

Green Walls in High-Rise Buildings

An output of the CTBUH Sustainability Working Group

Antony Wood, Payam Bahrami & Daniel Safarik



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Front Cover: Newton Suites, Singapore (see case study 2.4) © Patrick Bingham Hall

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Preface

In 2012 the CTBUH Sustainability Working Group launched *Natural Ventilation in High-Rise Office Buildings*, the first in a series of new CTBUH Technical Guides intended as a tool-kit for those designing and building the next generation of sustainable skyscrapers. As that initial guide was launched, United Nations statistics portrayed a rapidly populating and urbanizing world that was seeing almost 200,000 people urbanizing on the planet every day, projecting to take us from a global population of 7 billion at 51% urbanized in 2010, to 9 billion at 70% urbanized by 2050. The need to build a new or expanded city of one million inhabitants every week seemed stark.

In the two years since the Natural Ventilation guide was launched, the pressure on our cities at every level has increased – including through the escalating manifestations of climate change itself. It has also become clear that significant urban growth is not unique to the developing world alone. In the United States of America, population demographics show a 0.9% population growth nationally per year over the next decade. When this is considered across 320 million people, together with the fact that this urban growth/migration is not equitable across all cities (people are migrating generally into “sun belt” rather than “rust belt” cities), then urban centers such as Dallas are coping with a 50,000-person increase year on year. So the same question that faces many cities in developing countries such as China and India also faces many western cities – how are these new urban inhabitants accommodated?

It is becoming increasingly accepted that greater urban density is required to achieve more sustainable patterns of life to reduce energy consumption and thus combat climate change. The concentration of people in denser cities – sharing space, infrastructure, and facilities – offers much greater energy efficiency than the expanded horizontal city, which requires more land usage as well as higher energy expenditure in infrastructure and mobility. However, the full implications of this

As Ken Yeang declared almost 40 years ago, we need to start building our cities out of the soft and natural, as opposed to the hard and largely unnatural. Not only would this be a huge stride forward in addressing the environmental challenges of the period, but it would also create a new, exciting aesthetic that reflects the environmental age we live in.

push to greater density, especially vertical density, is not fully understood, and all manner of cities the world over – including even established skyscraper cities such as New York – are grappling with the question on how to move towards greater height and density.

Of all the design and technological options open to building designers, it is hard to argue that there are strategies that would have a greater impact – environmentally, socially, and aesthetically – across both building and urban scales than implementing green walls in significant quantity in our cities. Of course there are design approaches and technologies available that can reduce individual building energy consumption in a far more significant way than applying vegetation to the skin of a building. However, the key to green walls is that they can have significant benefits simultaneously upon implementation – to both the building and the wider urban surroundings. Many of these benefits are already well understood, and have been employed on vernacular buildings in some geographic regions for, literally, centuries.

On the scale of the individual building, these green wall benefits include reducing building operating energy for heating/cooling by either insulating or shading the façade, increasing occupant satisfaction and even productivity by connecting the inhabitant directly to natural elements, filtering pollution for improved internal air quality, potentially providing agriculture, reducing urban noise filtering to the building, and increasing property values. On the urban scale, the benefits include reduction of the urban heat island effect, improving urban air quality, sequestering carbon from the atmosphere, absorbing urban noise, improving aesthetics, and increasing biodiversity.

Of course there are also numerous challenges to overcome, and implications to consider, not least the impact of the vegetation on the building itself, at both the micro scale (potential façade damage through plant growth) and the macro scale (for example, the additional loading of the greenery on the building's structural systems). Green walls also require increased resources (primarily water and energy) to be sustained, and then there are questions of the ability of the greenery to sustain itself under the greater environmental pressures at height (primarily wind, especially vortex shedding). This guide positions itself at this nexus – between portraying the benefits, but also uncovering the issues and limitations.

On a personal level, I believe passionately in the positive benefits of green walls in our cities – not only in the somewhat limited way we have seen them used to date, but in a much more significant, meaningful way. Of course not everyone is convinced. I am reminded of a strong letter submitted to the *CTBUH Journal* by one of our members on our announcement of the “Vertical Forest” that is Bosco Verticale in Milan being awarded our 2013 Research Seed Funding grant, to enable further study into the completed building (of both the effect of the greenery on the energy consumption of internal spaces, and the stresses on the greenery at height itself). This very eloquent letter pointed out that putting greenery at height was a ridiculous concept, when you take into account the gymnastics the building has to go to, to accommodate such additions. It went on to explain that it would be far more effective and beneficial to the planet environmentally to restore one hectare of the Everglades than to put one hectare of trees on tall buildings. I do not

disagree with this premise, but my answer, as with so much of “sustainability,” is that it is not really a case of “either/or,” but actually “both – and as quickly as possible.”

As a Professor of Architecture, I believe that the benefits of green walls go far beyond energy savings or even occupant health and potential productivity gains. In my view, one of the largest disappointments with modern cities is the continuing embrace of a globalized template for high-rise architecture, which is homogenizing cities around the world. Not only do these cities now all largely look the same, they have not really progressed aesthetically beyond the Modernist steel-and-glass aesthetic introduced in the 1950s. Despite advances in so many fields, our high-rise cities are primarily still made up of rectilinear, air-conditioned, glass-and-steel hard boxes. These boxes have become far more efficient in energy terms, but the palette of materials we use – and the resulting aesthetic – does not really speak of the main global challenge we face in the early twenty-first century; that of widespread global climate change and the need for our cities to adapt differently. I have long felt that our architecture is desperately in need of a new aesthetic, appropriate to the unique challenges of the age, rather than the 70-year old predominant glass-and-steel aesthetic.

As Ken Yeang declared almost 40 years ago, we need to start building our cities out of the soft and natural, as opposed to the hard and largely unnatural. Not only would this be a huge stride forward in addressing the environmental challenges of the period, but it would also create a new, exciting aesthetic that reflects the environmental age we live in – cities made of green, in a literal, rather than tangential, way.

Of course there are huge challenges in implementing such a vision and, as the eighteen case studies in this book portray – revolutionary and pioneering as they are, we are still quite a way from achieving significantly softened buildings and cities. Projects literally dripping with greenery, such as One Central Park, Sydney (which unfortunately came too late to include in detail in this guide – see Figure 1) are unfortunately the rare exception, rather than the norm. So that is where this guide steps in – to show the best practice currently implemented in projects around the world, and to ask the questions and issues that raise up through their study. We hope you enjoy reading the guide, and reflect on your own position with respect to urban greenery generally, and green walls specifically. As Chair of the CTBUH Sustainability Working Group, I firmly believe that this is an important part of the arsenal in moving cities towards a more fundamental “Sustainable Vertical Urbanism.”

Antony Wood
Chicago, June 2014



▲ Figure 1: High-rise projects incorporating vertical greenery in a significant way, such as the 2014 One Central Park, Sydney, perhaps point the way forward for a new, exciting aesthetic for our cities – one linked to the main challenge of our age: climate change.
© John Gollings

1.0 Introduction and Background

1.1 Historical Overview

For centuries, green walls have been used in building construction to shade building walls and atriums, to shield buildings from wind, and to cultivate agricultural plants. The original concept of vertical vegetation, including a wide use of green walls, can be traced to the Hanging Gardens of Babylon (Köhler 2008), one of the seven ancient wonders of the world, dating from between 600 to 800 B.C. (see Figure 1.1). This tradition is still carried on in many hot-climate countries where different climbing plant species are grown along building envelopes and above atria to shade the façade from excessive sun exposure and to cool the air (see Figure 1.2). In Medieval Europe, ornamental climbing plants and fruit tree espaliers, trees that were trained to grow against a flat support or wall, were commonly grown in the courtyards of castles and palaces to provide shade and to harvest fruits and vegetables in limited horizontal space.

Vegetation was often integrated into the building traditions of many northern countries, which commonly used turf or sod (a top layer of soil consisting of grass and roots) as a façade or roof material. The Vikings covered building roofs and façades with turf, which

provided greater insulation against severe cold weather conditions (see Figure 1.3). A similar building practice was spread throughout the Northern Midwest prairies of the United States and Canada, where the first pioneers built houses from sod, stacking layers of prairie topsoil on top of each other to form building walls. Although sod provided adequate thermal insulation, it was not a good structural material due to its susceptibility to water damage from rain and snow. This inadequacy can explain the lack of remaining examples of sod houses in this region.

The link between humans and nature is now more important than ever, as more than half of the world's population resides in cities, where the natural environment is being substituted for the man-made. This is underscored by the fact that buildings located near natural environments, such as parks, have higher real estate values than those buildings without such amenities (Beatley 2010). The environmental sustainability movement has brought a new wave of interest in buildings incorporating plants into their construction. In recent years, building designers have been promoting the inclusion of plants into building envelopes, including roofs and exterior walls, which represent a large portion of a building's surface

area. Integration of plants into vertical elements of architecture has developed into the concept of green walls, which has become well-known in recent years through the "vertical gardens" of French botanist and designer Patrick Blanc (Blanc 2008).

Fueled by rapid global population growth and mass-urbanization, the number of global tall buildings have also been increased significantly over the past two decades. In the high-rise realm, many ideas concerning greenery in building design have been developed, such as the "Bioclimatic Skyscraper," "Eco Skyscraper," or "Vertical Landscape" (Yeang 1995) which integrates the relationship between the ecological and environmental; the idea of "Vertical Farming," which refers to the cultivation of plant and animal life within skyscrapers (Despommier 2010); the "Sky Garden" or "Sky Atria" which brings green social/communal spaces into buildings (Pomeroy 2013); and the "Landscape Façade," which is characterized by the presence of vegetation distributed along the façade.

The green wall typology is thus immensely diverse and includes green façades, living walls, vertical gardens, hanging gardens, bio-shaders, and bio-façades. Green walls have become



▲ Figure 1.1: Simulation of Hanging Gardens of Babylon, constructed between 600 to 800 B.C.
© Bine Rodenberger (cc-by)



▲ Figure 1.2: Potted plants covering the walls of a Spanish patio. © Javi (cc-by-sa)



▲ Figure 1.3: Icelandic turf houses.
© Glaumbaer (cc-by-sa)



▲ Figure 1.4: Examples of a Façade-supported green wall (top) and a façade-integrated living wall (bottom).
© Irina Susorova

an important design device for many architects and artists who integrate them into existing façades and the new construction of commercial, residential, and public buildings with great imagination.

1.2 Green Wall Definition and Typologies

The “green wall” or “vegetated façade” is defined as a system in which plants grow on a vertical surface such as a building façade in a controlled fashion and with regularly maintenance.

Climbing plants grow naturally on building façades by attaching themselves directly to vertical surfaces by means of various mechanisms. Self-clinging climbers and self-supporting woody plants can attach themselves directly to the façade surface or grow along the façade without any added support. Other plant species, including climbers with aerial roots, suckers or tendrils, twining climbers, and lax shrubs (ramblers), require an additional support such as trellises, netting, or wires attached to the façade surface to promote or sustain vertical growth.

The main elements of green walls are thus:

- ▶ plants
- ▶ planting media
- ▶ structures that support and attach plants to the façade
- ▶ the irrigation system

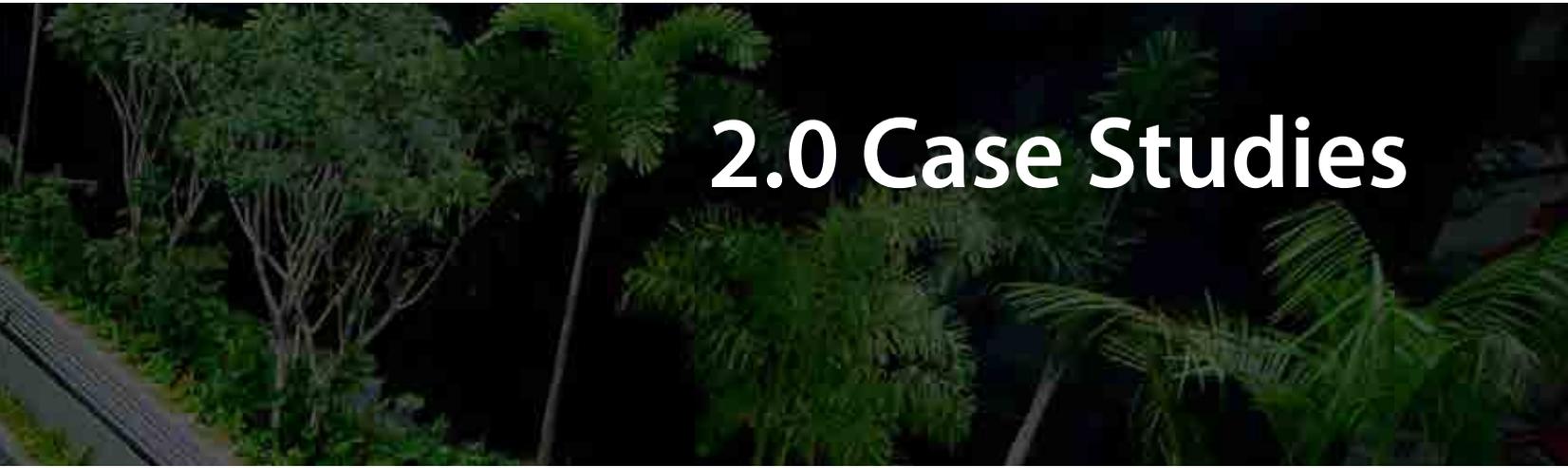
Depending on the plant species, planting media, and support structures used, one can distinguish multiple types of green walls (see Figure 1.5), which, for the purposes of this technical guide, are broadly grouped into two categories: “Façade-Supported Green Walls” and “Façade-Integrated Living Walls” (see Figure 1.4). In addition, certain case studies in this guide can be categorized as “Stepped Terraces” and “Cantilevering Tree Balconies.”

Façade-Supported Green Walls

A façade-supported green wall is a green wall system supported off a façade, but where the planting medium is not integral to the façade (see examples Figure 1.8). Usually the planting medium is carried in horizontal planters, which may be located on the ground or at multiple intervals along the height of the façade. Of the façade-supported green walls contained in the case studies in this guide, the offset from the wall varies from 200 millimeters at Helios Residences (see case study 2.12), to 2.87 meters at the School of the Arts (2.10), both located in Singapore.

A façade-supported green wall structural system is usually comprised of steel, wood, or plastic trellises externally attached to a building façade where climbing plants and vines are supported by horizontal, vertical, or diagonal trellis members. Green façades can be two-dimensional, formed by cables, ropes, and meshes, or three-dimensional, formed by rigid frames and cages.





2.0 Case Studies

Building Data:

Year of Completion

- ▶ 1993

Height

- ▶ 58 meters

Stories

- ▶ 17

Building Gross Floor Area

- ▶ 27,720 square meters

Building Function

- ▶ Office

Structural Material

- ▶ Concrete

Green Wall Overview:

Green Wall Type

- ▶ Façade-supported green wall (horizontal aluminum slats)

Location on Building

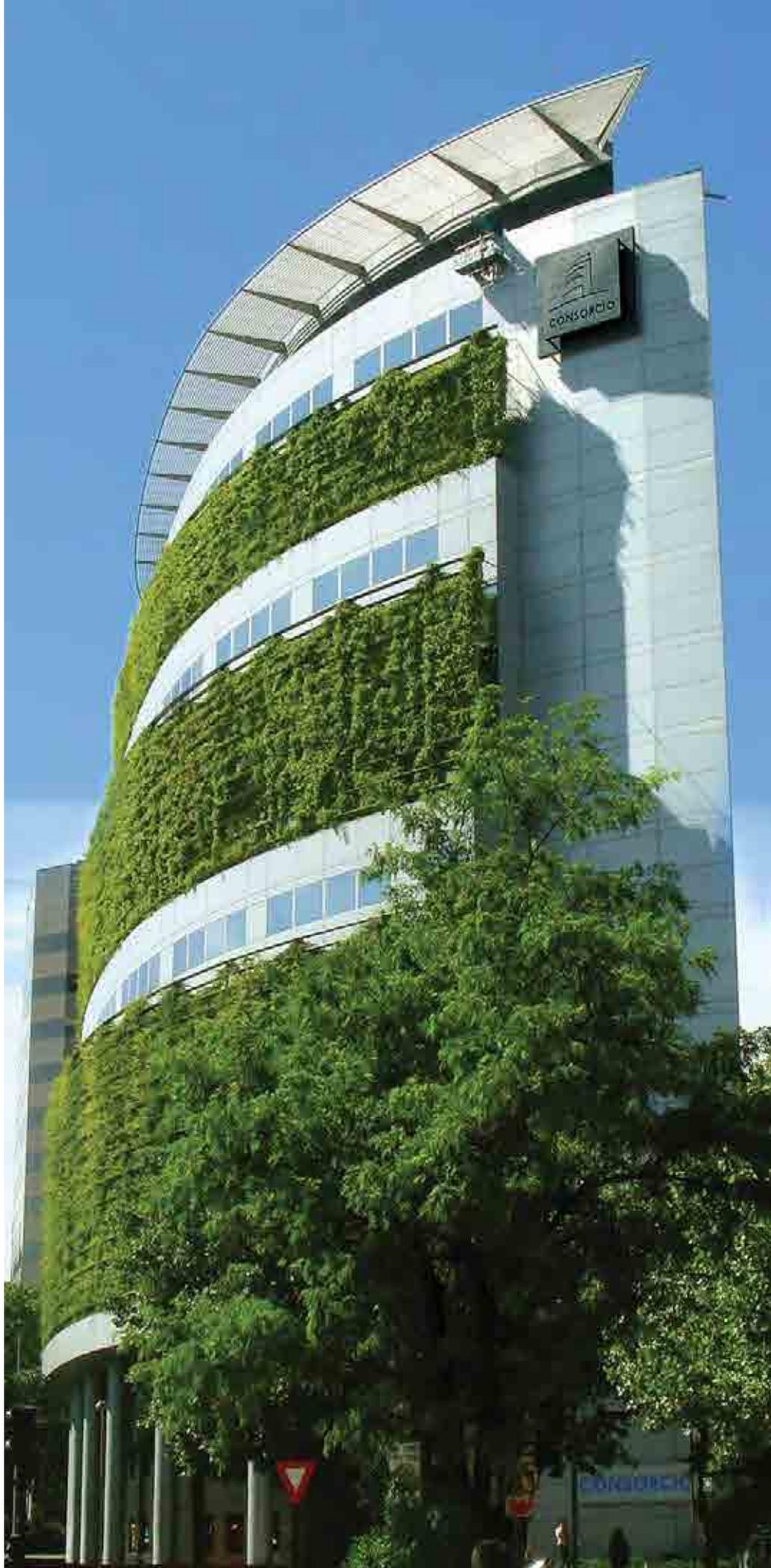
- ▶ On north and west façades, from 4th to 8th, 10th to 12th, and 13th to 14th floors

Surface Area of Green Coverage

- ▶ 2,293 square meters (approx.)

Design Strategies

- ▶ Horizontal aluminum slats, offset 1.4 meters from façade, support climbing plants over 2–4 floors in height
- ▶ Green wall split into three separate sections vertically, each with the support of one horizontal planter at green wall base
- ▶ Deciduous plants provide solar shade in summer, color in autumn/fall and admit solar/light during leafless months
- ▶ Coordination between occupiers and gardener to prune plants to control solar heat gain and light emittance
- ▶ Exterior street trees protect lower floors from solar heat gain/glare

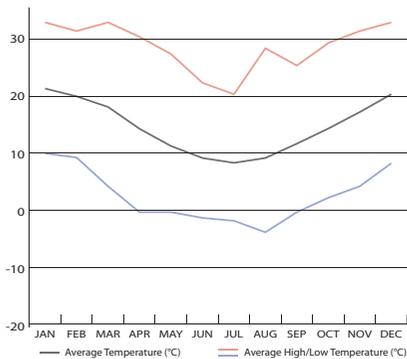


Case Study 2.1

Conсорcio Santiago Building Santiago, Chile

Local Climate

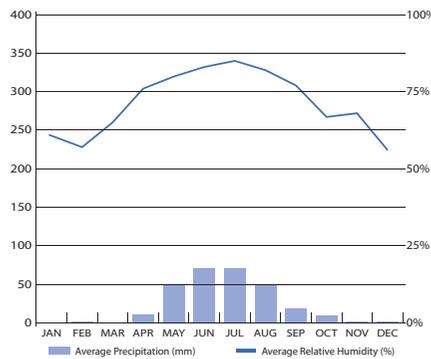
The climate of Santiago is Mediterranean, with typically hot, dry summers, and mild, moist winters (see Figure 2.1.1). In summer, November to February, temperature varies from 17 °C to 20 °C. The summer months can be quite windy and dry, with prevailing winds from the southwest. In winter, May to August, temperature varies from 0 °C to 13 °C. Temperatures in winter seldom drop below freezing. Rain falls mainly during winter, which is a more humid season. Snowfall is extremely rare in Santiago, although it is common in the Andes mountain range that looms above the city. Temperature inversions cause smog to be trapped in the valley for spells during the winter months. Santiago is considered one of the most polluted cities in the world, largely due to its location in a natural bowl, and the smog is at its worst in winter.



Average Annual Temperature Profile (°C)

Background

This office building is located in the Las Condes Neighborhood, in Santiago, Chile (see Figure 2.1.2). The floor plan of the building has the form of a “boat,” (see Figure 2.1.3) looking south with the alignment of the main façade generated by the main street axis that surrounds the building (El Bosque Avenue and Tobalaba Avenue). Initially, the plan was that the floor space would be divided into two sectors, with the first three floors occupied by Consorcio, while the higher floors would be rented; however, the Consorcio Company eventually occupied most of the floors in the building. The south side of the building is shaped as a high vertex, because there was an open angle of 148° between both avenues. This symbolically marks the beginning of the office area of the neighborhood. The west façade was curved to visually receive the pedestrians coming from the nearby subway and down the



Average Relative Humidity (%) and Average Annual Rainfall

▲ Figure 2.1.1: Climate profiles for Santiago, Chile.¹

◀ Figure 2.1.2: Overall view from south. © Enrique Browne

Climatic Data:¹

Location

- ▶ Santiago, Chile

Geographic Position

- ▶ Latitude 33.5° S
- ▶ Longitude 70.7° W

Elevation

- ▶ 550 meters above sea level

Climate Classification

- ▶ Warm Temperate, summer dry, warm summer

Mean Annual Temperature

- ▶ 14.4 °C

Average Daytime Temperature during the Hottest Months (December, January, February)

- ▶ 20.5 °C

Average Daytime Temperature during the Coldest Months (June, July, August)

- ▶ 8.7 °C

Annual Average Relative Humidity

- ▶ 58% (hottest months); 83% (coldest months)

Average Monthly Precipitation

- ▶ 30 millimeters

Prevailing Wind Direction

- ▶ Southwest

Average Wind Speed

- ▶ 2.5 meters per second

Solar Radiation

- ▶ Maximum: 976 Wh/m² (December 21)
- ▶ Minimum: 815 Wh/m² (June 21)

Annual Average Daily Sunshine

- ▶ 6.6 hours

¹The climatic data listed was derived from the World Meteorological Organization (WMO), British Broadcasting Corporation (BBC) and the National Oceanic and Atmospheric Administration (NOAA).

Building Data:

Year of Completion

- ▶ 2007

Height

- ▶ 120 meters

Stories

- ▶ 36

Building Gross Floor Area

- ▶ 11,835 square meters

Building Function

- ▶ Residential

Structural Material

- ▶ Concrete

Green Wall Overview:

Green Wall Type

- ▶ Façade-supported green wall (metal mesh)
- ▶ Tree planters and gardens on communal cantilevering balconies

Location on Building

- ▶ South façade: 6th to 36th floor (green wall); balcony tree/gardens every 4th floor
- ▶ Green walls to car parking podium on south, east and west façades, 1st to 5th floor

Surface Area of Green Coverage

- ▶ 1,274 square meters (approx.)

Design Strategies

- ▶ Trellis-supported green wall runs nearly full height of building from podium (30 floors)
- ▶ Green wall actually 30 overlapping separate one-story green walls, supported by horizontal planters at each floor
- ▶ Communal cantilevering “sky garden” balconies, with trees, significant planting and water features, every four floors
- ▶ Significant planting to individual unit balconies encouraged
- ▶ Luxuriant planting elsewhere, including car parking podium green walls and landscape podium top
- ▶ Vertical greenery, podium top and other site vegetation achieving 130% of plot as greenery



Case Study 2.4

Newton Suites Singapore

Local Climate

Located in an equatorial climate zone, according to the Af Koppen system, and classified as a fully humid zone, Singapore has little temperature and humidity variation between seasons, but instead experiences consistently high temperatures year-round (see Figure 2.4.1). Relatively stable air temperatures, high average humidity and significant rainfall makes Singapore a beneficial location for growing plants. The average temperatures range from 23 °C to 32 °C, with May being the hottest month of the year. A high relative humidity of near 90% in the morning moves to around 60% in the mid-afternoon.

Background

Newton Suites is a 36-story high-rise residential building located in downtown Singapore, adjacent to the commercial and retail hub of Novena (see Figure 2.4.2). The building site

is located at the edge of a high-rise zone and fronts a height-controlled area, which allows unique views of the central nature reserves. The building was carefully positioned on its narrow site, flanked by tall buildings on three sides. The tower sits on top of a five-story podium that serves as enclosed car parking for 125 cars, with public amenities for the residents located on the podium roof. The building features 118 residential units, located between the sixth and 36th floors of the tower, with two and three bedroom units arranged in a cluster of four per floor, with two top floors occupied by penthouse units.

Newton Suites is considered a high-rise building model appropriate for the tropical climate of Southeast Asia, based on passive climate-control design principles and maximizing the incorporation of nature into the building (see Figure 2.4.5). The natural landscape features were included in the architecture from the early design stage.

Climatic Data:¹

Location

- ▶ Singapore

Geographic Position

- ▶ Latitude 1° 22' N
- ▶ Longitude 103° 58' E

Elevation

- ▶ 16 meters above sea level

Climate Classification

- ▶ Equatorial, fully humid

Mean Annual Temperature

- ▶ 27.5 °C

Average Daytime Temperature during the Hottest Months (April, May, June)

- ▶ 28.3 °C

Average Daytime Temperature during the Coldest Months (November, December, January)

- ▶ 26.6 °C

Annual Average Relative Humidity

- ▶ 82% (hottest months); 86% (coldest months)

Average Monthly Precipitation

- ▶ 201 millimeters

Prevailing Wind Direction

- ▶ North

Average Wind Speed

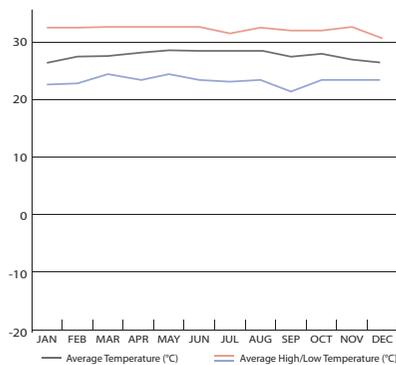
- ▶ 4.4 meters per second

Solar Radiation

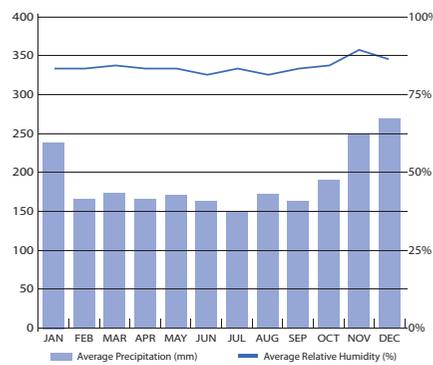
- ▶ Maximum: 837 Wh/m² (December 21)
- ▶ Minimum: 737 Wh/m² (September 21)

Annual Average Daily Sunshine

- ▶ 5.6 hours



Average Annual Temperature Profile (°C)



Average Relative Humidity (%) and Average Annual Rainfall

▲ Figure 2.4.1 : Climate profiles for Singapore.¹

◀ Figure 2.4.2: Overall view. © Patrick Bingham-Hall

¹The climatic data listed was derived from the World Meteorological Organization (WMO), British Broadcasting Corporation (BBC) and the National Oceanic and Atmospheric Administration (NOAA).

3.0 Design Considerations and Limitations

The table on the next two pages shows comparative data summarizing the 18 case studies profiled in this guide. This section of the guide discusses common issues that have arisen out of examining the case studies, which should be considered when designing green wall systems for high-rise buildings.

3.1 Climate Considerations

Local climate characteristics are among the most critical factors affecting choices of green wall design. Air temperature, relative humidity, wind speed, solar radiation, cloud cover, and monthly precipitation will all affect the viability of green wall types and plant species.

Across the 18 case studies in this book, though the largest percentage of installations are in year-round warm climates, it can be demonstrated convincingly that warm, tropical climates are not the only environments that can support external green walls. Green walls can take hold in a range of climates, given

Thick vegetation can have insulating and shading properties, helping to keep heat or cool air from leaking through the building envelope into the atmosphere, and limiting solar gain to the exterior surface of a wall or from transmitting through glass.

careful plant selection, façade orientation, and irrigation strategy.

This book uses the Köppen climate classification system. Based on this system:

- ▶ 5 projects are in Equatorial, fully humid zones
- ▶ 1 is in an Equatorial Monsoonal zone
- ▶ 3 are in Equatorial zones with dry winters
- ▶ 1 project is in a continental zone with snowy winters and fully humid, warm summers
- ▶ 3 projects are in Warm Temperate zones with fully humid, hot summers
- ▶ 2 projects are in Warm Temperate zones with fully humid, warm summers
- ▶ 1 project is in a Warm Temperate zone with warm summers
- ▶ 2 projects are in a Warm Temperate zone with a dry and warm summer

The climate zone characteristics for a project location should always be analyzed at the start of the project to determine plant species that can successfully grow in a green wall, and the established plant growing season. For instance, the growing period of green wall plants in equatorial, fully humid zones can be close to year-round, but the same growing period is only a few months for continental zones with snowy winters.

Climatic conditions also define “plant hardiness zones,” geographic areas classified by the ability of plants to withstand the typical minimum temperatures in that zone. For example, plants described as “hardy to zone 9” can withstand a winter temperature of 19 °F (–7 °C), the typical minimum in zone 9. There are 13 hardiness zones; the lowest number corresponds to plants that thrive in extremely cold

conditions (Agricultural Research Service 2014).

Examining the climates of projects in this guide, the lowest average annual temperature is 10.2 °C (Athenaeum, London, UK) and the highest is 28.5 °C (the Met and IDEO Morph 38, Bangkok, Thailand). At the same time, we see cities with average annual temperature swings as great as 0.3 °C to 23.1 °C (Milan). Thus we can conclude that vertical greenery is achievable in locations with average significant temperature variation, pending correct plant and system choice.

The range of humidity in the climates associated with the case studies is also quite large, ranging from Singapore with low annual variation (82% to 86%), to Santiago, Chile which experiences a 58% to 83% humidity swing between the hottest and coldest months.

The amount of daylight and solar radiation will affect plant species choices and wall orientation. While all plants need daylight and some sunshine, too much direct solar radiation for many plants can be destructive. The projects featured as case studies in this book range from receiving 4 hours of average daily sunshine (Bogota, Colombia) to 7.2 hours (Bangkok, Thailand). The amount of solar energy that actually penetrates to ground level can also be important, and as a function of elevation and cloud cover, can sometimes seem to contradict the hours of average sunshine data. In terms of daily sunshine and solar energy, the roles of Bogota and Bangkok are reversed, with Bogota at 2,625 meters above sea level receiving a maximum of 998 Wh/m², while Bangkok, at 1.5 meters above sea level, receives a maximum of only 748 Wh/m². At the minimum end of the solar radiation scale (based on the month when the location receives the least



▲ Figure 3.1: The 43% west façade greenery coverage of Consorcio, Santiago, reduces solar gain by 60%.
© Enrique Browne

sunshine), Bogota remains the sunniest location, and London is the least sunny.

The amount of precipitation is one determinant of how frequently plants will need to be irrigated, and which plant species can be supported in a green wall. Projects in this book range from an average monthly rainfall of 30 millimeters (Santiago, Chile) to 201 millimeters (Singapore). Each project has adopted an appropriate irrigation system to reflect the local climate and plant choice (see Sections 3.4 and 3.6).

Another important consideration is average wind speed at the green wall location and the green wall's exposure to wind. Plants are generally susceptible to wind and can be permanently damaged by high wind stress. Nevertheless, the case studies in this guide show that

external plant life can be supported in locations with average wind speeds of up to 4.4 meters per second, as demonstrated by the five projects in Singapore. Since locations in the tropics also experience occasional typhoon winds, it can be presumed that green walls engineered for such locations can also survive occasionally much stronger wind speeds.

3.2 Primary Functions and Design Objectives

The design team should clearly define the objectives of a green wall installation, yet still have the flexibility to adapt the installation if unexpected results transpire.

There are a multitude of differing objectives and motivations for green

walls across the projects featured in this guide, which are grouped accordingly and discussed below:

Improving the thermal performance of a façade and reducing building energy consumption

Thick vegetation can have envelope-insulating and shading properties, helping to keep heat or cool air from migrating through the building envelope into the atmosphere, and limiting solar gain to the exterior surface of a wall or from transmitting through glass. Thus, in short, green walls can help insulate a building in cold climates, and shade a building in hot climates. Evapotranspiration also creates small zones of cool air, particularly between the green wall and the building envelope, but also in some cases in the immediate vicinity along the building's exterior, which further assists the envelope's thermal transmittance in hot climates.

For instance, the Consorcio project in Santiago, Chile, with 43% of its west façade covered by greenery (see Figure 3.1), reports reduced solar radiation by 60% and 48% less energy use than 10 other comparable buildings nearby. Floors in Consorcio shaded by green walls actually use 35% less energy and are 25% cheaper to operate than other floors without green walls elsewhere in the same building. This is one of the more poignant examples in this guide. Such results may not be realistic in other cases, particularly in those situations with less green wall coverage or wider extremes of temperature. It should also be noted that it proved impossible to obtain energy performance data, even anecdotal evidence, for most of the case studies in this guide.

5.0 Appendix: Green Walls and Energy Efficiency

Report by Irina Susorova

5.1. The Effects of Green Walls on Energy Efficiency

The energy efficiency of green walls lies in their ability to affect heat transfer between a building's interior and exterior environment. The main exterior factors affecting heat transfer through a building's façade are (i) solar and thermal radiation from the atmosphere and the ground, (ii) air temperature, (iii) relative humidity, and (iv) wind speed. Plants and other elements of green walls, such as planting media or support structures, decrease the effects of these climatic factors on the exterior wall surface, which results in a reduction in heat transfer through the façade and, as a result, a decrease in heating and cooling energy consumption.

Understanding the energy balance of a vegetated wall and the individual thermal-physical processes is extremely important in order to evaluate the effects of a green wall on building thermal performance and potential energy savings. The image below shows a schematic diagram of the energy balance and heat flows through a

building's façade covered with a plant layer (Gates 2003), (Campbell 1998), (Jones 1992) (see Figure 5.1). The energy balance of a plant-covered façade accounts for multiple heat flows, including incoming solar radiation, infrared radiative exchange between the façade and sky, the façade and ground, the façade and the vegetation layer, convection to and from the façade, evapotranspiration from the plant layer, heat storage in the façade material, and heat conduction through the façade.

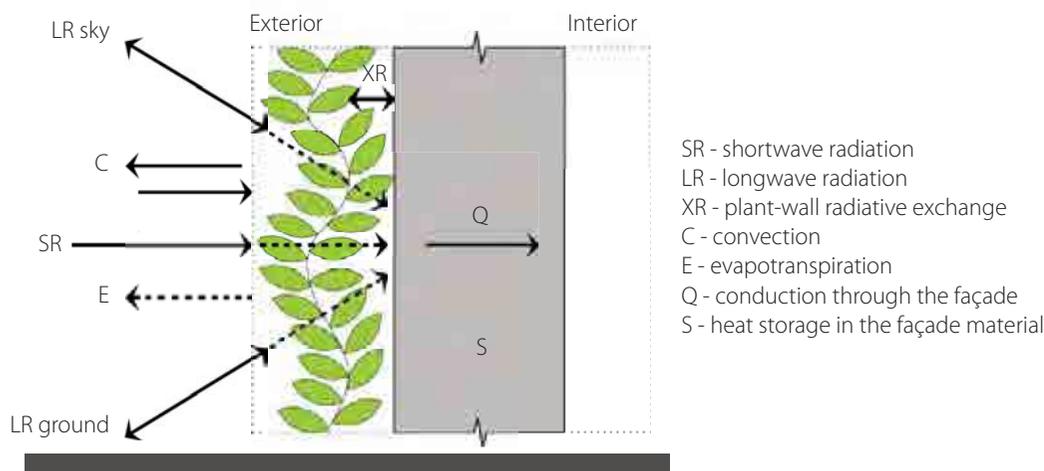
In general, the plant layer acts as an additional layer of thermal insulation and helps improve thermal performance of a building façade through:

- ▶ Shading of the exterior wall from incoming solar radiation
- ▶ Protection of the exterior wall from wind exposure
- ▶ Temperature cooling of the air adjacent to the exterior wall
- ▶ Increasing the exterior wall's thermal insulation value if the vegetated façade includes a layer of planting medium (soil or inorganic media) placed along the façade; as seen in living walls

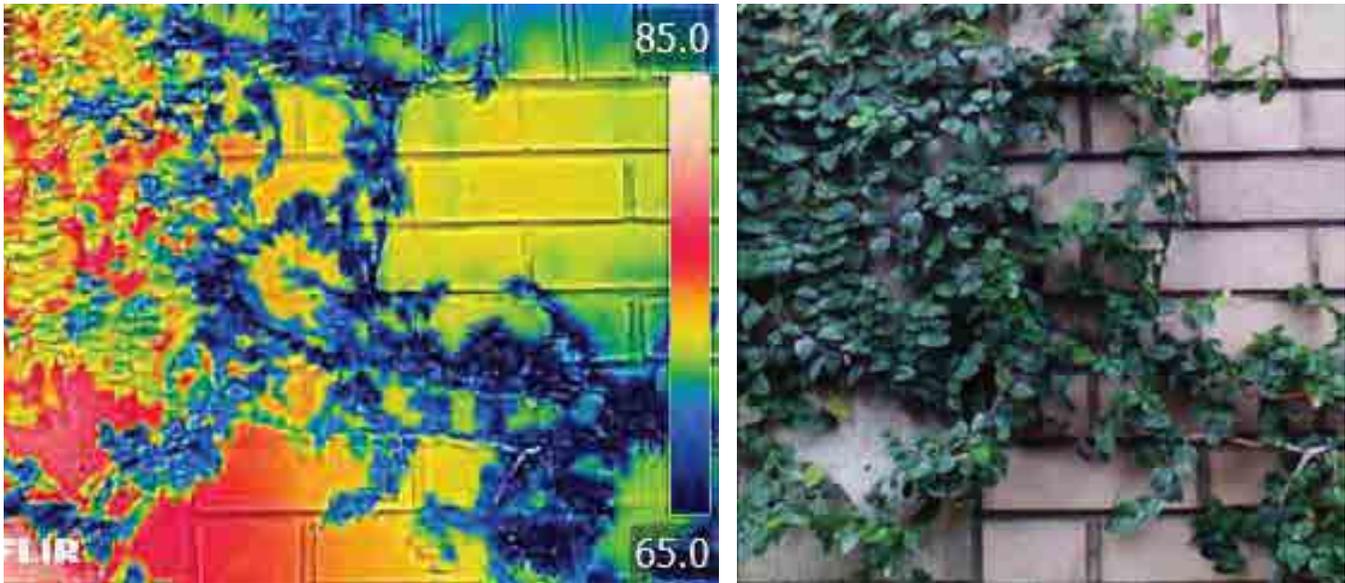
Plant shading

A layer of plants placed on a buildings' exterior wall intercepts a fraction of total radiation incident on leaves, reflects some radiation, and transmits the rest of it to the exterior wall behind it. Due to this shading effect, the façade surface temperature behind the plant layer and façade surface temperature gradient (the difference in temperatures between the exterior and interior surfaces) of the exterior wall are typically lower than those of a bare façade (Di 1999), (Evmorfopoulou 2009), (Hoyano 1988), (Wong N. H. 2010), (Perini 2011), (Peréz 2011), (Sternberg 2011), (Susorova 2013), (Susorova 2014). As a result, heat transfer through a vegetated wall, which is driven by the façade surface temperature gradient, is also reduced. This effect is illustrated by the infrared image of a Ficus pumila vine climbing along a brick wall taken at midday on a warm day (see Figure 5.2). The difference between the bare and plant-covered façade is approximately 12 °C (20 °F).

The amount of solar radiation transmitted to the exterior wall surface



▲ Figure 5.1: Energy balance of a vegetated façade. © Irina Susorova



▲ Figure 5.2: Infrared image of climbing fig (*Ficus pumila*) on a brick wall. © Irina Susorova

decreases exponentially with foliage density, which is typically expressed with leaf area index (LAI) (Campbell 1998). Leaf Area Index is the ratio of leaf area to a unit area of façade or floor and accounts for other plant parameters, such as leaf dimension, plant layer thickness, and density. The leaf area index is the total projected area of leaves per unit surface area, which varies with the plant leaf size, density, and age (see Figure 5.3). It is a ratio that varies from <1 , for young plants with loose foliage that does not cover the wall surface completely, to 3–5 for mature plants with dense foliage (Yu 2006), (Cameron 2014).

Plant shading helps reduce heat transfer through exterior walls, which leads to reduced building heat gain and cooling loads (Di 1999), (Susorova 2013), (Susorova 2014). This decrease in cooling load reduction can translate into reduction in annual space conditioning energy use and in peak electricity demand.

Plant shading has a significant effect on façade thermal performance only

when the exterior walls are exposed to sunlight. Shading plays no role at nighttime, on cloudy days, or when the vegetated façade is permanently shaded by surrounding objects (Hoyano 1988), (Evmorfopoulou 2009), (Wong N. H. 2010), (Susorova 2014). In fact, the façade surface temperature is typically higher at nighttime, depending on the foliage density, because vegetation somewhat obstructs the natural cooling of the façade, by radiation, to the night sky. The highest reduction in surface temperature and heat conduction through the façade is naturally observed for façade orientations that have the highest exposure to the sun. In fact, vegetation placed on the east and west walls in the northern hemisphere, yields the highest improvements in façade thermal performance (Evmorfopoulou 2009), (Perini 2011), (Susorova 2014).

Since plant shading is mainly used as a method of reducing heat gains and cooling requirements, it works well only in hot climates all year round and in temperate and cold climates during summer time. If used in winter time, the plant layer actually worsens thermal

performance of exterior walls exposed to the sun (east, west, and south) because it blocks solar radiation to the walls and increases heat loss from the interior space (Huang 1987). This problem can be overcome by using deciduous plants on critical façade orientations exposed to the sun. Such plants provide shading in the summer time and shed foliage during cold months.

Wind Reduction

The plant layer placed on exterior walls reduces wind that passes through its foliage. In conditions of decreased air movement near the façade surface behind vegetation, a layer of nearly still air forms around plant leaves and branches, acting as an additional layer of thermal insulation. For example, the studies by DeWalle and Mattingly, assessing the effect of vegetation windbreaks installed near buildings, observed that a row of trees placed in front of small buildings in cold climates resulted in a 29–48% reduction in wind speed on the façade (DeWalle, 1983), (Mattingly, 1977). According to

Cities are facing unprecedented expansion through population growth and urbanization in the coming decades, and the horizontal-suburban model of urban development is increasingly being discredited on sustainability grounds. With less available land to build on, the logical solution is to build upwards. However, a major human need – access to greenery – must be addressed by any viable plan for increased height and density.

Implementing green walls in our cities, including at height, is a key option for forging a more psychologically and physically healthy environment. In addition, there are building energy-conservation and numerous other benefits to be had through their adoption. Of course, there are more effective ways to reduce individual building energy consumption than to apply vegetation to the skin of a building. However, the most immediate argument for green walls is that they can have significant benefits simultaneously upon implementation – to both the building and the wider urban surroundings.

This guide thus sets out recommendations for selecting, implementing and maintaining green walls in high-rise buildings, including local climatic factors that need to be taken into account, and the risks of adopting different wall types. Recommendations are based on the analysis of 18 case studies and research undertaken by the Council on Tall Buildings and Urban Habitat. These detailed and richly-illustrated case studies represent the cutting edge in green wall design around the globe – embracing 11 cities, 9 climate zones, and green walls up to 69 stories in height.

This guide is intended for anyone working on the design and operation of tall buildings, with a specific interest in greening the environment, both at the building and the urban scale. This is the second technical guide from the Council on Tall Buildings and Urban Habitat's Tall Buildings & Sustainability Working Group, and the fourth guide in the *CTBUH Technical Guide* series overall. These guides are aimed at examining strategies for reducing the environmental impact of tall buildings, while taking the industry closer to an appreciation of the myriad factors that constitute sustainability in the context of tall.

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