ε_{gr} and ε_{leaf} = emissivity of the wall, sky, ground and plant layer, respectively.

The values are assumed as:
$\alpha_w = 0.7$,
$\varepsilon_w = 0.9$,
$\varepsilon_{sky} = 1$,
$\varepsilon_{gr} = 0.9$,
$\varepsilon_{leaf} = 0.96$.

The plant layer transmissivity, τ = exp (− κ_{leaf}).

Here, the radiation attenuation coefficient κ (taken as 0.4 W/mK), and the leaf area index *LAI* (assumed as 1.8). σ is the Stefan-Boltzmann constant. F_{sky} and F_{gr} are the view factors between the wall, sky and ground, T_{sky} is the temperature of the sky, T_{vw} is the temperature of the vegetated wall, T_{bw} is the temperature of the bare wall, T_{gr} is the temperature of the ground (assumed equal to T_{air}), T_{leaf} is the leaf temperature, h_{vw} and h_{bw} are the convection heat transfer coefficient of the vegetated and bare wall.

T_{sky} is calculated as a function of the air temperature and dewpoint temperature as:

$$T_{sky} = T_{air} \left(0.8 + \frac{T_{dew} - 273}{250} \right)^{0.25}$$

The view factors are calculated as a function of the tilt angle θ.

$$F_{gr} = 0.5 \left(1 - \cos\theta \right)$$
$$F_{sky} = 0.5 \left(1 - \cos\theta \right)$$

For the vertical greenery system, the tilt angle is equal to 90, resulting in both view factors equal to 0.5.

The equation for calculating T_{leaf} can be found in [1]. The necessary parameters are the thermodynamic psychrometer constant γ (0.000666 °C^{-1}), radiative conductance through air g_r, the leaf characteristic dimension D (0.12m), typical stomatal conductance of lower and upper leaf surface g_{sll} and g_{sul} (0.2 *mol/m² s*), leaf absorptivity α_{leaf} (0.5), relative humidity of the air *RH*, specific heat of the air C_{pair} (29.3 *J/molK*), air pressure P_{pair}.

In the simulations, various models for convective heat transfer coefficients have applied in many investigate [3]. Some of them are shown below:
Susorova used the following equation:

i.

$$h_{vw} = a + bV + cV^2$$

Where:
V = wind speed
a, b, and c = coefficients based on the material roughness. The wall surface is assumed to be of medium roughness, with the coefficients equal to 10.79, 4.192, and 0 respectively.

Morrison & Barfield and Stanghellini calculated h_{vw} using the Nusselt number, which is provided in equations iii and iv, respectively.

ii.

$$h_{vw} = \frac{Nu\lambda}{D}$$

iii.

$$Nu = 0.328\, Pr^{0.33} + Re^{0.5}$$

iv.

$$Nu = 0.37\,(Gr + 6.92Re^{0.5})$$

Where:
Nu = Nusselt number
$Re = \frac{DV}{v}$ = Reynolds number
$Gr = \frac{g\,\beta D^3}{v^2}\,(T_{air} - T_{leaf})$ = Grashof number
λ = air thermal conductivity
Pr = Prandtl number
g = gravitational acceleration constant (9.81 m/s^2)
β = thermal expansion coefficient of air (0.0034 K^{-1})
v = kinematic viscosity of air

The Ayata and ASHRAE models calculated h_{vw} on the basis of McAdams' equation and are presented in equations v and vi, respectively.

v.

$$h_{vw} = 5.9 + 4.1V \frac{511 + 294}{511 + T_{air}}$$

vi.

$$h_{vw} = 5.6 + 4V$$

Equations v and vi are applicable for V < 5m/s, otherwise h_{vw} is calculated from:

vii.

$$h_{vw} = 7.2V^{0.78}$$

Ultimately, in the Campbell & Norman model, h_{vw} uses the boundary layer conductance for heat transfer as follows:

viii.

$$h_{vw} = g_{bh} Cp_{air}$$

Where:

ix.

$$g_{bh} = 1.4 \, . \, 0.135 \sqrt{\frac{V}{D}}$$

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Appendix F: Köppen Climate Classification

Introduction

Wladimir Köppen (1846–1940), a German scientist, presented the first quantitative classification of world climates in 1900; it has been available as a world map updated in 1954 and 1961 by Rudolf Geiger (1894–1981).

Köppen studied plant physiology and discovered that plants are indicators of many climatic elements. His effective classification had been based on the principles of five vegetation groups identified by the French botanist De Candolle in reference to the ancient Greek climate zones [1]. Köppen's five vegetation groups distinguish plants from the equatorial zone (A), the arid zone (B), the warm temperate zone (C), the snow zone (D), and the polar zone (E) (Table F.1). A second letter in the classification considers precipitation (e.g., Df for snow and fully humid), and a third letter considers air temperature (e.g., Dfc for snow, fully humid with cool summer). Even though various authors published improved Köppen classifications or created new classifications, the original Köppen classification (here referred to as the Köppen-Geiger classification) is still the most commonly used climate classification.

Table F.1: The first two letters of the classification are used to calculate the Köppen and Geiger climate formula for the main climates and subsequent precipitation conditions. It should be noted that no precipitation differentiations are provided for the polar climates (E), only temperature conditions are defined. This key implies that the polar climates (E) must be determined first, followed by the arid climates (B), and then the equatorial climates (A) and warm temperate and snow climates (C) and (D), respectively [2].

Type	Description	Criterion
A	**Equatorial climates**	$T_{min} \geq +18\ °C$
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60$ MM
Am	Equatorial monsoon	$P_{ann} \geq 25\ (100 - P_{min})$
As	Equatorial savannah with dry summer	$P_{min} < 60$ mm in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60$ mm in winter
B	**Arid climates**	$P_{ann} < 10\ P_{th}$
BS	Steppe climate	$P_{ann} > 5\ P_{th}$
BW	Desert climate	$P_{ann} \leq 5\ P_{th}$
C	**Warm temperate climates**	$-3\ °C < T_{min} < +18\ °C$
Cs	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$,$P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
Cw	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Cf	Warm temperate climate, fully humid	Neither Cs nor Cw

D	**Snow climates**	$T_{min} \leq -3\ ^{\circ}C$
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
Dw	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Df	Snow climate, fully humid	Neither Ds nor Dw
E	**Polar climates**	$T_{max} < +10\ ^{\circ}C$
ET	Tundra climate	$0\ ^{\circ}C \leq T_{max} < +10\ ^{\circ}C$
EF	Frost climate	$T_{max} < 0\ ^{\circ}C$

To update the historical world map of the Köppen-Geiger climate classes, two global data sets of climate observations were chosen. Both are available on a monthly resolution 0.5-degree latitude/longitude grid. The first data set is provided by the University of East Anglia's Climatic Research Unit (CRU) [3] and consists of grids of monthly climate observations from meteorological stations containing nine climate variables, of which only temperature is used in this study. The temperature fields were derived from time-series observations, which were checked for inhomogeneities in station records using an automated method. This data set includes all land areas on the planet except Antarctica. It is publicly accessible (www.cru.uea.ac.uk) and will be known as CRU TS 2.1.

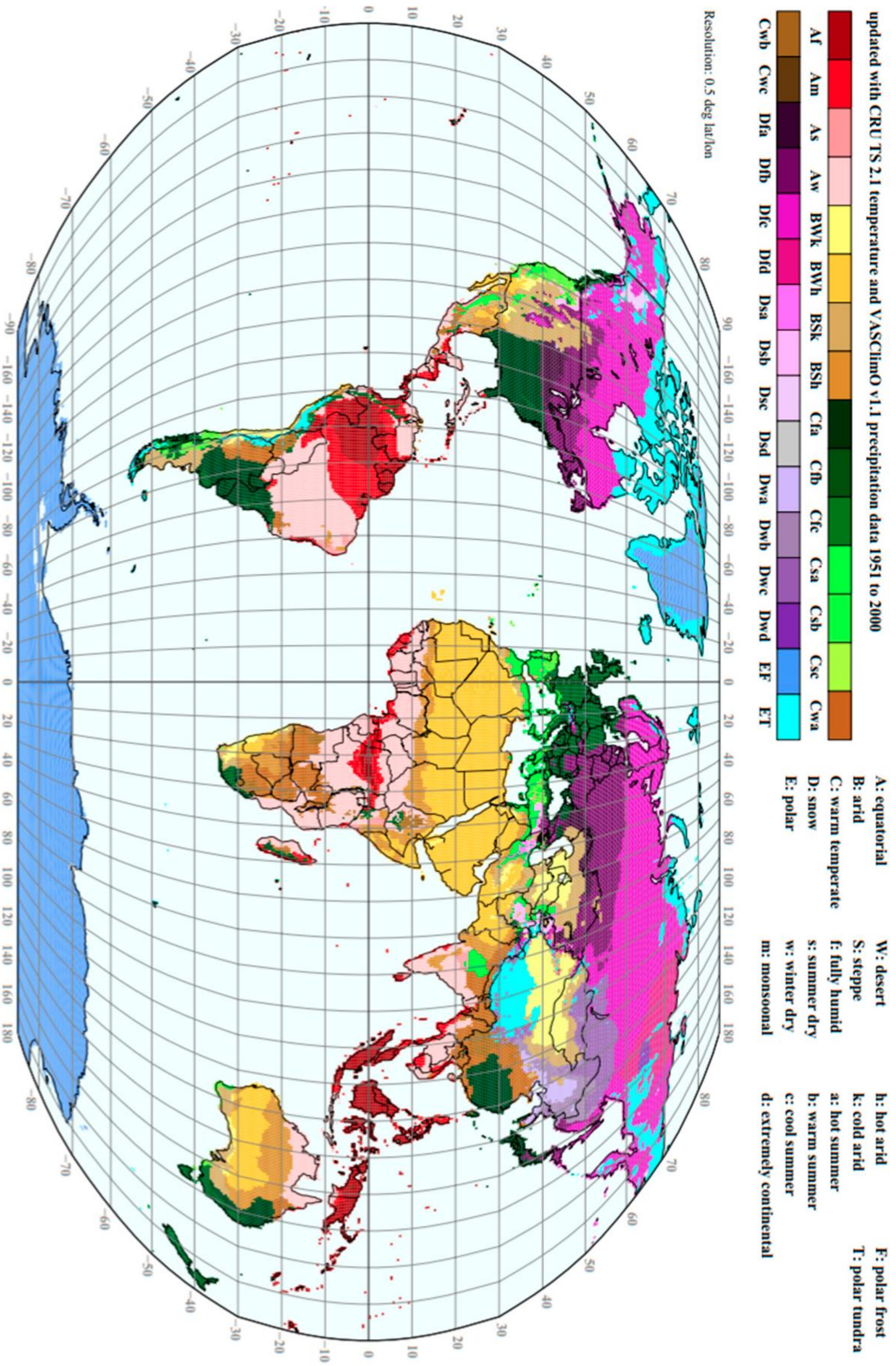
The second set of data [4] is presented by the German Weather Service's Global Precipitation Climatology Centre (GPCC). This new gridded monthly precipitation data set includes all land areas on the planet except Greenland and Antarctica. It was built on the GPCC's most comprehensive data-base of monthly observed precipitation data in the world. To reduce the risk of generating temporal inhomogeneities in the gridded data due to varying station densities, all observations in this station database are subjected to a multi-stage quality control. This set of data is known as VASClimO v1.1[3] and is free to use for scientific purposes (http://gpcc.dwd.de). Both CRU TS 2.1 and VASClimO v1.1 data cover the 50-year period 1951 to 2000 chosen for updating the Köppen-Geiger map in this study.

Figure F.1 depicts a world map of the classification of Köppen-Geiger climate for the period 1951 to 2000, updated with mean monthly CRU TS 2.1 temperature and VASClimO v1.1 precipitation data on a regular 0.5-degree latitude/longitude grid. All 31 climate classes have been represented by different colours, though one of them (Dsd) never appears on this map and others (Cfc, Csc, Cwc, Dsa, Dsb, and Dsc) appear only in very small areas. Nevertheless, this has no bearing on the classification because temperature data strongly suggest that Greenland's climate is either polar tundra (ET) or

[3] Variability Analysis of Surface Climate Observations

polar frost (EF), and thus is independent of precipitation (Table F.1) [2]. Table F.3 presented summary of the climate classification.

Figure F.1: On a regular 0.5-degree latitude/longitude grid, a world map of Köppen-Geiger climate classification has been updated with mean monthly CRU TS 2.1 temperature and VASClimO v1.1 precipitation data for the period 1951 to 2000 [2].



Combining the three letters shown in Tables F.1 and F.2 results in a maximum of 34 different climate classes. Three classes cannot exist by definition because a warm temperate climate (C) requires a temperature of the coldest month T_{min} above –3 °C, whereas an extremely continental climate (d) requires a temperature of the coldest month T_{min} below –38 °C. As a result, (Csd), (Cwd), and (Cfd) cannot be realized, leaving 31 climate classes. Köppen and Geiger recognized that not all of the remaining types occur in significant numbers, and thus not all of these types may be of climatological significance.

Table F.2: The key to calculating the third letter temperature classification (h) and (k) for arid climates (B), and (a) to (d) for warm temperate and snow climates (C) (D). It should be noted that for type (b), warm summer, a threshold temperature value of +10 C must be present for at least four months [2].

Type	Description	Criterion
h	Hot steppe / desert	$T_{ann} \geq +18\,°C$
k	Cold steppe / desert	$T_{ann} < +18\,°C$
a	Hot summer	$T_{max} \geq +22\,°C$
b	Warm summer	Not (a) and at least 4 $T_{mon} \geq +10\,°C$
c	Cool summer and cold winter	Not (b) and $T_{min} > -38\,°C$
d	Extremely continental	Like (c) but $T_{min} \leq -38\,°C$

Table F.3: Köppen–Geiger climate classification characteristics [5].

Group	Köppen–Geiger Subcategories			Characteristic
Tropical	Af	(A) (f)	Equatorial Fully humid	Tropical rainforest climate
	Am	(A) (m)	Equatorial Monsoonal	Tropical monsoon climate
	Aw	(A) (w)	Equatorial Winter dry	Tropical wet and savanna climate
	As	(A) (s)	Equatorial Summer dry	Tropical dry and savanna climate
Arid	BWh	(B) (W) (h)	Arid Desert Hot arid	Hot desert climate

	BWk	(B) (W) (k)	Arid Desert Cold arid	Cold desert climate
	BSh	(B) (S) (h)	Arid Steppe Hot arid	Hot semi-arid climate
	BSk	(B) (S) (k)	Arid Steppe Cold arid	Cold semi-arid climate
Subtropical	Csa	(C) (s) (a)	Warm temperate Summer dry Hot summer	Hot summer Mediterranean climate
	Csb	(C) (s) (b)	Warm temperate Summer dry Warm summer	Warm summer Mediterranean climate
	Cwa	(C) (w) (a)	Warm temperate Winter dry Hot summer	Monsoon-influenced humid subtropical climate
	Cwb	(C) (w) (b)	Warm temperate Winter dry Warm summer	Subtropical highland climate
	Cwc	(C) (w) (c)	Warm temperate Winter dry Cool summer	Cold subtropical highland climate
	Cfa	(C) (f) (a)	Warm temperate Fully humid Hot summer	Humid subtropical climate
	Cfb	(C) (f) (b)	Warm temperate Fully humid Warm summer	Temperate oceanic climate
	Cfc	(C) (f) (c)	Warm temperate Fully humid Cool summer	Subpolar oceanic climate
Continental	Dsa	(D) (s) (a)	Snow Summer dry Hot summer	Mediterranean-influenced hot summer humid continental climate
	Dsb	(D) (s) (b)	Snow Summer dry Warm summer	Mediterranean-influenced warm summer humid continental climate
	Dsc	(D) (s) (c)	Snow Summer dry Cool summer	Subarctic climate

	Dsd	(D) (s) (d)	Snow Summer dry Extremely continental	Extremely cold subarctic climate
	Dwa	(D) (w) (a)	Snow Winter dry Hot summer	Monsoon-influenced hot summer humid continental climate
	Dwb	(D) (w) (b)	Snow Winter dry Warm summer	Monsoon-influenced warm summer humid continental climate
	Dwc	(D) (w) (c)	Snow Winter dry Cool summer	Monsoon-influenced subarctic climate
	Dwd	(D) (w) (d)	Snow Winter dry Extremely continental	Monsoon-influenced extremely cold subarctic climate
	Dfa	(D) (f) (a)	Snow Fully humid Hot summer	Hot summer humid continental climate
	Dfb	(D) (f) (b)	Snow Fully humid Warm summer	Warm summer humid continental climate
	Dfc	(D) (f) (c)	Snow Fully humid Cool summer	Subarctic climate
	Dfd	(D) (f) (d)	Snow Fully humid Extremely continental	Extremely cold subarctic climate
Polar	ET	(E) (T)	Polar Polar tundra	Tundra climate
	EF	(E) (F)	Polar Polar frost	Ice cap climate

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Building Orientation in Green Facade Performance and Its Positive Effects on Urban Landscape Case Study: An Urban Block in Barcelona

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Abstract: This paper addresses the effect of building orientation efficiency of the green facade in energy consumption, for which the case study is an urban block in Passeig de Gracia, L'Eixample, Barcelona. Nowadays, many countries are faced with the trouble of the deficiency of energy resources and the incapability of saving them. Most of this energy is consumed in the cooling, heating, and artificial ventilation of buildings. For this reason, the development of an integrated strategy like a green facade is essential to transform buildings into structures that consume less energy and to improve the occupants' comfort conditions. From the perspective of the urban landscape, the green facade can influence the quality of life in cities due to its positive effects such as the purification of air, the absorption of carbon dioxide, and the mitigation of dust, as well as the aesthetic and psychological aspects. Such criteria are based on the adoption of suitable orientation for the green facade, which is the second layer of the facade in an office building with a curtain wall as the main facade. Since the most important factor in the implementation of a green facade is the building's orientation, the optimum orientation could be the key factor in regards to the reduction of energy consumption and cost and the improvement of overall energy efficiency. We used software that helped simulate the total energy consumption, the cost, and the energy use intensity annually and monthly. Consequently, after testing was carried out, it was proven that a green facade as a second layer with a southeast and/or a southwest orientation results in the maximum energy saving in a coastal city with a Mediterranean climate like Barcelona.

Keywords: vertical garden; green facade; building orientation; energy consumption; sustainability; urban landscape; simulation software

1. Introduction

In recent decades, countries have faced plenty of issues related to energy supplies and the effects of global warming and urban heat islands (UHIs) on energy consumption [1]. For this reason, architects and urban planners have proposed a newer design approach, namely the sustainable building design, to reduce the heat island effect and energy demand and minimize environmental effects [2]. The green facade is an element of sustainable building design which is gradually gaining popularity, and it is being applied extensively on a large scale [3,4]. Moreover, using plants in the facade (green facade) is a bioclimatic strategy that would be effective in reducing energy consumption in buildings, in addition to other psychological, aesthetic, and economic benefits [5].

Many studies have revealed the positive effects of the adoption of the green facade in buildings and those buildings' orientation on energy consumption efficiency [6].

A building with the right orientation can double the efficiency of the green facade as a second layer in the facade [1,2]. Utilizing the appropriate building orientation when applying a vertical garden could save a lot of money as it would no longer require heating and cooling expenditure costs; in fact, the building itself would provide a comfortable environment for occupants through energy reduction and cost reduction [3–5]. By using a green facade, occupants can reduce heating and cooling consumption. An extra benefit is that there is nothing that can fail or break down with a building that has the appropriate orientation for the application of a green layer in the building's facade; as a result, this strategy is called "passive solar" [6] due to the almost zero maintenance costs that could be incurred during the lifetime of the green facade. It is important to note that the choice of plants is to be taken into account as they must be suitable for the specific orientation of the building for such a facade to be successful. For example, a building orienting south must opt for sun-resistant plants [7,8].

Building orientation has been one of the primary considerations within construction for thousands of years in many cultures. One of the original references for building orientation and passive solar principals was by Socrates about 2300 years ago [6]. "Now in houses with a south aspect, the sun's rays penetrate the porticos in winter, but in the summer the path of the sun is right over our heads and above the roof so that there is shade. If then, this is the best arrangement, we should build the south side loftier to get the winter sun and the north side lower to keep out the winter winds."

Pérez et al. [4] summed up the green facades mechanisms when used as a passive system for energy savings: the shadowing effect of the vegetation shields the building's surface from solar radiation, and vegetation also provides thermal insulation, as when the plants' evapotranspiration occurs, the evaporative cooling in the substrate and the effect of the wind on the building change.

Nowadays, many countries have adopted different construction methods to obtain benefits from solar radiation and building orientations, like double skin and green facade as a second skin [2], especially in glass facades. In fact, it was discovered that building behavior in response to solar radiation could be changed in different climates by implementing passive solutions [9]. One way to reinforce passive solutions in buildings is to implement a green facade as a second layer in buildings, especially in Mediterranean climates as they would benefit the most from an environment without artificial devices [8].

In fact, one factor that causes the growth of a building's energy consumption is high temperatures, because they result in intolerable cooling demand [10–16]. It is estimated that midlatitude and temperate climates will face a significant increase in annual energy consumption because of climate change and urban heat island (UHI) scenarios as cooling will be required in autumn and spring as well [17,18].

The concept of building energy efficiency is related to the energy supply required which achieves suitable environmental conditions that could allow the reduction of energy consumption [19]. One of the best methods to reduce the cost of energy in buildings is a suitable heating and cooling design [20]. Variables of design and construction parameters should be optimized to design energy-efficient buildings [21]. Parameters that affect building energy requirements have been summarized by Ekici and Aksoy [22] (Table 1).

Table 1. Parameters that determine building energy requirements [22,23].

Physical–Environmental Parameters	Design Parameters
	Shape factor
Daily outside temperature (°C)	Transparent surface
Solar radiation (W/m^2)	Orientation
Wind direction and speed (m/s)	Thermal–physical properties of building materials
	Distance between buildings

In terms of urbanism, the green facade is one of the strategic implementations of urban green infrastructure (UGI) that can help urban landscape areas to achieve temperature reductions, causing the reduction of energy use within urban buildings, and it also has the added benefits of pollution reduction and the improvement of habitat biodiversity [24]. In high-density cities, the green facade could contribute to stress recovery and well-being, so the residents could benefit physiologically and psychologically from this UGI strategy [25].

The aim of this research was to investigate the impact of building orientation for a green facade on energy consumption. This paper presents a detailed description of the steps to take in order to benefit from the green facade as a second layer and its optimum orientation in Passeig de Gracia, L'Eixample area in Barcelona, Spain, by employing Autodesk Green Building Studio as a simulation software to prove the ability of the Green Building Studio to design high-performance buildings at a fraction of the time and cost of conventional methods [26,27].

2. Methodology

The methodology is based on the study of reducing energy consumption by applying green facades in different orientations, which causes an effect on the building's behavior. In addition, we discuss different strategies and architectural solutions to understand the reduction of energy consumption in buildings that have a green facade. Through the analysis of the previous research which explored the performance of a green facade by using a building simulation, we concluded that the structure and cavity depth in the application of the green facade are of great importance in regards to energy consumption reduction. For the first part, we selected an appropriate orientation (southeast), and we simulated a structure with different cavity depths. As a second simulation, we tested eight buildings with different orientations and specific cavity depths to understand the influence of different orientations on green facade performance.

To compare and observe the impact of this study, a single-skin run was added for each simulation. This is the advantage of using Green Building Studio, as it can recreate many simulations in one project, making it easy to compare the results in this case. The data created by the initial base run (no changes made in Green Building Studio and applied project default) were used for tests 1 to 6 with different cavity sizes and also in tests 1 to 8 which simulated different orientations.

2.1. Case Study and Scenario Descriptions

The scenario considering the green facade is generic; the application has a more complex building configuration. It was carried out in a green building design in Passeig de Gracia (street), L'Eixample area, in Barcelona (this area was designed by Ildefonso Cerdá in 1856) [28] (Figure 1). According to urban planning in Barcelona, each urban block has a 45° angle. The urban texture is continuous, dense, and compact; the average height of buildings ranges from 15 to 30 m. Given the different ages of planning, the size of the urban block varies within the city [15].

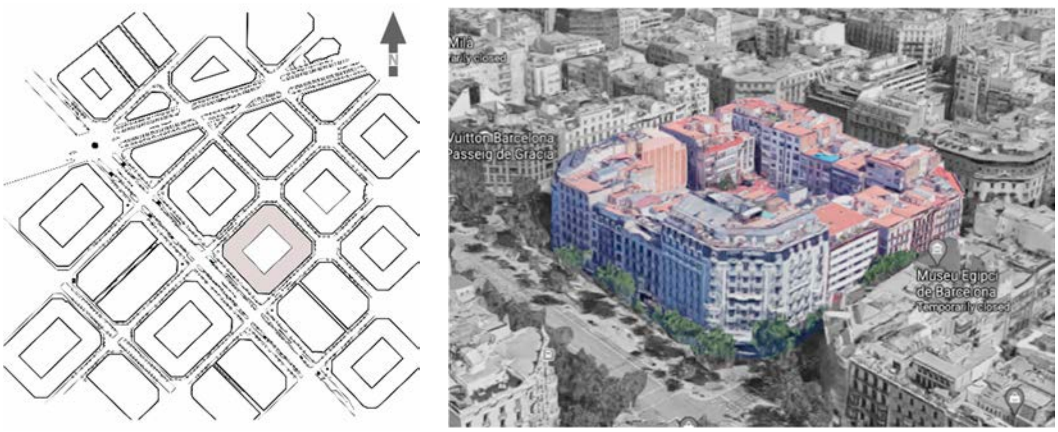


Figure 1. The case study is an urban block which is located in Passeig de Gracia, L'Eixample, in Barcelona. © By Author.

The case study is conceptual with cubic shape and a square plan in dimensions 10 × 10 m, 10 m high (Figures 2 and 3).

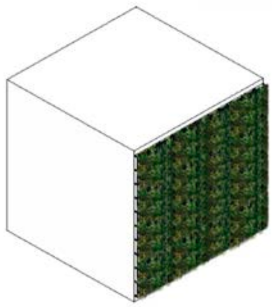


Figure 2. The morphology of the case study (10 × 10 × 10 m). © By Author.

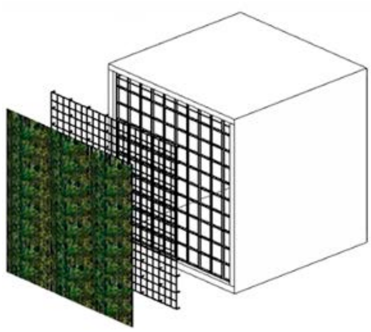


Figure 3. The layers of the facade. © By Author.

The main facade in this case study is a nonstructural curtain wall used only to separate the indoors from the outdoor weather. The curtain wall frame attaches to the building structure and does not carry the floor or roof loads. Regarding the methodology, the facade was considered in two simulations, and the first simulation included six tests, where test 1 was just a single skin (curtain wall) and tests 2 to 6 were green skins within a 10 to 50 cm cavity depth (see Table 2). This green facade is part of the facade that supports the green wall (horizontal aluminum slats) as a second layer that is applied to the facade. According to the classification of green walls that considers the horizontal aluminum slats as the continuous guides of an indirect green facade, this is a kind of green facade structure [29,30] (see Figure 4).

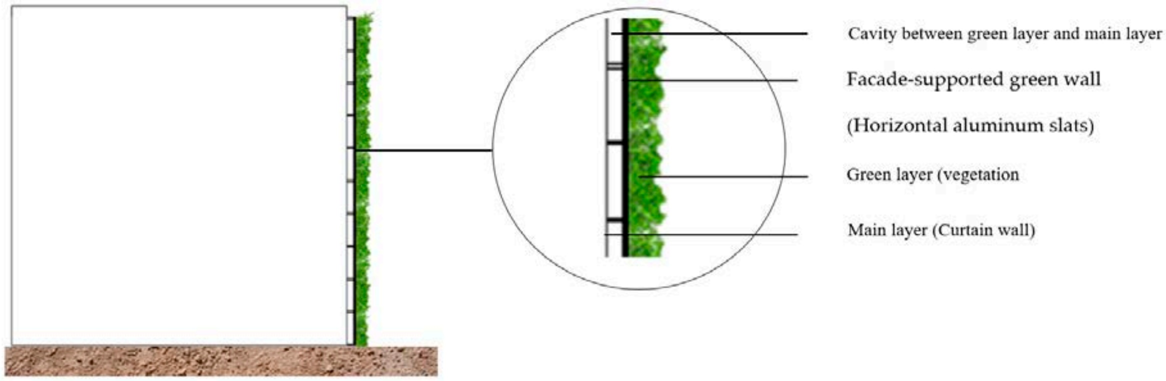


Figure 4. The implementation of the green layer on the facade with a cavity depth. © By author.

Table 2. The number of simulations with the same orientation but different sizes of the cavity depth. © By author.

Test	Facade Type		Cavity	Building Orientation	Facade Structure
	Single Layer	Second Layer			
1	Single-skin facade	-	0	Southeast	Curtain wall (main facade)
2	-	Green-skin facade	10 cm	Southeast	Facade-supported green wall (horizontal aluminum slats)
3	-	Green-skin facade	20 cm	Southeast	Facade-supported green wall (horizontal aluminum slats)
4	-	Green-skin facade	30 cm	Southeast	Facade-supported green wall (horizontal aluminum slats)
5	-	Green-skin facade	40 cm	Southeast	Facade-supported green wall (horizontal aluminum slats)
6	-	Green-skin facade	50 cm	Southeast	Facade-supported green wall (horizontal aluminum slats)

3. Results

The results are divided into two parts. The first section shows the energy consumed within the different sizes of the cavity in the green layer of the facade. The second section presents simulation results for energy consumed in different orientations through eight tests.

3.1. Analysis of the Energy Consumed with Different Cavity Depth Sizes in the Green Layer in Facade

By using the simulation program, the energy consumption was studied and analyzed for each of the five different cavities in the green facade and compared with the single-skin facade (curtain wall) as the main facade with a southeast orientation in L'Eixample area of Barcelona throughout one year, as shown in Table 3.

sustainability MDPI

Table 3. Comparison of energy consumption with different cavity depths in southeast orientation. © By author.

Name	Floor Area (m²)	Energy Use Intensity (MJ/m²/year)	Electric Cost (/kWh)	Fuel Cost (/MJ)	Total Annual Cost			Total Annual Energy		
					Electric	Fuel	Energy	Electric (kWh)	Fuel (MJ)	Carbon Emissions (Mg)
Green Skin 50cm Cavity	91	1,063.4	€ 0.13	€ 0.01	€ 1,675	€ 568	€ 2,243	13,397	48,897	--
Green Skin 40cm Cavity	91	1,063.6	€ 0.13	€ 0.01	€ 1,644	€ 579	€ 2,223	13,150	49,811	--
Green Skin 30cm Cavity	91	1,064.7	€ 0.13	€ 0.01	€ 1,668	€ 572	€ 2,240	13,342	49,216	--
Green Skin 20cm Cavity	91	1,045.6	€ 0.13	€ 0.01	€ 1,613	€ 570	€ 2,183	12,901	49,063	--
Green Skin 10cm Cavity	91	1,053.1	€ 0.13	€ 0.01	€ 1,602	€ 582	€ 2,184	12,817	50,045	--
Single Skin	91	1,081.3	€ 0.13	€ 0.01	€ 2,247	€ 396	€ 2,643	17,974	34,062	--

sustainability

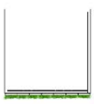
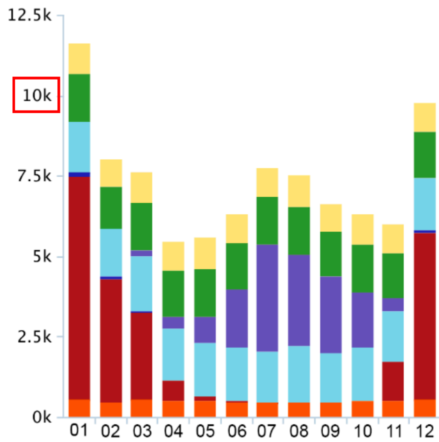
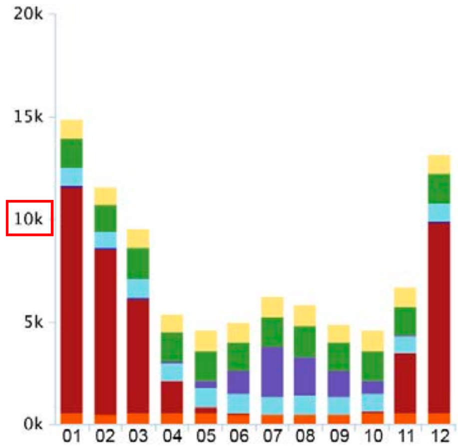
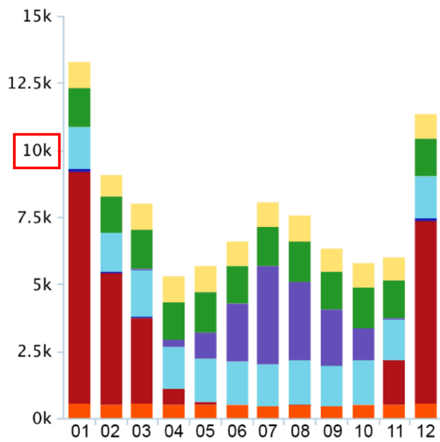
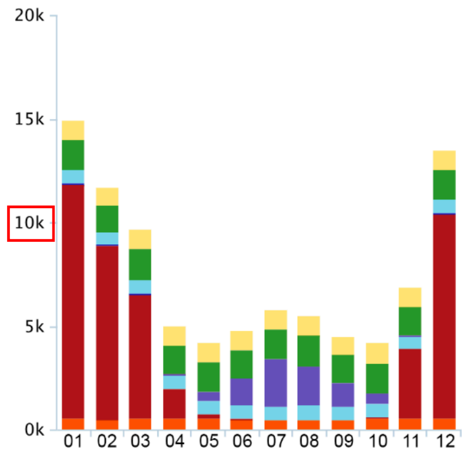
MDPI

Table 3 shows that the optimum cavity size for this orientation (southeast) was 20 cm because it reduced the total energy cost (annual), the energy use intensity (EUI), and the total annual electricity use. However, fuel consumption was increased because of the decreased effect of sunlight due to the covering of the facade with the vegetation. Nevertheless, it should be noted that nowadays most heating and cooling devices, as well as lighting and air conditioning systems, use electrical energy. As a result, reducing electricity consumption is the most effective way to reduce energy consumption.

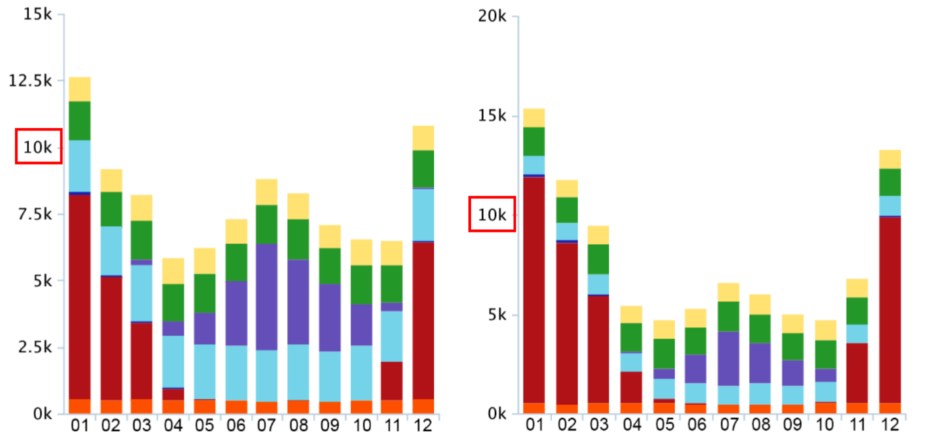
3.2. Analysis of the Energy Consumed in Different Orientations

After analyzing the first simulation (analysis of the energy consumed with different cavity depth sizes in the green layer of the facade), a 20 cm cavity depth size was chosen for the second simulation. In this section, we simulated the green facade building in different orientations with a 20 cm cavity depth (Table 4). As can be seen in Table 4, the building consumed more electricity for cooling in July, August, and September than in other months, and, by applying a green layer on the facade, the usage of electricity was reduced in all cases but the amount of reduction was different depending on the building's orientation. The most important data extracted from the simulation software were cooling and heating consumption; other energy consumption indicators like pumping or boiling water were not relevant for this research.

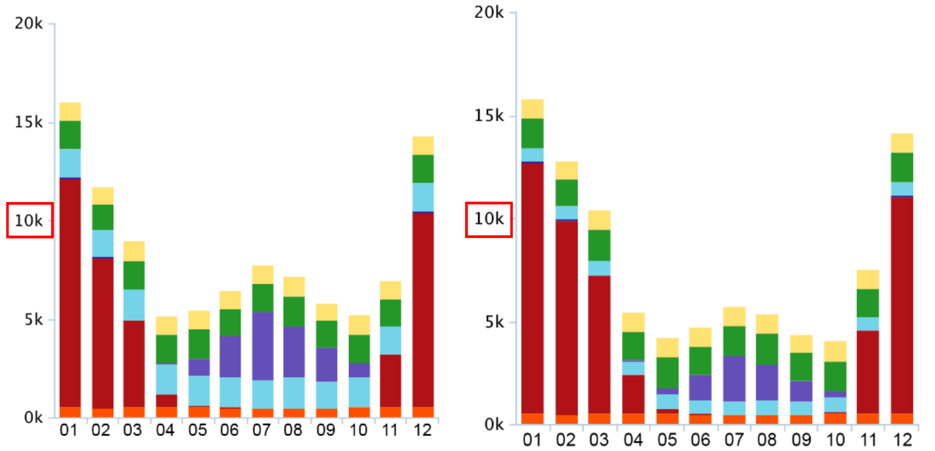
Table 4. Energy consumption comparison between a single-skin facade (curtain wall) and a green-skin facade in different orientations. © By author.

<table>
<tr><th rowspan="2">Building Orientation</th><th colspan="2">Monthly Data</th></tr>
<tr><th>Total Energy (Single-Skin Facade)</th><th>Total Energy (Green-Skin Facade)</th></tr>
<tr><td>Test 1: South
</td><td>
</td><td>
</td></tr>
<tr><td>Test 2: Southeast
</td><td>
</td><td>
</td></tr>
</table>

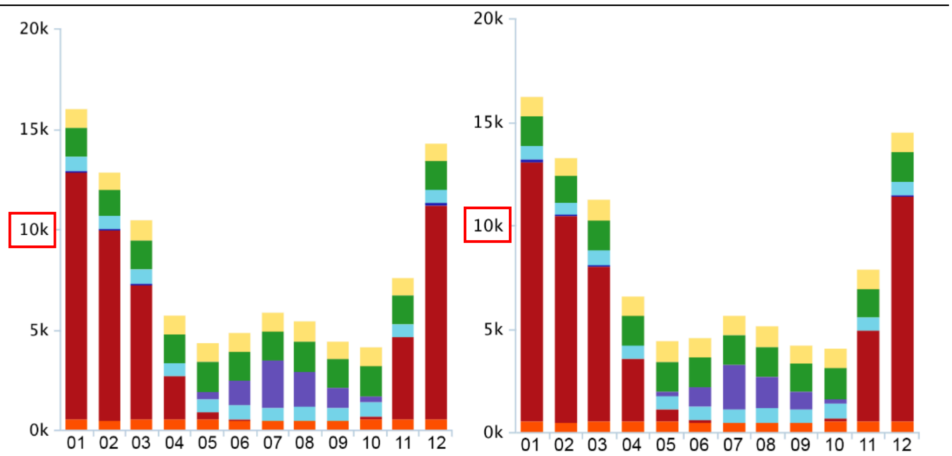
Test 3: Southwest



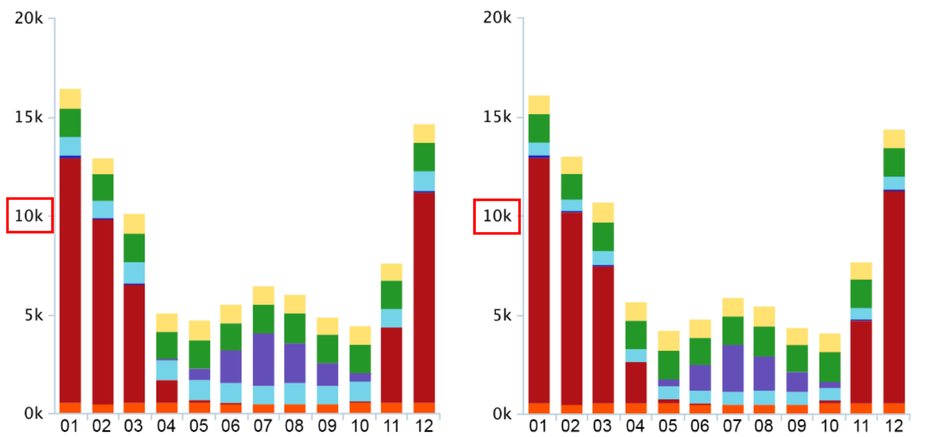
Test 4: East



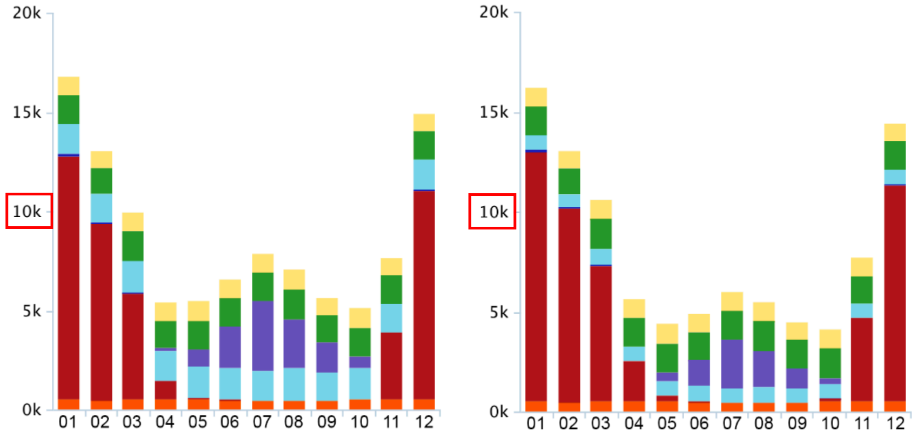
Test 5: North



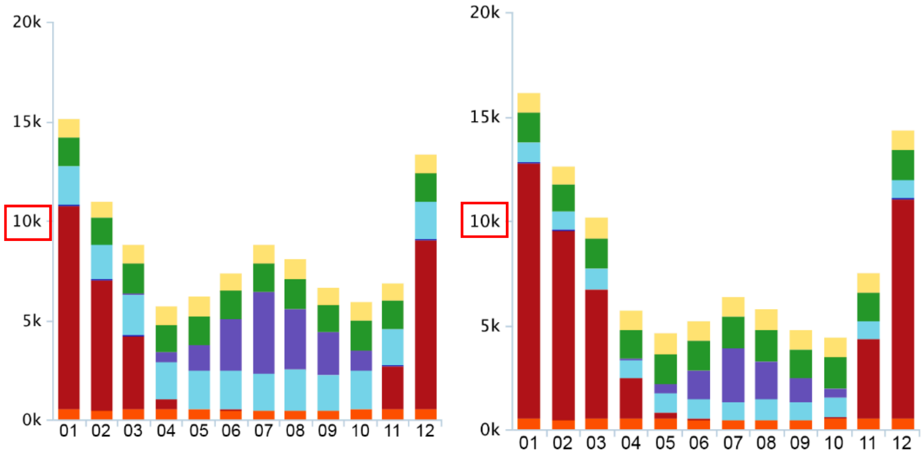
Test 6: Northeast



Test 7: Northwest



Test 8: West



Area Lights, Misc Equip, Space Cooling, Vent Fans, Pumps Aux, Space Heat, Hot Water

According to Table 5, which expresses the importance of building orientation in the performance of the green facade by comparing eight different orientations for the green facade, the green facade's performance varied from one orientation to another regarding the reduction of energy consumption. The southeastern green facade had the best performance in the reduction of energy use, especially in electrical energy, whereas the highest use of energy among orientations was found for the western green facade.

Table 5. Energy consumption and cost varying between eight different orientations. © By author.

			Energy Consumption at Eight Orientations							
			South	**South east**	**South west**	**East**	**North**	**North east**	**North west**	**West**
Total Annual Energy Cost (€)		Single Facade	€2600	€2633	€2863	€2641	€2242	€2403	€2711	€2888
		Green Facade	€2273	€2183	€2351	€2214	€2232	€2239	€2282	€2352
Total Annual Energy	Electric (KWh)	Single Facade	18,177	17,918	20,045	16,914	12,820	14,346	17,023	19,393
		Green Facade	13,782	12,880	14,364	12,692	12,441	12,766	13,111	13,891
	Fuel (MJ)	Single Facade	28,209	33,832	30,734	45,314	12,820	52,445	50,137	39,883
		Green Facade	47,365	49,287	47,824	53,952	58,220	55,378	55,335	52,965
Energy Use Intensity (MJ/m²/year)		Single Facade	1025.3	1076.6	1126.5	1162.7	1107.7	1139.6	1219.8	1201.0
		Green Facade	1061.7	1047.3	1089.7	1090.9	1127.8	1109.4	1122.6	1127.4

By considering the simulation of a green building in different orientations performed in this paper, it can be determined that the green facade's performance in regards to energy reduction results in different outcomes when angled at different orientations (Table 6). The northern and western green facades had a shortage of sun radiance, reducing the electrical use slightly and thus causing the use of energy for heating during winter and part of autumn and spring to not be sustainable. Such orientations obtain minimal performance of the green facade. In contrast, the total annual electrical consumption and cost in green facade buildings facing a southwest and/or a southeast orientation dropped significantly; this was thanks to solar energy, which has proven very effective for the green facade, that was captured by such orientations. These orientations use the maximum ability of the green facade for energy consumption, which can also be called passive energy. The green facade also provides shade, which reduces the use of cooling devices during hot weather; the second layer also protects the building during the cold weather and wind, consequently causing a change of building behavior.

Table 6. Annual electric and fuel end-use comparison between two types of facade (green and single skin) in eight different orientations. © By author.

			Annual Electric End-Use			Annual Fuel End-Use	
			HVAC	Lights	Other	HVAC	Other
1	South	Single Skin	54.3%	18.0%	27.7%	77.2%	22.8%
		Green Skin	39.8%	23.7%	36.5%	86.4%	13.6%
2	Southeast	Single Skin	53.7%	18.2%	28.1%	81.0%	19.0%
		Green Skin	35.5%	25.4%	39.1%	87.0%	13.0%
3	Southwest	Single Skin	58.6%	16.3%	25.1%	79.1%	20.9%
		Green Skin	42.2%	22.8%	35.0%	86.6%	13.4%
4	East	Single Skin	50.9%	19.3%	29.8%	85.8%	14.2%
		Green Skin	34.6%	25.7%	39.7%	88.1%	11.9%
5	North	Single Skin	35.2%	25.5%	39.3%	88.3%	11.7%
		Green Skin	33.3%	26.3%	40.5%	89.0%	11.0%
6	Northeast	Single Skin	42.1%	22.8%	35.1%	87.8%	12.2%
		Green Skin	35.0%	25.6%	39.4%	88.4%	11.6%
7	Northwest	Single Skin	51.2%	19.2%	29.6%	87.2%	12.8%
		Green Skin	36.7%	24.9%	38.4%	88.4%	11.6%
8	West	Single Skin	57.2%	16.9%	26.0%	83.9%	16.1%
		Green Skin	40.2%	23.5%	36.2%	87.9%	12.1%

Here, it is shown that all orientations represent the different performances of the green facade in energy consumption. The results of the second simulation are divided into eight tests below, and an annual electric end-use and fuel end-use comparison is made between a single skin (main facade that is the curtain wall) and a green skin (as a second layer that is vegetation) for each test.

Test 1: South Orientation

In the south green facade, annual electricity consumption decreased by about 24%. Energy use intensity (EUI) in the southern green facade increased by about 36.5 MJ/m^2/year, and the total annual energy cost decreased by approximately 12.5% (Figures 5 and 6).

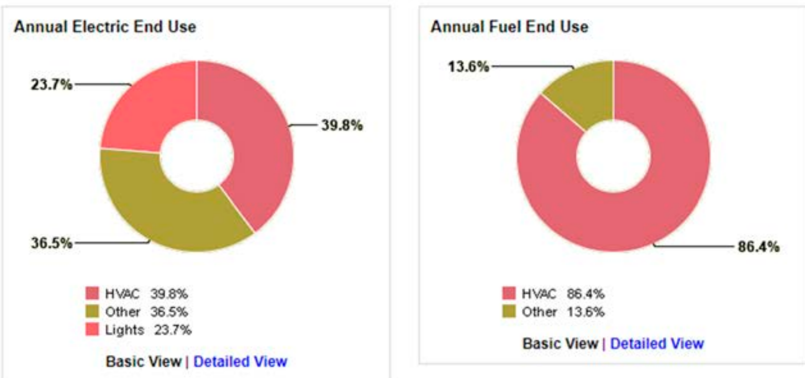


Figure 5. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the southern green facade. © By author.

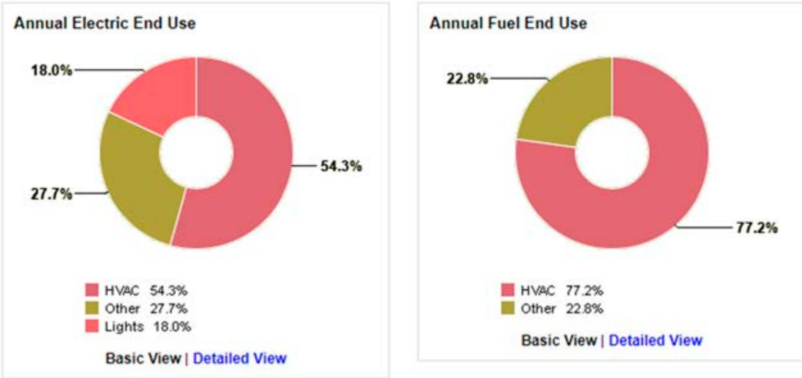


Figure 6. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the southern single facade. © By author.

Test 2: Southeast Orientation

In the southeast green facade, annual electric consumption was reduced by about 28%. The total annual energy cost decreased by approximately 17%, and energy use intensity (EUI) in the southeast green facade decreased by 29.4 MJ/m^2/year (Figures 7 and 8).

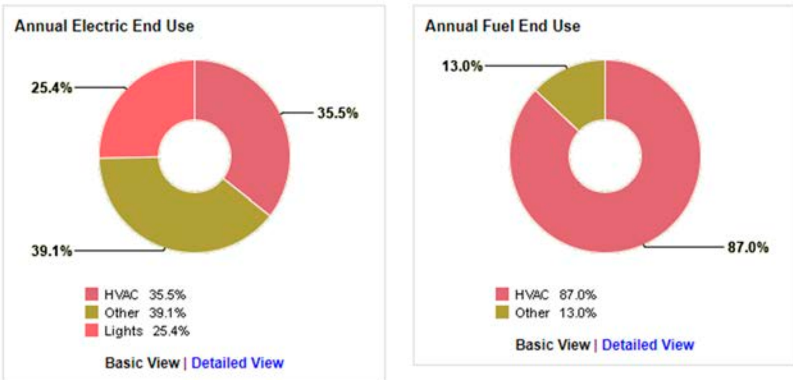


Figure 7. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the southeast green facade. © By author.

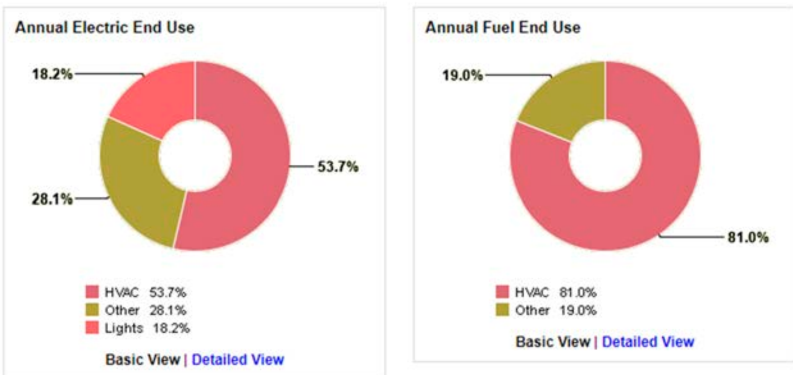


Figure 8. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the southeast single facade. © By author.

Test 3: Southwest Orientation

The southwest green facade showed a 71.2% reduction of annual electrical use. The total annual energy cost was reduced by approximately 17.9%, and energy use intensity (EUI) in this orientation decreased 36.8 MJ/m²/year (Figures 9 and 10).

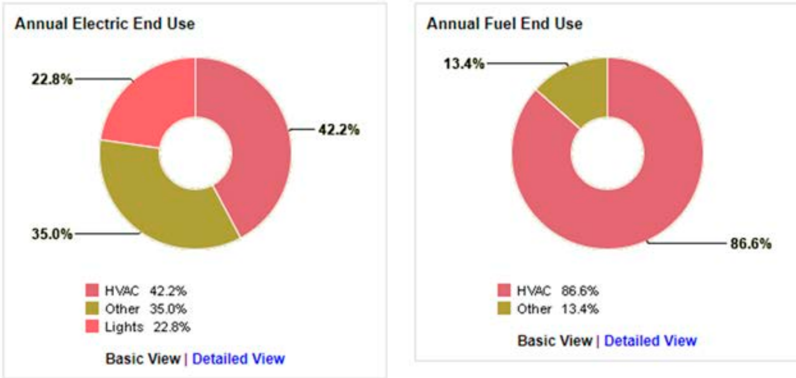


Figure 9. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the southwest green facade. © By author.

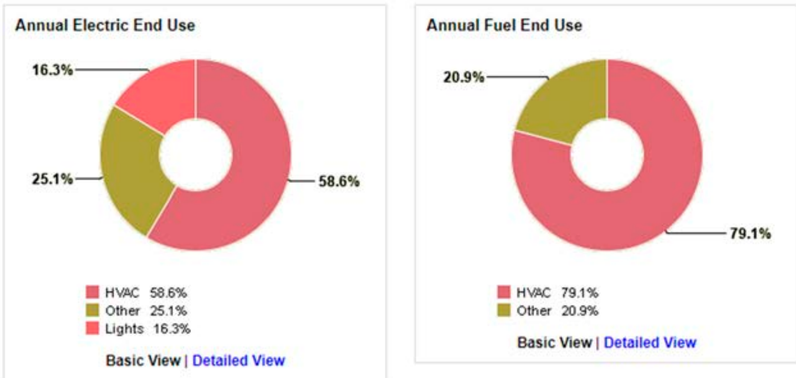


Figure 10. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the southwest single facade. © By author.

Test 4: East Orientation

For the eastern green facade, annual electricity consumption decreased by about 25%. Energy use intensity (EUI) in the east green facade fell by about 71.8 MJ/m²/year, and the total annual energy cost decreased by approximately 16% (Figures 11 and 12).

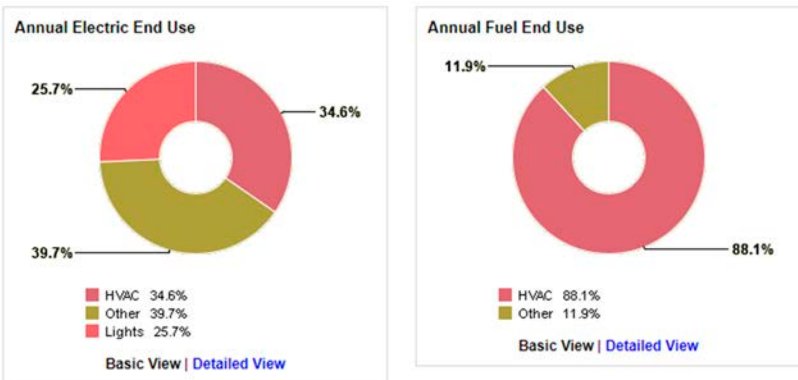


Figure 11. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the eastern green facade. © By author.

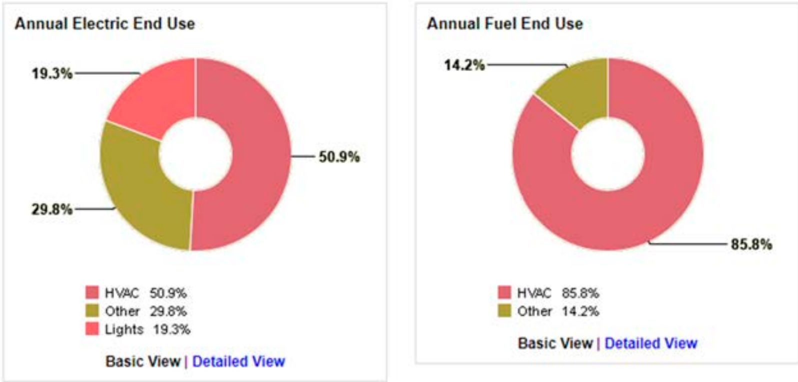


Figure 12. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the eastern single facade. © By author.

Test 5: North Orientation

In the north green facade, annual electricity consumption decreased by about 3%. Energy use intensity (EUI) in the north green facade fell by about 20.1 MJ/m^2/year, and the total annual energy cost was reduced by just about 0.5% (Figures 13 and 14).

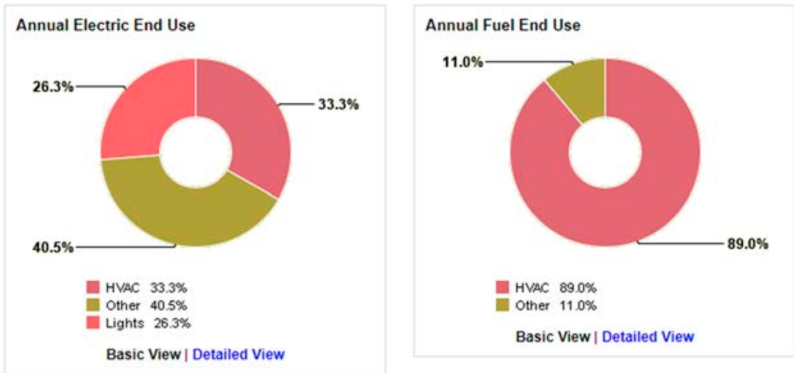


Figure 13. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the northern green facade. © By author.

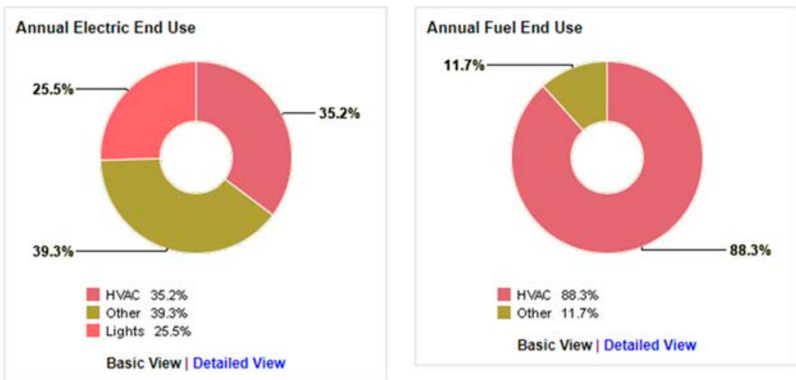


Figure 14. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the northern single facade. © By author.

Test 6: Northeast Orientation

In the northeast green facade, annual electricity use was reduced by about 11%. The total annual energy cost was decreased by just about 7%, and energy use intensity (EUI) in the northeast green facade fell by about 30 MJ/m^2/year (Figures 15 and 16).

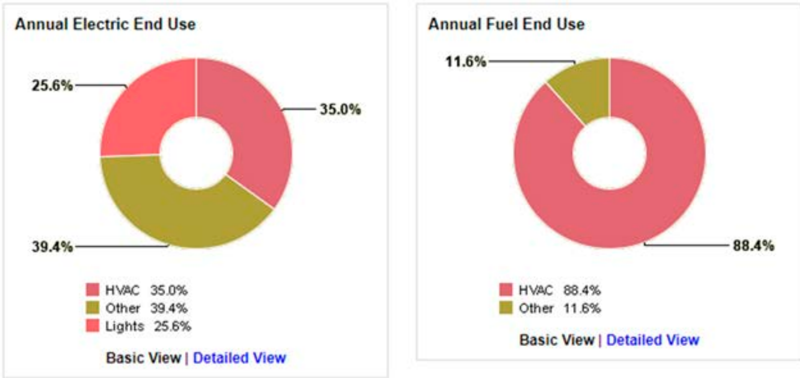


Figure 15. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the northeast green facade. © By author.

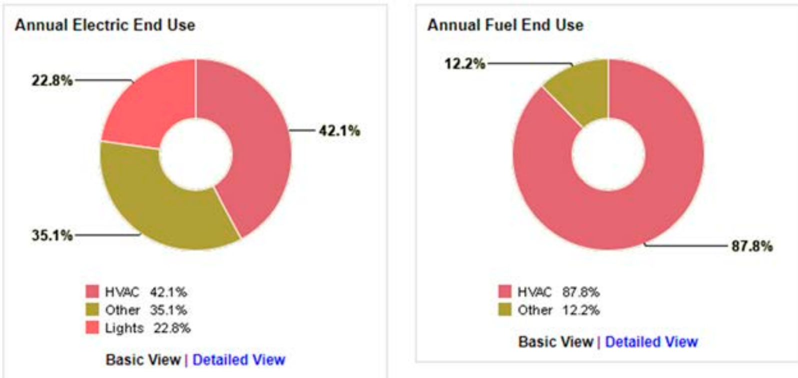


Figure 16. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the northeast single facade. © By author.

Test 7: Northwest Orientation

The northwest green facade showed a reduction in annual electricity consumption, which decreased by about 23%. The total annual energy cost decreased by just about 16%, and energy use intensity (EUI) in the northwest green facade fell by about 97.3 MJ/m^2/year (Figures 17 and 18).

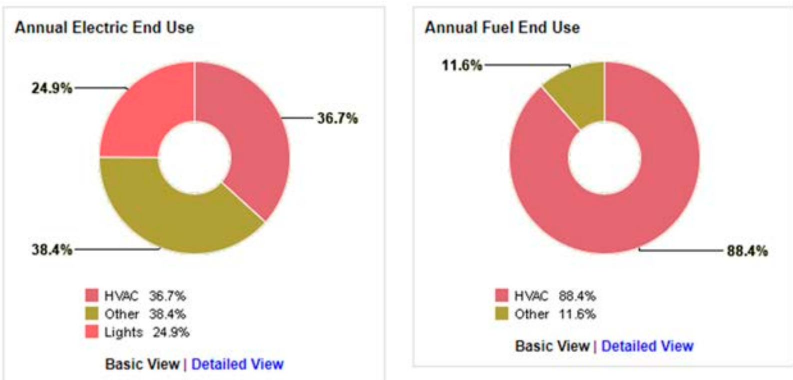


Figure 17. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the northwest green facade. © By author.

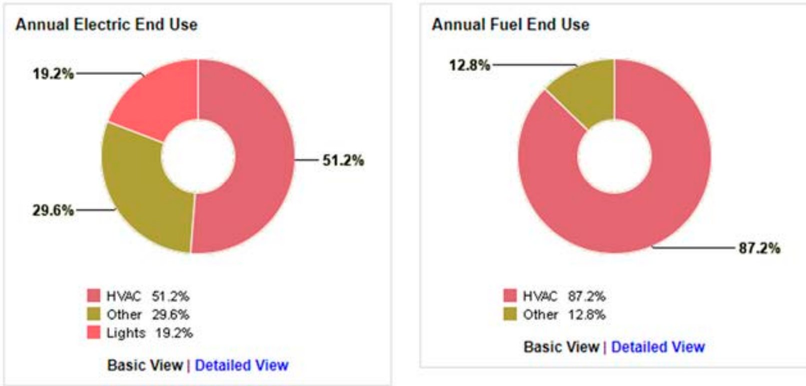


Figure 18. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the northwest single facade. © By author.

Test 8: West Orientation

In the west green facade, annual electricity use decreased by about 28.3%. The total annual energy cost was reduced by about 18.5%, and energy use intensity (EUI) fell by about 73.6 MJ/m²/year (Figures 19 and 20).

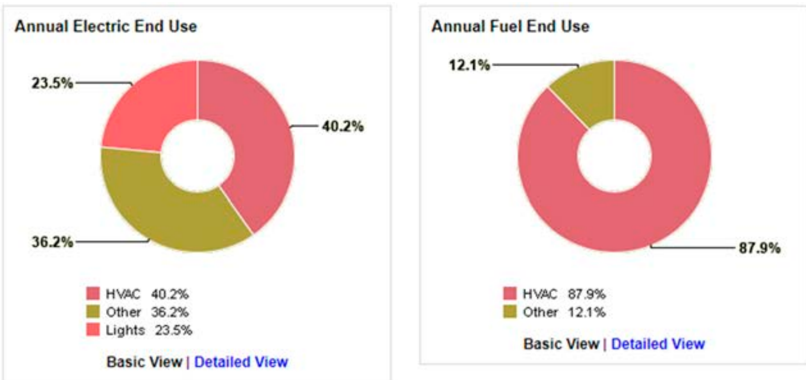


Figure 19. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the west green facade. © By author.

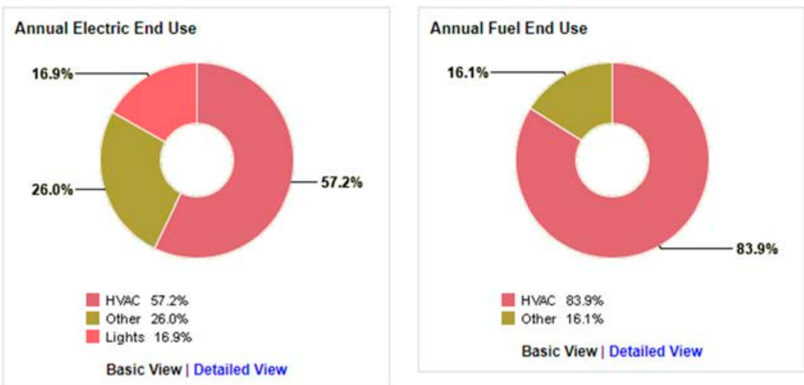


Figure 20. Annual electric and fuel end-use for HVAC, lights, and other (miscellaneous equipment) in the west single facade. © By author.

4. Conclusions

These results confirm that building orientation, as well as the geographical location and its climate, is a basic requirement for the green facade. It is important to consider the solar radiation quantity that the green facade receives, as it affects the thermal load and controls the thermal behavior and the amount of thermal comfort of the space [31]. In this study, green facades as a second layer were found to change the building behavior in response to solar radiation. This means that in the summer, as well as spring and autumn, occupants could cut down their use of electricity for cooling, therefore allowing the total energy consumption to be reduced significantly. As mentioned in the discussion, according to the simulation of the green facade in different orientations, the northern- and western-orientated green facades' performances were lower than those of facades in other orientations, while the southeast- and southwest-orientated green facades' performances were remarkable as their energy consumption was reduced by about 28%. Furthermore, for the southeast orientation, the total annual energy cost decreased by about 28%; for the southwest orientation, this decrease was 18%. In addition, the selection of an appropriate orientation for the green facade can affect the quantity of ventilation across the inside of the building, which consequentially affects the quantity of energy consumed.

Author Contributions: Conceptualization, F.B.M. and I.N.D.; methodology, F.B.M. and I.N.D.; software, F.B.M.; validation, J.M.F.M, I.N.D., and E.R.D.; formal analysis, F.B.M.; investigation, F.B.M.; resources, F.B.M.; data curation, F.B.M.; writing—original draft preparation, F.B.M.; writing—review and editing, F.B.M., J.M.F.M, I.N.D., and A.B.Y.; visualization, F.B.M.; supervision, J.M.F.M and I.N.D.; project administration, F.B.M.; funding acquisition, E.R.D. All authors have read and agreed to the published version of the manuscript.

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Evaluation of Thermal Comfort Performance of a Vertical Garden on a Glazed Façade and Its Effect on Building and Urban Scale, Case Study: An Office Building in Barcelona

Faezeh Bagheri Moghaddam *, Josep Maria Fort Mir, Isidro Navarro Delgado and Ernesto Redondo Dominguez

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Abstract: The aim of this paper is to investigate the thermal performance of vertical gardens by comparing the thermal comfort of bare (glazed) and green façades in the Mediterranean climate. The proposal consists of applying a vegetation layer on a glazed façade that could control solar radiation and reduce indoor air temperatures. This study investigates the thermal performance of green façades of an office building in the Mediterranean climate. For this purpose, the Gas Natural Fenosa Office Building as a case study was simulated, that is located on a site next to the coastline in Barcelona. Dynamic building energy simulation was used to determine and assess indoor thermal conditions and, for this reason, the IES VE as a simulation tool has been utilized. Thermal comfort was assessed through the adaptive comfort approach and results were analyzed and presented in the terms of indoor comfort conditions during occupied hours. As a result, the article shows that applying a green façade as a vegetation layer caused a reduction in the internal and external façade surface temperatures, as well as the indoor air temperature of the workplace. Additionally, enhancing indoor comfort in summer is closely associated with reducing the external surface temperature. In winter, it also protects the exterior surface from the low temperature of the outside, and all of this greatly increases thermal comfort performance.

Keywords: green façade; thermal comfort; air temperature; urban scale; building simulation; sustainability

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1. Introduction

Green façades as vertical greening systems have many ecological and environmental benefits in the urban scale, and some of them can be highlighted in urban rehabilitation: improving air quality, reducing the urban heat island (UHI) impact, improving stormwater management, and absorbing air pollutants from the atmosphere [1–5]. Urban greenery, such as green façades, has become a significant issue in recent years because the majority of the world's population lives in cities [6], must deal with global carbon emissions rising by 70%, and accounts for nearly 70% of energy consumption. Moreover, there is a growing trend in both carbon emissions and energy consumption [7], and land conversion to urban areas is expected to triple by 2030 [8]. Vertical greenery systems allow for increased vegetation in urban contexts while taking up no street space, enhancing biodiversity, and indirectly improving urban appearance. Some examples of vertical greenery systems, which present some typologies of hanging greenery as a solution for improving the environmental sustainability of buildings, have been proposed [9].

Environmental issues have many significant impacts, including human health, citizens' quality of life, and urban economic efficiency [8]. Green façades can be important for building energy efficiency and also urban microclimate mitigation [10–12]. A microclimate is described as any region where the climate differs from the surrounding region, and a large urban microclimate can affect not only temperatures but also rainfall, snowfall, wind, and air pressure. For all studies, six parameters of green façades have been suggested that should be considered in order to obtain an adequate quantification of thermal performance and microclimatic benefit. These parameters are solar radiation, air temperature, and wind speed in front of or away from the green façade and/or between the green façade and the wall [13].

Regarding previous studies, which revealed that the vegetation layer on the façade can reduce the temperature of external surfaces of the building envelope during summer [14,15], consequently, the green layer could improve indoor comfort in terms of air and surface temperature reduction [16]. Many parameters must be considered when investigating green façades, such as the orientation of the façades [17,18], as well as the water distribution [15,19] and climate conditions. Researchers have demonstrated, through a sensitivity analysis, that solar radiation, wind speed, relative humidity, and outside air temperature are important for weather parameters [20]. Green façades are especially useful for high solar exposure walls and where ground-level space is restricted, or where aerial obstructions restrict tree growth [21]. Through investigating vertical greenery systems in terms of direct and indirect environmental resources, it is possible that green façade systems could reach a condition of comprehensive sustainability in a 25-year lifetime [22]. Comprehensive sustainability is linked to full-cycle sustainability, which indicates that the environmental impact of a product (or service) is thoroughly analyzed at every stage of its life. The concept of comprehensive sustainability must be taken into account as a holistic, topologic, and synergetic approach that does not allow for the dualism between people and nature, which is at the origin of our current difficulties.

Green façades, as a design feature in a warming environment, are able to cool internal building temperatures, reduce building energy usage, and encourage urban adaptation [13]. Furthermore, several studies have shown that vertical greenery systems have a positive effect on the building envelope in terms of thermal comfort, especially during cooling periods [23]. Some research about green façades in the Mediterranean region has shown a possible reduction in surface temperature of more than 10.8 °C [14]. In addition, researchers compared a green façade (with climbing plants) to a bare façade, finding that the surface temperatures of the green façade were up to 15.5 °C lower than those of the bare façades, while those of the interior walls were up to 1.7 °C lower [24]. It is possible that accurate characterization of the green façades will be required to better understand the contribution of such systems to the enhancement of hydrothermal conditions, the infrared radiation emitted and intercepted by the green canopy, as well as the relative humidity. Moreover, when it comes to vertical greenery systems, the surface temperature and the inside temperature of the substrate may provide valuable information about the usefulness and thermal efficiency [16].

The capacity of vegetation layers to cool is linked to the shading and evapotranspiration effect of plants [25]. Cooling is accomplished by the leaves on the façade, absorbing solar radiation (as a result of phototropism [26]) and shielding the back wall. Moreover, during the summer, a vegetation façade lowers the temperature by evaporating water from the foliage's surface [1].

Several factors influence the cooling efficiency of vertical greenery systems [27], including façade orientation, which is particularly important in green façades because of the evapotranspiration and the shadow created by plants [18,28]. High-density foliage coverage, creating a stagnant air layer (cavity) behind the foliage [29], using supporting system materials and their insulation effect, and plant species characteristics [30] can all be used to improve the insulation properties of vertical greenery systems.

With vertical greenery systems, the potential energy saving for air conditioning in Mediterranean areas can be up to 40–60% [25,31–35]. According to research, green façades can save 1.30, 0.84, and 0.71 kW/h of energy per day for an 8.22 m^2 flat on sunny, cloudy, and rainy days in summer, respectively, and can save up to 16% of the electricity consumption for air conditioning in July, August, and September, which are the hottest months of the year [36].

Many investigations have been conducted to determine the performance of green façades and their effect on energy consumption, thermal efficiency, and temperature variation, which revealed that vertical greenery systems can reduce the energy demand for air conditioning by reducing indoor temperatures [25]. Further research is required to investigate building climate control by the potential contribution of green façades [37].

Glazed surfaces may have a major effect on occupants' thermal comfort for two reasons: their transparency enables solar radiation to enter the space and increase the glazed façade's inner surface temperature, and the temperature might differ greatly from temperatures of other surfaces, inducing long-wave radiant heat exchange and convective heat transfer to the adjacent space [38].

The aim of this study was to assess the thermal comfort efficiency of green façades in the Mediterranean climate by simulating and evaluating a pilot project developed in Barcelona using the IES VE software as a simulation tool. As the reduction in indoor temperature caused by a green layer is heavily affected by the building envelope layers, it is possible to infer that insulation content moderates the prevailing temperature differential between the inside and outside [35,39]. This study demonstrates how to use a green façade's cooling ability to improve thermal comfort while lowering energy consumption.

In Mediterranean regions, research on the exterior and interior surface temperatures of façades, and also the indoor air temperature of vertical greenery, revealed that this façade technology affects the microclimate, building thermal comfort, and energy use during the summer and winter [40–42]. While the number of green areas and other low-albedo surfaces must be maximized to reduce the UHI effect in cities [43], reducing air and radiant temperature by greenery systems at the urban scale directly affects outdoor thermal comfort as well [44].

2. Methodology

A green façade scenario was applied to the Gas Natural Fenosa Building, which is an office building, as a case study. This simulation was conducted by covering approximately half of the building façade with a 16 cm thick plant (ivy) layer, which could raise the R-value and reduce the U-value of the façade, as well as a 50 cm cavity between the glazed façade and the plant layer. Plants and their substrate on the façade would also increase the R-value, resulting in lower energy costs [45]. The dynamic Integrated Environmental Systems software (IES VE) was used to predict the thermal efficiency of the green façade in Barcelona. The IES subroutines, which are RadianceIES and Apache, assess the effect of a green façade on daylighting and thermal comfort. Thermal comfort is influenced by a number of factors. Environmental and personal factors are two types of those factors. Air temperature, humidity, radiant temperature, and air velocity are the environmental factors, and activity level and clothing are personal factors. According to the environmental factors, the results were analyzed to demonstrate the thermal comfort performance of the green façade in comparison with the bare façade (glazing façade).

According to the Spanish Regulations for Thermal Facilities in Buildings (RITE) (*Reglamento de Instalaciones Térmicas en los Edificios*), and the indoor air quality (IAQ) categories (IDA) that are classified based on building use, the office building is in IDA 2. With regard to this classification, the indoor air quality (IAQ) of office buildings must be good [46]. The RITE sets standards for thermal comfort in offices and the principles that were approved by the Occupational Risk Prevention Act (Law 21/1995 PRRLL). At the same time, the INSHT provides guidance for safe working practices in offices [47,48].

2.1. Climate Characterization

Barcelona is a Mediterranean coastal city with a Mediterranean climate. The Azores dominate the weather throughout the summer. Summers are hot and dry, with temperatures averaging about 28 °C. Furthermore, the months of July and August are the hottest in the year.

When the Azores prime passes southwards in the winter, westerly winds with a little more rain prevail in the Mediterranean. Barcelona may be shielded from the wintry winds that often blow from the Pyrenees through Catalonia by the nearby mountains. In addition, temperatures in Barcelona seldom fall below 0 °C in the winter, and the average winter daytime temperature is around 13 °C.

Figures 1 and 2 depict the sun's direction, angle, and number of hours of sunlight in Barcelona, Spain. For green façade implementation, accurate knowledge of sun paths throughout the year and climatic conditions is needed, as well as knowledge of orientation, landscaping, summer shading, solar collector area, and the cost-effective use of solar trackers.

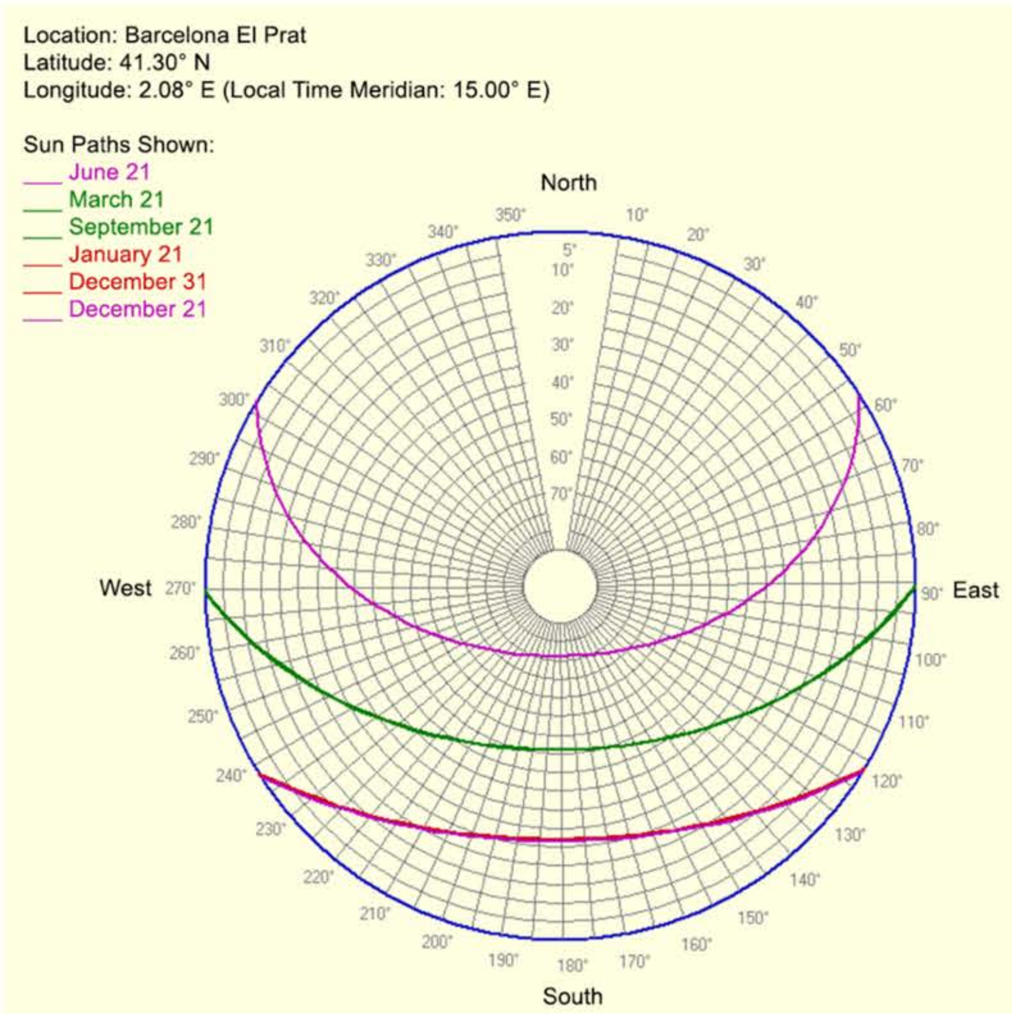


Figure 1. Barcelona sun path graph. © IES VE.

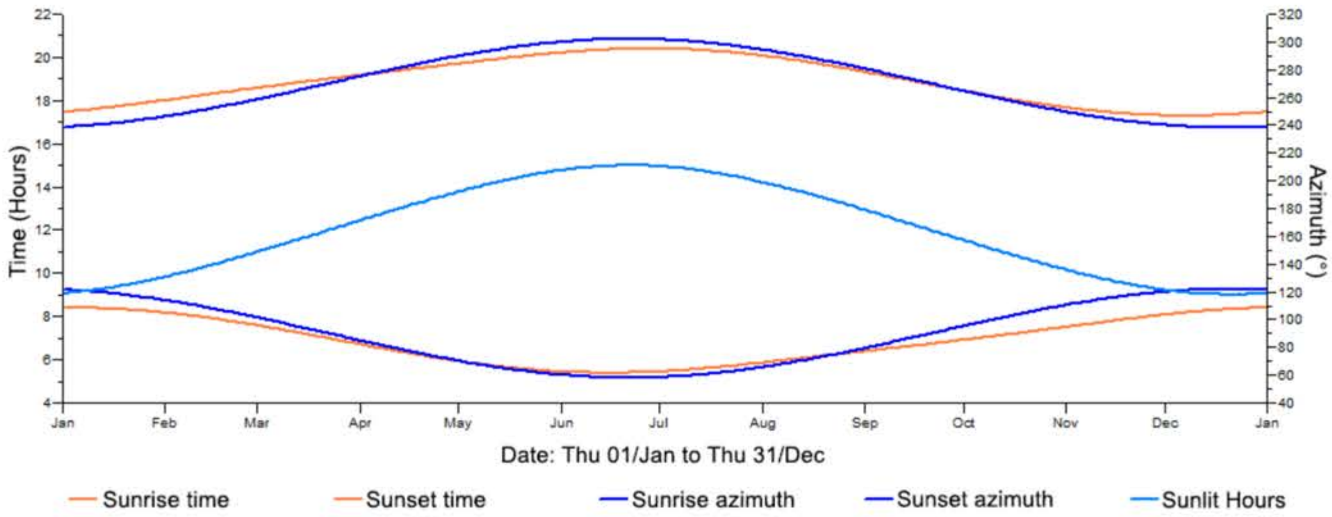


Figure 2. Graph of sun up/down parameters. © IES VE.

2.2. Model Validation

By comparing predicted and measured indoor space temperatures, the simulation results were used to validate the wall model (glazed and green wall). Knowing the variations in surface and indoor air temperature between the bare and green façades allowed for the estimation of other façade properties, such as a decrease in heat transfer through the façade (assuming a constant R-value for the façade itself) and thus the concurrent effective R-value of the vegetation layer. To adapt the direct solar radiation data to a vertical surface, the IES VE simulation technique was used to model and apply correlations between the two façades to the measured data. The most extreme days in the results, June 21 and December 21, were used for validation.

June 21 was chosen because the Northern Hemisphere has the longest duration of daylight and the sun takes the longest journey across the sky at the summer solstice, so there is more solar energy on this day than on other days, which is 15 h. On the other hand, there are 9 fewer hours of solar radiation on December 21.

According to previous studies, the R-value of a 16 cm thick ivy layer is 0.34 m^2 k/w [20], and in this article, plant coverage accounts for 50% of the entire façade by the Louver system.

The main façade configuration in the simulation was composed of two layers of 6 mm glass with a 12 mm air layer in the middle filled with argon gas and a metal frame as the structure. The glazed façade specification is depicted in Figure 3.

Apache dynamic simulations in IES VE using the El Prat Barcelona weather file (.epw), which contains data for variables, including dry bulb and wet bulb temperature, wind speed and direction, solar altitude and azimuth, and cloud cover for each hour of the year, were carried out.

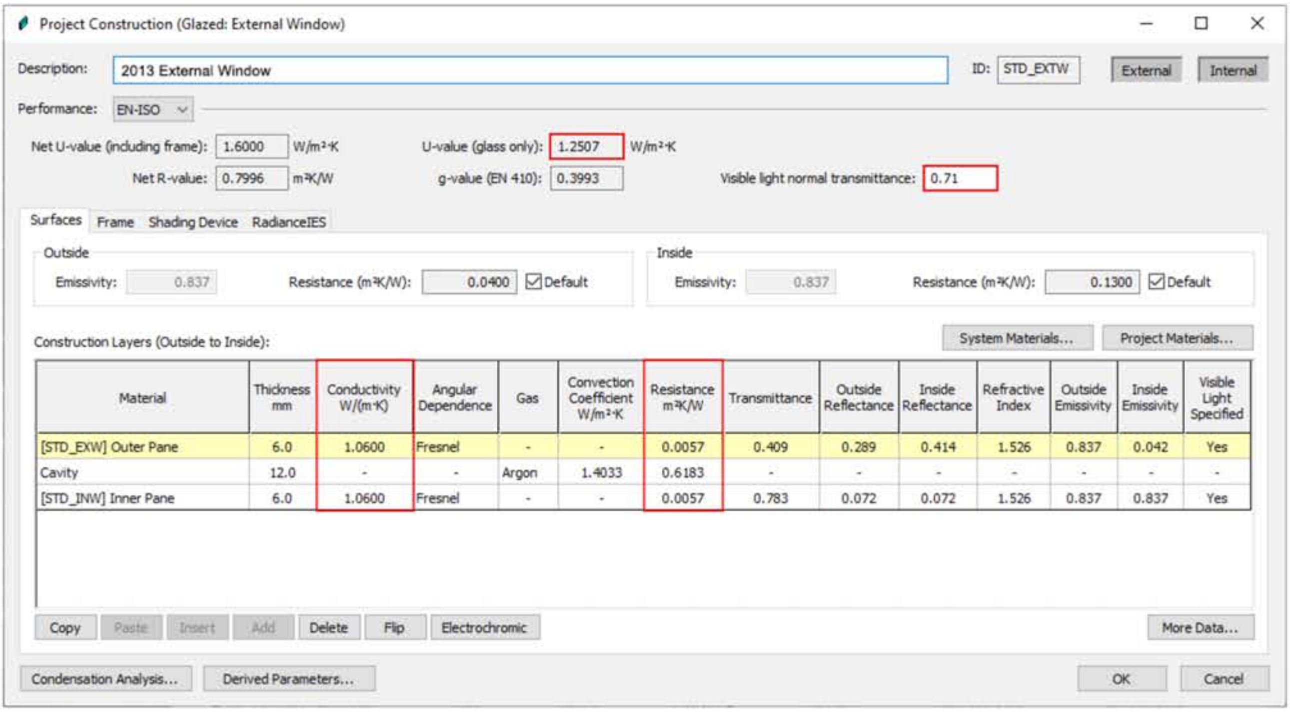


Figure 3. Glazed façade specification in IES VE simulation software. © By authors.

2.3. Model Characterization

This article's case study model is the Gas Natural Fenosa Building in Barcelona, Spain, which is a high-rise office building. This building has two lower horizontal glazed blocks sticking out and cantilevered from the main tower, which has 22 floors and stands 86 m tall (Figures 4 and 5) and was designed and constructed in 2007 by Enric Miralles and Benedetta Tagliabue.

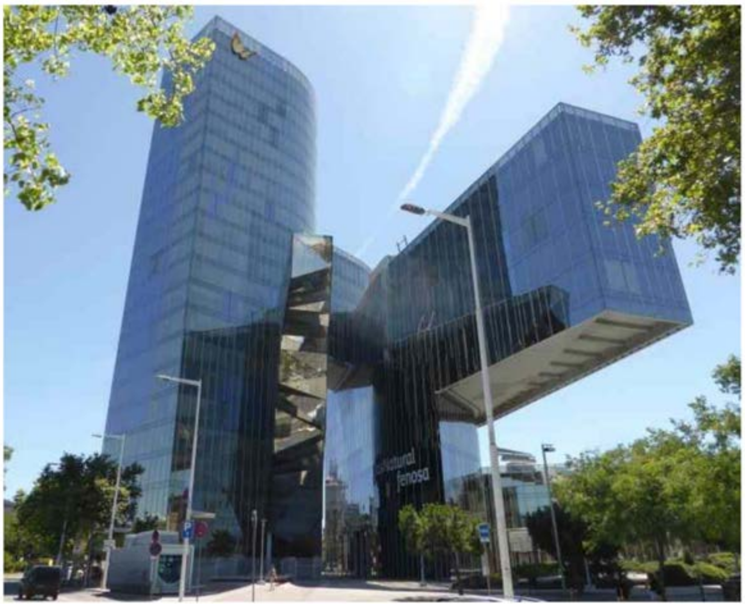


Figure 4. West view of Gas Natural Fenosa Building.

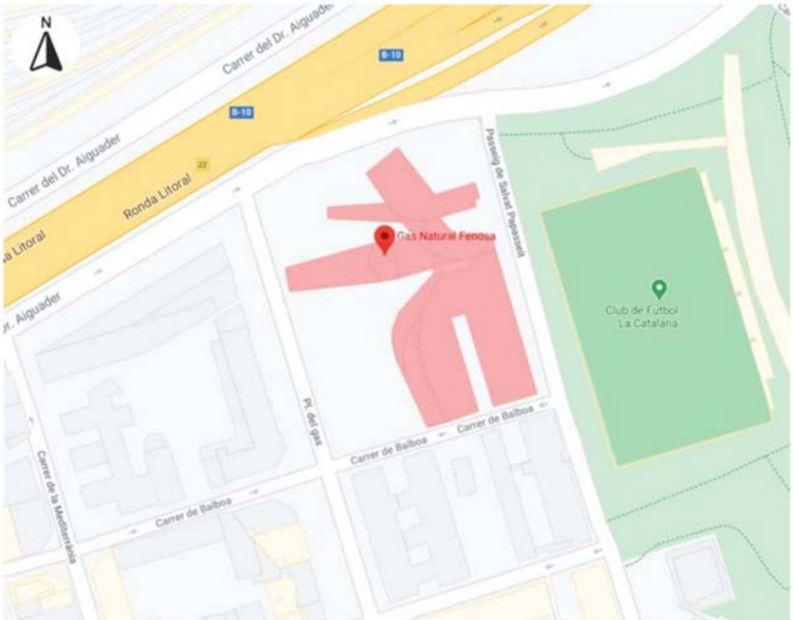


Figure 5. The location of the case study. © By authors.

A curtain wall (glazed façade) serves as the continuous façade that connects the three merged buildings. In this article, thermal comfort in both the bare façade (curtain wall) and green façade was analyzed using a building simulation approach in terms of daylight, predicted mean vote (PMV), radiant temperature effects, and air temperature in improving the thermal comfort efficiency of the green façade.

2.3.1. Evaluation of Daylight and Solar

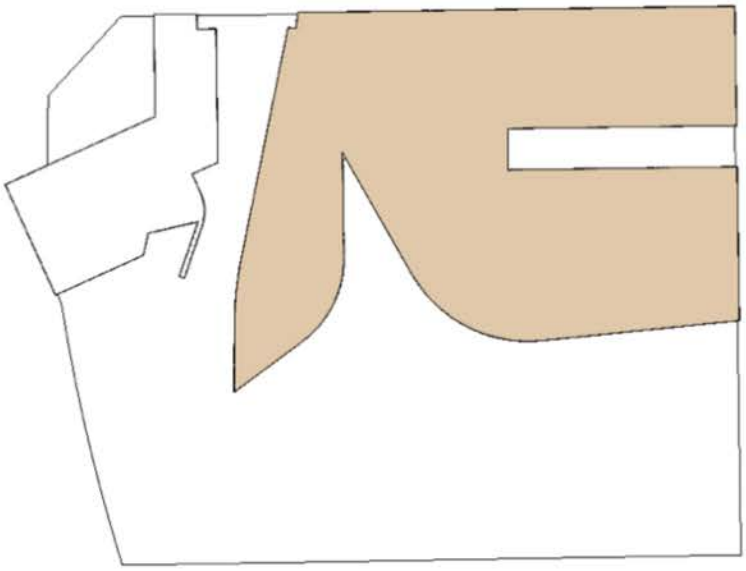
The fundamental requirements of building design include providing daylight, reducing glare, and maximizing the thermal efficiency of building façades which, in this study, involved applying a vegetation layer on the building façade as a façade technology. For this purpose, a part of the ground floor (Figure 6) was simulated within IES VE as a function of the RadianceIES (daylighting and electric lighting simulation) package, on a day in summer, which was 21 June at 12 p.m.

Under overcast sky conditions, the daylight factor was calculated as a ratio of internal illuminance on the working plane 85 cm above the floor level to external illuminance on the non-shaded horizontal plane [49,50].

As shown in Figure 6, daylight analysis carried out on a part of the first floor with a southern orientation. Southern façades are more affected by sunlight than other façades, according to a previous study that demonstrated the role of building orientation in green façade performance [18]. As a result of this, the southern façade was chosen for this article. The glazed façade induces solar radiation effects in this open plan office space on sunny summer days, causing the air temperature to increase. Variations in indoor thermal conditions during periods of intense sunlight cause discomfort in the bare façade (glazed).

Barcelona has some of Europe's best winter daylight hours. The average number of daylight hours in December, January, and February is 10 h, while the number of daylight hours in June, July, and August is about 15 h (Table 1). According to Figure 7a–d, which shows the aspect of daylight in terms of thermal conditions in both bare and green façades, comparing each result can help understand the aspect of the green façade that can protect the building from solar radiation during the summer.

(**a**) 3D view.



(**b**) Ground floor plan.

Figure 6. The portion of the Gas Natural Fenosa Building used for daylight simulation is shown in brown. (**a**) 3D view, (**b**) ground floor plan. © By authors.

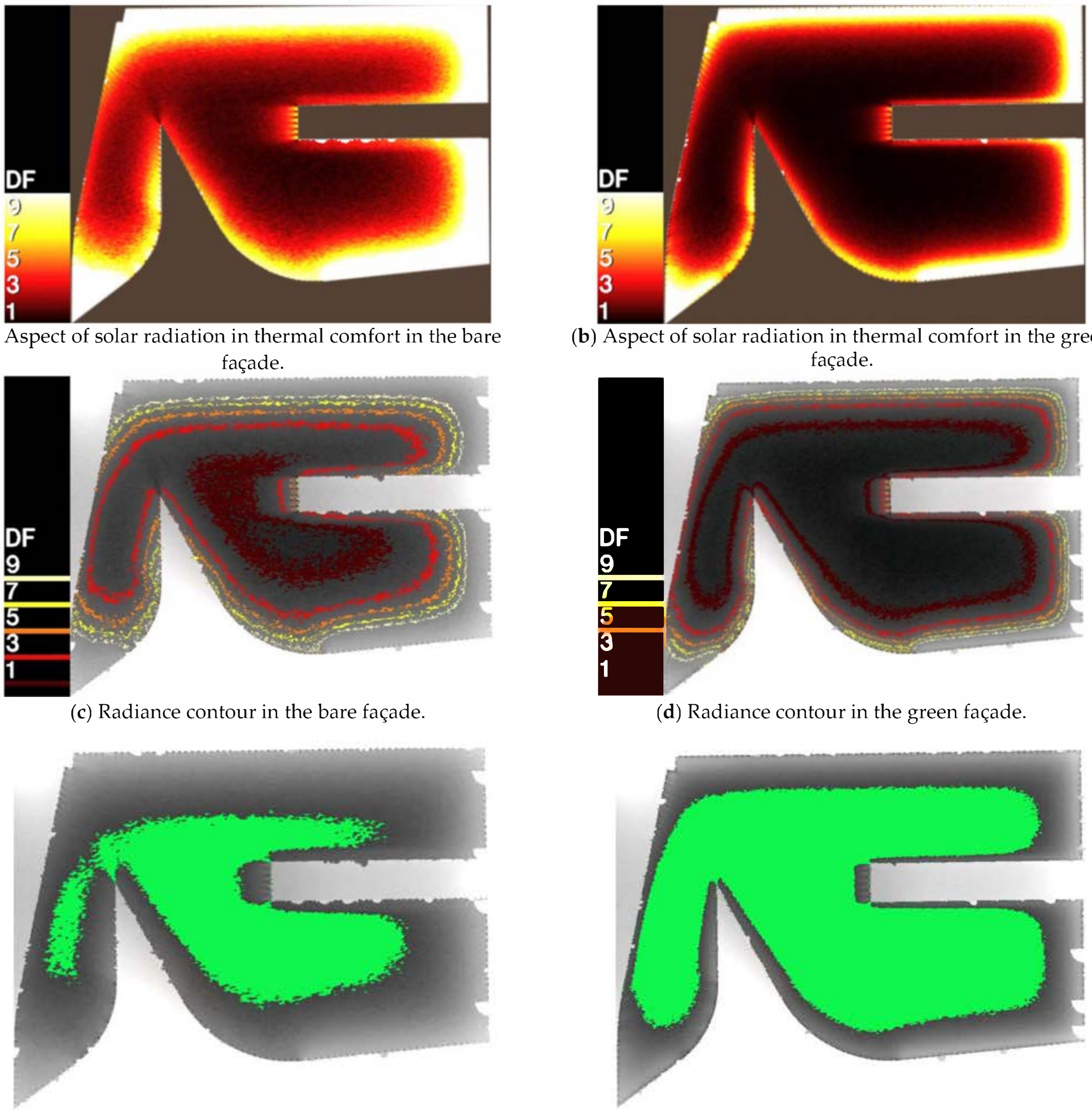
Table 1. Average hours of daylight in Barcelona.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hours of light	10	11	12	13	15	15	15	14	12	11	10	9
Hours of twilight/night	14	13	12	11	9	9	9	10	12	13	14	15

In analyzing the daylight factor threshold (Figure 7e,f), the value of daylight factor (DF) based on sky component (SC) was 2.00 DF, which, according to CEN European Daylight Standard (EN 17037), is the standard value [51] and, regarding the daylight threshold result:

- Threshold < 2.00 DF = 19.70% in bare façade;
- Threshold < 2.00 DF = 40.94% in green façade.

That is, in the glazed façade, 19.70% of the open space office has less than 2 daylight factors (DFs), indicating that during the day, the workplace has wonderful light and does not require artificial light, whereas, in the green façade, this value is 40.94%, less than 2 daylight factors (DFs). Thus, using artificial light with a green façade is more advanced than using it with a glazed façade.



(**a**) Aspect of solar radiation in thermal comfort in the bare façade.

(**b**) Aspect of solar radiation in thermal comfort in the green façade.

(**c**) Radiance contour in the bare façade.

(**d**) Radiance contour in the green façade.

(**e**) Daylight threshold level in the bare façade.

(**f**) Daylight threshold level in the green façade.

Figure 7. Daylight analysis of a part of the first floor in terms of daylight and thermal comfort in the bare and green façade on 21 June at 12 p.m. © By authors.

Figures 8 and 9 perfectly illustrate the effect of daylight on thermal comfort with bare (glazed) and green façades. According to the values of the daylight factor in Figures 8 and 9, the vegetation layer will shield the glazed façade from unwanted solar gains during hot summer days by as much as 50%. However, it should be noted that the use of artificial light is needed to protect the glazed façade via the vegetation layer.

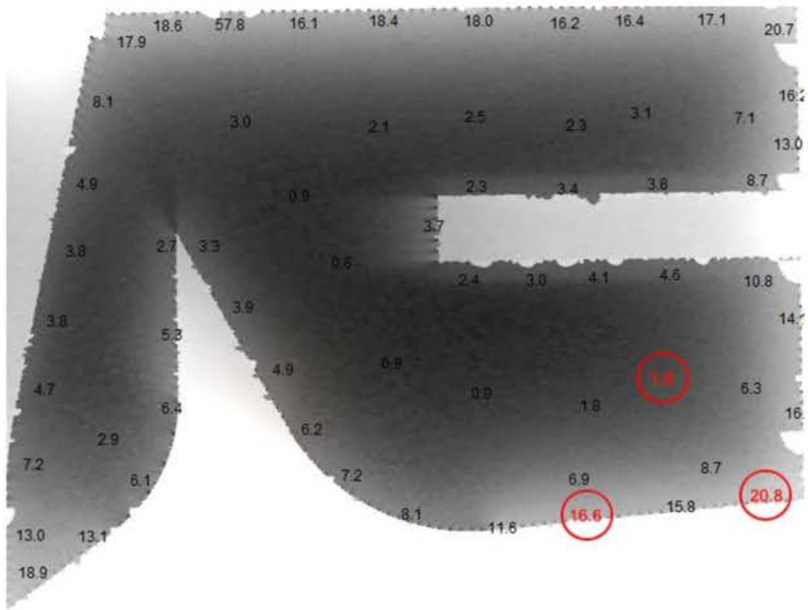


Figure 8. The illuminance plan shows the number of daylight factors (SC) on the bare façade. © By authors.

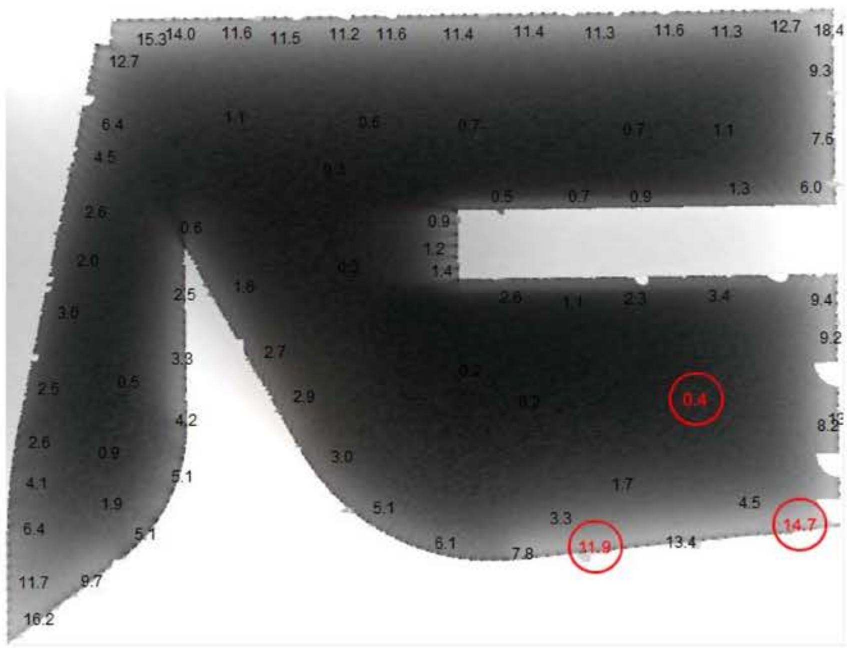


Figure 9. The illuminance plan shows the number of daylight factors (SC) on the green façade. © By authors.

2.3.2. Predicted Mean Vote (PMV)

The predicted mean vote (PMV) is an empirical score of the human sensation of thermal comfort that has been adopted as an ASHRAE 55 and ISO standard. PMV is a scale that ranges from −3 to +3, with 0 representing ideal thermal comfort, +3 indicating too hot, and −3 indicating too cold. In this report, the results were achieved in two days in winter and summer, 21 December and 21 June.

Another attribute to consider is the predicted percentage of dissatisfaction (PPD), which is a function of PMV [52]. Figures 10 and 11 show the PMV value of both the bare and green façades, allowing for a comparison of the bare and green façades in terms of PMV and PPD. As a result, the PMV value of the green façade is similar to the ideal thermal comfort (0) of the bare façade (glazing façade). During working hours on 21 December and 21 June, PPD in the green façade is approximately 11.8% and 18%, respectively, but this value was increased by 14.6% and 26% in the bare façade; additionally, the PMV value in the green façade in both figures is closer to the ideal thermal comfort (0) than in the bare façade.

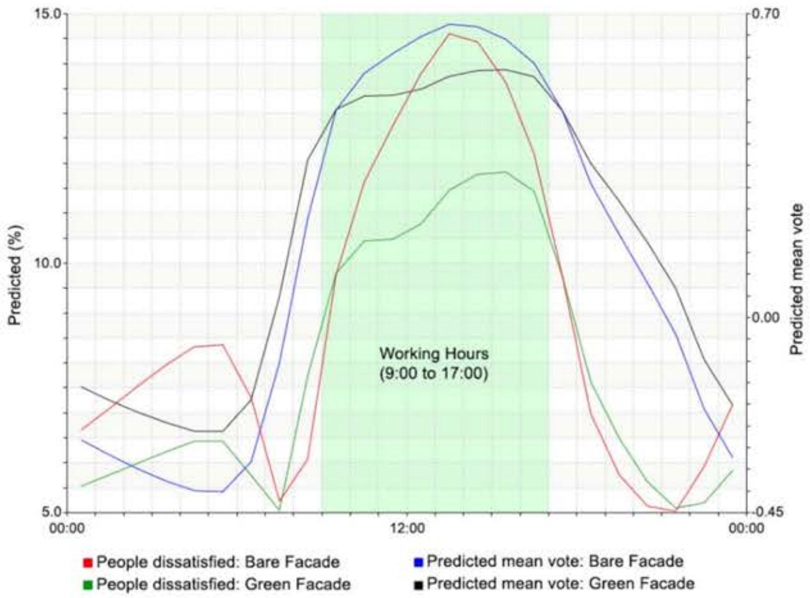


Figure 10. Comparison between predicted mean vote (PMV) and the predicted percentage of dissatisfaction (PPD) on 21 December. © By authors.

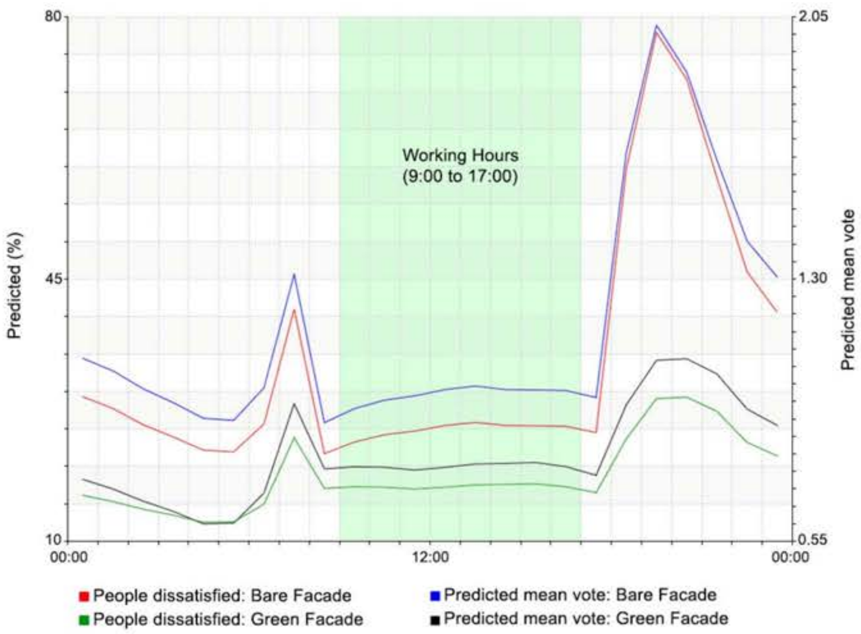


Figure 11. Comparison between predicted mean vote (PMV) with the predicted percentage of dissatisfaction (PPD) on 21 June. © By authors.

2.3.3. Mean Radiant Temperature

The radiant temperature can be determined using measured temperature values of the surrounding walls and surfaces, as well as their locations in relation to an individual [53]. Spaces with large areas of glass can exhibit greater differences between mean radiant temperature and air temperature. In winter, a cold surface can lead to cool radiant temperatures, and high solar gains can lead to high radiant temperatures since variations in outdoor temperature and solar radiation during the day affect the radiant temperature and therefore the thermal comfort [54].

Due to the mean radiant temperature on 21 December (Figures 12 and 13), the maximum temperature in both the bare and green façades was 24.5 °C and 23.2 °C, respectively, and on 21 June (Figures 14 and 15), the radiant temperature in the bare façade was 26.6 °C and in the green façade it was 24.3 °C. These variations indicate that a green façade will shield the building envelope from cold weather in the winter and hot weather in the summer, but with different behaviors in each season.

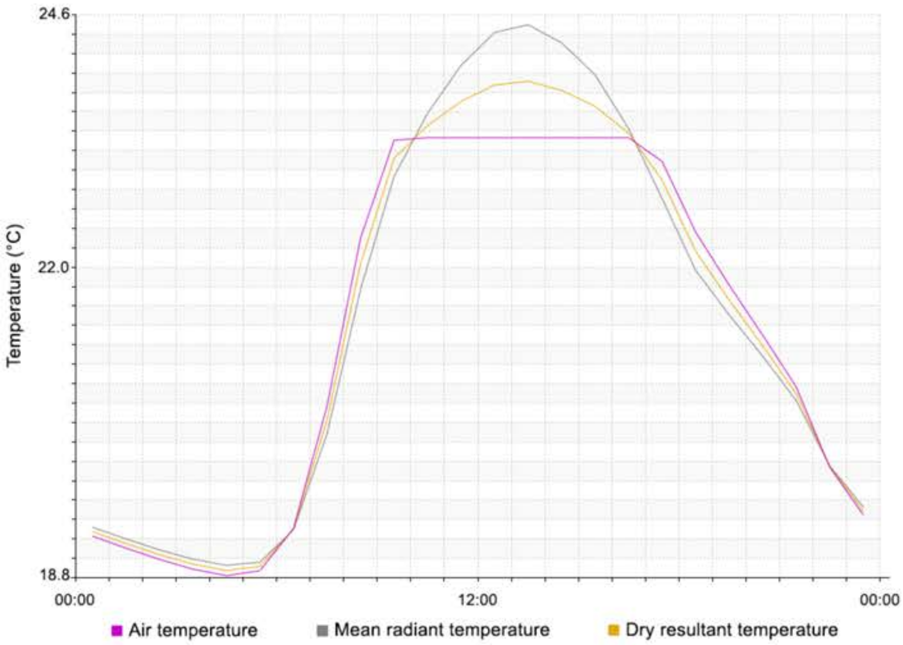


Figure 12. Radiant temperature effects on the bare façade on 21 December. © By authors.

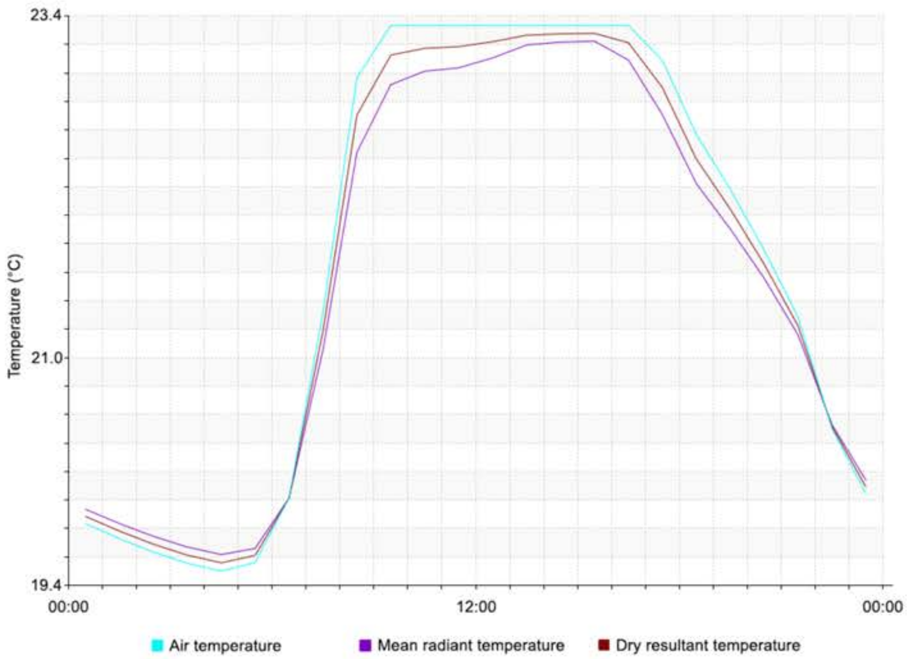


Figure 13. Radiant temperature effects on the green façade on 21 December. © By authors.

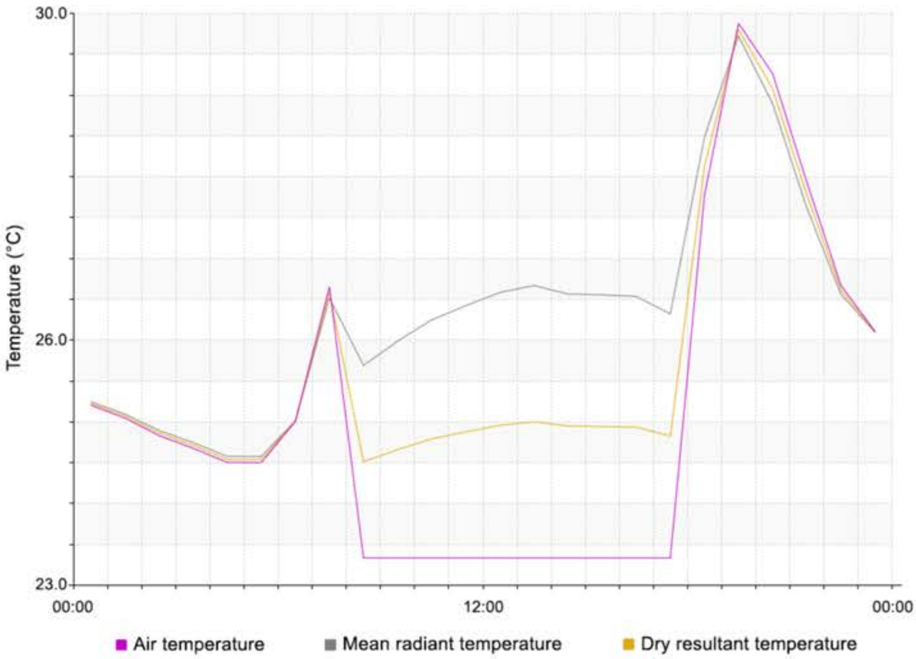


Figure 14. Radiant temperature effects on the bare façade on 21 June. © By authors.

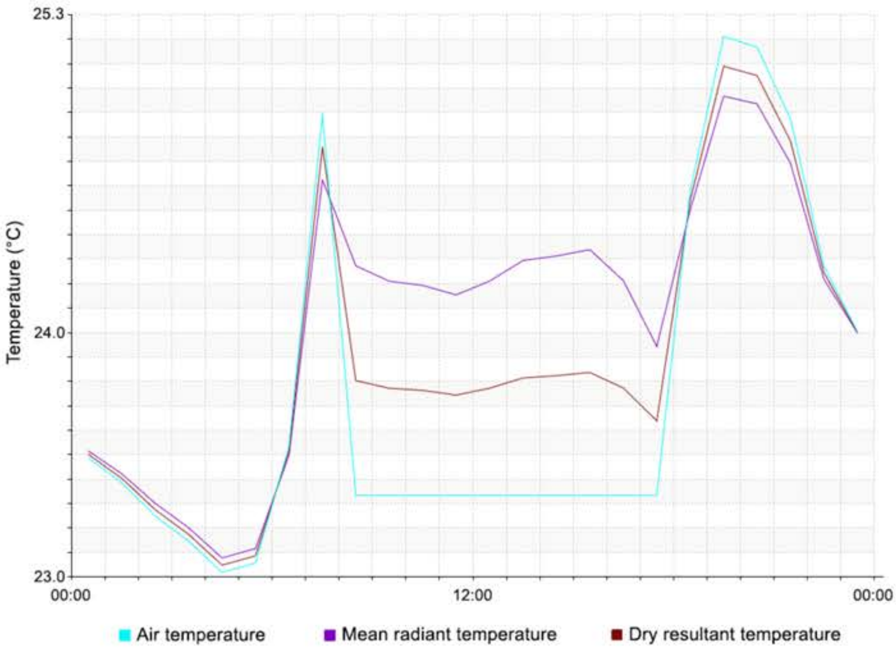


Figure 15. Radiant temperature effects on the green façade on 21 June. © By authors.

2.3.4. Air Temperature

Figures 16 and 17 show that the difference between the minimum and maximum indoor air temperature during December (winter) in the bare façade is approximately 7 °C; however, this difference is approximately 6 °C in the green façade. In June (summer), this disparity is approximately 9 °C in the bare façade and just 4 °C in the green façade. These values indicate that the indoor air temperature in the green façade is almost the same during the summer (Table 2), meaning that the indoor temperature is optimal and comfortable, allowing air conditioner usage to be reduced, resulting in lower energy use. Furthermore, the difference in air temperature between bare and green façades over a year (Figure 18) demonstrated how much greenery could influence indoor air temperature, thus improving thermal comfort.

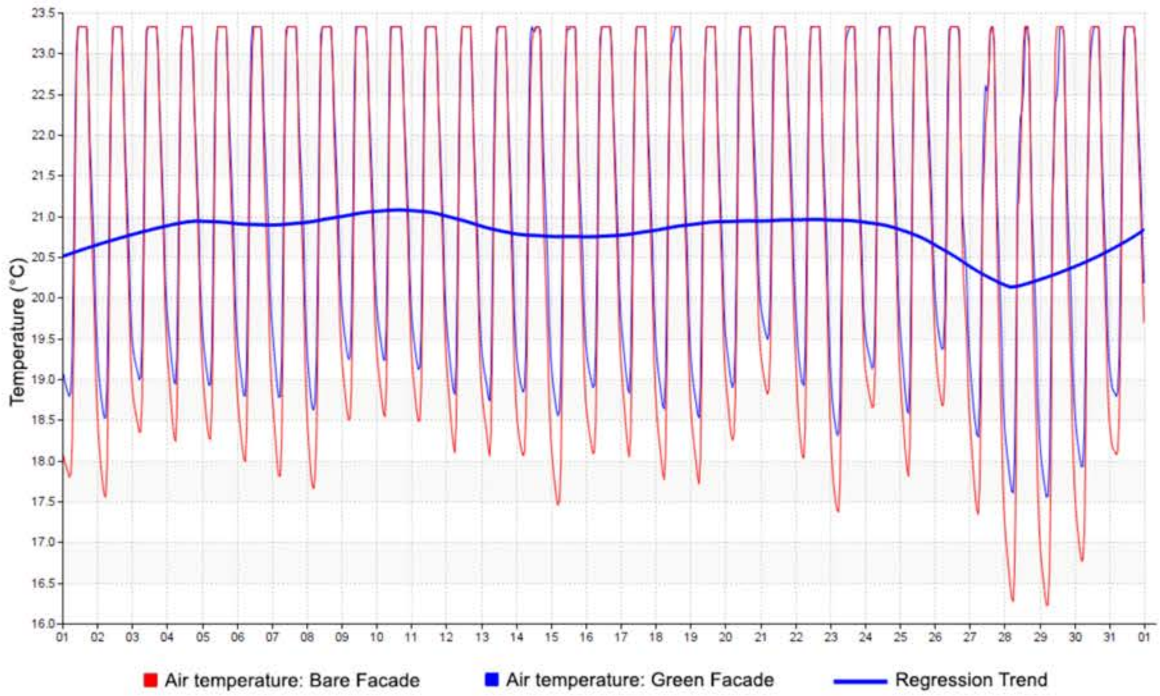


Figure 16. Indoor air temperature ranges from 1 December to 31 December in both the bare and green façades. © By authors.

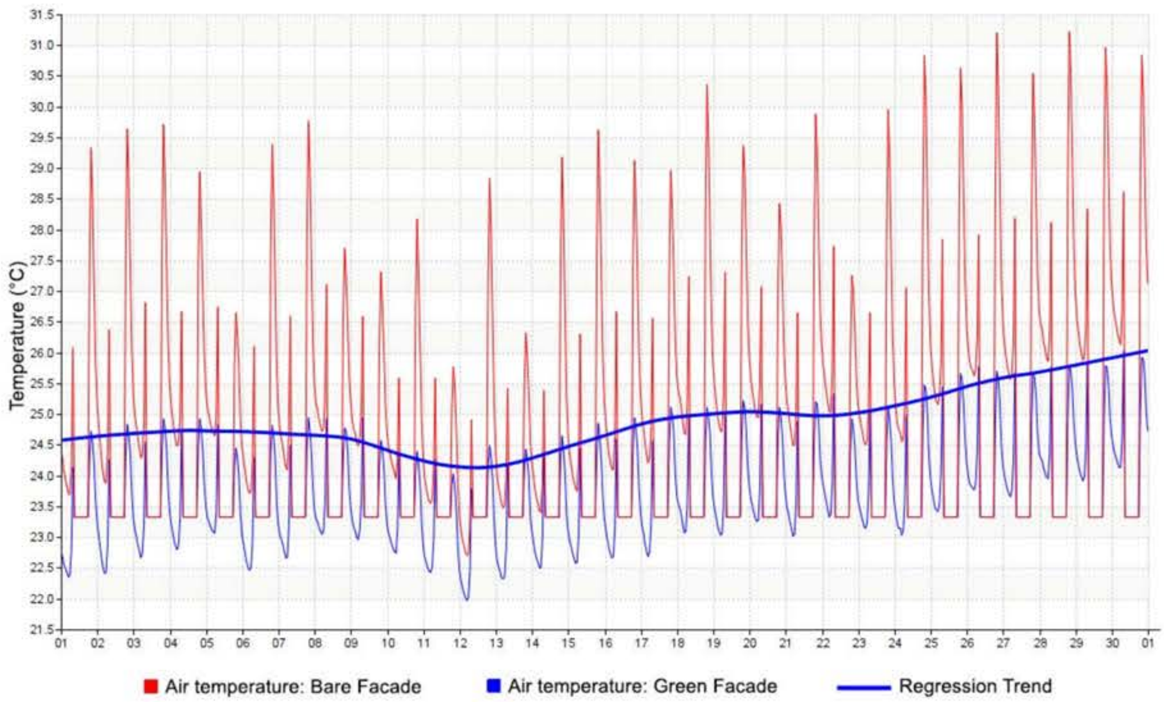


Figure 17. Indoor air temperature ranges from 1 June to 31 June in both the bare and green façades. © By authors.

Table 2. Indoor air temperature in December and June in both bare and green façades. © By authors.

	December		June	
	Min	**Max**	**Min**	**Max**
Bare Façade	16 °C	23.5 °C	23.4 °C	31.3 °C
Green Façade	17.5 °C	23.5 °C	22 °C	26 °C

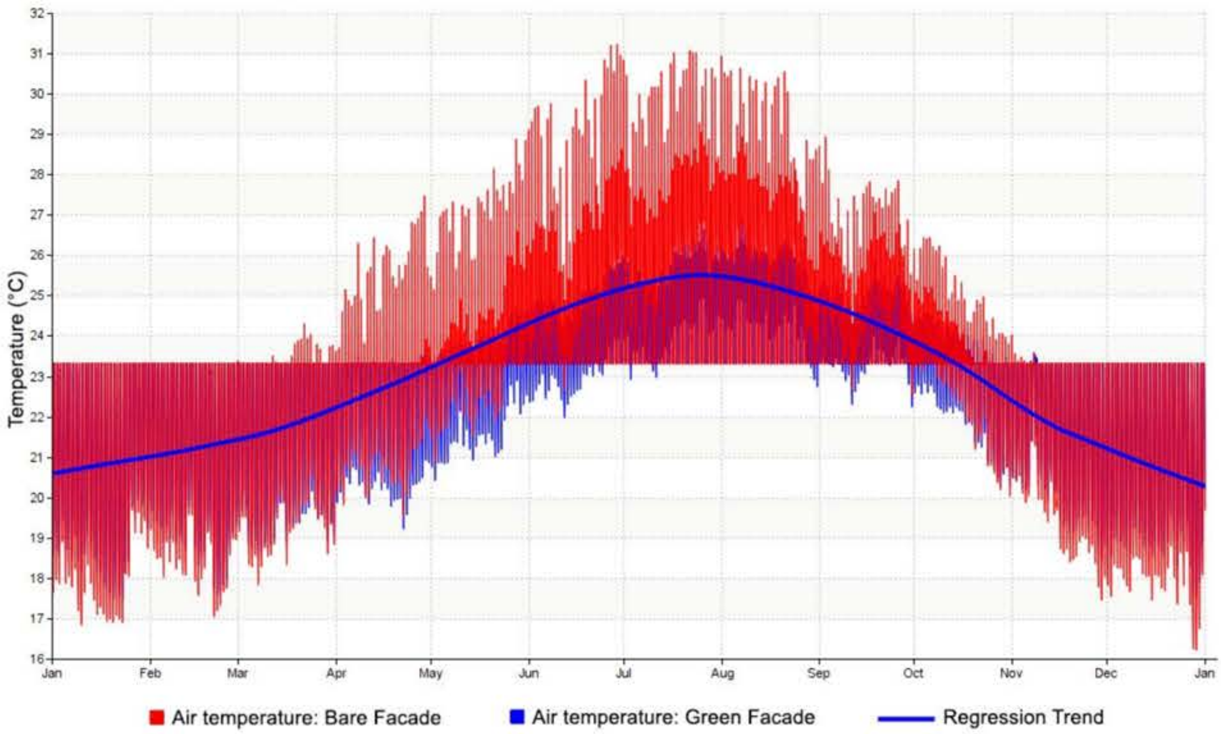


Figure 18. Indoor air temperature ranges from 1 January to 31 December in both the bare and green façades. © By authors.

3. Results and Discussion

The study analyzed the thermal comfort in the bare and green façades, energy consumption, and various environmental factors for space with the glazing façade on summer and winter days.

By the simulation of the Gas Fenosa Natural Building as a case study, it can be seen that a high radiant temperature in summer in the bare façade (glazed) causes an increase in the PMV. Additionally, it causes indoor thermal discomfort. Due to lowering the radiant and air temperature in the green façade, thermal comfort was improved.

3.1. Thermal Comfort

Thermal comfort is described as "that state of mind that expresses satisfaction with the thermal environment" by the international standard EN ISO 7730. In general, it is a comfortable condition in which an individual does not feel overly hot or cold.

By examining the daylight aspect of thermal comfort, predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD), mean radiant temperature, and air temperature, it is clear that each of these environmental variables could be very successful in improving thermal conditions. These elements are critical in improving living standards and ensuring long-term sustainability on a large scale.

Figures 19 and 20 illustrate the effect of solar radiation on cooling load in the bare (glazed) and green facades. Installing a vertical garden (green façade) on the building's façade could increase thermal comfort. This goal can be accomplished by simply adding a percentage of vegetation to the building's façade; the percentage depends on the building orientation, environmental conditions, building morphology, type of plants, and plant density.

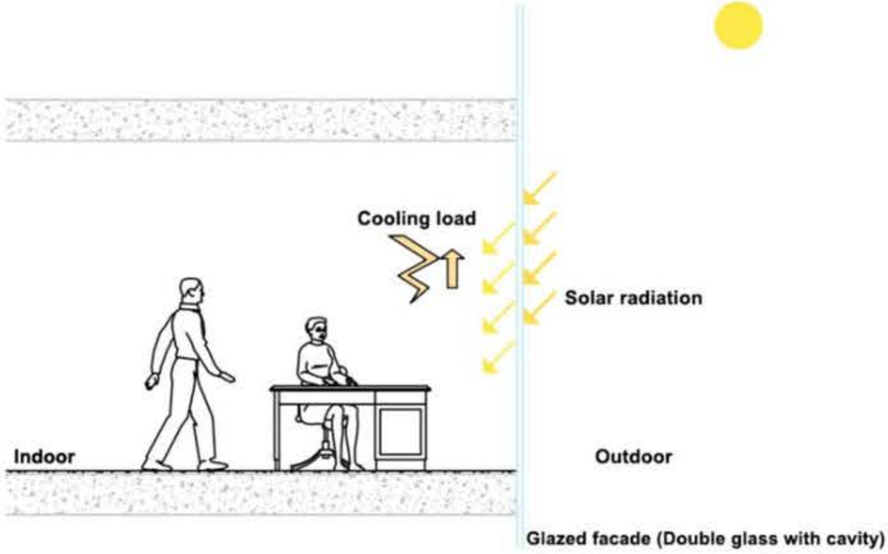


Figure 19. Section drawing to better understand the effect of solar radiation on indoor cooling load in the glazed façade. © By authors.

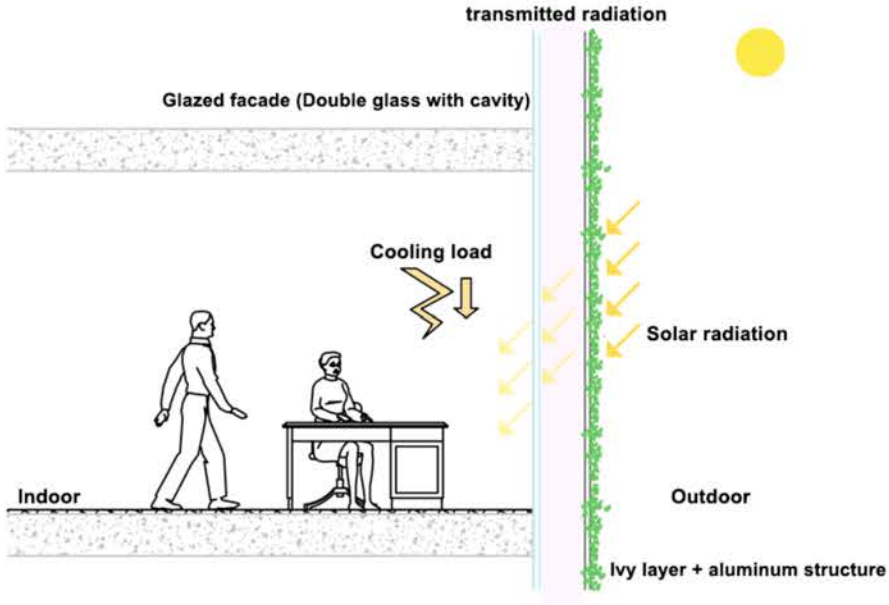


Figure 20. Section drawing to better understand the effect of solar radiation on indoor cooling load in the green façade. © By authors.

The increased solar radiation on the façade had a greater impact on the decreased surface temperature of both bare and green façades. As a result, the beneficial effect of the green façade as a second layer, as well as its efficient thermal resistance, increases dramatically with solar radiation; when the solar radiation level is high, the resistance of the plant layer is also high, due to blocked radiation transmission to the exterior wall surface.

As a result, the green façade has many advantages in climates and environments with high levels of solar insolation. The plant layer is also very good at cooling glazed façades that are subjected to high levels of solar radiation.

3.2. Energy Consumption

According to the simulation results, by lowering the air temperature in the summer and maintaining the same indoor air temperature in the winter, thermal comfort will be increased, and as a result, energy demand will be substantially reduced (Figure 21).

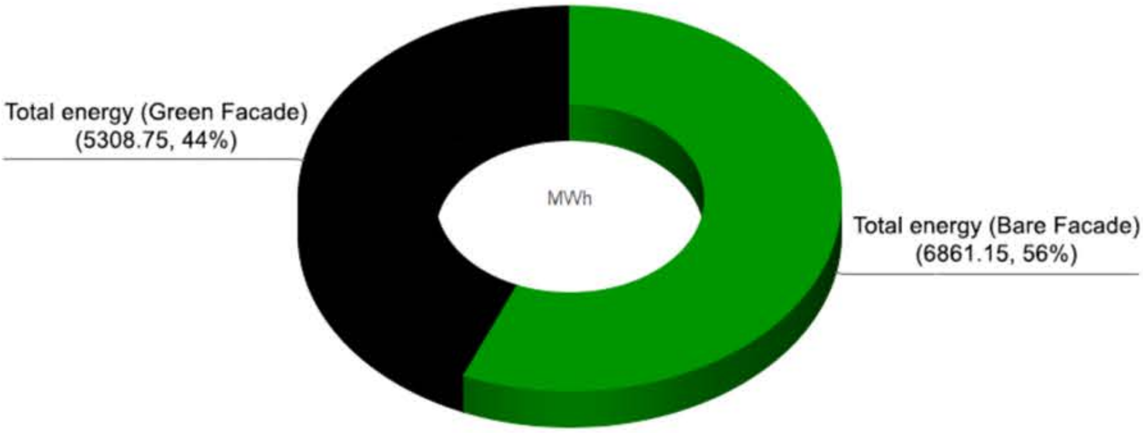


Figure 21. Total energy use of the Gas Natural Fenosa Building in one year. © By authors.

Due to high solar radiation during summer, the solar radiation is strong and passes through the glazing façade to indoor spaces with the bare façade, increasing the use of air conditioners and hence energy use.

The building's glazed façade naturally connects the interior with the environment and creates a sense of openness and space and provides light, but when designing a building with a glazed façade, the weather conditions must be considered, and due to Barcelona's weather conditions, the building's façades face about 15 hours of solar radiation during the summer and about 10 hours of solar radiation during the winter. Winter in Barcelona is mild and brief, and the majority of the year is hot. The building's actions will change if a shading layer, such as a green façade, is applied. According to simulation findings, the green façade protected the building façade from extreme solar radiation, resulting in a lower indoor air temperature, radiant temperature, and PMV, as well as lower total energy usage (Figure 21), chiller energy (Figure 22), and total electricity (Figure 23).

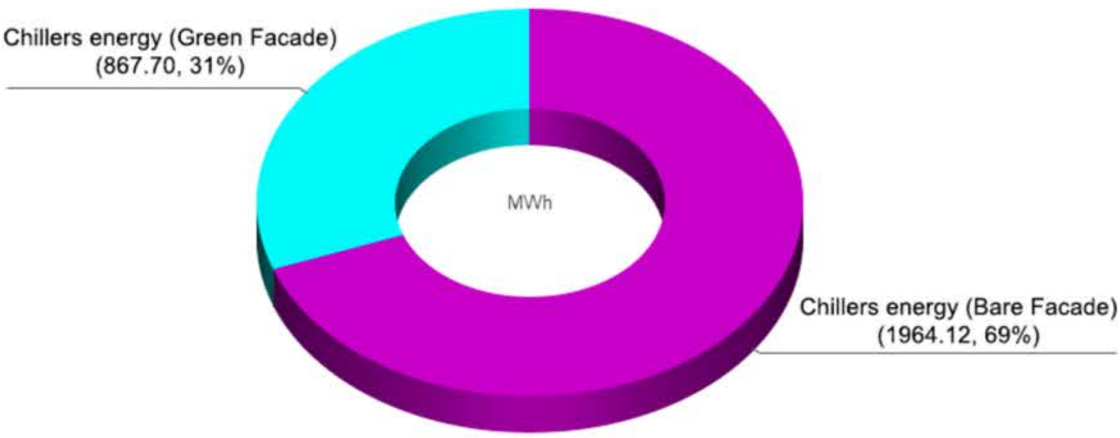


Figure 22. Chiller energy use of the Gas Natural Fenosa Building in one year. © By authors.

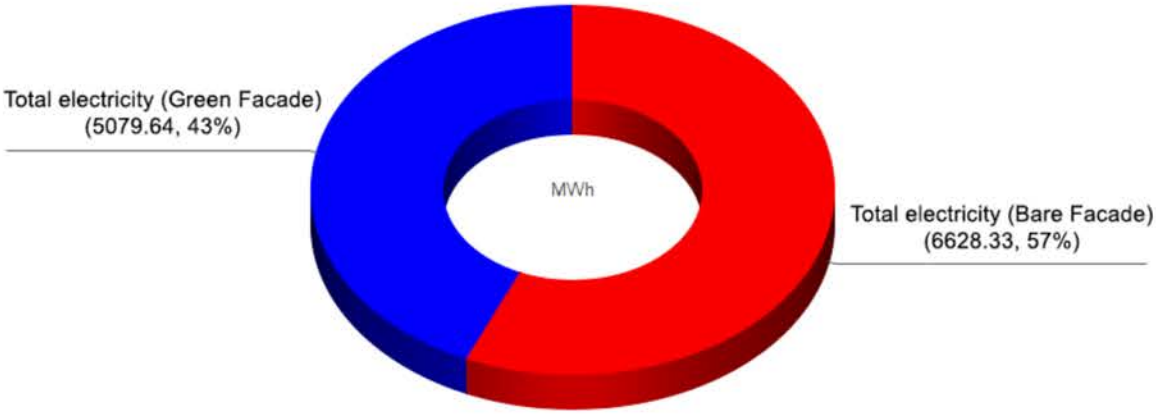


Figure 23. Total electricity uses of the Gas Natural Fenosa Building in one year. © By authors.

4. Conclusions

Green façades, as a part of urban green infrastructure (UGI) in the sense of vertical greenery, have been described as a collection of human-made elements that provide multiple ecosystem services at the building and urban scales. Regarding the Spanish Regulations for Thermal Facilities in Buildings (RITE), the office building's indoor air quality (IAQ) must be good at a minimum, and this research revealed that by adding a percentage of vegetation on the glazed façade, it is possible to achieve more than good air quality in the workplace while also improving indoor air temperature during the four seasons. Green façades serve many purposes, the most notable of which are improved thermal comfort efficiency, air quality, and building energy savings, as well as the reduction of the urban heat island effect. In this study, IES VE software, as a building simulation tool, was used to simulate the façades of an office building. The simulation model for thermal performance of the green façade as an exterior wall was considered, as well as the evaluation of daylight through the bare façade and vegetation façade, the difference between indoor and outdoor air temperature, mean radiant temperature, the value of predicted mean vote (PMV), predicted percentage of dissatisfaction (PPD), and the investigation of plant R-value. The model was validated using building simulation results from two days, 21 June and 21 December, as well as a one-year analysis that measured thermal comfort efficiency and energy consumption of bare and green façades as a refurbishment option for an existing building located near the coast in Barcelona. The simulation results prove that a vegetation layer on a façade can effectively reduce exterior surface temperatures of façades, daily temperature fluctuations indoors, and overall heat transfer through the exterior wall, particularly on days with high insolation. The results also indicate that green layers with thick leaves (high value of sun resistance) are possibly the most effective in reducing façade surface temperatures and heat transfer through façades, and as a result of this reduction, electricity and overall energy usage in the building can decrease. On hot sunny days, a vegetation layer on the glazed façade was calculated to reduce indoor air temperature by more than 5 °C, providing an efficient R-value that depends primarily on wall orientation, plant type, plant layer density, and green façade structure type.

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Conflicts of Interest: The authors declare no conflict of interest.

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