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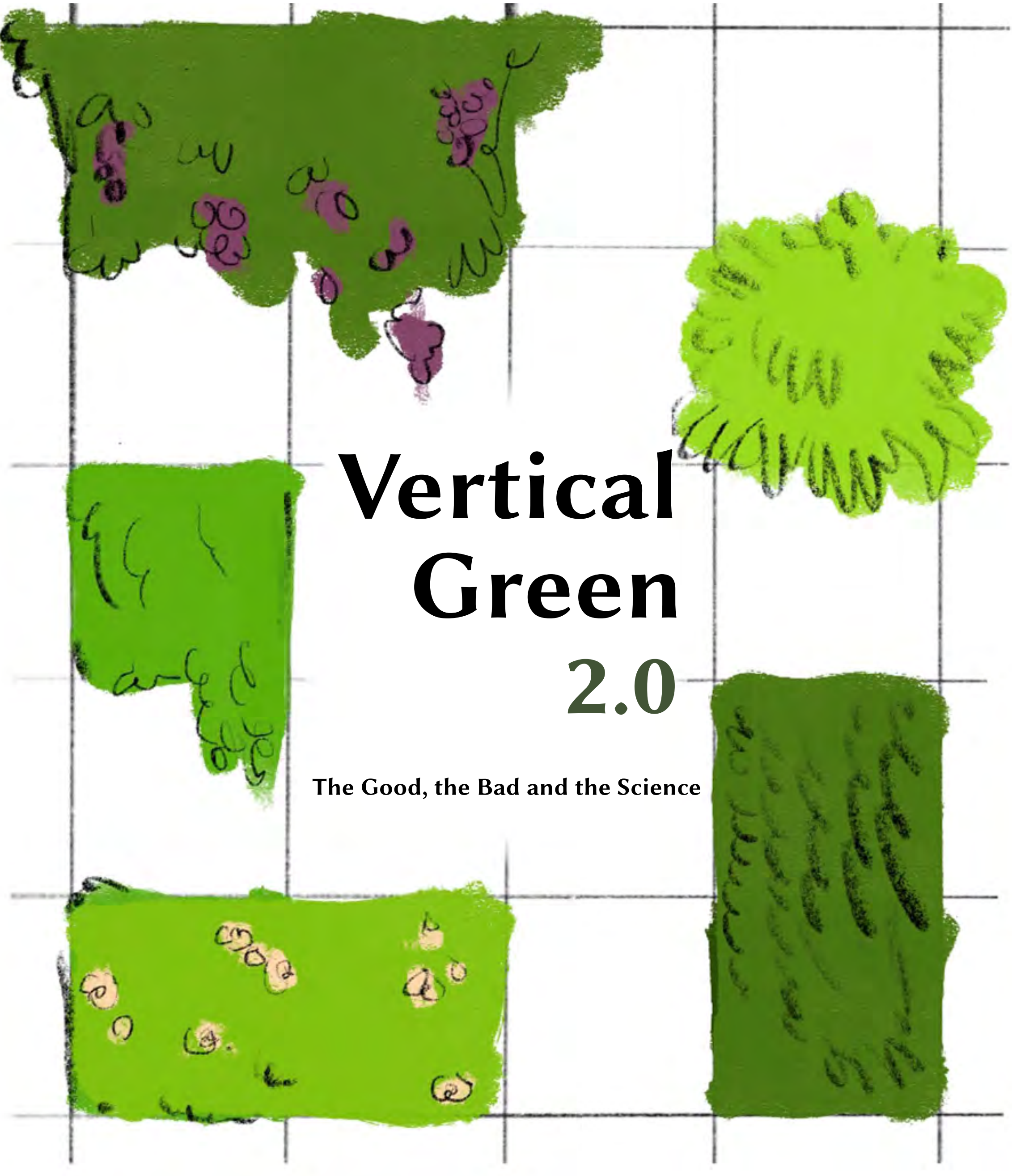

Vertical Green

2.0

The Good, the Bad and the Science

Universitätsverlag der TU Berlin

Karin A. Hoffmann | Sebastian Schröder | Thomas Nehls
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Vertical Green 2.0 – The Good, the Bad and the Science

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PREFACE

Please have a closer look on the title page of this book. In the upper left you find grapes – juicy and exuberant accepting trellis as support but not as a limit. When building greening prospers, architects have to accept that buildings behave naturally – they green, they bloom, fruit, may change color, wilt, and finally die. As vertical greenery brings back nature into the most artificial part of the city, it can solve some of the problems which arose when cities went too far from nature.

This book presents the results of the international, interdisciplinary research project 'Urban Vertical Green 2.0'. It was part of the Sustainable Urbanisation Global Initiative (SUGI)/ Food-Water-Energy Nexus, a call established by the Belmont Forum and the Joint Programming Initiative (JPI) Urban Europe. The aim of the call was to develop options for a sustainable urbanization. In the project, vertical greenery systems (VGS) as part of urban green infrastructure and as a nature-based solution, have been investigated and further developed by scientists and practitioners from the Technische Universität (TU) Berlin, the University of Natural Resources and Life Sciences (BOKU) Vienna, Green4Cities GmbH (G4C) Vienna, the Urban Planning Institute of the Republic of Slovenia (UIRS), and the National Taiwan University (NTU).

We address stakeholders interested in the implementation of VGS from an interdisciplinary perspective. We present our project findings ranging from the current perspective of stakeholders, VGS design and maintenance, potentials for optimizing the food-water-energy nexus to governance, planning and financing issues.

Writing this book would not have been possible without the tireless and very constructive contributions from all project partners and investigators, helpful discussions and review cycles of our extended working groups and PI's and the valuable contributions of our students within student projects, bachelor's, master's and PhD theses.

We are grateful to the Belmont forum, the JPI and our national funding agencies for supporting our project, the university library of the Technische Universität Berlin for the formal lectorate and guidance through the publishing process. We hope to deliver answers regarding VGS as part of a catalogue of multifunctional nature-based solutions fostering transitions from grey to greener and more livable urban environments.

Thomas Nehls and Karin A. Hoffmann

CONTENTS

Chapter I

INTRODUCTION

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1 Vertical Greening Systems – Definition and general introduction

In today's urbanized societies, there is a growing awareness of the quality of urban space, the importance of urban resilience to climate change and of ensuring public health. Vertical greening systems (VGS) as part of green infrastructure can contribute, especially in densely built-up areas, to extending ecological corridors, offering experience with nature, and having a positive effect on the urban water and energy cycle and thus foster circularity in cities.

In this book, in accordance with the COST Action "Circular City Re. Solution" (CA17133, Langergraber et al., 2021, three types of VGS are defined: Ground-based, pot-based and wall-based green facades (see Figure I.1 and chapter III).

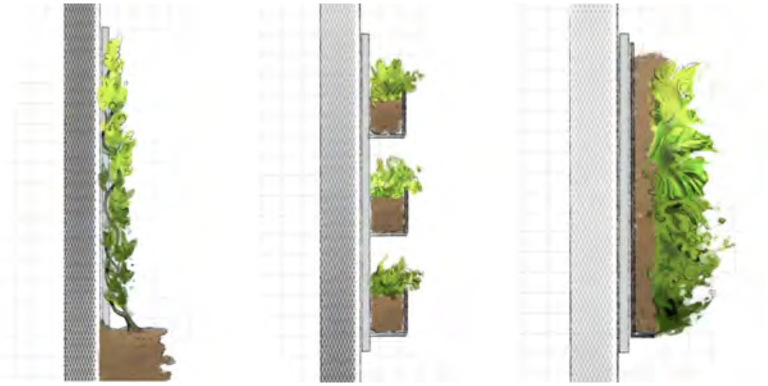

Figure I.1: Ground-based (left), pot-based (middle) and wall-based (right) green facade (image by Bibi Erjavec)

The three types of facade greenery are grouped under the term "Vertical Greening Systems" (VGS). According to the definitions of the European Commission, the International Union for Conservation of Nature (IUCN), and the CA17133, VGS are among the "Nature-based solutions" (NBS) that offer potential for the transformation of cities in ecological and social terms. The concept of growing plants on facades is not new. In central European inner cities for example, especially ground-based green facades are not uncommon. Still, urban stakeholders involved in construction and spatial planning often have reservations towards implementing VGS or have knowledge gaps especially on innovative systems.

In the following four chapters of this book, potentials and obstacles towards VGS implementation are discussed from four perspectives: chapter II is devoted to the perspective of key stakeholders and presents work addressing their views on current and future potentials of VGS implementation. In the next chapter (chapter III), VGS designs are discussed with focus on irrigation as well as possibilities for automated maintenance through robotic systems. This chapter is followed by chapter IV, interlinking VGS with urban biomass, water, and energy cycles, and presenting quantitative experiments and models. The book concludes with chapter V on the integration of VGS into existing and possible future governance, planning and financing models. To further introduce the topic, this chapter continues with providing insights into the historical development of VGS, the current implementation status of the focus cities Berlin, Vienna, Ljubljana, and Taipei, as well as an overview of obstacles and benefits of VGS.

2 Historical development of Vertical Greening Systems

Facade greening has evolved gradually over time, based on past knowledge, following the development of building techniques, research, and advancements in technology.

The use of green roofs and walls was linked both to the knowledge of the insulating potential of the combination of plant material and soil, and to the effects of natural elements on people and living environment. Historically, simple vegetated buildings were known to retain heat in buildings in cold climates and to reduce heat or retain coolness in warm climates. These characteristics are one of the main arguments for the use of vegetation on the building envelope.

The history of greening buildings probably begins with ancient cultures especially in relation to ziggurats or stone buildings. Babylonian hanging gardens are said to be the first known example of covering buildings with vegetation. The hanging gardens were probably terrace or roof gardens on ground-floor buildings with greenery hanging over the terrace's edges. In a description of an Egyptian garden dating from c. 1400 BC support structures for vegetation as a structural element covered by plants (vines) are mentioned as well (Ogrin, 1993).

Regarding the Roman Empire, greening buildings was common. Various sources indicate that growing vines on the balconies was common in Pompeii. The historian Pliny the Younger (23–79 AD) wrote about the use of structures for climbing plants for shading purposes and trees for green roofs (Peck, 1999). The vine was not only an agricultural plant but was also used to cover architectural structures and create ambience in the garden.

In the Middle Ages pergolas and other structures were covered by various plants (often roses) and used to provide shade in the summer. They were mainly used in so-called 'pleasure gardens'. During the Renaissance, vertical structures appeared mainly in the gardens of the aristocracy. The key starting point was the connection of house and garden. There are historical examples of designs such as Villa Quaracchi with a garden divided by a pergola. The cultivation of fruit trees and the use of thermophilic (exotic) plants along the facades or walls of sunny sides started to develop then (Ottelé, 2011). In the garden art of France in the 17th and 18th centuries the architectural approach of creating espaliers and palisade trees and parterres with large green pergolas to provide shade while strolling through the extensive gardens became widespread. In several cases, the technically sophisticated cast-iron structures were also unadorned, reflecting the admiration for construction techniques and materials at the time. In this period the same climbing plants from America were already used, which are still broadly used today (Ottelé, 2011).

New possibilities for vertical greening were brought by new gardening techniques and cultivation processes that allowed plants to grow without parent soil, i.e. in planters and containers. The advancements in construction techniques and materials in the 19th century, especially the invention of reinforced concrete and other construction techniques allowed new possibilities for design (Giedion, 2008). For example, the architect Hector Horeau introduced installing planters that were filled with soil and plants on Paris boulevards – an early example of a horticultural system that collected and distributed rainwater to meet the needs of plants (Lambertini, 2007).

At the beginning of the 20th century, the use of climbers for green facades was expanding, particularly in German-speaking countries. This trend was possibly derived from the Art Nouveau and the movements of the time (Garden City, Arts and Crafts) (Dunnett & Kingsbury, 2010).

During the modernist period, vegetation was incorporated into buildings by several architects, including Le Corbusier and Frank Lloyd Wright, but these were mainly plantings on roofs and terraces. Geoffrey Bawa who worked in tropical climates tried to merge architecture with landscape also by using green roofs and facades.

Modernist designers, however, favored the presence of pergola structures without plants. As a pioneer of green modernism Stanley Hart White is considered also as one of the pioneers of vertical gardens. In 1938, he created a prototype green wall consisting of plant unit elements made of wire baskets filled with substrate. His designation of living wall element was 'Vegetation-Bearing Architectonic Structure and System' which defines the crucial characteristic of green walls – the fusion of plant material with a load-bearing construction (Hindle, 2013).

The Brazilian artist and landscape architect Roberto Burle Marx is considered being one of the pioneers of modern vertical garden design and the initiator of modern practices. His design was based on use of soil-independent plants in urban context. His close collaboration with architects and interest in plants emerged the use of new techniques, often in the context with little or no access to the ground. By using climbers and planting in facade planters along the walls at the edge of the plaza in Sao Paolo, he integrated vegetation into the primary architectural context (Adams, 1991).

In the 1960s, with the environmental movements, there was a tendency to incorporate sustainable design principles into architectural design.

The green city incentive programs were developed in Germany (in the 1980s), one of the most famous projects was realized at Paul-Lincke-Ufer in a residential neighborhood in Kreuzberg district (Berlin), which resulted in the greening of the facades with climbing plants (Ottelé, 2011).

In contemporary architecture the use of vertical greenery is usually part of an architectural language. For example, the Dutch pavilion at the EXPO in Hannover (MVRDV, 2000), with six levels of presented landscapes is conceived as a presentation of sustainability. The pavilion, designed by MVRDV, addresses issues of population density and the role of nature, thinking of a 'new nature' as a mix of technology and nature (MVRDV, 2000). The pavilion presented sustainability only short time, as today it is abandoned and is planned for renovation.

Within the broader concept of building greening, the use of green roofs has expanded in recent decades. The practice of wall-based green facades is currently developing both in Europe and worldwide, especially in countries with warmer climates. Different techniques for the use of plants have been developed. Climbing vegetation is no longer the key as developed systems allow plants to grow from wall pockets or layers or plastic composite modules. In these wall-based systems, the supply of water and nutrients is crucial, which has led to the use of hydroponics. These types of greening have become a 'trend', made famous by vertical garden designer Patric Blanc, "the creator of vertical garden". Sekaran (2015) listed important turning points such as introduction of stainless-steel cable systems, cable and wire-rope net systems and modular trellis panel systems in early 1990s and first major application of trellis panel system installed in California, the MFO Park – a multi-tiered park structure in Zurich in 2002. Since 2005, green wall design became popular all over the world, particularly in southeastern Asia, especially Singapore.

3 Vertical Greening Systems in partner cities

3.1 VGS in Ljubljana

Ljubljana, the capital of Slovenia, is a relatively small city with approximately 300,000 inhabitants and is generally considered to be a green city. During the VG 2.0 project the presence of vertical green in Ljubljana both on building facades and other built structures such as retaining walls has been examined. The findings suggest that in most cases vertical greenery on buildings is used on walls facing railroad lines and roads, especially along pedestrian sidewalks. In addition, vertical green in courtyards and gardens is used, but to a lesser extent. It is presumably an important element creating ambience in outdoor living space.

Regarding the types of VGS, ground-based green facade are predominantly found in Ljubljana both on buildings and on other wall structures, which was found on 98 % of the inventoried cases. The wall-based green facades and pot-based green facades are in the minority, both in terms of abundance and proportion of greened vertical surface. These are mainly used as noise barriers and separating walls. Vertical greenery is present altogether on 1 % of the building stock in the urban area of Ljubljana. The greened buildings are mainly single-family houses (40 %), followed by blocks of flats, garage buildings, agricultural buildings, and to a lesser extent office and administrative buildings, hotels and service buildings. 56 % of the inventoried greened structures have been buildings while 44 % have been other built structures.

3.2 VGS in Berlin

In Germany, an increasing interest for building greening can be detected through past years. However, funding programs and public authorities focus rather on roof greening (Kühle, 2020). The predominant VGS type in Berlin is the ground-based green facade, often Virginia creeper which can be found on many residential buildings.

A city-wide inventory of VGS found the number of VGS and wall coverage decline between 1985 and 2018. Of the 550 VGS present in 1985, only 426 still existed, corresponding to a decline in covered wall area of almost 50 %. According to the author, this decline is due to obsolescence of plants, changed perspective of owners towards facade greening and renovation works on facades (Koehler, 2019).

The implementation of building greening has been targeted by different building greening incentives during the last decade in Germany. The city of Berlin for example started the funding program "Gründach-PLUS" (engl. GreenroofPLUS, note by the author), with up to 75 % direct subsidy. In other German cities (Munich, Cologne, Frankfurt, Stuttgart, Düsseldorf and Essen) the authorities launched programs with integrative funding of roof, court and facade greening support. The city of Leipzig specifically targeted facade greening measures with the program "Kletterfix – Gruene Waende fuer Leipzig" (BuGG, 2019). Other cities, such as Hamburg, have recently readjusted former roof greening programs to incorporate facade greening support (Hamburg – Grüne Fassaden).

According to the German Association of Building Greening (BuGG), an increasing number of German cities implemented direct subsidy programs and legal determination of roof as well as facade greening throughout the last decade. However, facade greening still has a rather low priority for public authorities compared to roof greening. Within the legal framework, the German building code (BauGB) regulates facade greening as single case or as compensatory measure, both can be used to bind implementations. In principle, agreements on building greening can be incorporated in urban development contracts (Kühle, 2020).

The Institute of Agricultural and Urban Ecological Projects (IASP, 2018) has compiled qualities of facade and roof greening and evaluated each ability in order to develop an updated biotope-area-factor (BFF, chapter V, info box on BFF). Here, effects of facade greening appear similar or even more positive on health, air quality and micro-climate, compared to roof greening (IASP, 2018). However, besides such considerations and benefits, prejudices remain. Building contractors and investors in practice often reject concepts which consider facade greening (Kühle, 2020).

Figure I.2: Green facades in Berlin (images by Bjoern Kluge and Karin A. Hoffmann)

3.3 VGS in Vienna

Vienna has a long tradition of vertical green. Inner courtyards were often overgrown with grapevine or self-climbing plants (*Parthenocissus sp.*, *Hedera sp.*). The baroque gardens of Schönbrunn are flanked by arches with climbers and high formal cut hedges. On the outside of villas of the 19th century climbing structures for plants were often included in the design of the facades.

In the 1970s the artist Friedensreich Hundertwasser claimed that niches in the facades of the houses should be dedicated as habitats for trees (Manifesto for “tree residents”). At the same time, the architect Harry Glück set an extraordinary example for the integration of vertical green in social housing: Up to the 13th floor terraces with huge planters are provided for every flat, and on the 15–27th floor Loggias are provided for the inhabitants. (Fassbinder, 2014; Nextroom, 2021). In 2002, together with Helga Fassbinder, he initiated the project Biotope City, a partly social housing project with 2200 m^2 of vertical green and balconies for most of the flats (IBA-Wien, 2021).

The municipality of Vienna is initiating lighthouse projects on their own building stock. Vienna’s biggest pot-based green facade was built in 2009 on the MA48 during its thermal renovation. The cities’ current goal is to implement vertical green on ten facades per year.

In addition, to encourage vertical greening implementation, the city of Vienna offers consulting and funding (MA19 2021, MA22 2019, Presse Service der Stadt Wien, 2020; also see chapter V).

Figure I.3: Hundertwasserhaus, VGS in Biotope City, and MA48 (images by Irene Zluwa)

3.4 VGS in Taipei

The total population of Taipei City is about 2.55 million, and the population density ranks first in Taiwan. The average green space per citizen in Taipei City is only about $5.9\,\mathrm{m}^2$, far below the $9\,\mathrm{m}^2$ recommended by the World Health Organization. At the end of the second quarter of 2019, there were 896,000 residential homes in Taipei City (Taipei City Government, 2019). Vertical greening systems can potentially increase green space provision especially in densely populated areas in the future.

Outstanding examples of VGS in Taipei City can be found in the greened wall in the underground plaza of the 101 Building (Poly Vigor Inc., 2018), the high-scale double-layered green walls in the case of Guan De Xingya, the Innisfree building in Ximending neighborhood, at Caifu Xinhai Road and Yongping Senior High School.

In addition, many green walls are common in construction site fences in Taiwan. According to the "Improvement plan for obstructing traffic and public safety during building construction in Taipei City", safety fences must be designed and planned including elements as painting, canvas, stickers, setting up green plants, etc. (Taipei City Government, 2009). The following works are typical VGS at construction site fences in Taipei City: new construction of collective housing by Yuanlih Group, the Huagu Fuli Building, the construction of Xinyi A7 Commercial Building, the residential commercial building in Neihu District, the urban renewal residential building by Yiyang Construction Co., where Taiwan native species are used, and new constructions by Sunty Development Co. – the design of the fence greening totem. Crop plants are very often used on greened fences. Once the site fence is demolished, the crops can be harvested. Therefore, in the project Vertical Green 2.0, appropriate tools have been developed to suit this idea (see chapter III).

Figure I.4: Dandy Hotel, construction site on the NTU campus, construction site in downtown Taipei (images by Chung-Kee Yeh)

4 Benefits and Ecosystem Services provided by VGS

VGS as bio-technical functioning units provide benefits outbound to the public and inbound to the inhabitants of the greened building. The services provided by VGS can be described as ecosystem services (ES) according to the Millennium Ecosystem Assessment (MEA, 2005). Provisioning services, regulating services, supporting services and cultural services (non-material benefits) can be distinguished and are described in the following.

4.1 Benefits of VGS provided to the public

Facades, which are visually present in the urban public space, influence the surroundings of the buildings. Greening these structures has therefore an impact on the public space and adds provisioning, regulating, supporting and cultural functions to it. Other than the aesthetics of VGS, the regulating services regarding the energy balance and microclimate, rainwater management, reduction of air pollution and noise are discussed. However, greened buildings also enable cities to produce biomass for food, biomaterial, and energy production, they enhance the plant biodiversity and provide food and habitats for animals.

Microclimatic effects of VGS – reduction of the UHI

In the mid latitudes climate change leads to increasing heat wave frequencies, lengths, and peak temperatures. Amplified by the urban heat island (UHI), this leads to increasing heat stress in cities (Buchin et al., 2016). The modern life is spent indoors rather than outdoors. In Germany, for instance, people spend on average 15.7 hours of the day indoors. (Brasche & Bischof, 2005) Therefore, heat stress must be controlled indoors. This is often not accounted for in UHI detection as commonly satellite-based surface temperatures are measured during the day – which is wrong and insufficient. It is wrong, as only the surface temperature is characterized but not the air temperature.

The relation between surface temperature and air temperature is – if at all – sufficient only during nighttime. Therefore, surface temperatures can only be used to describe the night UHI (does not apply for water bodies). However, as the satellite observations focus on horizontal images of the cities, climate adaptation strategies for urban areas suggest establishing more green spaces such as green roofs, parks etc. However, it is mainly the increased vertical surface that causes the higher air temperatures in built up parts of the cities during nighttime. Building walls absorb solar radiation during the day and transform it to sensible heat – increased air temperature. VGS are systemic solutions to this problem as they cover the surfaces of buildings, absorb solar radiation and keep the building surface cool by transpiration cooling. VGS have proven their potential to cool down building's interior space and the building surfaces (Hoelscher et al., 2016). Regarding the effect of VGS on the public space, the scientific results are vague. Jaenicke et al. (2015) found that greening a facade only slightly reduces the heat stress of pedestrians in front of the greened wall. The reduction of the surface temperature of single buildings does not necessarily mean that VGS have a detectable impact on the UHI effect. At least, this was seldom if never measured. Hoelscher et al. (2016) for instance did not find a detectable impact of a VGS on the air temperature 30 cm in front of the greening that was up to 17 K cooler than the not-greened wall. However, from the energy balance perspective, every well-irrigated VGS transforms solar energy into latent heat and thus reduces the transformation from solar radiation to sensible heat. Therefore, simulation studies and conceptual discussions always find reducing effects of VGS on the UHI effect (Pfoser, 2016). If more building surfaces would be greened, that would have greater effects for the air temperatures in the street canyon. The main question remains how big the fraction of the building surfaces is, that can be greened in reality (windows, monument protection, acceptance etc.) and if such a realistic greening would lead to detectable effects for the public space (for more information see chapter IV).

Rainwater management

For the successful cultivation of VGS, irrigation is a crucial factor. Irrigating with rainwater instead of tap water has a great potential to contribute to run-off reduction and increased evapotranspiration. Pearlmutter et al. (2021) found that the roof run-off potential in six European and middle-Eastern cities would limit the implementation of VGS. Greywater was discussed as a valuable resource for balancing out drought periods. In that way VGS can contribute to wastewater reuse. Compared to street trees, an 850 m^2 wall-based green facade in Vienna/Austria could reach similar rates of water consumption as five trees (Kühle, 2020).

Regarding rainwater retention, several VGS can store rainwater and thus mitigate the problem of flooding by stormwater events (Tiwary et al., 2018). In addition, VGS can be used as NBS that are used to empty stormwater retention cisterns in between stormwater events.

Air pollution reduction

VGS have been investigated regarding their potential to reduce air pollution in cities. It has been shown that VGS can immobilize particulate matter at their leaf surfaces (Ottelé, 2011) and vegetation can absorb and transform gaseous pollutants (Dettmar et al., 2016). However, that does not mean that the air pollutant concentrations in the public space are reduced in a detectable and relevant dimension. To talk of potentials is misleading if we have no information about the dimension of vertical greening that can be achieved (Perini & Roccotiello, 2018). In the meantime, it is much more promising to reduce the emission of air pollutants at its source rather than to count on VGS immobilizing the same amounts with the same rate. Interestingly, and apart from their allergenic potential VGS can also potentially emit volatile organic compounds (VOCs) that are or can be transformed to air pollutants such as ozone. Churkina et al. (2017) showed that this is of special relevance in heat waves. For VGS that would happen in the street canyon and in front of the windows.

Noise reduction & reduced noise propagation

Noise can be heard if there is no barrier between the source and the receiver or if it is reflected and propagated from the source to the receiver. Thus, noise reduction for the receiver can be achieved if noise is attenuated or completely absorbed, if there is a barrier between the source and the receiver, or if it is not reflected but absorbed. The noise reduction depends on the material inserted between the source and the receiver. VGS can reduce sound intensity particularly in lower frequencies mostly due to sound attenuation in the substrate layer (Wong 2010). In addition, the vegetation layer is contributing to acoustic insulation by scattering in high frequencies. The acoustic design of VGS should include both thickness and composition of substrate and vegetation, and the execution of the supporting structure and connections between the modules (Pérez et al. 2016). However, due to installation and maintenance costs acoustics should not be the main consideration for VGS implementation (Wong 2010). In general, the presence of greenery in the public space reduces the perception of noise – in fact, the perception of an equally noisy space with or without greenery differs, as we perceive greener environments as less noisy (intermodal perception of visual and auditory stimuli).

Urban biodiversity

As a VGS increases the abundance of plants and potentially animals on a former vegetation free area, it potentially enriches the species composition (biodiversity) of a reference area. Obviously, the impact on the biodiversity itself very much depends on where VGS are implemented (species-rich or species-poor area) and in their design, especially regarding possible habitats, plant species composition and maintenance. Green facades can also link existing habitats in the sense of a step stone between habitats, that enables passage of organisms in the urban environment. That is especially of relevance in densely built-up areas with lack of green spaces.

Green space provision

Buildings are part of the public space. Buildings with facade greening facing public space therefore provide the contact to nature for the city inhabitants. As plants seasonally change the appearance, VGS are visually a very present element in urban space. There is flowering, but, depending on the plants, the texture and color change as well at different times of the year (like for example *Parthenocissus tricuspidata*). The perception of buildings and the surrounding public space is affected by vertical greenery. The aesthetics potential depends on the ability of the designers to integrate natural elements into architecture.

Identity, symbolic role

The green building design can become an identity element or even the symbol of a specific part of the city like “for the one museum in Paris, greened by Patrick Blanc”. It can help to form the image of a quarter, especially if facade greening is implemented on a larger scale (Vauban quarter in Freiburg, Germany). Use of green on buildings’ facades which are visually exposed to the public space increases not only uniqueness (Bosco verticale, Milano, Italy) or demonstrates “green thinking” (or green-washing). It is also a symbol for merging nature and artificial, man-made structures. This can raise awareness of green in urban environments. At the same time, it can also raise philosophical discourse on those two entities and their priorities in our life.

4.2 Benefits of VGS provided to individuals / at the building scale

Investigating effects of facade greening on buildings has been done in different studies. Greening as facade construction element has potential to improve building temperature regulation, light, ventilation, electrical energy, water management and can have a positive impact on facade materials.

Building thermal performance and energy consumption

The potential for reducing building heating and cooling requirements by implementing VGS depends on various factors such as climate, building volume and envelope type and plant coverage. Research has proven the effect of adiabatic cooling in summertime from implementing facade greening (Schmidt, 2009).

Hoelscher (2018) even determined advantages of building cooling by facade greening compared to other urban green infrastructure taking into consideration covering the major part of building facades and providing sufficient irrigation. With regard to buildings' energy performance primary energy can be reduced by vertical greenery for cooling in summer in central Europe – it becomes relevant especially for poorly insulated buildings. Ottelé (2011) states the insulating effect of green facades is about 1–2 % of modern wall insulation which is similar to the ability of technical blinds (Kühle, 2020). The effects on the buildings in winter relate to the specific climate and use of VGS. Nevertheless, in central Europe the energy performance and insulation standards determine external wall structure and the VGS are only additional element with possible capability to create buffer against the wind during winter times.

Light and ventilation

Depending on the system and plant selection VGS can provide glare cover in summer by shading and replace some types of technical systems (Pfoser, 2016). Deciduous plants in ground-based green facades that lose their leaves in winter can ensure a sufficient light provision during winter. In addition, VGS can support natural ventilation that emerges through effects of air cleaning and humidification as well as cooling of supply air (Schmidt, 2009).

Building and water management

Greywater from the building and stored rainwater can be used for irrigation of VGS. The water saving potential depends on the chosen system connected to the water use system of the building and plants (Kühle, 2020).

Noise insulation

Noise insulation which means the noise transmit through and reflect from the VGS can be expected from wall-based green facades or in some cases in pot-based green facades, with substrate layer. Factors that influence noise reduction include the depth of growing media and material used as structural components of the wall-based green facade.

Facade material assessment / protection of building facade

In research the protection of facade from weather conditions such as heavy rainfalls, wind, temperature extremes and temperature variations as well as UV-radiation is defined as possible benefit of the VGS (Köhler et al., 2012; Pfoser, 2016). Preventing building material from heating and decreasing the effect of wind pressure can extend the facade's life cycle. In addition, the vegetated walls can be protected from vandalism and graffiti.

Economics / property value

VGS are in many cases installed as an element to provide visual attraction and can also present the building as local landmark. As it is often presented as a sustainable and green investment it is often the identifying element for users or owner of the building and can therefore contribute to increasing the property value.

Well-being

As most types of green infrastructure, VGS as natural component have restorative impact as well as other benefits connected to public health and well-being. As an element in the living surrounding, people can benefit from direct contact to plants. By contributing to decreasing extreme temperatures in summertime they have a positive effect on heat stress.

Food production

Vertical farms are a growing trend connected to hydroponic production in green houses and can be found in the urban environment as well. In wall-based or pot-based green facades, vegetables or herbs can be grown. The systems can be used in many ways and functions (home production, school garden, representative walls etc.). On the other hand the production of biomass can be one of the uses of green walls (as energy source). Vertical food production requires specific maintenance and treatment (fast growing plants, regular cutting etc.).

5 Ecosystem disservices of VGS

Despite the development of green strategic concepts and development of NBS such as green roofs and green facades, there are still reservations against green facade implementation. In a study on obstacles and elaboration of measures for an integrative implementation of VGS in German Cities, Kühle (2020) focussed on the identification of key stakeholders, their relation and interconnected obstacles towards VGS implementation. Four key challenges connected to VGS are: lack of quantification methods to evaluate facade greening, the deficient cost benefit analysis, lack of participation and knowledge transfer and inadequate maintenance.

Obstacles such as high financial costs, management and maintenance problems, lack of regulations etc. result in untidiness, damages of facades and other problems connected with dissatisfaction about the systems. The disadvantages of vertical greening are linked to the specific types of VGS. In most cases, the problems derive from inadequate design or the use of inappropriate plants or support structures.

5.1 Financial costs (general)

As vertical greening technology is still evolving, the costs for designing and constructing a green wall are still very high, especially for wall-based systems. High cost of installation and maintenance is seen as the main reason for investors to give up the implementation of VGS. The overall cost depends on the system, the amount of required maintenance, green wall height and scale as well as the availability of required materials, transportation, and labor costs.

Maintenance is often done by facility-companies (especially in case of social housing) or outsourced facility companies, sometimes also by the executing planning company which supervises the primary plants' growth. When high costs result in budget cuts, long-term investment for maintenance can often not be secured resulting in poor conditions of the plants or adverse effects for the building structure. The assumption of maintenance work by residents can save maintenance costs, although safety risks need to be considered and responsibility issues clarified.

The design of VGS (especially wall-based and pot-based systems) can be complex, so standardizing the materials, quality and cost of vertical greening would facilitate comparability between different types of greening and thus make it easier to decide which type of VGS to choose.

5.2 Cost-benefit analysis and greenwashing

The cost-benefit analysis is a useful instrument and decision-making tool. But some impacts of facade greening on the environment are still only qualitatively defined, due to insufficient data, missing evaluation options or quantitative acquisition possibilities.

Even though some effects of VGS are not easy to consider in cost-benefit analyses, a comprehensive evaluation method is needed to weigh problematic implementations and unsustainable solutions against well-adapted and balanced systems in terms of use of materials, energy consumption in life cycle etc. Intransparent evaluation methods bear the risk of false claims of sustainable investments in the form of 'greenwashing'. There are examples of high-tech and resource intensive innovations which are reaching the limits of reasonable design such as rotating facade trees and high-ended facade systems. Another extreme example of the modern use of plants on buildings are green high-rises or 'vertical forests'. The basic issues related to such projects need to be evaluated through sustainable design analysis and be verified over time.

5.3 Maintenance

Green walls are living elements which need maintenance to realize their potential. With insufficient maintenance, the systems deteriorate and green solution becomes inefficient and unsustainable both economically and environmentally. It can cause user complaints, and systems may need to be replaced prematurely or removed completely. In addition, a lack of maintenance and a general poor state of the systems can lead to technical problems of the water and nutrient supply systems or on the building surface. The maintenance of VGS includes different stages, similar to other GI types: establishment maintenance (during first two years), routine maintenance (to ensure the green wall is maintained to a minimum standard – pruning and removal of leaf litter etc.), cyclic maintenance (less frequent to maintain safety and functionality), reactive maintenance (in cases the component of the system fails), renovation (change the design or some parts). In the project the routine maintenance solutions were addressed by developing possible robotic system for specific work that must be done in vegetation period (see chapter III). The VGS that is to be installed should not exceed the skills, technologies and resources of the client and maintenance team. Lack of maintenance can be detected in the building practice which causes other preconceptions of VGS to arise.

As a solution to the problem some researchers suggest that maintenance conditions should be linked to building permits and that the inclusion of facade greening in public tree inventories can be an instrument for monitoring maintenance of green facades (Kühle 2020).

5.4 Mounting on the facade

Supporting systems are connected to the buildings' walls and represent the base for the VGS, comprising both built, artificial and natural material. These structures are adding loads to the facades. In addition, there are concerns about supporting facade elements which can be used as an access to the building interior and upper floors if the systems are connected to the ground and climbing is possible. Technical solutions should be adopted taking into consideration extreme weather events, especially when using larger plants (trees, shrubs). The soil and plant root system should be taken into account to avoid damages and moist problems. Especially direct systems (with climbers) can grow into facade fugues and are able to make damages by their growth of thickness. The air gap between plants and building can be adjusted to guarantee ventilation in front of the facade. Generally, the risk of building damages is low in the case of a professionally planned VGS as most damages can be related to the plants' properties. Regular maintenance and supervision to avoid facade damage should be executed in 6 to 24 month intervals (Köhler, 1993) Another technical problem connected to maintenance, reported by Magliocco & Perini (2015) concerns the gutter or standpipes. Reinwald et al. (2018) remarks also on trough-greening-systems in which space for roots is too limited and irrigation systems sometimes insufficient.

5.5 Fire safety

According to Kühle (2020), uncertainties about fire protection determinations lead to mistrust in facade greening among investors. With published requirements of maintenance from German DFV (Association of German fire brigades) the "maintenance order" has to be provided in the building approval. As fire loads depend on the maintenance of plants (including irrigation, fertilization, trimming) long-term guarantees of maintenance have to be determined already during the planning process (Bachmeier, 2020).

5.6 Anthropocentric ecology

Although biodiversity is recognized as a common good introducing VGS as habitats for flora and fauna people may perceive green facades problematic because of expected increase of insects and presence of small animals. Mayrand et al. (2018) found a high amount of spiders in wall-based systems, whereas ground-based green facades were dominated by insects (especially bugs). Fallen leaves may raise discontent among inhabitants as a sign of untidiness and lack of maintenance. Schloesser (2003) assigns this fear to people without any experience with VGS. Although people with VGS experience are influenced by similar factors, they had less reservations towards VG.

5.7 Planning, regulation, public participation

Spatial planning documents often do not address VGS. Nevertheless, it can be affected by regulations that address issues associated with management of vegetation considered as fire risk, access by emergency services, management and disposal of waste material, drainage, elements which cause negative impacts on lightning and traffic signs, use of elevated working platforms etc. The related requirements are connected to the site (distances, built structure etc.) and buildings (load-bearing capacity, fire safety, accesses, energy efficiency standards etc.). Public participation in the planning and design process is important as a general approach for successful urban planning.

The same approach can be used to implement VGS on specific buildings, especially in residential areas. Lack of or insufficient information about VGS and missing integration of inhabitants in the planning process can lead to public dissatisfaction with the final result.

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Chapter II

PERCEPTIONS AND ATTITUDES TOWARD VERTICAL GREENING SYSTEMS

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1 Users and stakeholders involved with Vertical Green

This part of the book is dedicated to stakeholder analysis, research regarding the impact on stakeholders, and user engagement. Diverse groups of people were included, such as academia, experts, businesspersons, policymakers, and citizen groups. These groups are included in several research tasks that have been developed and performed to examine their professional or personal experience with vertical green. The instance where personal beliefs were most expressed are the benefits and barriers for implementing vertical green, namely the reservation against greened facades. These were noticed in each of the presented research items (questionnaires, interviews, and workshops) and in their visual preferences toward vertical green (research on the perception of green walls).

Greening of buildings includes historical buildings covered with climbers and the latest feature of developing green wall structures. Similarly, as with all features that are known in certain (old) form and start flourishing through research and development followed by modern design, they can be seen from different perspectives and tend to be colored by individual viewpoints. This duality was also observed when we approached users and stakeholders in the project; apart from their professional attitude, when they expressed their perception of vertical green, their personal feelings were also present.

1.1 Stakeholder analysis

A stakeholder is “a person such as an employee, customer, or citizen who is involved with an organization, society, etc. and therefore has responsibilities toward it and an interest in its success” (Cambridge University, 2021). Broadly, it can be any person who is professionally or personally involved or interested in certain matters. When dealing with issues that require the perception of stakeholders, stakeholder analysis is a method that brings the required information or basis for further approaching and including stakeholders in the process.

Stakeholder analysis is the process of identifying people related to certain issues (e.g., development of certain areas, renovation projects) and grouping them according to their hierarchy of participation levels, interest, knowledge, and influence in the project. Stakeholders are grouped according to diversity. The results of analysis enlist appropriate contacts and information for each stakeholder group.

In terms of project scope, stakeholders were identified in a stakeholder analysisperformed by three project partners (UIRS, TUB and G4C). As a result, a stakeholder list was prepared for each country: Germany, Austria, and Slovenia. The listed stakeholders were mainly based (located) in one of the three cities included; however, some stakeholders were working at the national or regional level, and municipal officials, as in the case of Slovenia, which has only 2 million inhabitants, apart from Ljubljana, other city municipalities and municipalities, including urban centers with regional significance, were included.

Further four main groups of stakeholders were selected for inclusion in the detailed analysis. They are:

- Citizens,
- Municipal officials (municipality),
- Property developers and builders, and
- Experts (vegetation engineers, landscape architects, architects).

These four groups were selected to participate in the online survey. Prior to that, municipal officers in Ljubljana were interviewed in detail regarding the role of specific departments in the city administration. In Berlin, experts and municipal officials participated in two workshops and interviews.

- **Citizens** are considered as (general) public or persons with personal interest, and not professionally linked with planning, implementation, maintenance, and possession of vertical green. They can either favor/show reluctance toward vertical green or have no opinion. Citizens' sub-groups are also owners or renters in buildings with or without green facades, desiring to have one or oppose if vertical green (VG) investment becomes an issue (an option).

Figure II.1: Potential stakeholders involved in vertical green development (image by Bibi Erjavec)

- **Municipal officials** are part of public administration providing administrative and/or legislative roles. As municipalities vary in size and number of employees in municipal administration (i.e., at least in Slovenia), we have asked to include the most competent or relevant municipal officials to implement spatial development and investments, including vertical green. For this reason, mayors, chairpersons, representatives of spatial planning, environmental, investment, and other key departments were included in the research.

- **Property developers** are also stakeholders in their professional roles, but like experts they can also be personally involved. They may be interested in implementing VG for benefits such as improvement of financial contribution toward investment because by executing VG, the value of the developed area may rise, or if they could manage to negotiate a higher building density under the condition of implementing a certain amount of VG. However, their interest may last only until the point of sale. They usually work with investors and, in this case, municipal officers who support public investments.
- An **expert** is a general term that includes stakeholders who are interested, required, and involved in certain problems professionally. They either possess certain knowledge and skills, work at the field level, have previously or currently worked in subject-related projects, or may likely work in the future. While involving experts, one should consider that apart from their professional engagement, they can also have personal preferences in favor or against certain thematic developments. In the case of vertical green projects, experts were divided into three groups: (1) landscape architects and planners, architects, urban planners, and vegetation experts, sustainable energy, environmental quality, nature protection, horticulture, urban forestry, gardening, maintenance, public health, and similar; (2) experts in the building and construction sector; and (3) a third group involved in implementing and maintaining VG.

1.2 On-line survey for three cities and four stakeholder groups

Course of on-line survey

This research focuses on three main cities, Berlin (Germany), Vienna (Austria), and Ljubljana (Slovenia), and this also coincides with research institutions involved in the project. Being the capital cities of countries, these three cities are also interested in and amicable for new developments and investments in architectural and innovative urban designing.

When comparing the three capitals, it is worth mentioning that each has its own tradition and development structure of vertical greening of buildings, and the contemporary green facades vary in number and type.

Various methods and tools are used to involve stakeholders in planning and research, among which questionnaires and surveys are still the most used tools for surveying citizens' perceptions and preferences, as they are reproducible, comparable, and easy to implement. Four different questionnaires targeting four different stakeholder groups were provided using Google Forms. All three partners used the same questionnaires, which were translated into national languages. The introduction and general questions were the same for all, with specific questions for each group. The questionnaires were structured as follows:

- Introduction and definition of vertical green
- Questions regarding knowledge on vertical green (involvement in projects; personal experience),
- Opinion regarding benefits of vertical green and barriers to vertical green
- Questions regarding experience with vertical green (personal or projects implemented)
- Detailed questions regarding projects implemented
- Opinion on "Future of vertical green"
- Personal information

Stakeholders listed on one of the four groups were sent an e-mail invitation, including the link to the assigned form. Stakeholders' contacts were collected through prior stakeholder analysis. The Ljubljana survey in December 2019 and July 2020 was conducted for one month during both terms. The Vienna surveys were also conducted in December 2019 and July 2020. The Berlin surveys were performed between February and April 2021.

The rather complex structure of the survey (four groups, four questionnaires with only some directly comparing questions, open responses, Likert scale) makes statistical analysis and evaluation inappropriate, so only basic statistics were calculated.

Table II.1: Participating stakeholders by city and group

	Number of responses		
Stakeholder groups	Berlin	Vienna	Ljubljana
Citizens	94	21	30
Municipal officials	21	12	52
Property developers and builders*	3	5	6
Experts	4	22	33
Total per city	122	60	121
Total	303		

* The Ljubljana group consisted mainly of builders (5) and one property developer; the Berlin group comprised of only builders;Vienna had two property developers

A qualitative analysis, however, provides relevant information on specific questions for each group, especially the descriptive ones. All four groups were asked about their views regarding the benefits and barriers of vertical green, allowing observation of different views among different stakeholders. Apart from the revealing attitudes, "professional" stakeholders, namely municipal officials, experts, and property developers, were also questioned on their professional experience with green walls. This was examined in detail and considered for funding, mechanisms, and reasons for troubles or success. The survey allows some comparison (for questions common to all four groups) between the four stakeholder groups in each city and the differences for each group regarding residence. first, specific results regarding questions that were adjusted to a certain group are presented, followed by the results for questions that are common to all four groups: benefits and barriers.

Results for citizens group

Introductory questions for the citizens group are as follows. Response to the question “Are you familiar with the term ‘vertical green’?” was positive at 97.2 % in Berlin, 95.2 % in Vienna, and 63.3 % in Ljubljana. A high percentage (90.3 %) of respondents from Berlin, Vienna (95.2 %), and Ljubljana (86.7 %) had already noticed vertical green in the public space. The results reflect the state of VG in these cities, thus confirming the value of personal practical experience for awareness. Finally, personal experience with green facades was questioned in the citizens group, as 8.3 % of respondents from Berlin, 10 % from Vienna, and 3.8 % respondents from Ljubljana lived in a building with a greened facade.

The open-ended question “What do you understand by the term ‘vertical green’?” provides a further insight into citizens’ perception of this term:

- Walls are covered with plants.
- Greening of facades.
- Greening of built vertical elements such as walls.
- Walls and fences with plants, to a greater or lesser extent, climbing on them.
- A wall that has pockets of earth in which there is greenery, or it is for climbers.
- Plants that climb buildings.

Similar answers show that citizens commonly understand greening of facades and other vertical structures (walls, fences, balconies, wires, pillars, and trellis mesh).

Some participants differed in climbers from special designated structures such as pots and meshes. One participant mentioned a social aspect: “greening of publicly accessible walls and greening of facades in urban environments.” Berlin citizens provided more detailed responses, mentioning the possible benefits of vertical green systems and plants:

- Uninterrupted vertical systems with very urban climate and coolness of interior rooms.
- Watered vertical building surfaces.
- Enter with floor-standing cleats with or without cleats (*Hedera helix, Fallopia baldschuanica*) or wall-mounted systems (plant heads and modular systems).
- The vertical surface is directly attached to the buildings or with a structure.
- To cool off the building and the interior to the courtyard.
- Application of house facades in urban areas to promote local (micro) climate Use of vegetation (different kinds) to cover or complement the facade of a building.
- The aim is to gain access to several benefits such as temperature mitigation, ecological connectivity, energy cost reduction, food production, decoration, and social policies.

Similarly, citizens of Vienna mentioned plants overgrowing outside walls, roofs, and other built structures, including watering and technical support for plants such as mosses, grasses, and flowers.

More diversified answers from Berlin and Vienna citizens also reflect greater familiarity with vertical greenery, as a larger share of buildings in these two cities are covered with greenery (traditional as well as new systems) than in Ljubljana. Moreover, more VG planning and governance statutory and non-statutory activities and measures are being implemented in Berlin and Vienna.

The results show that the percentage of people enjoying and appreciating vertical green in public spaces is very high: 97.3 % of respondents from Berlin, 100 % from Vienna, and 84.6 % from Ljubljana. The possibility of an open-ended answer revealed a few intermediate or negative answers, but also some enthusiasm.

- To some extent it enlivens the space, the problem is overgrown surfaces or too many vertical green areas, and due to insects.
- Suitable perhaps for walls, not so much in the case of facades. This is very close to the condition of vegetation.
- It takes away too much light (*Hedera helix*).
- Don't appreciate it but understand its benefits.
- Robber ladders, spread of fire, and insects in the building are part of the system and are therefore exciting.
- Diversity is great, but I still do not need lovely little critters in the house. Building work is really interesting, as it creates a new building identity, and I wonder why there are not more!

Results for municipal officials group (Municipality)

The questionnaire for municipal officials was oriented more toward professional experience than personal perception. The questions considering benefits and barriers reveal opinions, therefore, these answers are interpreted separately (see subsection 1.3). In Slovenia, answers from several municipalities (apart from Ljubljana) were included. For some bigger municipalities, including Ljubljana, various offices/departments participated in the study. In Austria, in addition to the diverse departments at the city and districts of Vienna, two other municipalities were included. In Berlin, several departments at the city and district levels were included.

First, respondents were asked about involvement in projects involving vertical green, share of involvement in projects, not involved but have experience with vertical green, or do not have experience differs. In Berlin, 31.8 % officials were already involved, 22.7 % had some experience, and 45.5 % had no experience with vertical green. In Vienna, 25 % officials were involved, 33.3 % had some experience with vertical green, and 41.7 % had no experience. In Ljubljana, 79.4 % officials had no experience, 10.4 % had some experience, and only 8.3 % were involved in "vertical green projects" of the involved officials, most (for all cities) were involved in 10 projects, including vertical green.

Most of the projects including vertical green were financed:

- by the local government (30 % for Berlin and Ljubljana, and 25 % in Vienna),
- 22.7 % of private funding in Berlin (Note: this question had a large share of "I don't know" answers),
- 31.3 % by private companies and,
- 18.8 % through private-public partnerships, and the same amount from only citizens in Vienna.

The following questions were oriented toward acquiring more information on financing models, funding channels, and legal framework conditions for municipalities to promote vertical green, which resulted in acquiring specific information on concrete measures or documents.

The reasons for preventing municipalities from implementing more vertical green were also assessed; lack of both knowledge and financial resources seem to have a big role in Ljubljana (both 50 %; multiple answers were possible); lack of cooperation from competent authorities (50 %) and financial resources (36.4 %) in Berlin. In Vienna, lack of knowledge about vertical green, inexperience about the quantifying costs and benefits, and lack of cooperation of competent authorities had the same share (26.3 %).

From the perspective of spatial planning, the question of priorities in the city, where the municipality focused on implementing vertical green, was also interesting, as regions lacking in green spaces, areas requiring building renovation, and parts in need of spatial identity, and neighborhoods with environmental problems were highlighted. Further priorities of implementing vertical green pertaining to the function and structure of urban areas revealed that functionally mixed areas (city center), residential areas, and industrial areas are the focus in Berlin, city zones with environmental problems, and areas lacking in green spaces are the focus in Vienna; in Slovenia, residential areas were not mentioned apart from high-density neighborhoods (20 %), functionally mixed areas and industrial areas are the main concern, similar to Berlin.

Results for property developers and builder groups (developers, constructors, builders, suppliers)

The questionnaire for property developers was similar to that for municipal officials; both groups are also supposed to work together in various construction projects, including vertical green. The initial questions were oriented toward the competencies and knowledge of respondents; in Berlin, two thirds (66.7 %) were involved with projects including vertical green, half of them were familiar with projects including vertical green, and in Vienna 20 %. The projects where respondents were involved applied ground-based greening, horizontal planter systems or a combination of the latter and climbers, shelf-like-systems, pocket systems, and moss walls. The most recommended method is ground-based greening. The systems applied were supplied either with tap or rainwater. Property developers and builders in all three cities justify the implementation of vertical green if there is public support (funds), as this increases real estate value, or if vertical green is recognized as a compensatory measure. If there were difficulties or problems with greening or irrigation, it was largely due to lack of care,organization of care, specific climatic events (frost, heat), failure of irrigation, or there were other problems with watering.

Results for experts (biotechnology, landscape architects, architects)

Experts are also involved in projects dealing with vertical green, however involving more research, design, and planning; later, they are also expected to cooperate with property developers and municipal officers in implementing projects, so the three groups are likely to cooperate in common projects.

Experts are mostly involved in housing projects (100 % in Berlin, 21.4 % in Vienna, 68.9 % in Ljubljana), housing projects built with public funding (Vienna 19.6 %), public buildings (75 % for Berlin, 46.9 % for Ljubljana), and commercial buildings (100 % for Berlin, 17.8 % for Vienna, and 40.6 % for Ljubljana).

Experts were further questioned in detail about systems; they can recommend based on their experience, and ground-based systems are mostly recommended compared to pocket and vertical systems (13 to 6 in the case of Vienna; 11 to 5 in the case of Ljubljana), and shelf-like systems, ground-based systems, and vertical systems were recommended for Berlin (four answers altogether).

1.3 Benefits of Vertical Green

The perceived benefits of vertical green were rated on a five-point Likert scale, where it is assumed that the strength/intensity of an attitude is linear (true, rather true, half-half, rather not true, not true, and an additional possibility of no answer). Totally, 19 benefits were stated:

- Microclimate changes (reduction of heat, improvement of both air quality and thermal comfort)
- Compensation of sealed surfaces
- Noise reduction
- Sustainable rainwater management (buffer effect during heavy rain events)
- Greywater management (use of fecal-free, slightly polluted wastewater)
- Creation of additional useful areas (for urban gardening, food production)
- Enrichment of biodiversity in urban spaces
- Contribution to achieve environmental goals at the national and European level
- Contribution to reducing climate change
- Social aspects (quality of life, well-being)
- Health aspects
- Educational aspects

- Increase in the value of the outdoor environment of the greened building
- Increase in the real property value
- Insulation of the greened building
- Reduced energy requirements of the greened building
- Image promotion of the greened building of a green property developer/owner
- Aesthetics, cityscape, and promotion of a green city image

The answers were summarized first according to the four groups of stakeholders and then according to three cities to provide an overview of the most important benefits.

- The beneficial impact of VG on microclimatic changes was selected as the most important (rated first for all four groups and in all three cities).
- The second most important benefit varies. In Berlin and Ljubljana, enrichment of biodiversity in urban spaces was selected, followed by social aspects (quality of life and well-being).
- In Vienna, enrichment of biodiversity was selected as third, and the third place goes to social aspects in Ljubljana.
- Image promotion of a green city and aesthetics were accorded next importance, followed by increase in the value of outdoor surroundings of greened buildings, and image promotion of the greened building, thus representing economic benefits from the surroundings and the building itself.

There were no significant differences observed among the four stakeholder groups; again, the most important benefits can be addressed as ecological, aesthetic, and economic benefits for the real property.

1.4 Barriers for Vertical Green

The perceived barriers of vertical green were researched in the same way as benefits, rated on a five-point Likert scale by stakeholders. The nineteen barriers are listed as follows:

- Lack of knowledge about opportunities and impact of vertical green in society (including lack of demand)
- Very high implementation costs
- Very high maintenance costs
- Insufficient funding
- Complex legal framework
- Architecture does not come into effect due to VG – loss of building identity
- Concerns about facade damage (due to construction, plants, irrigation)
- Concerns about fire safety
- Concerns about hygiene (small animals, leaves)
- Concerns about aesthetics in the winter months
- Concerns about vandalism
- Offered systems are not technically mature
- Irrigation is not mature
- Too little planning knowledge
- Too little technical knowledge
- No sustainable construction
- Lack of political interest
- Lack of interest on the part of the planners
- Lack of interest on the part of the property developers

The answers were first summarized according to the four stakeholder groups and then based on three cities to provide an overview of the most important barriers. For Berlin and Vienna, lack of knowledge in society and lack of demand was the most stated answer, for Ljubljana lack of interest among property developers, immediately followed by lack of knowledge in society or lack of demand. The following barriers include very high maintenance costs (Berlin and Vienna) and concerns about hygiene (small animals, leaves). For stakeholders from Ljubljana, lack of political interest, high maintenance costs, and too limited planning knowledge.

For Berlin stakeholders, lack of interest among property developers, followed by concerns about fire safety risks, concerns for facade damage and limited technical knowledge are important. For Vienna, after lack of interest on the part of property developers, insufficient funding, and complex legal framework is followed by concerns about facade damage. The elaboration of responses for certain stakeholder groups show that:

- Citizens, municipal officers, and developers share first priority, which is lack of knowledge in society/demand; for experts, the priority is lack of interest among property developers, followed by lack of interest in society, high maintenance, implementation costs, insufficient funding, and lack of political interest.

- Citizens are concerned about lack of political interest, implementation costs, funding, and facade damage.

- Municipal officers are concerned about fire safety, maintenance costs, poor technical knowledge, and a complex legal framework.

- Property developers and builders mentioned costs (maintenance and implementation), concerns regarding fire safety, loss of building identity, aesthetics during winter months, technical maturity of offered systems, poor technical knowledge, and lack of interest among property developers and planers (responses of developers were more dispersed).

2 Promoting and implementing Vertical Green through stakeholder cooperation

2.1 Co-creation regarding Vertical Green design and implementation

Co-creation refers to a form of collaborative innovation. It can involve any act of collective creativity that is jointly experienced by two or more people (Sanders & Simons, 2009), and the process of sharing and collectively improving ideas between diverse stakeholders or involved status groups. Generally, co-creation represents the opposite process to a top-down approach. It can also be understood as a customer-driven approach in the context of marketing and economics, where this concept first emerged in 1999 as the Cluetrain Manifesto, calling for a global conversation between companies and the people they service (Levine et al., 1999; Sanders & Simons, 2009). However, both form and content of the co-creation process are still debatable, specifically because the origin of the concept is not related to "traditionally creative disciplines" such as design, architecture, urban planning but to business and commercial theory and practice. This is applied across the entire design process, namely cocreation within communities, companies and organizations, between companies and their respective business partners, and between companies and the people they service, widely referred to as customers, consumers, users, or end-users (Sanders & Simons, 2009). Van Wingerden et al. (2017) define co-creation as a new model of leadership that involves collaboration between the different members of a community to achieve a common goal or end (van Wingerden et al., 2017). This definition does not differ essentially from the middle part of the "Ladder of Citizen Participation" named "Tokenism", including levels of public engagement such as informing, consultation, and placation (Arnstein, 1969).

Use of the approach within the business environment to increase commercial competitiveness and consumption, somehow opposes its use in the domain of urban planning and design, especially public open spaces where it is related to better quality of life, public good, and urban justice; it is expected to go even further in participatory planning and co-designing, and expanding the area of collaboration to the whole spatial development and management process (Šuklje Erjavec, 2017). The complexity of co-creation as a comprehensive process in the area of practical urban development is presented in the scheme (see Figure II.2), and it was developed particularly for the open space development process, which also means for urban green spaces (Žlender et al., 2020). This duality of co-creation approaches is well reflected in the duality of the concept of vertical green, especially when considering new, technically sophisticated living walls and modular vertical green systems, wherein vertical green is not only an element of the building or urban area but also a singular product developed for business. Therefore, in the case of vertical green systems, co-creation could be used to improve the product and increase its commercial competitiveness, and in the urban planning process from analysis and evaluation to setting priority areas and buildings or measures for VG implementation, to planning proposals and decision making at the urban or building level to design solutions and for maintaining VG. Within the vertical green project 2.0, we addressed the latter, although some outcomes, such as robotic management maintenance systems and water management systems form part of innovative product development.

Co-creation is also a trans-disciplinary approach in science, applied science, field research, and participatory processes. From this perspective, a transdisciplinary group of scientists working together can be considered as co-creation. To facilitate co-creation in science, Vertical Green 2.0 – vertical greening project for liveable cities – co-created innovation for a breakthrough in an old concept involving experts from diverse disciplines that are relevant for different vertical green aspects. The issue of co-creation was already embedded in the project proposal, as co-creation and participative operation models were considered the logical form of several project activities.

Figure II.2: Co-creation stages, activities, tasks of actors and likely results within public open space development process (adapted after Goličnik Marušić and Šuklje Erjavec (in press) and Šuklje Erjavec and Ruchinskaya (2019)) (image adapted by Bibi Erjavec)

Using a trans-disciplinary, stakeholder-oriented co-creation approach, we intend to reassess traditional urban greening and combine innovations and fundamental research from urban planning and design, ecohydrology, mechanical engineering, water engineering, and economy to enable decision-making using a nexus approach considering both the co-benefits and trade-offs of nature-based solutions for future cities.

The diversity of actors involved in co-creation and the relationships between them are vital for the success of a process. From the beginning of the project, we would aim to build on a co-creation process with stakeholders affected by and influencing VG operations in the private, public, and industrial sectors to identify their requirements, supply chains, profit and non-profit oriented business models, and governance structures of VGs in urban spaces. The various stakeholders involved in the project include decision makers at the municipal level to experts, developers, citizens, and students. The diverse methods applied correspond with different stakeholder groups, and several targeted workshops, interviews, and surveys were conducted to explore opinions and to interpret the obstacles of VG implementation as challenges for improvement and innovation.

Based on the knowledge gained from the participatory techniques during the project, it was established that an important part of inclusiveness is to gain greater social value by implementing vertical green structures. Enabling accessibility for all groups and innovative ways in which all can take part in designing, planting, maintaining, and enjoying vertical green in an urban environment have been proposed several times. Here, we can only mention projects, such as Garage Grande in Ottakring, Vienna (GB, 2021), which successfully proves that co-designing vertical green structures must be applied more frequently to enhance communities' social life and inclusiveness.

2.2 Interviews and workshops with municipal officials in Ljubljana

Activities with stakeholder groups of municipal officials in Ljubljana were planned in two steps. first, semi-structured interviews were conducted with the representatives of most relevant departments for implementing vertical green. Information that was gathered through interviews was assessed and used as input for the second step – a workshop with a wider group of municipal officials and representatives of public services.

Interviews were also conducted on the potential of facade greening with representatives of the departments of city administration of Ljubljana in January and February 2019.

Seven municipal officers, leaders of key departments mostly related to vertical green implementation were interviewed separately.

Interviews were conducted by a professional external interviewer and recorded and summarized in an expert report.

The interview content was semi-structured, using a questionnaire prepared and discussed with members of the Urban Planning Institute of the Republic of Slovenija (UIRS) project, but allowing sub-questions and further explanations. The questions were structured to block elaborating on (a) general acceptance, attitude toward green walls, and the advantages and disadvantages of green walls, (b) knowledge and attitude toward practice of VG in Ljubljana, and (c) key stakeholders for implementation of VG.

Only a few interviewed individuals had direct experience with the process of green wall implementation. All the interviewed individuals expressed enthusiasm for green walls and were keen on exploring the potential of integrating green walls into urban fabric. They are aware of the benefits of green walls. For example, they mentioned reduction in the urban heat island effect, reduction in the number of fine particles, rainwater retention, and noise protection.

The main concerns regarding green walls that have been pointed out in the interviews are maintenance costs and aesthetic characteristics during the winter months. However, most of the concerns were personal rather than professional opinions. The expressed risks related to green walls included the apprehension that they could be used by developers to gain permission to increase the density of buildings because if a green wall is added, it could become an opportunity to reduce the number of open green areas. High-density urban areas have been characterized as most appropriate for green wall implementation. Publicly owned buildings have been identified as suitable. Particularly, facades with no windows on lower buildings, such as production halls, gyms, schools, and kindergartens, were identified for didactic reasons.

Following the interviews, a workshop was conducted for Ljubljana municipality officers in February 2019. This study aimed to discuss green wall potential and implementation potential at the municipal level, and it was attended by fourteen invited representatives of eight different city departments and public services of the city administration of Ljubljana, and this could play a relevant role in decision making, planning, implementation, and management of VG in the city. The workshop consisted of two parts. The first part presented in more detail the potential and possibilities for vertical green implementation in cities.

The second part aimed to check the attitude of representatives of various departments and services of the city administration to green walls and to support them in co-creating the comprehensive process of implementing a green wall for a chosen building type from initiating and deciding to implement an imaginary case. This last part offered interesting insights into the challenges of planning and implementation of green walls, specifically in a situation where city services do not yet have experience with this new dimension of greening. Therefore, the workshop made several presentations on green walls, emphasizing on different types of green walls, their characteristics, and potential use. The benefits and costs were also discussed, and the estimations were grounded in evidence-based data and real cases from Ljubljana were presented.

In the second part of the workshop, the participants were divided into three groups, and the tasks assigned for each group were as follows:

- imagine five initiatives for a green wall justifying any initiative (justification).
- Choose one of five initiatives (voting or discussion).
- Develop the selected initiative in terms of procedure from initiative to implementation and maintenance, including the definition of project management steps, actors/responsible persons, funding, and location.

The selected case was analyzed in terms of benefits and risks for initiators and at the city level. five benefits, five concerns, and fears, and general benefits and risks of the considered green wall was elaborated through a group discussion. Each group worked on the selected case by structuring the process of respective green wall implementation, and the actors were defined (i.e., who makes the decision for the green wall on general/green wall in question? who else is important in the decision-making process, for example, for giving consent, voting for the green wall?).

The selected cases included:

(a) Greening of vertical flat elements of urban furniture and structures (construction side fences, retaining walls)

(b) Renovation of selected elementary schools, including green wall implementation in Ljubljana

(c) Vertical greening of the Center for Reuse Building

In the workshop, it was pointed out that larger focus is required on building stakeholders' capacity, that is, representatives of various departments of city administration. The content of the capacity building process would include benefits, threats, type of implementation, and the financial aspects of implementation. The potential involvement of various departments of green walls depends on specific characteristics of the respective project or the type of building and administrative domains. Additionally, some focus should be placed on planning documents and acts that regulate location selection and implementation of potential green walls.

Figure II.3: Photographs from workshop sessions
(images by Damjana Gantar and Karin A. Hoffmann)

2.3 Workshops and interviews with experts, decision-makers and planners in Berlin on obstacles towards VGS

Two workshops were held according to the methodological framework of 'Future Workshop' (Muellert & Jungk, 1987) and 'Constellation Analysis' (Schoen et al., 2004) in combination with followed semi-structured interviews in Berlin. The targeted stakeholders were academia, and decision makers on municipal level as well as contractors, architects and building owners. The aim of research was the analysis of obstacles to VGS with the following research questions: Which aspects currently prevent a wider distribution of facade greening in Germany? On this basis measures for a wider implementation of VGS were elaborated and discussed. The first collection of obstacles on the implementation of facade greening has been carried out with relevant stakeholders during a Future Workshop (FW) in September 2018. The results have been used for a draft of the Constellation Analysis (CA) by the TUB project team (see Kühle, 2020), which then served as the basis for discussion in the CA workshop in February 2019. After the stakeholder workshops, a written documentation, analysis, and visualisation of the workshop results were created and followed by more in depth literature research. Afterwards, editing of the CA in a project team consultation involved discussion of the results and revision, rearrangements, reorganisation, and addition of further elements as well as relations between elements. In the next step, the resulting CA-edit was verified in six expert interviews. The aim of the interviews was to gain insights from stakeholder groups that had not been involved in the previous workshops to obtain as complete a picture as possible. In a last step, the CA was presented and discussed in an external stakeholder online-conference, Urban Vertical Green 2.0, as part of the Green Infrastructure Future Summit in September 2020. Various stakeholders were involved to integrate the viewpoints and perspectives of different actors working on the subject. The background of participants reached from representatives of public real estate developers, greening companies, district authorities, tenant's associations, scientists from different (inter-)national faculties, research companies, students, municipalities, interest groups, federal offices to real estate agents and architects.

Figure II.4: Future Workshop (image by TUB)

The results demonstrate obstacles to facade greening involve extensive aspects from building practice to social circumstances and stereotypical opinion within actor groups. The workshop discussions show similarities as well as differences, which is also due to different methodical approaches, as participants of the FW started with fundamental discussions about obstacles and finished with approaches towards a wider implementation. The participants of the CA workshop discussed a CA-draft and ended up with a rearrangement of the CA.

The final results provide a comprehensive overview of the factors that prevent more implementations of facade greening in Germany and likely elsewhere. Four main obstacles need to be emphasized:

- lack of quantification methods of benefits
- lack of cost-benefit analysis methods
- lack of regulation and provision of maintenance
- lack of participation and know-how (including early expert integration)

As a matter of fact, obstacles that are discussed within relevant stakeholder groups are still equivalent to some of those found in the literature of the last two or three decades (Kühle, 2020). Besides obstacles to facade greening, stakeholders of the workshops and interview partners also discussed measures that can be applied in order to increase implementations of facade greening. Here, special emphasis should be placed on best-practice examples, which also require transparency in order to be successful. Moreover, participants stated that administrative maintenance support has to be increased.

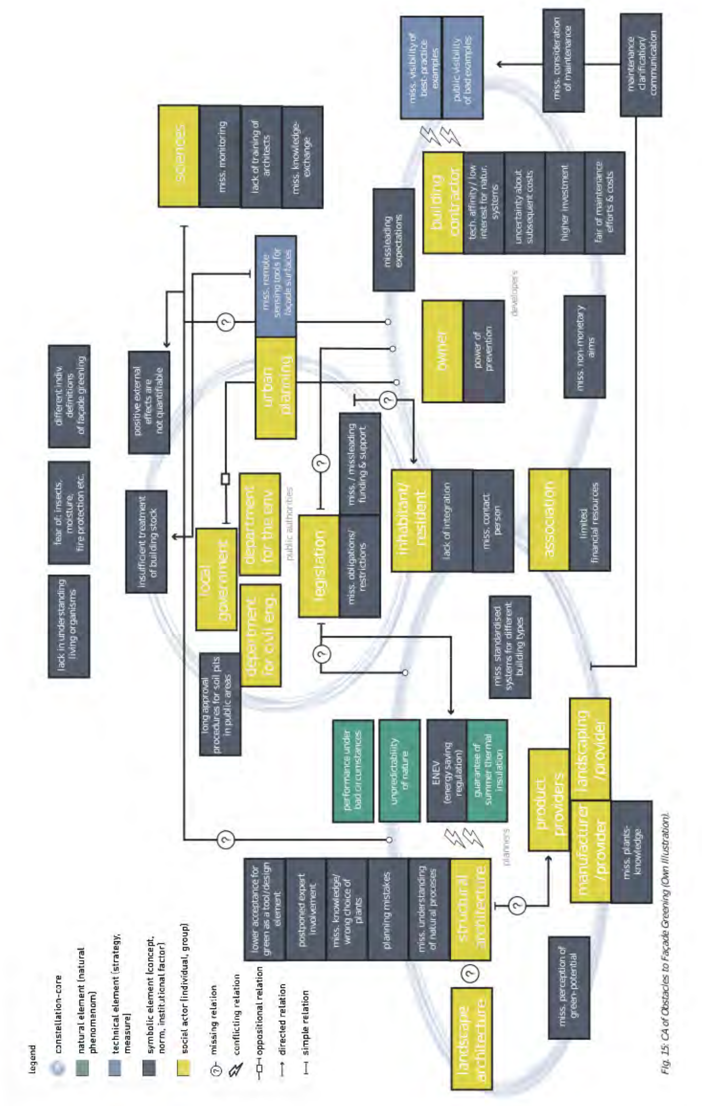

Figure II.5: Constellation analysis of obstacles to VGS (Kühle, 2020)

One idea is to integrate facade greening into public tree cadastres, which would ensure access to relevant information and simplify maintenance. Framing facade greening as a public ecosystem service and enforcing maintenance through building permits can ensure publicly or privately organized maintenance. Yet better know-how about plants and climbing systems is important e.g. by introducing assessment systems, and early expert knowledge (ibid.).

The analysis on obstacles of facade greening with different actor groups throughout workshops and interviews was helpful to provide a systematic overview across the building industry. The aim is to contribute to a wider acceptance of facade greening in order to benefit from its possible social, economic and environmental benefits. However, further research on the applicability of measures is necessary, as only recommendations can be drawn from the presented outcomes provided within this project (see Kühle, 2020).

3 Perception of Green Walls

The present research on the perception of green walls is part of a PhD program at the University of Ljubljana, Faculty of Architecture (topic: How Green Facades Impact Perception of Urban Spaces and Microclimate: The Case of Ljubljana; PhD candidate Jana Kozamernik, supervisor Prof. dr. Alenka Fikfak). In this chapter, we present a follow-up of a previously published study that was conducted in two European countries, The Netherlands and Slovenia in 2019: How Green Facades Affect the Perception of Urban Ambiences: Comparing Slovenia and the Netherlands (Kozamernik et al., 2020a). Here, we present the results of the extended study with the addition of responses from Germany as well.

The question of perception of green walls in an urban environment cannot be separated from the spatial context of buildings/architecture. Vertical greenery is used in different types of buildings across various spatial contexts and forms. The integration of green elements into the building envelope is usually connected with the architectural and design concepts of an individual building. The entire envelope, especially the facade, plays an important role.

Due to the intrinsic characteristics of living material (i.e., vegetation), the expression of green is in constant contrast with that of non-living elements. Modern technology, systems, and the use of vegetation make it possible for designers to play with geometries, patterns, and textures, allowing them to create anything from diverse overgrowth to homogenous abstract surfaces, and hence the identity of both the building and the surrounding environment (Kozamernik, 2020b).

Incorporating natural elements into architecture can be studied from several perspectives, including design and technological processes and systems and construction issues, building performance, such as energy consumption and sustainable use of removable sources on the one hand, and the intrinsic question of incorporating living material on/into the built forms from a philosophical discourse of merging entities and addressing greening as a value or contribution to the environment with these aspects also connected to public perception of green in built environments. Public perception and evaluation of urban open spaces with the green elements were examined in the Netherlands, Slovenia, and Germany. The online survey included images of various spatial situations in which the respondents conveyed their opinions.

3.1 Spatial characteristics, urban greenery, and perception of space

In studying the urban environment as an experience of a city, the socio-psychological aspect is interconnected with other aspects that affect perception and public opinion. Perception is a process that involves all senses and is composed of several stages. According to Rasmussen (2001), the perception of a built environment and architecture is a complex process, and space needs to be experienced. Perception involves people's senses and can be described as a process composed of three stages: a) sensing, b) processing and organizing information, and c) cognition, including interpretation and evaluation. The intermodal perception of space is based on various senses, but most information is obtained through sight. The scope of the study was to address the visual channel and introduce opportunities for examining it through different study areas in the future.

The investigation of green walls in various urban open spaces through the perception of different types of vertical greenery and various forms in the urban environment also deals with questions about people's attitude toward green elements in their living environment, and the relationship between natural elements in traditional and newly emerging forms. As the use of building envelope systems depends on climate, research results are not necessarily transferrable and comparable across countries. For example, Greek research (Tsantopoulos et al., 2018) showed that the aesthetic aspect of greening buildings in Athens is significantly more important and present in the minds of people than its impact on improving the microclimate and environmental parameters. A Malaysian study (Mansor et al., 2017) revealed that a major part of residents appreciated vertical greenery as a form of street art, and the effect on the environment does not seem important (Kozamernik et al., 2020a). Another study by White and Gatersleben (2011) investigated if green buildings with green roofs and/or green walls are more valued than those without integrated vegetation, finding that people show preference for green buildings. The results from the stakeholder survey presented in section 1 (Users and Stakeholders Dealing with Vertical Green) show the beneficial effects based on which the impact on microclimate was emphasized in three countries, followed by biodiversity and social aspects highlighted as important benefits, with no significant differences among the four stakeholder groups. Addressing different aspects of the importance of ecology, the aesthetical and economic benefits of the real property were stressed.

Addressing visual perception within the scope of the qualitative criteria, this research aimed to examine attitudes toward vertical greenery in different European countries. The key questions arising in this regard are as follows: Does the presence of green facades affect the perception of a pleasant ambience? Is the amount of vegetation important, and do people show preferences for certain types of vertical greenery systems?

3.2 Research questionnaire and visual stimuli

Addressing visual perception, a survey on green walls in urban contexts was conducted in three European countries: Slovenia, the Netherlands, and Germany.

The method used is described in detail in how green facades affect the perception of urban environments by comparing Slovenia and the Netherlands (Kozamernik et al., 2020a). The questionnaire included questions referring to the images of urban scenes (visual stimuli) and questions investigating respondents' sociodemographic characteristics. In addition to general questions, additional questions were provided to establish possible impact on respondents' preferences (e.g., questions about their living environment). The images were prepared and used in the questionnaire as individually presented stimuli. Different urban environments and options for incorporating vertical greenery were shown; each open space was presented in three versions: a) without greenery on the walls, b) with a medium amount of greenery on the walls, and c) with dense or a high amount of greenery on the walls. In terms of the type of vertical greenery, images featured either green facades or living walls.

The selected examples were pictures of different urban environments, open areas used as walk-through spaces, such as streets and pedestrian areas, and other multipurpose areas where people perform various activities (e.g., squares and playgrounds), spaces next to various types of public buildings, residential areas, and shopping centers. Photographic simulations were prepared, and digital images were manipulated using the digital image editing program, where editing focused only on changing the facades, while excluding the impact of other factors (Kozamernik et al., 2020a).

3.3 Analysis of responses and results about people's preferences

Statistical calculations were made, and valid data obtained from surveys sampled in Slovenia, the Netherlands, and Germany were combined into a single database. The analysis was conducted by examining the following design indicators: ratio between the built and green environments, type of vertical greenery system, and type of urban space. The respondents comprised 59.9 % women and 40.1 % men. In all three countries, the survey included people of various ages, mainly an active working population and young individuals.

Preferences regarding the images presented were examined through the frequency distributions of respondent ratings of individual images in the survey, which showed a tendency of concentration and skewing in a negative or positive direction. Based on the calculated means, a rating was obtained for each image.

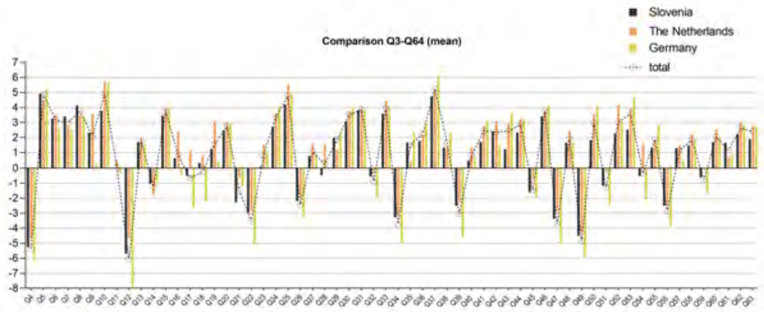

Figure II.6: Graph representing average ratings of each image by country (Slovenia, Netherlands and Germany) in perception research (image by Jana Kozamernik)

By ranking the visual stimuli from those rated as most positive (most attractive) to those rated as most negative (unattractive), the ten least attractive images were categorized in general group A images (without vertical greenery, nine images). They feature outdoor areas such as shopping centers, residential areas, public buildings, and street ambiences. An overview of images with the highest average ratings shows that most of the respondents evaluated green open spaces as more attractive, and the ten best rated images included group C images (high amount of greenery on the walls) and group B images (medium amount).

By analyzing all three versions of an individual urban space, the analysis shows that among all the 20 spaces presented, group A images were rated the lowest and group C images the highest, with a minimal difference between the ratings of groups B and C images in some cases. The frequency distributions of individual image ratings show differences between the Slovenian, Dutch, and German samples; however, a similar rating trend can be observed in all the other countries.

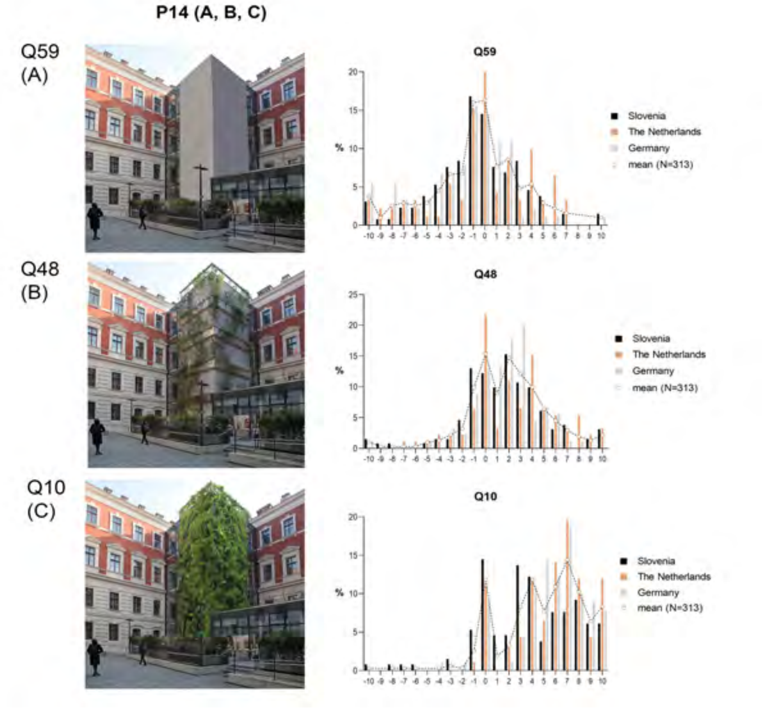

Figure II.7: Illustrations of three versions (A, B, and C) of one of the twenty cases (urban space '14') presented in the perception study, and frequency distributions of ratings by country (Slovenia, The Netherlands and Germany) (image by Jana Kozamernik)

The results indicate that the amount of greenery has an impact on respondents' opinions about urban spaces. On average, considering all the answers from the three countries (n=313), images of urban spaces without vertical greenery (group A) were rated 3.95 points lower than those featuring vertical greenery. On average, groups B (medium amount of greenery on the walls) and C (high amount of greenery on the walls) were rated as more attractive, and group C was rated as favorite with 1.22 points.

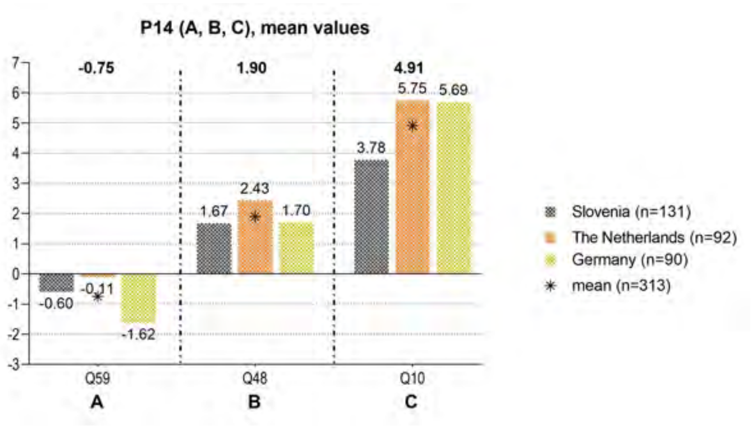

Figure II.8: Graph representing respondent values for urban spaces in variations A, B, and C, and distribution of ratings by country (image by Jana Kozamernik)

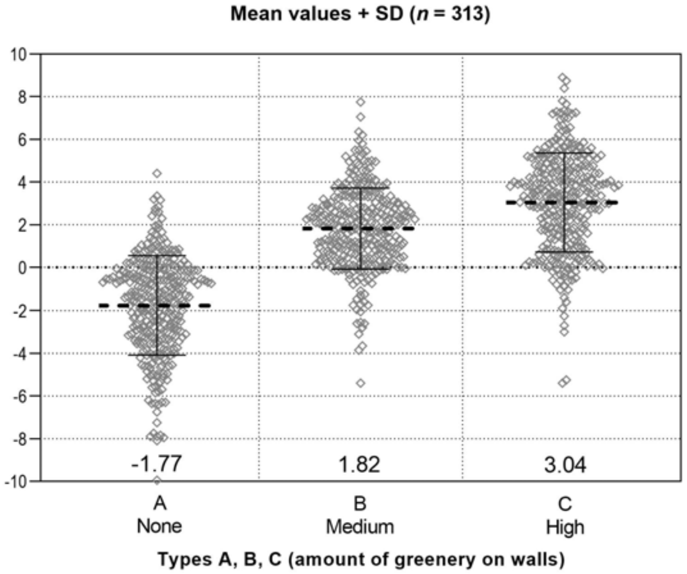

Figure II.9: Diagram representing values of categories of walls (A) without greenery, (B) medium amount of greenery, and (C) high amount of greenery
(image by Jana Kozamernik)

A comparison between the Slovenian, the Netherlands, and German samples shows that the Slovenian respondents rated the images lower than their Dutch counterparts; additionally, German respondents rated images across a wide range, with images of group A usually lower and images of group C often higher than those for Slovenia and the Netherlands.

Evaluation of the attractiveness of the type of vertical greenery showed that, on average, images showing green facades (ground-bound climbing systems) were better rated than images of living walls and green walls. The maximum mean values are comparable for both types of green facades; however, the mean for GF is higher than for LW and GW at 0.65 points. In examining the evaluation of images by type of green walls (i.e., green facade or living wall/green wall), certain limitations must be considered in relation to the methodological approach, as most images showed urban ambiences, with green facades visible from afar and not up within a close range.

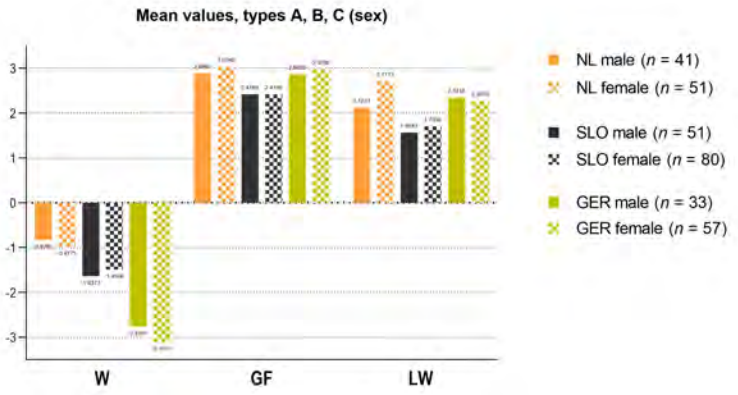

Figure II.10: Diagram representing values of categories of walls (A) without greenery, (B) medium amount of greenery, and (C) high amount of greenery
(image by Jana Kozamernik)

3.4 Users' perception of Vertical Green in an urban context: Preconceptions and benefits

The study results show similar trends in evaluating different ambiences in the three countries (Slovenia, the Netherlands, and Germany) and certain differences between specific demographic groups. Even though urban ambiences with vertical greenery presented here were evaluated as preferred over urban ambiences without green walls, the standard deviation among the answers was quite high. The results also show that the traditionally well-known type of vertical greenery (i.e., green facades, a ground-based green facade with climber plants) is the preferred type of vertical greenery compared to modern types (i.e., living walls/green walls, with panels and structures that are fixed on facades or walls and allow placement of plants and substrate on the entire surface or involve the use of planted containers). During the analysis, it was evident that sociodemographic characteristics and the living environment influenced respondents' preferences and perceptions, as an interesting difference in ratings was observed between the perceptions of residents in downtown areas and those living in other urban environments. The distinction was noticeable between Slovenian and Dutch answers from respondents living in downtown areas, as Slovenes rated all groups of images lower than the Dutch, and the difference was even more pronounced in the ratings of images with vertical greenery (Kozamernik et al., 2020a). This vital information from the first part of the research led to the evaluation of not only the need for green features but also their acceptance in different urban areas. Nevertheless, green walls must be implemented and considered from all aspects of architectural design as successful systems. Regardless of the system used, maintenance must be foreseen at the design stage, as only well-maintained green walls can have the desired positive influence on the built environment (and/or building).

As perception includes not only sensing and processing information but also cognition, including interpretation and evaluation (Rasmussen, 2001), the study introduced questions about public opinion in these three countries. The participants from Slovenia, the Netherlands, and Germany were asked to identify the benefits of facade greening. The highlighted benefits include improvement of visual attractiveness and appearance of the buildings, which were rated with the highest estimates.

On the other hand, respondents (in the first and extended study) had difficulty in accepting that green walls improve the energy efficiency of buildings (during summer) and did not identify the connection between attractiveness and other benefits and impact on real property value (Kozamernik et al., 2020c).

In expressing their attitude toward possible problems and negative myths about green walls being installed on buildings, the potential problems and hazards with the highest average scores were lack of maintenance, management responsibility problems, cost of maintenance and management, and cost of implementation. From the average values, the most highlighted hazards derived from the physical characteristics of vertical greenery were retention of moisture on walls, insects in crevices and spaces, facade damage, presence of small animals and allergens, and shedding of leaves. The minor problems from the study are loss of building identity, vandalism, fire safety, and neglected appearance all year round (Kozamernik et al., 2020c).

4 On the future of Vertical Green from stakeholders' perspectives (conclusions)

A broad spectrum of people were involved in the research on stakeholders' perspectives, from those involved personally and professionally to the general public who may not even be interested in vertical greenery, but are affected by the quality of the living environment, including green areas in their part of the city or street. Due to stakeholders' diversity, the various methods used to capture their perceptions differed: various types of questionnaires, interviews, and workshop methods were used and adapted to the knowledge and properties of each group. Essentially, the questionnaires for the four stakeholder groups targeted the specific knowledge and experience of professional stakeholders and citizens as end-users. The questionnaires regarding perception targeted the specific viewpoint of visual preferences of the VG.

The interviews with municipal officials (Ljubljana) and experts (Berlin) identified valuable and in-depth information from specific departments and professions, and the workshops were a step toward generalization and bringing the results of individuals closer to common forms and contents.

From the researchers' perspective, the reactions that accompanied the responses and assessing directly from the replies, it is noted that most people take this question rather personally and are concerned, which is far from being irrelevant to them when they imagine having a green facade. Answers regarding benefits and barriers, potential problems, negative myths and obstacles, including fears, were present in some form in the research.

The main concerns are the high costs of implementation and maintenance of vertical green buildings. Concerns that express a more personal view are regarding aesthetics (during winter months, concealing interesting architecture or built heritage), concerns or fears involve damage to buildings, insects and pests, and fire protection issues and safety issues; on the other hand, VG is seen as enhancing biodiversity, green spaces, and climate conditions.

Figure II.11: Benefits and barriers expressed by stakeholders (image by Bibi Erjavec)

As information on the benefits and barriers were gathered from different groups and by different methods, calculation of the most expressed or prevailing is not possible. An overview of all the answers on barriers brings forward concerns connected with higher costs, maintenance, responsibilities, hygiene, and aesthetics.

The benefits mentioned could be classified as ecological (reduction of urban heat island effects, lowering of air pollution, noise reduction, retention of rainwater, improved environmental awareness), social (quality of life, learning, urban food production, socializing, sharing responsibilities), aesthetic (better view, improved look of building, more green spaces or just an impression of green), and economic (increase in the value of outdoor surroundings of the greened building and promotion of the greened building).

Professional stakeholders (experts and property developers) acknowledge the importance that more vertical green is planned and implemented, and that it requires legal provisions and financing to promote vertical green. A more widespread implementation of facade greening is hindered by the lack of regulation and provision of maintenance, lack of participation and know-how, and lack of cost benefit analysis and quantification methods of benefits.

The project results supported by previous findings and experiences set the framework for improving implementation of vertical green systems regarding priorities (expressed needs and problems) in urban areas. In addition, stakeholders' concerns should be addressed in co-creative and participatory activities supported by expert knowledge.

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Chapter III

DESIGN AND MAINTENANCE OF VERTICAL GREENING SYSTEMS

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In section 1, various forms of vertical greening systems (VGS), the plants and materials used in these systems, as well as the required maintenance steps and general aspects for planning, are presented. While section 2 discusses the building types wherein VGS can be used, section 3 delves into specific topics related to irrigation: water sources for VGS, automated irrigation, and the calculation of tank sizes for rainwater application. The design approach for multiple water use developed and operated within the project is presented in section 4. In section 5 the implementation potential for VGS is discussed. Finally, section 6 presents approaches for a cable-driven robot that can utilize various tools for maintaining large VGS. In addition, tools for cutting and a system for changing the planter boxes and software routines are noted.

1 Types of Vertical Greening Systems (VGS)

In an ideal natural habitat, plants grow directly in the present soil, where their roots have adequate space to stretch out and develop an appropriate root system for an optimal plant supply with water and nutrients. When plants grow on the facade of a building, several factors (soil, water, light, and nutrition) are adversely affected. At this point, the affected factors must be compensated by design and maintenance. Depending on the design, construction, and plants, VGS can be classified into three categories: ground-based green facades, pot-based green facades, and wall-based green facades.

1.1 Ground-based Green Facades

> “A Ground-based green facade is a wall completely or partially covered with greenery. The climber plants are planted in the ground (soil, technical, or recycling substrates) or in containers (filled with soil) and grow directly on the wall, or climb using climbing aids (e.g., on a frame) connected to the wall.”
>
> (Langergraber et al., 2021)

This green facade is the most extensive VGS type with the lowest installation and maintenance costs. Although artificial irrigation and fertilization are not necessary, they will help to improve the growth and vitality of the plants.

Self-clinging climbers are plants that can climb directly on the wall with the help of aerial roots (e.g., *Hedera helix*) or suckers (e.g., *Parthenocissus tricuspidata*). The self-clinging climbers growing directly in the ground (in soil or a technical substrate), can reach a maximum height of 25 m. Pre-cultivation is impossible because it takes several years to cover the entire facade. Maintenance is only required when the branches reach windows, roofs, or drainage systems. This type of VGS requires the lowest installation and maintenance costs. Plants that require a climbing aid are classified based on their method of climbing (Twiners, Climbers, or Scramblers). The climbing aid (rope, net, or stiff structure) is primarily made of metal. Trellie-trees are trees cut into a special form that will lead their branches upward on the facade of a building. Its climbing aid is primarily made of wood, has no carrying function, and is only required for guiding the plants' growth direction. Maintenance necessitates cutting and guiding branches, and this task is more complicated for trellie-trees. Installation costs may vary based on the size of the plants but these costs are primarily affected by the design and material of the climbing aid (see Figure III.1 and Table III.1).

Figure III.1: Ground-based green facades with self-clinging climber (left), on climbing aid (middle), and trellie-tree (espalier tree, right) (images by Irene Zluwa)

Table III.1: Variations of ground-based green facades

	Type	Examples of plant species	Plant growing media (PGM)	Construction material	Max. Height (m)	Maintenance	Costs
1.1	self-clinging climbers	*Hedera helix*	Soil or technical substrate or mixture of both	-	25–30	Pruning of branches, if they reach windows, roofs or drainage systems	Installation: 0.4 € m^{-2} (Pfoser, 2016)–50 € m^{-2} (BMK, 2020)
		Parthenocissus tricuspidata			15–30		
		Parthenocissus quinquefolia			10–15		
		Hydrangea petiolaris			10–15		
1.2	plants need a climbing aid		Soil or technical substrate or mixture of both	Material: metal, hemp, wood, (plastics, fibre-glass)		Pruning of branches, if they reach windows, roofs or drainage systems; Guidance of branches on the climbing aid	Installation: 100–500 € m^{-2} (BMK, 2020); Maintenance: 10–15 € m^{-2} per year (Pfoser, 2016)
		Tendril and leaf-twining climbers:		Tendril and leaf-twining climbers:			
		Clematis vitalba		need a grid or net-structure	12–14		
		Vitis Vinifera			8–10		
		Ramblers and Scramblers:		Ramblers and Scramblers:			
		Rosa sp.		need a horizontal structure to lean on	2–6		
		Rubus henryi			2–5		
		Jasminum nudiflorum			3–5		
		Twining Climbers:		Twining Climbers:			
		*Wisteria sinensis**			8–30		
		Fallopia baldschuanica		need vertical structures with diameters from 4–50 mm. If the supporting structure is a grid, the raster has to be 10 cm minimum (FLL 2018). * Plants with a high secondary thickness-growth need stiff metal structures (diam. 25–50 mm)	8–15		
		*Celastrus sp.**			12–14		
		Actinidia sp.			8–10		
		Aristolochia macrophylla			8–10		
		Wisteria floribunda			8–10		
		Lonicera sp.			6–8		
1.3	with trellie-trecs (espalier trees)	Was invented for fruit trees (i.e., *Malus domestica*, *Pyrus sp.*, *Amelanchier lamarckii*) but can also be applied to other species (Koehler et al., 1993, Dunnett & Kingsbury, 2010)	Soil or technical substrate or mixture of both	Mostly wooden grid as aid for guiding of branches	2–10+	Pruning and guiding of branches needs special knowledge	

1.2 Pot-based Green Facades

> "A Pot-based green facade involves the use of planted containers, such as pots or planters, filled with artificial (technical) soil-less substrate or soil or a mixture. They can be placed on the ground or directly on buildings or balconies. They can be used with almost any type of plant; for example, climbing plants, trees, and/or shrubs."
>
> (Langergraber et al., 2021)

Irrigation and fertilization is necessary; regular checks must also be conducted to confirm its efficiency. The implementation of balconies is a common solution for providing improved accessibility to VGS for maintenance, irrigation, and supervision. Pots can either be integrated into the structure or placed on the balcony. A wide spectrum of plants can be used in this VGS type; the combination with climbers or trees allows maximum greening and generates extended living space for inhabitants of the building. Costs and maintenance efforts differ significantly, in terms of the type of plants and whether maintenance is conducted by the inhabitant or outsourced to professionals. Depending on the size (and weight) of the planter pots, and the type (and static condition) of the facade, a pot-based green facade can be attached directly to the facade (on a subconstruction) or require a support structure to transfer the load into the ground. In most cases, large planter-pots are used for climbers, whereas small pots are planted with small shrubs, annual and perennial plants, or grasses. On balconies, irrigation and fertilization can be manual or automated; however, in pot-based green facades (Table III.2), automated irrigation is necessary. Fertilization can be automated by adding liquid fertilizer to the irrigation water or with depot fertilizer during maintenance. In addition, plants must be pruned at least during spring, unwanted species must be removed, and dead plants must be replaced. The costs for installation (and maintenance) are notably higher, compared with those for ground-based green facades (see Figure III.2 and Table III.2).

Figure III.2: Pot-based green facade directly attached to the facade (left) on balcony (middle) and on supporting structure with climbing aid (right) (images by Irene Zluwa)

Table III.2: Variations of pot-based green facades

	Type	Plant species	Plant growing media (PGM)	Construction material	Max. Height (m)	Maintenance	Costs
2.1	Planter pots on balcony	Small needle trees (e.g. *Pinus mugo* 'Mops' *Picea glauca*) or Mediterranean small shrubs, such as *Lavandula angustifolia* or *Salvia Rosmarinus*, are often seen on balconies	Technical substrate in layers: PGM-layer	Material for planter pots: concrete, metal, wood, or plastic	Total building height	For climbers, for climbers with climbing aid: See Table III.1	Installation cost of the balcony
		Also possible: all other types of annual and perennial plants, climbers, and trees	Drainage/ water-storage-layer	Climbing aid: See Table III.1		Pruning and cutting of annuals and perennial plants	Installation Greenery: 10 € m^{-2}
2.2	on supporting structure*	Annual and perennial plants, grasses, shrubs, climbers, and trees	Technical substrate in layers: PGM-layer	Material for planter pots: concrete, metal, wood, or plastic	Total building height	For climbers, climbers with climbing aid and trellie trees, see Table III.1	Installation: 250–1000 € m^{-2}
			Drainage/ water-storage-layer	Climbing aid: See Table III.1		Pruning and cutting of annuals and perennial plants	Maintenance: 25 € m^{-2} per maintenance
2.3	Pots attached to facade	Small shrubs, annual and perennial plants, grasses. The most persistent perennials for VG are: Sedum-species, *Geranium macrorrhizum*,*Bergenia cordifolia*, and *Heuchera sp.*)	Technical substrate in layers: Depending on the product one or more layers are used	metal or plastic	Total building height	Cutting and replacement of plants (1–6 times per year according to aesthetical issues and design concept)	Installation cost of the balcony Maintenance: 10–70 € m^{-2} per maintenance

*with or without climbing aid

1.3 Wall-based Green Facades

> "A Wall-based green facade (or green wall) comprises panels and technical structures (3D-frames filled with technical substrate) that are seeded or planted. These panels and structures are fixed onto facades or walls, or can be designed as stand-alone systems and allow the placement of plants and substrates on the entire surface. Some systems allow for the removal of panels during winter."
>
> (Langergraber et al., 2021)

Irrigation and fertilization is necessary; regular checks must also be conducted to confirm its efficiency.

In contrast to the systems described in prior sections (subsection 1.1 and subsection 1.2), in wall-based systems, the plant growing media (PGM) is installed parallel to the facade, thereby leading to difficulties in water management. Wall-based green facades are installed in modules next to each other or as a continuous layer. These systems typically consist of geotextiles filled with mineral wool or a technical substrate, fixed in a frame. The layers are thinner, compared with other systems, and must be irrigated and fertilized continuously because of the lack of buffer space. The panels can either be seeded or planted, and modular wall-based green facades are often pre-planted before their montage. During maintenance, plants are pruned and, if dead, are replaced one or more times in a year (see Figure III.3 and Table III.3).

Figure III.3: Modular (left) and continuous (right) wall-based green facade (images by Irene Zluwa)

Table III.3: Variations of wall-based green facades

	Type	Plant species	Plant growing media (PGM)	Construction materials	Max. Height (m)	Maintenance	Costs
3.1	Modular	Small shrubs, annual and perennial plants, grasses	Technical substrate or mineral wool, geotextiles	Foil, geotextiles, metal, plastic	Total building height	Cutting and replacement of plants (1–6 times per year, according to aesthetic issues and design concept)	Installation: 500–1500 € m^{-2} (BMK 2020). Maintenance: 10–70 € m^{-2} per maintenance
3.2	Continuous	Small shrubs, annual and perennial plants, grasses	Soil or technical PGM or a mixture of both	Material for foil, geotextiles, metal, plastic	Total building height	Cutting and replacement of plants (1–6 times per year, according to aesthetic issues and design concept)	Installation: 500–1500 € m^{-2} (BMK 2020). Maintenance: 10–70 € m^{-2} per maintenance

2 General aspects for planning and maintenance of VGS

For implementation of vertical greening, the design recommendations for VGS types should be defined by professionals while considering local conditions (such as climate conditions and exposition of facade) and the appropriate type suitable for the location and building. Table III.4 provides a checklist with criteria that should be considered before implementation.

Table III.4: Site Checklist (Sekaran, 2015)

Analysis term	Information to know
Climate considerations	Maximum and minimum temperatures of the site Local rainfall volume and distribution throughout the year Local variation of sun, shade, and wind throughout the year Potential effect of the building height on some climatic factors
Nearby environment	Assessment of opportunities or risks that nearby vegetation will have on site: fire risk, weed or pest invasion, biodiversity migration
Weight loading	Load-bearing capacity Estimated transient load, particularly wind forces
Irrigation	Water collection and storage opportunities, as well as opportunities for delivery of irrigation water and co-locating stored water with other greywater systems in the building
Structure and green wall size	Size of usable wall area Available vertical space for plants from ground level Any slopes or angles to the wall Quality of existing wall materials

Additional aspects should also be integrated in the planning process: plants should be hindered from growing in gaps of the facade to avoid damage to building parts. The distance between the VGS and facade should be chosen properly, according to plant growth. Wall-based green facades should have an air gap between the VGS and the facade of the building for ventilation reasons. The effects of the material on the temperature changes must be considered. During the planning process, maintenance must always be considered foremost. The most important questions that will influence the VGS design are:

- What is the structure of the accessibility of the system? How is irrigation and fertilization provided?
- How often will the system be maintained and who will conduct the maintenance?

The effort and costs required for the maintenance of VGS depend on the height (accessibility) and the system type (available root space and type of plants). Options and restrictions for the accessibility of VGS are listed in Table III.5.

Table III.5: Options and restrictions for the accessibility of VGS

Height	Tool	Opportunities and restrictions
< 1.80 m	Direct access	Easy to maintain, surveillance is easy
< 7 m	Ladders, scaffolds	Scaffold and ladder have to be set up
< 100 m	Cherry picker	Requires access to the facade/free space to stand
> height of building	Industrial climbers	No limit in terms of height, anchor point for the rope must be on the building
< height of building	Maintenance elevators, bridges, or balconies attached to the building	No limit in terms of height, but should be considered during the planning process for the building
< height of building	Automatized solution	Tools on rails, Robots or drones

The accessibility of VGS through ladders, cherry pickers, and industrial climbers of building-integrated maintenance aids (e.g., maintenance elevators or bridges) represent common methods for the maintenance of VGS, whereas automated solutions (using robots or drones) are currently being developed. The first steps for automated maintenance using robotic systems are described in section 6.

3 Irrigation of Vertical Greening Systems

Adequate irrigation and fertilization are key factors for healthy, long-lasting VGS. Ground-based green facades with climbers can be operated more easily than wall- or pot-based green facades. Systems connected to the ground allow for the direct use of rainwater and may survive without artificial irrigation. Most wall- or pot-based systems require specific irrigation systems, which must be properly planned. This section does not include discussions regarding watering for VGS in general, but instead addresses three specific topics: Which water sources can be used for the irrigation of VGS? What are the options for automated irrigation control? How can the necessary tank size be calculated for rainwater reuse?

3.1 Water sources for VGS irrigation

Tap water is typically used for irrigation of VGS. Other sources include groundwater or surface water (derived from rivers, lakes, and ponds). To save drinking water resources, rainwater or treated greywater can be utilized as an alternative (Table III.6) for resourceful irrigation.

Table III.6: Possible water-sources for the irrigation of VGS

Water source	Description
Tap Water	Drinking water
Ground Water	Direct supply from a nearby groundwater body using a well and pump
Surface Water	Extraction of irrigation water from a nearby surface water body (e.g. river or pond)
Rainwater	Water from precipitation, collected from sealed or non-sealed surfaces (e.g. (green-) roofs, terraces, paths, and roads)
Treated wastewater	Reuse of treated water from different sources (e.g. wastewater or greywater); Qualification for reuse is defined in reuse guidelines and regulations Table III.7

Figure III.4 presents a scheme of the components for a sustainable water circle in a house. Rainwater from the roof is collected in a tank.

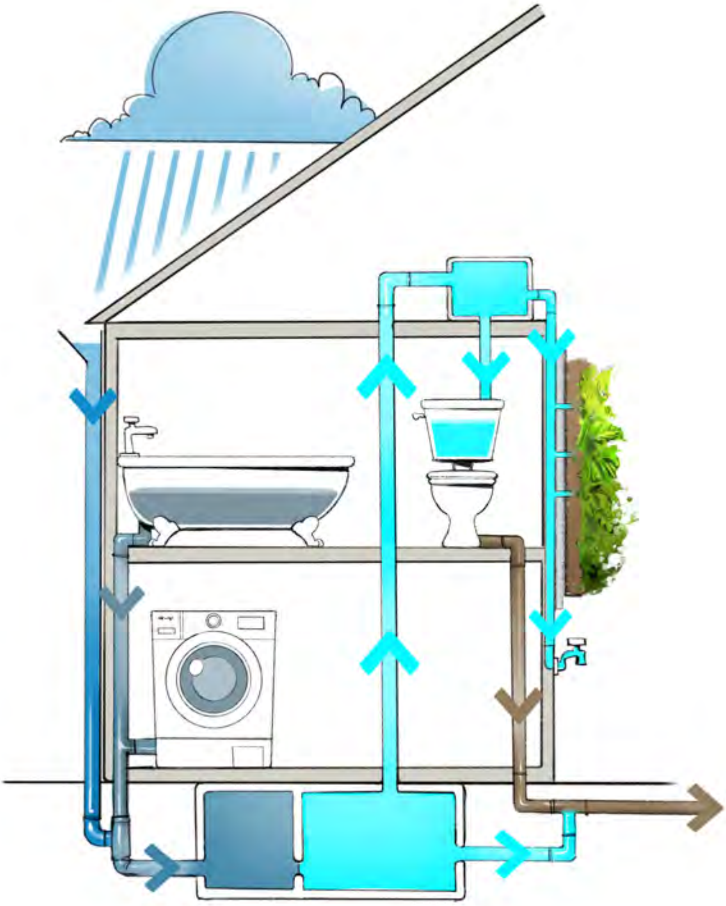

Figure III.4: Components for the irrigation of VGS. (image by Bibi Erjavec)

In addition, greywater from various sources, such as the shower, washing machine, kitchen, and dishwasher are collected in the tank after treatment to fulfil the legal requirements for water reuse, as presented in Table III.7. The tank must be cleaned every 10 years. To protect the tank from freezing, it can be emptied during winter, placed indoors in frost-free ground, and be isolated or heated. In storage systems (rainwater or treated wastewater), an additional water supply can be useful when there is insufficient water collected. Important: The possibility of reflow to the tap water pipe should be eliminated ("Systemtrenner B3A", or free-falling system). Water from this tank can be used for toilet flushing, garden irrigation, or irrigation of the VGS. The irrigation control panel (Table III.8) should be easily accessible.

Available water reuse guidelines from the EU and other countries are listed in Table III.7.

Table III.7: Water reuse guidelines and regulations focusing on urban irrigation reuse practices

	Europe		Austria		Germany
	Regulation 2020/741/EU		ÖNORM EN 16941−2		DWA–M 277
Parameter	Eatable Plants, direct contact	Seeded crops	Spray application	Garden Irrig.	Public and priv. areas
COD ($mg\ L^{-1}$)		125			
BOD$_5$ ($mg\ L^{-1}$)	$\leq$ 10	25			
TN ($mg\ L^{-1}$)					
TSS ($mg\ L^{-1}$)	$\leq$ 10	35			
Turbidity (NTU)	$\leq$ 5		< 10; for disinfection < 1		< 2
Surfactants anionic ($mg\ L^{-1}$)					
DO ($mg\ L^{-1}$)				> 1	
O$_2$ saturation (%)					> 50%
pH (-)				5–9.5	6.5–9.5
EC ($\mu s\ cm^{-1}$)					
E.Coli (cfu 100 $m\ L^{-1}$)	$\leq$ 10	$\leq$ 10000	0	250	$\leq$ 1000
Enterococci (cfu 100 $m\ L^{-1}$)			0	100	
Legionella (cfu 100 $m\ L^{-1}$)	< 1000		10		

The main parameters of interest are pathogens because they directly affect human health. Threshold values depend on the type of application (e.g., spray applications, drip irrigation, or subsurface irrigation). A general recommendation is a disinfection stage after the wastewater or greywater treatment unit to minimize risks related to direct contact (DWA-M 277). Other important parameters are the total suspended solids (TSS) and turbidity. These parameters can influence the irrigation system by enhancing clogging behavior.

3.2 Variations of automated irrigation

Adequate irrigation of the VGS is essential for their functionality. Different types and designs of VGS require differing amounts of water. A table listing the different water demands for the three main types (ground-, wall-, and pot-based) is provided in chapter IV. Water demand is highly dependent on the volume of plant growth media and its water storage capacity. The options for irrigation control devices are presented in Table III.8. However, despite the precision of the irrigation control, excess water may remain, and thus needs to be discharged in the sewer system, an infiltration area, or to a recycling system for further irrigation.

A mechanical timer is a low-tech solution suitable only for private systems that require a pump. The timer will run every day in units of 15 minutes. It must be re-timed after power interruption. Manual changes are necessary to address water demands based on different seasons. Digital timers are slightly more flexible; they have a buffer storage to memorize settings in case of a power interruption, and up to 20 starting times (in units of 1 minute) are possible. However, they are only recommended for low-tech, private systems that require a pump.

Irrigation computers are available in various forms, from low-tech to high-tech options, and are able to regulate one or more magnetic valves (for different irrigation circles) and different starting times. Some computers can be programmed to provide more water during summer.

In addition to time-based irrigation control, there may be sensors that overrule the programming when activated. A frost sensor will deactivate irrigation below air temperatures of 2 to 5 °C to avoid freezing in pipes. A rain sensor will deactivate the irrigation when it rains. Soil moisture sensors can stop irrigation if the substrate is too moist.

Table III.8: Available devices for irrigation control

Device	Time scale	Water circles	Description
Mechanical timer	15 min	1	Must be re-timed after power interruption; the manual seasonal adaptation required is suitable only for low-tech systems that require a pump
Digital timer	1 min		Only for low-tech, private systems that require a pump
Irrigation computers	1 min	≥ 1	Adaptation to different seasons must be conducted manually; some devices can be controlled through a smartphone app; external control is only possible with internet access
Computers with additional sensors	1 min	≥ 1	Frost sensor: Automatic deactivation of irrigation at temperatures below 5 ℃ (2 ℃). Rain sensor: Automatic deactivation of irrigation when it rains. Temperature: Reduce or increase irrigation at defined temperatures. Soil moisture sensor: Stops irrigation if substrate is too moist. Weather forecast: No irrigation when there is predicted rainfall
Sensor-based systems		Minimum of one sensor per circle	Regulation of irrigation by Soil moisture sensors: Sensor should be placed in the plant roots and under a dripline. The sensor needs to be calibrated for the substrate. High possibility of errors. Installation has to be carefully done and tested. Float ball (ebb and flow system): Floating device switches the irrigation on and off; does not work in winter.

Computers connected to a weather station can reduce or increase irrigation according to wind, air temperature, and rainfall, and some computers can even include weather forecasts.

Sensor-based systems regulate irrigation using data from soil moisture sensors. Different types of sensors are currently available in the market, but the development of such technology is in the starting phase. Particularly in technical substrates, difficulties have been noted in measuring the amount of water in the PGM. A low-tech sensor would be irrigation controlled by an ebb and flow system with a floating device that switches the irrigation on and off mechanically.

Problems with the floating device being stuck can also occur, and this solution does not function when the water is frozen in winter.

Some computers can be controlled and surveyed via smartphone apps; however, an internet connection would then be required. A water meter (analog or digital) is recommended as a control device to survey the amount of water used for the irrigation of the VGS. If there is a constant water flow, this indicates that a pipe is broken; if there is no water flow when the system is expected to irrigate, this indicates a problem with the water supply. Digital water meters can be connected to the computer and provide an alarm if the water flow is too high or low. However, no technical device can replace the human eye by observing a plant and directly checking the system.

3.3 Guidance for integrating rainwater harvesting in VGS irrigation systems

The use of rainwater for the irrigation of VGS is often mentioned as a sustainable alternative to that of piped drinking water in the literature but the practical details of such systems (e.g., run-off areas, quality, and technical design) have yet to be thoroughly examined (Prenner et al., 2021). To address this knowledge gap, a conceptual model is presented to provide a detailed description of the processes and influencing factors involved. Details of the conceptual model are described in chapter IV. To properly design a rainwater harvesting (RWH) system for the irrigation of VGS, a destination between several modules must first be created (Table III.9).

Table III.9: Description of the modules of the calculation section

RWH yield and storage size Table 3.3	The water quantity that can be harvested from a certain area is known as the yield is calculated, and the size of the storage tank is determined. Both are based on the equations used in ÖNORM EN 16941-1 (2018).
Pipes (gravitational flow) Equation 3.3	Pipes that contain water flowing by gravitational forces only. The equation used by Wyly-Eaton is used to determine the pipe diameter.
Pipes (pressurized flow) Equation 3.3	Pipes that contain water flowing by additional gradients; for example, those created by pumps. The calculation of the diameter is based on the equations used by Prandtl-Colebrook and Darcy-Weisbach.
Pumps Equation 3.3	To overcome certain elevation differences in specific situations, pumps are required.The calculation shows the pumps appropriate for different situations, and some examples are listed.

Each module can be calculated on its own; however, the modules depend on each other. The calculations for the RWH area as well as the storage and back-up water supply are based on ÖNORM EN 16941-1 (2018).

RWH yield and storage size

There are different starting points for calculating the required RWH yield and storage size.

(a) Known RWH area and known VGS area

(b) Known RWH area and unknown VGS area

Based on ÖNORM EN 16941-1 (2018), this guidance offers two options for the calculation of starting point A, namely, the basic and detailed approaches. The choice depends mainly on data availability. Furthermore, the guidance offers one calculation method for starting point B. Table III.10 presents the required data for each calculation approach.

Table III.10: Data requirement for the calculation approaches

	Basic Approach for known VGS size	Detailed Approach for known VGS size	Approach for unknown VGS size
Starting Point	A	A	B
	Parameters required for the calculation:		
Total rainfall	Per year	At least per month, but use of a lower resolution is advised	Per year
VGS water demand	Per year	Same resolution as "Total rainfall"	Per year
Duration of dry period	yes	-	yes
Max. non-potable water demand per day	yes	-	yes
Size of one panel	-	-	yes
Max. available wall area	-	-	yes
Vertical greened area of one panel	-	-	yes

(a) Basic Approach for known VGS size:
The yield of the RWH area and the demand of the VGS area are calculated independently, thereby indicating that they need to be compared by the user. The user must then decide whether the RWH area is sufficiently large. If not, a larger or additional RWH area must be selected.

(b) Detailed Approach for known VGS size:
The yield of the RWH area and the demand of the VGS area were interlinked during the calculation.

(c) Approach for unknown VGS size:
The RWH area is crucial for determining the VGS size.

The following two figures illustrate the differences between the basic and detailed approach. In Figure III.5, the precipitation pattern used for the calculations is presented. While the cumulative precipitation is equal for both approaches, monthly patterns are only represented by the detailed approach. As indicated in Figure III.6, the actual monthly water demand of a VGS varies based on the season. This variation is not represented in the basic approach.

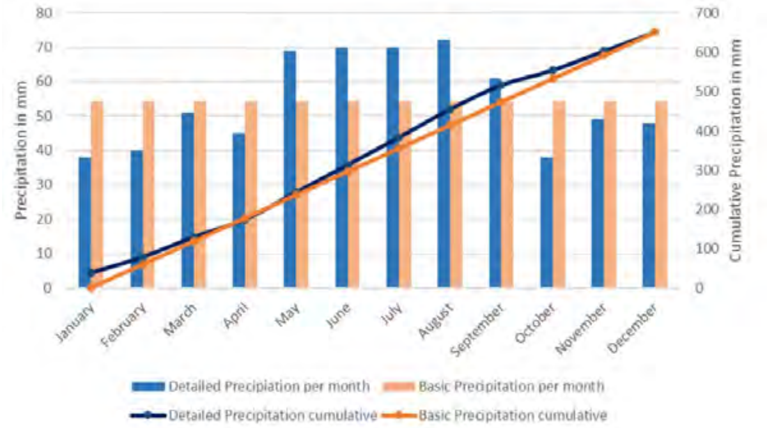

Figure III.5: Comparison of the detailed and basic approaches regarding the precipitation pattern on the example of Vienna

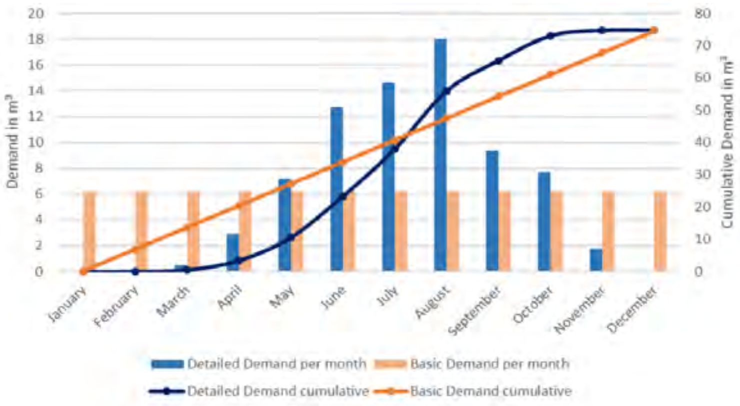

Figure III.6: Comparison of the detailed and basic approaches regarding the VGS demand pattern on the example of Vienna

Rainwater harvesting (RWH) yield The RWH yield was calculated using the same equation for all the approaches as follows:

$$Y_r = \sum A_i \cdot h_i \cdot e_i \cdot \eta_i \tag{III.1}$$

where	A	roof or ground area	m^2
	t	Time step	d
	h	Total rainfall per time step	L
	η	Hydraulic treatment coefficient	
	e	surface yield coefficient	
	Y_r	Rainwater yield per time step	$\mathrm{L\,d^{-1}}$

The surface yield coefficient *e* changes according to the material and angle of the surface area. Table III.11 indicates the number to be used. The ratio of the outflow of the treatment facility to the inflow of the treatment facility is described by the hydraulic treatment coefficient *n*.

Storage size The water demand per (vertical) square meter and day *Dd* of the VGS is either based on the evapotranspiration and the water balance, or if this is unavailable, a defined irrigation amount. The water demand is set in relation to 1 m² of the vertical area and day.

Table III.11: Surface yield coefficients depending on the material of the collection surface (based on ÖNORM EN 16941–1, 2018)

Collection surface	Surface yield coefficient
Smooth surface roof	0.9
Rough surface roof, pitched	0.8
Flat roof	0.7 to 0.8
Green roof	0.3 to 0.5
Sealed areas	0.8
Non-sealed areas	0.5

The vertical greened area (VGA) is considered to be similar to the vertical area of the VGS. The dry period *dd* describes the average maximum dry days that the storage tank needs to overcome until the next potential rainfall (ÖNORM EN 16941-1, 2018). This depends on local precipitation, and must be checked individually.

Water demand quantification: Basic approach for known VGS size Equations for the demand and storage size calculations using the basic approach.

$$D_{p,d} = D_p \cdot VGA \tag{III.2}$$

where			
	$D_{p,d}$	VGS water demand	$\mathrm{L\,d^{-1}}$
	D_p	VGS water demand per area	$\mathrm{L\,m^{-2}\,d^{-1}}$

In the next step the total daily water demand is determined.

$$D_{N,d} = D_{p,d} \cdot ((D_{f,d} - D_{p,d}) \cdot s) \tag{III.3}$$

where			
	$D_{N,d}$	total VGS water demand	$\mathrm{L\,d^{-1}}$
	$D_{p,d}$	VGS water demand	$\mathrm{L\,d^{-1}}$
	$D_{f,d}$	max. VGS water demand	$\mathrm{L\,d^{-1}}$
	s	Storage coefficient	

Finally, the storage is dimensioned.

$$V = D_{N,d} \cdot d_d \tag{III.4}$$

where			
	V	water storage	L
	$D_{N,d}$	total VGS water demand	$\mathrm{L\,d^{-1}}$
	d_d	duration of dry period	d

At the end of the calculation it is time to compare the rainwater yield from the chosen RWH area and the water demand required by the VGS.

- Difference too large: a smaller RWH area can be chosen, a larger VGS can be irrigated or the system needs to be designed for lots of overflow.
- Negative difference: a larger or additional RWH area is required to completely irrigate the VGS by rainwater. Alternatively, also a backup water supply amount can be considered. Or simply a smaller VGS can be chosen.

Water demand quantification: Detailed approach for known VGS size For the detailed approach different scenarios can be set up, using different storage volumes and/or different RWH areas. The output is then the generated overflow and the required backup water. Which means not the equations lead to the optimal storage volume, but it is your choice to select the optimum out of backup, overflow and storage tank size.

The equations required for this approach are:

$$S_{r,m} = min(a,b) \begin{cases} a \ D_{p,m} \\ b \ V_{r(m-1)} \end{cases} \tag{III.5}$$

where			
	$S_{r,m}$	Abstraction from storage	L
	$D_{p,m}$	VGS water demand current month	L
	$V_{r(m-1)}$	water storage end of last month	L

The determination of the water volume available at the end of a month:

$$V_{r,m} = min(a,b) \begin{cases} a\ V_{r(m-1)} + Y_{r,m} - D_{p,m} + B \\ b\ V \end{cases} \tag{III.6}$$

where			
	$V_{r,m}$	water storage end of month	L
	$V_{r(m-1)}$	water storage end of last month	L
	$Y_{r,m}$	Rainwater yield current month	L
	$D_{p,m}$	VGS water demand current month	L
	B	Required Backup	L
	V	water storage	L

Water demand quantification: Detailed approach for unknown VGS size The first equation calculates the maximum number of panels which can be supplied by the given RWH area. Regarding the equations this approach is based on the basic approach for known VGS sizes. In first place, the focus is here on the panels.

$$D_{p,d} = D_p \cdot VGA \tag{III.7}$$

where			
	$D_{p,m}$	VGS water demand current month	L
	D_p	VGS water demand per area	$\mathrm{L\,m^{-2}\,d^{-1}}$
	VGA	Vertical greened are of the VGS	$\mathrm{m^2}$

Next the number of panels which is possible for a certain RWH area is determined.

$$np = \frac{Y_r}{D_{p,d}} \cdot VGA \tag{III.8}$$

where			
	np	Number of panels	
	Y_r	Rainwater yield per time step	$\mathrm{L\,d^{-1}}$
	$D_{p,d}$	VGS water demand	$\mathrm{L\,d^{-1}}$
	VGA	Vertical greened are of the VGS	$\mathrm{m^2}$

The following equation shows which area the number of panels np require. It is important not only to determine this value but also to know the maximum available wall area of the building. This gives the answer to how many panels are possible and also how large the collecting area for the rainwater can be.

$$A_p = n \cdot np \tag{III.9}$$

where	A_p	Area of panels	m^2
	n	Size of one panel	m^2
	np	Number of panels	

The maximum number of panels restricted by the wall area is calculated next.

$$np_{w_{max}} = \frac{A_{w_{max}}}{n} \tag{III.10}$$

where	$np_{w_{max}}$	Max. number of panels	
	$A_{w_{max}}$	Max. available wall area for VGS	m^2
	n	Size of one panel	m^2

Now the storage size is determined, the following two equations are the same as in the basic approach for known VGS sizes. However, the last formula is not included in the basic approach.

$$D_{N,d} = D_{p,d} \cdot ((D_{f,d} - D_{p,d}) \cdot s) \tag{III.11}$$

where	$D_{N,d}$	total VGS water demand	$\mathrm{L\,d^{-1}}$
	$D_{p,d}$	VGS water demand	$\mathrm{L\,d^{-1}}$
	$D_{f,d}$	max. VGS water demand	$\mathrm{L\,d^{-1}}$
	$D_{p,d}$	VGS water demand	$\mathrm{L\,d^{-1}}$
	s	Storage coefficient	

The storage required for one panel is dimensioned.

$$V = D_{N,d} \cdot d_d \tag{III.12}$$

where	V	water storage	L
	$D_{N,d}$	total VGS water demand	$\mathrm{L\,d^{-1}}$
	d_d	duration of dry period	d

The last equation defines the storage volume which is required for the whole number of panels.

$$V_r = np \cdot V \qquad \text{(III.13)}$$

where			
	Vr	storage volume for all panels	L
	np	Number of panels	
	V	water storage	L

Pipes

To determine the right diameter of the pipes, the head loss hv must be focused on. There are various approaches to address this problem. The first approach is to use a simulation tool, such as EPANET (EPA, 2000). that was developed by EPA (2000); the second option is to calculate by hand by using the following equations based on Darcy-Weisbach.

Pressurized pipe flow Determining the appropriate diameter for pipes with pressurized flow is based on the equations used by Prandtl-Colebrook and Darcy-Weisbach. The main criterion for determining the appropriate pipe diameter is the head loss hv, which increases as the pipe diameter decreases.

The calculation follows the following procedure:

$$A = \pi/4 \cdot d^2 \tag{III.14}$$

where	A	Cross sectional area of pipe	m^2
	d	inner diameter of pipe	m

Next the velocity is determined.

$$v = \frac{Q_s}{A} \tag{III.15}$$

where	v	velocity in pipe	$\mathrm{m\,s^{-1}}$
	Q_s	max. flow rate per second	$\mathrm{m^3\,s^{-1}}$
	A	Cross sectional area of pipe	m^2

The Reynolds number *Re* is required to determine whether turbulent or laminar flow is dominant in the pipes at the before calculated velocity ν. The rule is, when *Re* is lower 2320 the flow is considered laminar and when *Re* is greater 2320 the flow is turbulent.

$$Re = \frac{v \cdot d}{\nu} \tag{III.16}$$

where	Re	Reynold's number	
	v	velocity in pipe	$\mathrm{m\,s^{-1}}$
	d	inner diameter of pipe	m
	ν	kinematic viscosity	$\mathrm{m^2\,s^{-1}}$

The absolute roughness of the surface is calculated by the following formula.

$$\epsilon = \frac{K}{d} \tag{III.17}$$

where	ϵ	Absolute roughness of surface	
	K	Roughness	m
	d	inner diameter of pipe	m

The Darcy-Weisbach friction coefficient λ is a coefficent which is determined iteratively. The used formula is a form of the Prandtl-Colebrook equation. The approach is to find out a close enough friction factor λ which is then further used in the Darcy-Weisbach equation.

$$\lambda = \left(\frac{1}{2 \cdot \log \frac{2.51}{\varepsilon \cdot \sqrt{\lambda}} + \frac{K}{3.71 \cdot \upsilon}} \right)^2 \tag{III.18}$$

where	λ	Darcy-Weisbach friction coefficient	
	K	Roughness	m
	ϵ	Absolute roughness of surface	
	ν	kinematic viscosity	$\mathrm{m^2\,s^{-1}}$

The Moody number gives the difference between the hydraulically rough and transitional area.

$$\mathit{Moody} = \mathit{Re} \cdot \sqrt{\lambda} \cdot \varepsilon \tag{III.19}$$

where	$Moody$	Moody number
	Re	Reynold’s number
	ϵ	Absolute roughness of surface
	λ	Darcy-Weisbach friction coefficient

The pipe friction coefficient I_r is determined next.

$$I_r = \frac{\lambda \cdot v^2}{2 \cdot g \cdot d} \cdot 1000 \tag{III.20}$$

where	I_r	Pipe friction gradient	‱
	λ	Darcy-Weisbach friction coefficient	
	v	velocity in pipe	$\mathrm{m\,s^{-1}}$
	g	Acceleration of gravity	$\mathrm{m\,s^{-2}}$
	d	inner diameter of pipe	m

The local individual losses $h_{v,l}$ account to the total head loss h_v and are therefore determined.

$$h_{v,l} = \zeta_l \cdot \frac{\nu^2}{2 \cdot g} \tag{III.21}$$

where	ζ_l	Loss coefficient for local losses	
	v	velocity in pipe	$\mathrm{m\,s^{-1}}$
	g	Acceleration of gravity	$\mathrm{m\,s^{-2}}$
	h_{vl}	Total local individual losses	m

finally, the head loss h_v determined.

$$h_v = \left(\lambda \cdot \frac{L}{d} + h_{v,l}\right) \cdot \frac{\nu^2}{2 \cdot g} \tag{III.22}$$

where	h_v	Head loss	m
	λ	Darcy-Weisbach friction coefficient	
	L	Length of the pipe	m
	d	inner diameter of pipe	m
	ν	kinematic viscosity	$\mathrm{m^2\,s^{-1}}$
	g	Acceleration of gravity	$\mathrm{m\,s^{-2}}$
	h_{vl}	Total local individual losses	m

Pumps

The determination of the pumps depends on the water quantity Q, the geodetic height h that needs to be overcome, and the head loss h_v. The geodetic head h_{geod} and head loss h_v are added up to the total head H. The head loss, h_v, is calculated as described in the previous chapter.

Determination of a pumping curve

$$h_{geod} = h_{irrigation} - h_{tank} \tag{III.23}$$

where	h_{geod}	Geodetic head	m
	$h_{irrigation}$	VGS irrigation level (above sea level)	m
	h_{tank}	tank level (above sea level)	m

The total head h_{total} consists of a geodaetic head h_{geod} and head loss h_v.

$$h_{total} = h_{geod} - h_v \tag{III.24}$$

where	h_{total}	total head	m
	h_{geod}	Geodetic head	m
	h_v	Head loss	m

To define the points of the pumping curve, a coefficient c is defined.

$$c = \frac{Q \cdot h^2}{h_v} \tag{III.25}$$

where			
	c	Head loss coefficient	
	Q_s	max. flow rate per hour	$\mathrm{m^3\,h^{-1}}$
	h_v	Head loss	m

The flow rates are defined around the maximum flow rate VGS in equal steps to obtain a representative pumping curve. To define the head losses for each of these flow rates, the above equation is used again, but the pumping curve coefficient *c* is the known value. Then, flow rates Q_h and total heads h_{total} are used for the chart.

Finding an appropriate pump Appropriate pumps can be found on the websites of the suppliers depending on the flow rate and total head loss. Detailed information is listed in ÖNORM EN 16941-1 (2018)

Design for rainwater use

Generally, a RWH system should have a back-up water supply when continuous flow is required. For this purpose, different water sources can be taken into account, based on availability (Table III.6). In the case of an additional connection to the drinking water supply, the entry of non-potable water into the drinking water supply system must be avoided in any case (ÖNORM EN 16941-1, 2018). A non-mechanical backflow prevention arrangement of water fittings where water is discharged through an air gap into a receptacle that has, at all times, an unrestricted spillover to the atmosphere (WRAS, 2020).

- The surface area for rainwater collection determines the amount of water available.
- Two main types of calculation, the basic and detailed approaches can be used.
- The required data should be collected at least on a monthly basis.
- Key knowledge: To respect seasonal patterns of precipitation and plant water demand, the detailed approach and data at a fine timescale (at least monthly) is important.

4 Development of a VGS design with multiple water uses

As a co-creation of the Institute of Soil Bioengineering and Landscape Construction and the Institute of Sanitary Engineering and Water Pollution Control at BOKU University (Vienna, Austria), a multifunctional pot-based green facade was developed, installed and operated for 3 years (Pucher et al., 2020). The objective of the development was to design a resistant, easy-to-maintain VGS with multiple water uses. The following scenarios were intended:

(a) Daily irrigation to provide the highest possible evaporative performance for urban cooling. (Tap water was used for irrigation, as this is the usual water source for VGSs (Ottelé et al. 2011).) However, the use of greywater for resource-efficient irrigation was also investigated. For this “typical” application of a VGS, a planting with the longest possible flowering period that is attractive all year round was desired.

(b) Integration of rainwater and irrigation to achieve the lowest possible water demand. Since dry periods can occur, the plantings should be drought resistant.

(c) The purification of raw greywater. Due to the need for purification of greywater, a high amount of water would flow through the plant growing media (PGM). Therefore, plantings must be adapted to constantly humid site conditions.

To fulfill the abovementioned aims, the following steps of the design process were conducted.

Step 1: Selection of a VGS for healthy plant development that supports a high range of species and that also follows the requirements to function as a greywater treatment system

Step 2: Development of a simple low-tech irrigation system

Step 3: Assembly of a substrate to support multiple water sources, including tap water, rainwater and treated greywater

Step 4: Identification of suitable plants

The results of the design steps are described in detail below.

Results of the design process

Step 1: Selection of a VGS for healthy plant development that supports a high range of species and that also meets the requirements of a greywater treatment system. Design recommendations specific to greywater treatment include the substrate choice (mainly with regard to hydraulic conductivity), the irrigation volume and interval and the number of planter pots needed, mostly described as the total horizontal surface area. General recommendations include the following (Cross et al., 2021):

- Surface area per person: 1 to 2 m^2
- Height per pot: $>$ 20 cm
- Hydraulic loading rate: 0.1 to 0.5 $\mathrm{m}^3\,\mathrm{m}^{-2}\,\mathrm{d}^{-1}$
- Organic loading rate: 10 to 160 $\mathrm{g}\mathit{COD}\,\mathrm{m}^{-2}\mathrm{d}^{-1}$
- Hydraulic conductivity: 10 to 4 $\mathrm{m\,s}^{-1}$
- Porosity: 0.4 $\mathrm{m}^3\,\mathrm{m}^{-3}$

To achieve the requirements of 90 $\mathrm{L\,d}^{-1}$ on 1–2 m^2 and to provide enough root space for healthy plant development, an existing VGS (pot-based green facade) was adapted in its proportions. The dimensions of the aluminum pots are h = 20 cm, w = 18 cm/20 cm, and l = 150 cm. A special fleece is inserted as an insulation and ventilation layer, over which approximately 17 cm of plant substrate is added. One test wall consisted of 10 planter pots that were mounted above each other at a distance of 15 cm and fixed on an aluminum sub construction. Four walls were set next to each other. The regular irrigation scenario (a) was tested in wall 2 with tap water and wall 3 with greywater. The dry scenario (b) was investigated in wall 1, and the greywater purification scenario (c) was examined in wall 4.

Step 2: Development of a simple low-tech irrigation system. A common irrigation system using drippers in each pot leads to a high maintenance effort due to clogging of the small irrigation lines and possible failure of individual drippers. In particular, clogging issues can increase when water sources other than tap water are used. While one conclusion could be to only use tap water to reduce clogging effects – this is not a sustainable practice, as water reuse measures, especially of irrigation water, are needed to meet the water demands without depletion of freshwater resources. To overcome the described issues, a cascading water flow regime was developed and is illustrated in Figure III.9 (Pucher et al., 2020). Water enters the top planter pot using one pipe, flows through the pot and thereby fills up the impounded reservoir (height 2 cm). Then, the water flows further down into the next planter pot. A gutter at a distance of 10 cm prevents clogging of the pipe by the roots of the plants (Figure III.8). The water stored in the impounded reservoir is used by the plants either directly by root-water uptake or is first transported upward by capillary rise in the substrate before being taken up by the plant roots.

Figure III.7: Test wall at BOKU (from left to right): low irrigation once a week (scenario b), daily watering (scenario a) with tap water, daily watering (scenario a) with greywater, hourly watering (scenario c) for greywater treatment) (image by Irene Zluwa)

Figure III.8: Details of the aluminum pot (images by Irene Zluwa and Rebecca Braunegger)

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Piping was made of PVC pipes (22 mm) with pressed connectors, which are common for water pipes. These pipes are durable and more leakproof than the screw connections used for agricultural irrigation systems. Walls 1 and 2 were irrigated with tap water, and walls 3 and 4 were run using greywater. For greywater use, a tank was set up from which the water was pumped to the greenery. The speed of the water supply was set to 0.3 L/min to avoid overflow in the planter pots. The excess water of the last planter pot flows out of the system. This water should be transported back to the storage tank and reused to achieve sustainability.

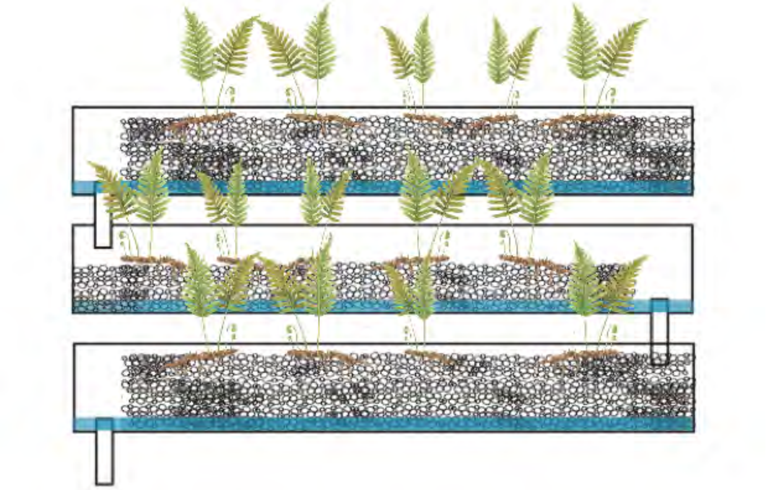


Figure III.9: Cascading flow scheme (image by Irene Zluwa)

Step 3: Development of plant growing media (PGM). In this project, a parameter list was developed to provide a guide to the necessary parameters and their proposed ranges of values (Table III.12). Based on these recommendations, the PGM for the system in this project was chosen. The final components of the PGM included expanded clay (4–8 mm), zeolite (1–2.5 mm), perlite (0–6 mm), sand (0.06–2 mm) and crushed expanded clay (0–8 mm) in equal volumes.

Table III.12: Description of the developed substrate

Parameter	Range of values	Developed PGMBOKU	Source
Hydraulic conductivity ($m\ s^{-1}$)	$> 10^{-5}$; $< 10^{-3}$	3.9 10^{-3}	(OENORM B 2506-3, 2016)
Capillary rise (cm)	>10	26.3	(GGS, 2015)
Porosity (-)	> 0.35	0.448	(DIN EN 13041, 2012)
Water capacity ($m^3\ m^{-3}$)	> 0.20	0.29	(DIN EN 13041, 2012), (OENORM B2606-1, 2009)
Air capacity ($m^3\ m^{-3}$)	> 0.10	0.16	(DIN EN 13041, 2012)
pH	> 5.5; < 9.5	8	(OENORM L 1086, 204AD)
Dry bulk density ($kg\ m^{-3}$)	n/a	777.24	(OENORM B2606-1, 2009)
Wet bulk density ($kg\ m^{-3}$)	n/a	1075.83	(OENORM B2606-1, 2009)

Step 4: Identification of suitable plants. To find suitable plants for the different water use scenarios, 39 plant species were tested. Wall 2 was irrigated with 25 L tap water per day, and wall 3 was irrigated with 25 l greywater per day (scenario a). Tap water (25–50 L per week) was used in wall 1 (scenario b), and wall 4 was treated with 90 L greywater per day (scenario c).

In scenario (b), for low water demand, only 4 species survived in good condition (*Heuchera x cultorum* ‘Berry Smoothie’, *Aster ageratoides* ‘Asran’, *Geranium wallichianum* ‘Rozanne’ and *Satureja montana*). For the sufficient water scenario (a), which was irrigated every day, in addition to those recommended for the dry scenario, the species *Iris barbata nana* ‘Brassie’, *Rudbeckia fulgida* ‘Goldsturm’, *Hemerocallis middendorfii* and *Salvia officinalis* were very suitable. *Iris pseudacorus*, *Bergenia cordifolia*, *Calamagrostis x acutiflora* ‘Karl Foerster’, *Fragaria x ananassa* ‘Delikatess’, *Allium schoenoprasum*, and *Rosmarinus officinalis* ‘Miss Jesopp’s Upright’ were also in good condition. In the greywater treatment system (scenario c), the species *Eupatorium cannabinum*, *Mentha aquatica*, *Sedum telephium*, *Eriophorum vaginatum*, *Thelypteris palustris* and *Lythrum salicaria* were suitable (see Table III.13).

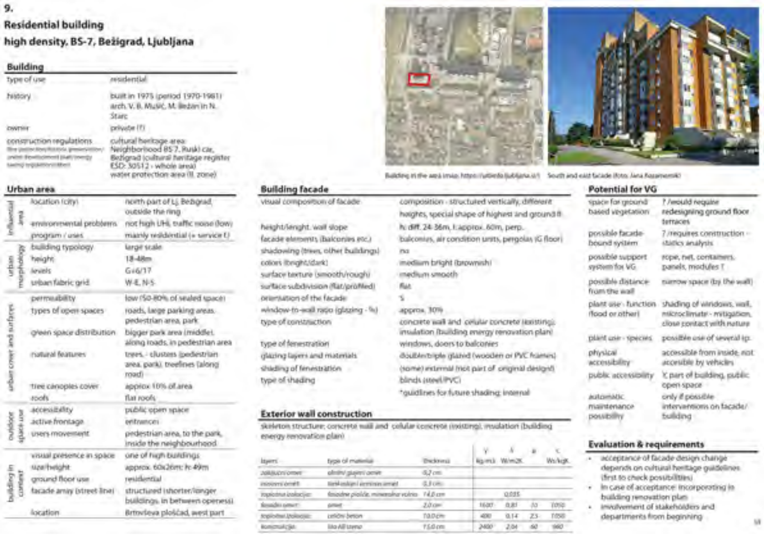
Table III.13: Suitable plants for different water use scenarios in the pot-based green facade

Daily irrigation (scenario a)	Irrigation 1-2 times/week (scenario b)	Greywater treatment (scenario c)
Aster ageratoides Asran	*Aster ageratoides* Asran	*Eupatorium cannabinum*
Heuchera x cultorum Berry Smoothie	*Heuchera x cultorum* Berry Smoothie	*Mentha aquatica*
Geranium wallichianum Rozanne	*Geranium wallichianum* Rozanne	*Sedum telephium*
Satureja montana	*Satureja montana*	*Eriophorum vaginatum*
Iris barbata nana Brassie		*Thelypteris palustris*
Rudbeckia fulgida Goldsturm		*Lythrum salicaria*
Hemerocallis middendorfii		
Salvia officinalis		
Iris pseudacorus		
Bergenia cordifolia		
Calamagrostis x acutiflora Karl Foerster		
Fragaria x ananassa Delikatess		
Allium schoenoprasum		
Rosmarinus officinalis Miss Jesopp's Upright		

It was noticed that more water was better for the plants than dry conditions, and a similar result was seen in the measurement of the biomass (chapter IV), where the highest biomass was produced in the wall with the highest intensity of watering. Comparing plants irrigated with treated greywater and tap water, no differences in plant development could be detected after 2 years of operation. In addition to those explored for the above-mentioned adaptations, a larger range of plants should be tested, and a longer testing period is necessary to investigate the comprehensive potential and performance of the presented multifunctional VGS.

5 Implementation potential of Vertical Greening Systems in Vienna, Ljubljana and Berlin

To address the question regarding the type of buildings that are suitable for VGS, building catalogues were created in the three partner cities (Vienna, Ljubljana, and Berlin). Each building catalogue provides an evaluation of different building types based on their vertical green implementation potential. Building types are presented through different examples of existing buildings selected to represent the relevant building characteristics of each city. Due to the differences between the three cities, the first step of analysis for the building catalogue was conducted separately, by considering various studies as well as the specific city characteristics related to building morphology. However, the key starting point in the analysis of building types for the building catalogue was identical for all cases and focused on the evaluation of different aspects and characteristics of the building type that are relevant for determining vertical green implementation potential. Every building example was documented in an evaluation form regarding its physical features, such as size, height, building structure, function, facade/wall construction, history of origin and regulations, ownership, and position in different scales of urban context. The documentation of a building is presented in Figure III.10. For the city of Ljubljana, nine buildings were selected as representatives of different construction styles and functions: industrial, commercial/shopping, public, and different types of residential buildings. Building types were surveyed and analyzed using GIS data, article reviews, and field surveys.



9.
Residential building
high density, BS-7, Bežigrad, Ljubljana

Building

type of use	residential
history	built in 1975 (period 1970-1981) arch. V. B. Mušič, M. Bežan in N. Starc
owner	private (?)
construction regulations (fire protection/historic preservation/urban development plan/energy saving regulations/other)	cultural heritage area: Neighborhood BS 7, Ruski car, Bežigrad (cultural heritage register ESD: 30512 - whole area) water protection area (II. zone)

Urban area

influential area	location (city)	north part of Lj. Bežigrad, outside the ring
	environmental problems	not high UHI, traffic noise (low)
	program / uses	mainly residential (+ service f.)
urban morphology	building typology	large scale
	height	18-48m
	levels	G+6/17
	urban fabric grid	W-E, N-S
urban cover and surfaces	permeability	low (50-80% of sealed space)
	types of open spaces	roads, large parking areas, pedestrian area, park
	green space distribution	bigger park area (middle), along roads, in pedestrian area
	natural features	trees - clusters (pedestrian area, park), treelines (along road)
	tree canopies cover	approx 10% of area
	roofs	flat roofs
outdoor space use	accessibility	public open space
	active frontage	entrances
	users movement	pedestrian area, to the park, inside the neighbourhood
building in context	visual presence in space	one of high buildings
	size/height	approx. 60x26m; h: 49m
	ground floor use	residential
	facade array (street line)	structured (shorter/longer buildings, in between openess)
	location	Brtovševa ploščad, west part

Building in the area (map: https://urbinfo.ljubljana.si/) South and east facade (foto: Jana Kozamernik)

Building facade

visual composition of facade	composition - structured vertically, different heights, special shape of highest and ground fl.
height/lenght, wall slope	h: diff. 24-36m, l: approx. 60m, perp.
facade elements (balconies etc.)	balconies, air condition units, pergolas (G floor)
shadowing (trees, other buildings)	no
colors (bright/dark)	medium bright (brownish)
surface texture (smooth/rough)	medium smooth
surface subdivision (flat/profiled)	flat
orientation of the facade	S
window-to-wall ratio (glazing - %)	approx. 30%
type of construction	concrete wall and celular concrete (existing), insulation (building energy renovation plan)
type of fenestration	windows, doors to balconies
glazing layers and materials	double/triple glazed (wooden or PVC frames)
shading of fenestration	(some) external (not part of original design)
type of shading	blinds (steel/PVC) *guidlines for future shading: internal

Exterior wall construction

skeleton structure: concrete wall and celular concrete (existing), insulation (building energy renovation plan)

layers	type of material	thickness	γ kg/m3	λ W/m2K	μ	c Ws/kgK
zaključni omet	[illegible]	0,2 cm				
osnovni omet	[illegible]	0,3 cm				
toplotna izolacija	fasadne plošče, mineralna volna	14,0 cm		0,035		
fasadni omet	omet	2,0 cm	1600	0,81	10	1050
toplotna izolacija	celični beton	10,0 cm	400	0,14	2,5	1050
konstrukcija	lito AB steno	15,0 cm	2400	2,04	60	960

Potential for VG

space for ground based vegetation	? /would require redesigning ground floor terraces
possible facade-bound system	? /requires construction - statics analysis
possible support system for VG	rope, net, containers, panels, modules ?
possible distance from the wall	narrow space (by the wall)
plant use - function (food or other)	shading of windows, wall, microclimate - mitigation, close contact with nature
plant use - species	possible use of several sp.
physical accessibility	accessible from inside, not accesible by vehicles
public accessibility	¼ part of building, public open space
automatic maintenance possibility	only if possible interventions on facade/ building

Evaluation & requirements

- acceptance of facade design change depends on cultural heritage guidelines (first to check possibilities)
- In case of acceptance: incorporating in building renovation plan
- involvement of stakeholders and departments from beginning

58

Figure III.10: Example for the evaluation list of the building catalogue of Ljubljana (image by Jana Kozamernik)

In Berlin, five typical buildings were registered. In Vienna, most buildings could be evaluated because of the inclusion of the topic in two student projects. In the first year, 57 buildings (different in age, function, and construction style) of Vienna's 16th district were identified and analyzed. The district was selected because of its high degree of sealing, densification, and architectural structure. For the classification of building ages, three categories were defined while referring to information maps of Vienna's cultural heritage (City of Vienna, 2020):

- Old buildings up to 1918 (first World War)
- Interim and post-war buildings up to the modern era (1976)
- Modern buildings after 1976

In addition, information about building structures provided by the City of Vienna was used to derive additional information about the building type and age, if available. The selected examples were recorded and are marked in the map presented in Figure III.11. Criteria for evaluating the possibility of the implementation of VGS were as follows:

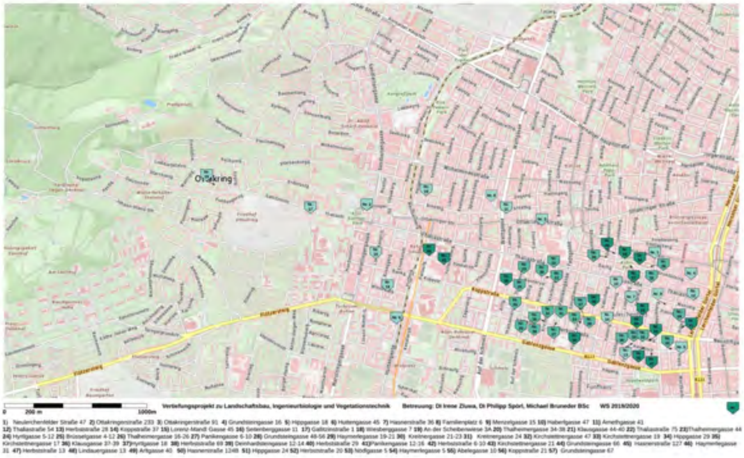


Figure III.11: Houses evaluated on their potential for VGS in Vienna's 16th district (light turquoise: old buildings up to 1918, turquoise: interim and post-war buildings up to the modern era (1976), old buildings up to 1918 (image by Michael Bruneder)

1. Is there a possibility of utilizing a ground-based green facade? Requirements for this option would be an unsealed surface next to the building or the possibility of unsealing.

2. In case of using the pavement for the installation of a planter-pot on the ground, 2.5 m must remain empty.

3. Buildings using a thermal insulation with a composite system should not be greened with self-clinging climbers.

4. Buildings higher than Vienna's "Bauklasse 3" (building height 9–16 m) need to be adapted for fire protection restrictions (see MA22, 2019).

5. The aesthetic characteristics of the building should remain unchanged.

This information was put in a matrix, thereby leading to the following results for the potential for VGS on buildings in Vienna's 16th district:

Old Buildings (Building age up to 1918): Among the 19 analyzed buildings, four buildings had sufficient space for ground-based green facades or for the installation of trays on the ground. In six buildings, pot- or wall-based systems were considered as potential options. Only a subtle greenery is recommended because of the rich ornamental decoration of the four buildings. Only one building had a balcony, and the other was retrofitted with a terrace, thereby leading to the potential for vertical greenery.

Buildings from 1918–1976: A total of 23 buildings were analyzed. In nine cases, there was sufficient space on the pavement for the installation of the planter-pots. The results show that 20–21 buildings were suitable for pot- or wall-based green facades, and eight buildings had balconies.

Buildings after 1976: Among 15 buildings, not a single building had sufficient space in front of the building for ground-based green facades. Pot- or wall-based green facades were possible on 12 buildings, and seven buildings had a balcony.

Based on the aforementioned analyses of the first year, the following conclusions can be provided: From a technical perspective, on all building types and building ages, some type of VGS is possible. However, the limiting factor is more aesthetic and depends on personal taste. In the second year, aesthetic perspectives were included to the aforementioned criteria list: buildings with a strong design concept and historical buildings with rich ornamental facades were excluded. Additionally, the size of the quarter selected for evaluation was reduced to an area called Deinhardstein-“Grätzel”. Therefore, the entire building stock can be included. Among 264 buildings, 203 were found suitable to be retrofitted with VGS (Figure III.12). A field analysis was conducted in specific neighborhoods to assess the potential for VGS on the existing built fabric. The analysis related to buildings could then be extended to include other criteria related to the influential area or the ambient – street, square, courtyards, etc. In this context, parameters of the nearby environment, such as the characteristics of horizontal surfaces (paving, green areas, permeability, and vegetation), and the presence of green elements, such as trees, are identified. The potential for green facades is recognized as a contribution to spatial quality, especially when a lack of green elements is noted in the built fabric. In these areas, their implementation is also encouraged through renovations. However, the design goals and considerations for the VGS must also be evaluated.

Figure III.12: Buildings suitable for VGS (green) and unsuitable for VGS (red) in the Deinhardstein-Grätzel (Vienna) (image by Samuel Schnöll)

The criteria of analysis of buildings and open spaces are a key factor in the decision-making process for green facades and the use of this type of facade. These criteria can also be an integral factor of the guidelines for their implementation, to be included in planning documents at the city level (chapter V).

6 First steps for robotic solutions in VGS maintenance

Machinery technologies for VGS maintenance can be considered a subset of agricultural machinery, so the objective for the use of agricultural machinery also applies here (Schön, et al., 1998). The use of tools, equipment and machinery is an essential characteristic of human activity. The following objectives were pursued with technology:

- Improvement of production. This means increasing yields, reducing losses and cultivation risk, and increasing product quality.
- Improvement of labor productivity. This objective includes, for example, saving labor time and increasing labor comfort.
- Improvement of economic efficiency
- Plant selection

When comparing maintenance of VGS to traditional agriculture, the main difference is the direction of the Earth's gravity facing parallel to the planted area. As a result, the technologies have to be adapted for the working procedures and for movements in the crop. For example, a conventional undercarriage is no longer needed and must be replaced by vertically arranged rails, wire rope hoists or other technical solutions common to lifting equipment. According to Schmal (2017), the amount and type of construction material is crucial to obtain a positive CO2 balance in a green facade. Due to the extensive structure needed, the approach of having interchangeable modules is not seen as an environmentally friendly solution for large VGS from our point of view. In the following, stationary plants and a moving tool are assumed. Machine technology systematic can be oriented towards the tasks of machines during plant life and structure.

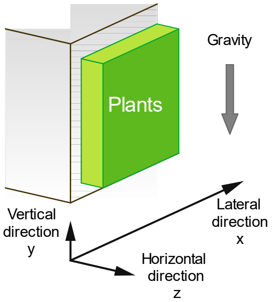


Figure III.13: Direction of gravity

Table III.14: Morphological system describing machine technologies for vertical greening

Characteristic	Variants						
Crop production process	Tillage	Planting and sowing	Fertilization	Plant protection	Irrigation	Harvest	
Automation level	Manual	Partially automated	Fully automated				
Type of energy	Human energy	Electrical energy	Chemical energy	Hydraulic energy	Pneumatic energy		
Energy supply	Powerline	Energy storage on board					
Guidance of tool	Parallel motion structure	Serial motion structure	Structure with changing base connections	Unguided			
Degrees of freedom of the tool	0	1	2	3	4	5	6
Camera	No	Yes					
Image processing	No	For control of the movement	For determination of plant condition	For control of the working process	For all control tasks		

The following scheme (Table III.14) lists possible variants or partial solutions for different characteristics and helps to develop new solutions and products by combining these.

With this scheme, solutions for different crop production processes can be discussed. At the beginning of the project in Summer 2018, the steps needed for VGS maintenance were not well documented. During an international stakeholder workshop on 26.09.2021 at TU Berlin, the general requirements for harvest and maintenance technologies were determined by the stakeholders. The stakeholders again underlined the urgent need for inexpensive maintenance. In addition, the need for differentiation between private and professional use was expressed. On the one hand, parts of the public community have a high interest in interacting with VGS; on the other hand, the need for fully autonomous systems was expressed. With low-tech and multifunctional high-tech systems, our research project reflects these different interests very well.

Table III.15: Different approaches to moving a tool corresponding to the ground

Parallel motion structure	Serial motion structure	Structure with changing base connections	Unguided
Cable driven robot	Motion portal	Canadarm2	Agricultural Drone

The following pages describe the multifunctional high-tech system developed during the project. Available solutions could not be found on the market. During a literature search in 2018, no comparable research projects could be identified. This changed significantly in 2019/2020 when two other projects with the same aim began publishing the first results.

- The Fraunhofer IPA and the Institute for Energy Efficiency in Production (EEP) of the University of Stuttgart started the project "Green Wall Robot – automated, smart green facades". On the one hand, the team presents a design study of a cable-driven robot. On the other hand, they describe ideas for a rail-driven system that can exchange and maintain greening modules. (Reisinger, Bregler, Kraus, 2019)
- The University of Technology Sydney (UTS) started "The Green Wallbot" project. In the executive summary of the project report, the following product is described: "Wallbot, a robotic installation to inspect, monitor and maintain green walls offers the chance to reduce OHS issues and maintenance costs associated with green walls" (Figure III.14). The developed robotic prototype is comparable to our multifunctional high-tech solution. However, the final solution found by the UTS was limited to data collection and could not physically maintain the plants. (Wilkinson, Carmichael, Khonasty, 2021)

Four main concepts could be identified for positioning a tool head corresponding to greening. These are a parallel motion structure, a serial motion structure, a "walking" structure with changing base connections and an unguided, free moving drone. These concepts and examples of real implementations are shown in Table III.15.

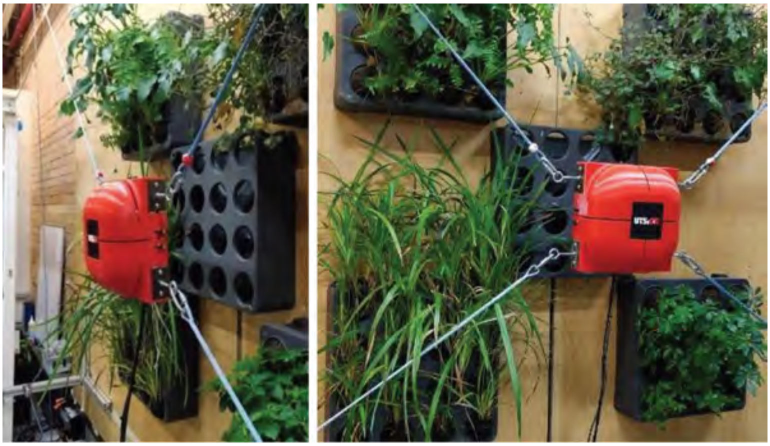


Figure III.14: Wallbot Prototype of the UTS (Wilkinson, Carmichael, & Khonasty, 2021, Copyright © 2021, Emerald Publishing Limited)

For the development of the multifunctional high-tech robot at the TU Berlin, concepts were then evaluated with a benefit analysis following the VDI 2225 guideline. The drone performed worst due to safety and efficiency reasons. The motion portal is a state-of-the-art solution, but the structure needs to be very massive and is thus expensive for the required workspaces. The concept of having a structure with changing base connections walking along the facade sounds very promising and works successfully for pictured applications in space without gravity. Automatic, stiff and safe coupling to connectors on the greened facade was assumed by the author to be critical. In addition, either many connectors in a dense arrangement or very strong connectors are needed. Although this concept has not yet been demonstrated to prevail, it is worth further assessment. The concept with the highest score in the benefit analysis was a parallel driven cable robot. A system with a comparable working space was set up by researchers at the University of Duisburg-Essen during the LEAN project. In the benefit analysis, this concept scored well with its potentially large working space, robustness, safety and energy efficiency. As found later, the same discussion with the same conclusion was made by the UTS. (Wilkinson, Carmichael, Khonasty, 2021)

6.1 Cable suspended robot

An incompletely restrained positioning mechanism with 4 transmission elements driven by 2 brushless DC motors will be set up for this task (Figure III.15). The transmission elements on each side run parallel and are assumed to be stiff. In this configuration, the height (y) and the horizontal motion parallel to the facade (x) can be controlled by the winch motors. The orientation around the y and x axes is constant for all poses. One uncontrolled degree of freedom is a swinging movement orthogonal to the facade. Forces in this direction will not affect the cable tension. This allows a downsizing of the winch motors. The distance to the facade is regulated with rotors. A laser level is installed with a rotary laser parallel to the facade. A self-built laser level detector measures the position of the laser level corresponding to the robot. This information is used to dynamically control the rotor power. The second remaining degree of freedom is a rotation movement around the axis orthogonal to the facade. This degree of freedom would be avoidable with more cables, but the orientation is stabilized and limited by gravity. Small deviations of the robot around this axis can be accepted as long as the position of the tool head can be held in the desired position. This can be achieved by counteracting the rotation of the robot with the installed turning axis for the tool head.

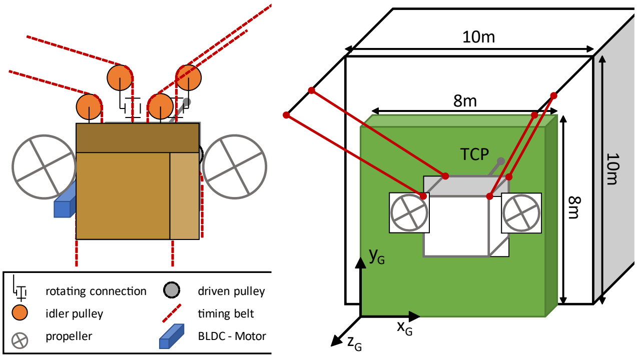


Figure III.15: Mechanical concept of the robot (left) and working space and coordinate system (right)

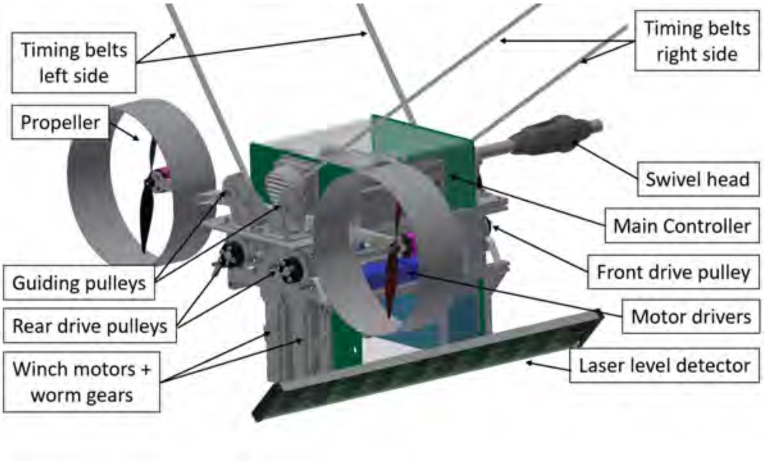


Figure III.16: Virtual prototype of the maintenance robot

Figure III.17 shows the actual prototype. The winches to drive the pulleys are driven by 400 W BLDC motors from Nanotec® in combination with worm gears. The thrust to control the distance to the facade is generated by two rotos that run in contrary directions to avoid torque on the robot. The rotation of the tool head is realized with a worm gear and a 2 DOF Robolink W cable-driven joint from Igus®. The three turning axes are driven by stepper motors. The system is powered by a custom-made Li-ion battery with a nominal voltage of 44,4 V, a charge of 20 Ah and a continuous current of 100 A. The system is controlled with a Raspberry Pi 3 running CODESYS. A PiXtend extension makes all in- and output industries compatible. The final mass is approximately 47 kg. Figure III.20 shows the prototype at the test site. The system was tested at the TU Berlin test site. Initial tests were carried out to verify the precision of the tool head movement. The red marker in Figure III.18 was drawn by the robot. The precision of the toolhead parallel to the facade resulting from the cable-driven mechanism was in the target range of 1 cm. The precision perpendicular to the facade resulting from the rotor system was worse than expected. With an optimized controller design, the following precision perpendicular to the facade could be achieved. The static accuracy is also in the range of 1 cm, but great deviations occur in dynamic operations.

Figure III.17: Maintenance robot at the Berlin test site (image by Sebastian Schröder)

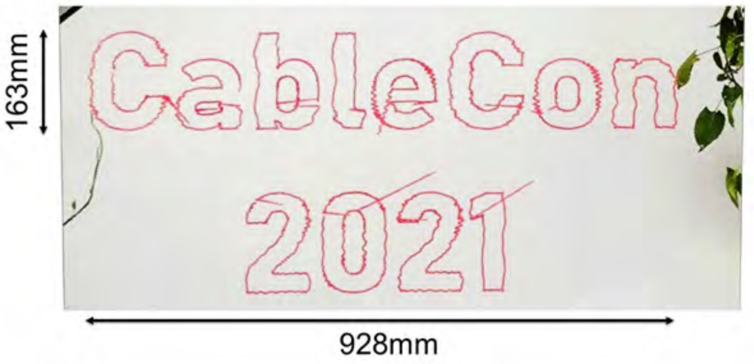


Figure III.18: Text as an example of the accuracy in the horizontal and vertical directions of the robot

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In addition, the power consumption and noise of the rotor systems were greater than expected and what would be tolerated in a real application. Real tests were performed with two different cutting tools.

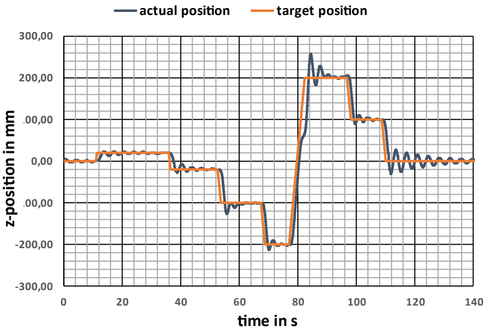


Figure III.19: Diagram of actual and target position over time

The rotary scissor tool head was successfully used to cut the lower part of the Fallopia. For cutting the upper parts, the connection beam on the wall had to be installed approximately 2 m above the highest plants. At the time of cutting, the greenery had been growing for a whole season and had become sprawling. From time to time, the robot became stuck in the plants during cutting. This prevented automatic operation. Thus, the robot was controlled manually. After the first cut, automatic cutting cycles were successfully tested. It is recommended that greenery be cut several times per year. This allows reliable automatic cutting procedures and probably gives a more aesthetic look to the greenery. Pneumatic-driven pruning shears were successfully used to cut single stronger branches on the facade. A cable robot is still seen as the best solution for maintaining large green facades. The backcuts requested by most of the stakeholders could be carried out with the prototype. The regulation of the distance to the wall via rotors did not meet the expectations. In the following prototypes, the tool head should be actuated with a longer linear axis perpendicular to the facade.

Figure III.20: Test site before (left) and after (right) the first cut (images by Sebastian Schröder)

6.2 Rail-driven robot

The research team at National Taiwan University (NTU) was responsible for the design and development of the reduced and simplified prototype body for testing, the development of tools for harvesting and the design of sensor systems and information processing.

Development of an Automatic Transportation System for Vertical Green Walls

At present, most of the plants on VGS are ornamental flowers. In recent years, scholars have successively investigated whether crops can be planted on green walls. In addition to maintaining the functions of the green walls, they need to be demolished at the end of the construction period in Taiwan. With the green wall being destructed eventually, crops can also be harvested from the wall. Based on the abovementioned purpose, this research used a three-axis gantry mechanism as a hardware platform to develop an automatic plant pot handling system applied to a VGS. This system is equipped with machine vision and image processing technologies to assist the overall electro-mechanical system. The overall system functions include the placement and removal of hanging pots, and the ability to replace the wilted plants with hanging pots when the plant withering is found through image recognition during the growth of the crop.

The automatic handling system developed is used for vertical green walls as shown in Figure III.21. In the experiment, a wall-based system is used, which has the advantages of diversified plantings, convenient maintenance and management, etc. VGS, *Ocimum basilicum var. thyrsiflora* and *Capsicum annuum* were planted on the VGS. The three-axis gantry mechanism is set up at the front end of the green wall as the moving platform of the handling system.

The gantry mechanism model is a Farmbot Genesis v1.4 and defines the horizontal movement direction of the mechanism as the green wall x direction and the vertical movement direction of the mechanism as the green wall y direction. The x-direction moving mechanism uses a timing belt and pulley system, and the y-direction moving mechanism uses a screw system. A webcam is installed on the organization as machine vision to assist the overall system in achieving automatic identification.

The self-designed image processing system in this research can analyze the centroid position of the hanging pots with plants on the VGS and uses this centroid position to convert between the pixel distance and the actual distance to obtain the moving position required by the overall transport system. Then, the function of hanging the pots and automatically unloading the pots can be achieved.

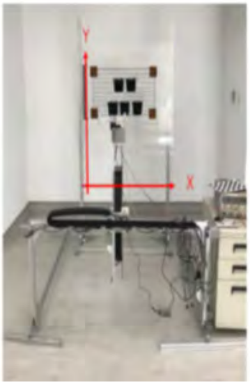


Figure III.21: Setup of the vertical green wall and gantry mechanism (image by Chung-Kee Yeh)

In this study, deep learning-YOLOv3 was used to assist in distinguishing living plants and wilted plants. The recognition rate of living plants was 93.75 % and that of wilted plants was 66.67 %.

The design of the potted plant transplant gripper takes the protruding outer edge of the upper side of the hanging pot as the contact target of the gripper. The development board Arduino UNO controls the servo motor set on the left side of the gripper to make the gripper rotate and close. The protruding outer edge of the hanging pot touches the gripper, and then the FarmBot manipulator lifts the whole pot up and detaches it from the grid, transports the hanging pot to the placement area and releases it. Two microswitches are arranged on the right side of the gripper, the purpose of which is to sense whether it touches the hanging pot to compensate for the distance error judged by machine vision. The potted transplant gripper is shown in Figure III.22.

Figure III.22: Prototype of potted plant transplant gripper (image by Chung-Kee Yeh)

The overall dimensions are l = 190 mm x w = 170 mm x h = 174 mm. The potted transplant gripper can handle hanging pots up to 4.5 kg, and the success rate of stable clamping during the operation can reach more than 95 %, which means that this gripper design based on the principle of holding up the hanging pot is feasible.

6.3 Tools for VGS maintenance

Several tools for harvesting and cutting were developed. All developed tools for cutting are based on commercially available horticultural products. The requirements depend strongly on the strength of the branches. Two different tools are needed. One tool is used to cut many thin branches and leaves, and one tool is used to cut single stronger branches. In this book only the final prototypes are shown.

Rotary scissors tool

For the development of the cutting tool for thin branches, many hedge and grass trimmers were tested. The biggest problem was the sticking of individual branches in the blade and the drivetrain. The best results were observed with a modified rotary scissor head from the manufacturer Stihl. Due to its low likelihood to propel stones, it is increasingly used instead of brush cutters for conventional green space maintenance. The unit consists of two circular oscillating blades with sharpened teeth that can cut in any direction. It is supposed to be driven with a long shaft inside the handle. The motor at the top end of the handle was used as a counterweight. The whole drivetrain was reconstructed due to the high weight and the unsuitable mounting position of the motor. For the new drivetrain, a Bosch GSR 35 cordless drill was modified and adapted to the gear of the Stihl rotary scissors (Figure III.23). The cutting unit can be adapted to the swivel head of the multifunctional robot. The robot with rotary scissors can be controlled manually with a remote control, or preconfigured cutting programs can be used.

Pruning Shear

To cut single branches with a width of up to 20 mm, a pneumatic driven pruning shear was adapted to be used at the robot (Figure III.24 and Figure III.25). A very compact pneumatic system was developed to power the unit. It consists of a compressor, conventionally used in air suspended swing seats, a small air tank and a valve terminal. The system has proven to cut branches up to 20 mm and is intended to be used on the robot with manual control only.

Figure III.23: Modified rotary scissor tool head for cutting thin branches and leaves (images by Sebastian Schröder)

Figure III.24: Pruning shear installed at the robot (image by Sebastian Schröder)

Harvesting gripper

The design of the harvesting gripper allows the cutter to obtain sufficient kinetic energy for cutting in a small space, and the clamping process does not require sensor feedback.

Figure III.25: Pruning shear during test cuts (image by Sebastian Schröder)

The movement of the mechanism is simplified into a three-link mechanism with a high pair type to form an open chain, and a servo motor is used to drive the mechanism to run. This mechanism is also equipped with a hammer to transmit rotational kinetic energy, which shortens the width of the front end when the claws are opened while retaining the original cutting design and clamping performance. The leading angle at the front end of the gripper makes it possible to move the stems and leaves to both sides when reaching the plant. The fasteners are spring pins to improve durability. The harvesting gripper is shown in Figure III.26. The overall dimensions are l = 155 mm x w = 41 mm x h = 70 mm. It is estimated that the prototype harvesting gripper can generate 42 mJ of cutting kinetic energy. After preliminary harvesting tests, it was found that the harvesting gripper opening and the driven cam should be operated separately, and the opening width can be limited to a smaller range. The rotation angle of the active cam is adjusted on site, and the angle is 56° when opening, 40° when releasing, and 100° when resetting. In addition, the average durability of this harvesting gripper can reach 361.6 times.

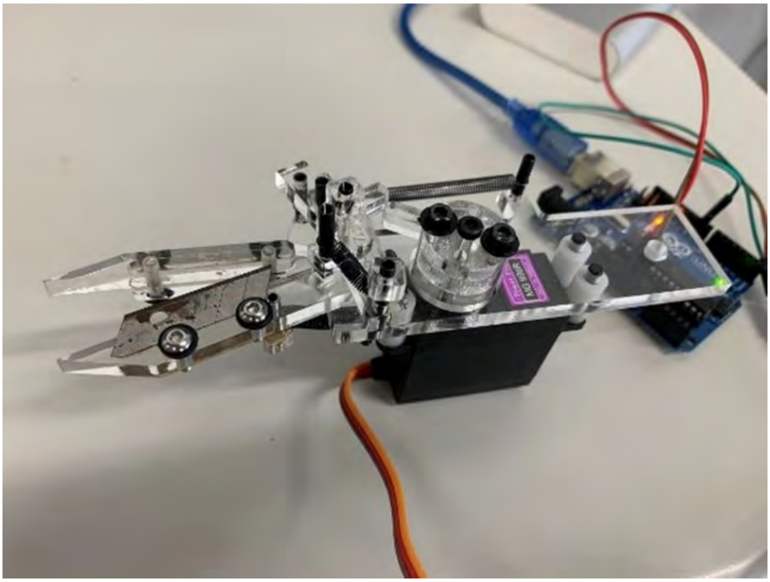
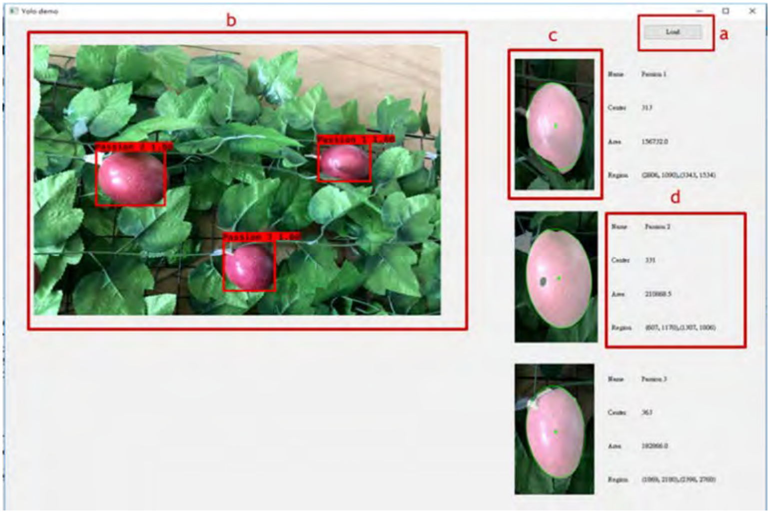


Figure III.26: Prototype of harvesting gripper (image by Chung-Kee Yeh)

6.4 Information technology for VGS maintenance

Application of Deep Learning to the Image Recognition of Fruits on VGS Before an automatic harvesting machine is introduced, the machine must be able to see or sense the fruit. In this study, passion fruit suitable for growing in Taiwan's climate and walls was used on a VGS. Furthermore, positioning, fruit size and fruit number calculation, and boundary contour detection are performed so that the machine can recognize fruits and vegetables. Here, the passion fruit model, the vine model and the iron frame were used to simulate passion fruits growing on a VGS. The passion fruit wall model of this experiment is shown in Figure III.27, left. The test image was input into the trained YOLO v3 model, and the bounding box was output, as shown in Figure III.27, right. To make the picture more readable, the image near the original bounding box area is combined with the picture after image processing, and the center point is found in the outline range and presented in a human–machine interface, as shown in Figure III.28.

Figure III.27: Passion fruit wall model (left) and bounding box of a passion fruit (right) (images by Chung-Kee Yeh)



Name Passion 1
Center 313
Area 156732.0
Region (2806, 1090),(3343, 1534)

Name Passion 2
Center 331
Area 210868.5
Region (607, 1170),(1307, 1806)

Name Passion 3
Center 363
Area 182066.0
Region (1069, 2180),(2396, 2760)

Figure III.28: GUI function bar and display after importing pictures

The characteristics of this study are as follows: (1) After improving the YOLO v3 algorithm, the whole fruit can be framed. (2) There are approximately three hundred training materials, which can have good results on the YOLO v3 deep learning model.

(3) This method can be effectively used in the harvesting system of VGS to achieve the functions of fruit identification, fruit number calculation, and accurate positioning of the fruit center point, enabling machine vision. (4) The average accuracy of transfer learning is 97.93 %, and the time it takes to train the model is relatively short. (5) This experimental procedure is highly versatile, so the experimental procedure is expected to be applied to the identification of other fruit plants, such as oranges, strawberries, mangoes, etc. Another example of the application of deep learning to VGS robots is the image recognition and harvesting of colorful peppers, which mainly relies on machine vision to identify the target object and performs harvesting tasks through a three-axis robot. The image recognition component involves training the "plants with mature colorful pepper fruits" model through YOLO v4 and using image processing to realize single feature analysis to identify mature colorful pepper fruits. The harvesting control part mainly uses image servo control to locate the identified colorful pepper fruits. finally, the depth information of the target pepper is read through the depth camera, and the harvesting task is realized through open-loop control. The system identification process of the entire harvest is shown in Figure III.29. The picking strategy is to first find the colorful pepper plant closest to the plane of the robot gripper as the first harvest target, slowly approach the plant, and use a depth camera to read the depth information of the pepper fruit in the plant, choose the fruit with the closest depth information as the first target fruit, and finally pick it through image servo control. In a good experimental environment, the success rate is 85.3 % for pepper plant identification and 100 % for pepper identification when there is no overlap of peppers, which makes identification difficult, and there is no leaf obscuration that causes difficulty in harvesting. The harvest success rate was 76.7 %.

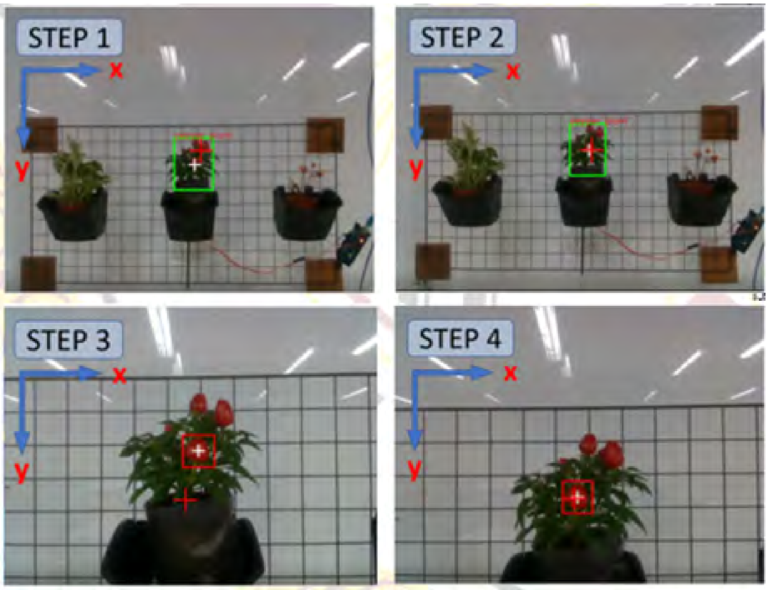


Figure III.29: System identification process for harvesting

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16

Chapter IV

VERTICAL GREENING SYSTEMS IN THE URBAN FOOD WATER ENERGY NEXUS

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1 Introduction

The concept of the food-water-energy nexus (F-W-E) creates an evident linkage in understanding single interconnected sectors (Hoff, 2011). This interdisciplinary, holistic view is expected to enable a coherent, overreaching policy for sustainable development. It is supposed to be based on resource consistency, efficiency, and sufficiency. Thus, it should increase security in the supply of food, water, and energy by considering the linkages in and between those individual sectors (Howarth and Monasterolo, 2016; Avellán et al., 2017).

Interdependencies between the food, water, and energy sectors can be identified at different scales. A tangible viewpoint can be established at the building scale, as inhabitants rely on food production, drinking water, sanitation, and energy supply. Recognizing these dependencies leads to some design and management principles for the implementation of Nature-based solutions (NBS), specifically vertical greening systems (VGS). VGS can be designed and managed as separate add-ons for buildings. However, they can also be integrated into existing process chains in the food, water, and energy sectors and ideally optimize them, thus transforming the abstract nexus concept into reality. Using otherwise "wasted" resources is crucial for achieving this aim at the building scale.

The development of plants depends on the availability of water, nutrients, and sunlight. Buildings as functional urban units produce wastewater, thus wasting water and nutrients and emitting heat from their surfaces, originating from shortwave solar radiation absorption. These streams can be exploited and defanged in VGS for producing biomass or food, for example, grapevine, hops, fruits, vegetables, and herbs, investigated in the course of this project.

Water is a key element for humans and the global ecosystem. Worldwide, water consumption by humans comprises the following sectors: 69 % agriculture, 19 % industrial applications, and 12 % used in municipalities. In Europe, 21 % of water withdrawals account for agricultural use, 57 % for industry, and 22 % for municipalities (Aquastat, 2015). Until 2050, an increase of 50 % in water demand is expected (OECD, 2012), caused by population growth and urbanization. The implementation of urban greenery is supposed to increase the urban water demand. Currently, freshwater or tap water is used for irrigation. The sustainability of this practice is challenged by the increasing effort to generate a paradigm shift toward circular economy principles in urban water management and foster water reuse practices (Pearlmutter et al., 2021). Regarding energy, the buildings and construction sector is one of the most substantial global contributors to final energy use (36 % in 2018) and energy- and process- related carbon dioxide emissions (39 % in 2018). The production of construction materials such as steel, cement, and glass is responsible for 11 % of the process-related carbon emissions (IEA, 2019).

Once constructed, the built environment with its high fraction of vertical surfaces, sealed areas with little or no vegetation, street canyons, and the dominance of dense mineral materials forms an urban climate that differs from rural surroundings. It is often visible in higher air temperatures, reduced relative humidity, and lower wind speeds (Endlicher, 2012). In summer, the urban heat islands (UHI) (Oke, 1982) can lead to heat stress both indoors and outdoors, increasing heat-related morbidity and mortality (D'Ippoliti, 2010). Sangiorgio et al. (2020) stress the relevance of land cover types and greenery in cities to reduce urban heat island intensities. Facade greenery as an urban NBS helps counteract summerly heat stress as it cools building surfaces and can also be used to reduce operational energy, especially during the cooling season (Pérez, 2014).

In this chapter, we present the capabilities of VGS to address the F-W-E nexus by contributing to food and biomass production, water treatment, and reuse to reduce freshwater depletion and energy consumption.

2 Food and biomass production potentials

One of the main obstacles mentioned in stakeholder discussions about facade greenery is the unsolved problem of costs for maintenance, pruning, and biomass waste disposal (Kühle, 2020). Perrini and Rosasco (2013) for instance, calculate with 31 € per m² of biowaste disposal from pruning. This is kind of absurd if biomass is regarded an energy resource. However, the potential biomass production of VGS is too small to be relevant for energy conversion at the building scale (Schmal, 2017), it is more reasonable to produce valuable products such as fibres, pharmaceuticals or food. VGS can be used to produce a variety of food products. Climbing plants (e.g., selfclimbers, clingers, with and without tendrils, spreading climbers with their bristles, spines, and offshoots, see chapter III) do not comprise an individual plant family but build a form taxon. Climbers can be found in many plant families, including some foodrelevant like hops (*Humulus lupulus*) beans (*Phaseolus*), grapevine (*Vitis vinifera*), but also some tomato varieties (*Solanum lycopersicum* var. Himmelsstürmer), blackberries (*Rubus sp.*), and kiwi plants (*Actinidia sp.*). In addition, wall-based green facades offer plenty of opportunities to cultivate edible plants. Is VGS integrated production an option for urban gardening and farming?

In this project, we investigated food production potential in Berlin, Germany and Vienna, Austria. On a western-oriented test wall located on the inner-city campus of TU Berlin, Germany, ground-based green facades were installed, and their biomass production was monitored in 2020 and 2021. The systems comprise eight plant containers with a volume of 1 m^3 each, planted with hops, beans, grapevine, and mile-a-minute as a non-food reference used by Schmal (2017).

2.1 Hops (*Humulus lupulus*)

Humulus lupulus or common hop is a herbaceous, perennial climbing plant and one of the most expensive crops. The part of the plant which is above ground dies in autumn, and new shoots grow from the woody roots back in spring. In a natural environment, hop plants use other shrubs or trees as climbing aids. However, in agriculture, 5.5 m to 7.5 m high frames or ropes are used for optimal harvesting. The flowers of the female hop plant are used for beer flavoring and preservation. Hop production for breweries is spread in the northern and southern hemispheres between 35° and 55° latitudes where the seasonal change in sunshine hours allows blooming. Most agricultural areas used for hop production are located in Germany and the US (60 % of the total) (Lfl 2011).

In 2018, students from the Technische Universität Berlin (TUB) developed the idea and a prototype of “facade brew”, an integrated facade greenery and urban hops production (funded by climate KIC Berlin). The selected brewery then refused to brew with the harvested hops because of hop quality issues. However, in an art project in Vienna, a local branded beer was crafted with the flavor of hops growing on an empty parking house (González-Méndez and Chávez-García, 2020). On the test stand at TU Berlin (Figure IV.1), hemp ropes allowed plant growth of 8.5 m and 11.75 m in 2020 and 8.5 m in 2021. On a 3 m wide wall, approximately 5.9 kg of wet biomass was harvested at the beginning of October 2020, equivalent to 578 g of dried biomass (dried at 105 ℃). During the vegetation periods (that began in early to late March for both years), the occurrence of pests (aphids in 2020 and spider mites in 2021) substantially influenced the vitality of hop leaves and thus, the overall growth.

2.2 Beans (*Phaseolus coccineus*)

Runner bean or *Phaseolus coccineus* is a herbaceous climbing plant that can reach heights of 2–4 m and at times up to 7 m. It is an annual plant in central Europe, but it can be perennial in warmer climates.

Figure IV.1: *Humulus lupulus* in spring (left) and summer (middle) and harvested blossoms (right) (images by Karin A. Hoffmann)

Sown in May, it is a fast-growing climber withbright red flowers that produce bean pods of approximately 20–25 cm in length. It can be used as an ornamental plant or for food production. At the test stand of TU Berlin, maximum heights of 3.3 m (2020) and 7 m (2021) could be reached, resulting in 1 kg and 1.7 kg of dried beans on a wall of 1.5 m width in 2020 and 2021, respectively. In June and July, the bean plants tended to be infected by Aphis fabae; an aphid commonly found in bean plants (Figure IV.2). The application of beneficial insects such as ladybugs (*Coccinella septempunctata*) could reduce but not stop the spread of aphids.

2.3 Grapevine (*Vitis vinifera*)

As discussed in Korb (2018), increased temperatures due to the urban heat island (UHI) effect, lower risk of frost, and more extended vegetation periods compared to the rural surroundings enhance Berlin's suitability for grapevine cultivation. However, depending on the wall orientation and the surrounding buildings, sunshine hours can be reduced and may not meet the requirements of the plant. With yearly precipitation sums of approximately 600 mm, there is enough water available for irrigation. However, because of the heterogeneous precipitation patterns in the inner-city area and on the facade (windward versus the leeward side of a facade), and the heterogeneous retention capacity of urban soils, additional irrigation should be considered (Korb 2018). At the Berlin test site, the grapevine was planted in two plant containers (Figure IV.3).

Figure IV.2: Bean pod at TU Berlin test site (left), bean plant infected by *Aphis fabae* and with applied larvae of *coccinella septempunctata* (middle); harvested beans (right) (images by Karin A. Hoffmann)

In both monitored vegetation periods of 2020 and 2021, the leaves of the grapevine plants were entirely harvested by passers-by in spring, assumingly for personal consumption. Therefore, plant growth and the production of grapes decreased, and biomass production potential could not be quantified on-site. However, the production of vine leaves seems to be an additional opportunity for food production codeveloped by the Berlin communities. Some varieties have especially large leaves and no trichomes (Greek for “hair”) at the backside of the leaves suitable for stuffed vine leaf production, including Callastra.

Figure IV.3: Grapewine at TU Berlin test site in June 2020 (image by Karin A. Hoffmann)

Rubino (2019) developed a method based on the Solar Energy Building Envelopes model (SEBE) regarding the areas potentially usable for vine production. He determined suitable vertical areas for grapevine production in an inner-city area of approximately 1.8 km^2 in Berlin, Germany (Figure IV.4). The growing season is determined by the number of consecutive days above the threshold temperature during the year. In addition, the grapevine has specific requirements of sunshine hours and irradiation, which are highly heterogeneous in the urban morphology depending on wall orientations and neighboring obstacles. Considering the irradiation requirements, Rubino found a total suitable area for the indicated district of 229,902 m^2 vertical space and 143,258 m^2 if only consecutive meters on the wall were considered. However, at the moment, the state of the art of vertical food production on facades is more hypothetically than approached, primarily because of harvesting issues and access and limited root space.

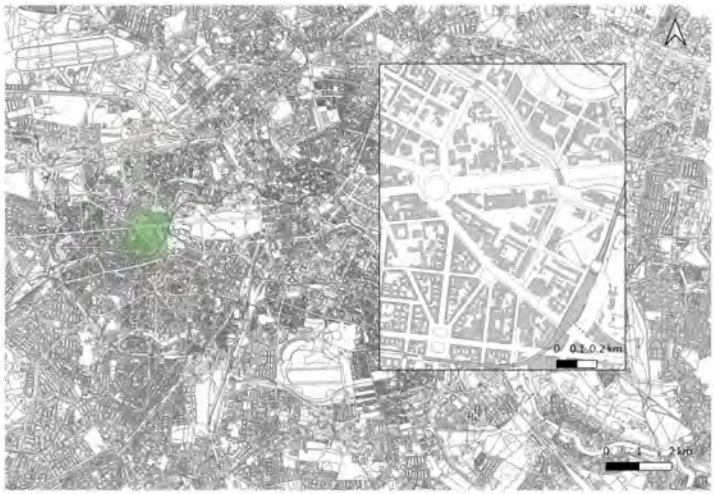

Figure IV.4: Study area in Rubino (2019) for potential vertical grapevine production areas in Berlin, Germany (image by Karin A. Hoffmann with spatial data from FIS-broker 2022)

2.4 Herbs, fruits and vegetables

At the University of Natural Resources and Life Sciences in Vienna (BOKU), the prototype of a “Vertical Farmers Garden” was operated for one growing season (Figure IV.5). The plant species were selected with respect to traditional gardens in Austria, including espalier trees (*Malus sp.*, *Pyrus sp.*), vegetables (*Lactuca sativa Solanum lycopersicum*, *Cucurbita pepo*, *Capsicum annuum*), herbs (*Allium schoenoprasum*, *Mentha × piperita*, *Valeriana officinalis*, *Satureja hortensis*) fruits (*Fragaria × ananassa*, *Physalis peruviana*), and edible flower species (*Calendula officinalis*, *Borago officinalis*, *Hemerocallis*, *Tropaeolum majus*, *Helianthus annuus*). The “Vertical Farmers Garden” had an appealing view (Figure IV.7) and good plant coverage during summer, but the harvest was poor mainly because of the poor accessibility. The heavy staircase had to be moved to pick up every single strawberry. For the case of private urban farming (gardening), the height of the VGS should be reduced to a reachable unit. To test the possibilities of small-scale urban farming, a self-made system made of simple racks with common planter boxes and soil (Figure IV.6) was installed and investigated in a master thesis (Berger, 2022). The harvest of the year 2019 per m^2 was 5570 g of tomatoes (*Lycopersicon esculentum* ‘Gelbe Birne’), 966 g (*Allium schoenophrasum*), 282 g chives (*Lactusa sativa L. var crispa*), 2476 g bell peppers (*Capsicum annuum* ”Blockpaprika rot”), 253 g *Fragaria ananassa* and 410 g Rosemary (*rosmarinus officinalis*) (Berger, 2022). The harvest of vegetables (tomatoes and peppers) in a self-constructed VGS was approximately half the harvest that could be produced with conventional farming methods. Solutions such as the self-made rack system allow urban farming in VGS on small spaces such as balconies.

One direction for production on a larger scale in a pot or wall-based green facade could be to grow herbs (e.g., *satureia montana*, *thymus officinalis*, *salvia offcinalis*, and *salvia rosmarinum*), which only require one cut per year and could be combined with other maintenance. In the demonstrator system at BOKU, the average harvest (fresh biomass) per plant was 134 g for *Mentha aquatica*, 23 g for *Allium schoenophrasum*, 18 g for *Rosmarinus officinalis*, 13 g for *Thymus vulgaris*, 40 g for *Satureja montana*, and 13–50 g for *Salvia officinalis*, depending on the amount of irrigation (Braunegger, in preparation).

Figure IV.5: Staircase for the accessibility of the VGS at the University of Natural Resources and Life Sciences, Vienna (BOKU) (image by Irene Zluwa)

3 Water

For general recommendations on irrigation design, readers are referred to chapter III – Design and Maintenance. The VGS is generally implemented within the building envelope. At this scale, the irrigation water mainly comes from the tap water supply infrastructure (Prenner et al., 2021). In the scientific literature, a considerable emphasis is placed on the water demand and sustainable irrigation practices to support the function of VGS fully, whereas the actual water source plays only a minor role (Prenner et al., 2021; Segovia Cardozo et al., 2019).

Figure IV.6: DIY System at the University of Natural Resources and Life Sciences, Vienna (BOKU) (image by Berger)

Figure IV.7: Vertical Farmers Garden at the University of Natural Resources and Life Sciences, Vienna (BOKU) (image by Irene Zluwa)

The use of rainwater is crucial. Sánchez-Reséndiz et al. (2018) showcased a full-scale implementation of a VGS for thermal energy investigation at the building scale in Mexico. They concluded that on-site rainwater harvesting is insufficient, and other resources, such as wastewater reuse, should be included as a sustainable practice. Pearlmutter et al. (2021) used a process-based model to simulate water demand of VGS planted with grass and a rather simple static model to predict rainwater roof run-off at the building scale for typical buildings in Copenhagen, Berlin, Rome, Lisbon, Istanbul and Tel Aviv. They demonstrated that rainwater is not sufficient to meet the water demand for VGS and that other sources are needed, especially during the dry seasons.

Water reuse, a topic with rising importance in the last decade, is an option. Pearlmutter et al. 2021 demonstrated, that quarter-oriented rainwater harvesting is an option or that greywater could fill the supply gap in the dry season, thus supporting a greened area big enough to evapotranspirate the full roof runoff at least in some cases. The introduction of a circular economy (CE) for urban resources and material flow is a crucial concept for the future of urban water management (Nika et al., 2020; Atanasova et al., 2021). In CE, rainwater run-off and wastewater are no longer regarded as waste but as a resource. In addition to water, nutrients such as nitrogen and phosphorous are typically lost in the linear wastewater treatment and discharge scheme. A critical factor that facilitates this change is the approach and scale of the wastewater system. The state of the art in central Europe focuses on centralized wastewater treatment plants with the only purpose to treat and discharge. As suggested by Masi et al. (2020), re-use oriented approaches and technologies are needed to facilitate the above-mentioned paradigm change.

VGS can play a role for the task to treat and use waste waters onsite. While their capability to treat water has been proven by the technology of treatment wetlands (Stefanakis, 2019), the added benefits and ecosystem services go hand in hand with the need for climate change adaptation and mitigation, increase in biodiversity, and public health (Masi et al., 2020).

A key component is the concept of source separation. Domestic wastewater is the sum of used and polluted water in a household. A differentiation based on the source of use can be made, namely black water from toilets, including urine and feces, yellow waters from urine diverting systems and greywater (GW), including water from bathroom sinks, showers, washing machines, usually excluding dishwashers and kitchen sinks. GW represents 60–80 % of the total wastewater quantity with a daily volume of 35–117 L per person, depending on the country (Boano et al., 2020). For the treatment of GW, low intensity technologies, including NBS, can be applied, for details see Cross et al. (2021).

Within the last decade, mainly wall-based and pot-based VGS systems for the treatment of GW have been developed and applied (Boano et al., 2020; Addo-Bankas et al., 2021). As horizontal urban space is scarce and expensive, vertical implementation is an alternative. Using VGS to treat greywater on-site, two objectives can be pursued: water treatment onsite and energy-neutral irrigation of VGS. This technological approach is highly promising because all other functions and benefits of VGS (see also chapter I) rely on a steady and sufficient water supply. Several studies proofed the concept, demonstrated an acceptable pollutant removal behaviour (Masi et a., 2016; Fowdar et al., 2017; Boano et al., 2020) and provided full-scale implementation results (Zraunig et al., 2019; Lakho et al., 2021). However, compared to the field of treatment wetland research, where the technology has been researched and implemented since the 1950's, the application of VGS for GW treatment is a young research field.

Table IV.1: Data requirement for the calculation approaches

Type	Location	Plant Type	Water consumption per m^2	Reference
Pot-based	Delft	Perennial	$1\,L\,d^{-1}$	Ottelé et al. (2011)
	Madrid	Climbers	$8\,L\,d^{-1}$	Oquendo-Di Cosola et al. (2020)
	Madrid	Climbers	$2\,L\,d^{-1}$	Oquendo-Di Cosola et al. (2020)
	Los Angeles	Climbers	$6\,L\,d^{-1}$	Natarjan et al. (2015)
	Portugal	Climbers	$340\,L\,yr^{-1}$	Manso et al. (2018)
	Vienna Kandlg.	Perennial	$280\,L\,yr^{-1}$	GrünPlusSchule (2018)
	Vienna Schumeierpl.	Perennial	$370\,L\,yr^{-1}$	GrüneZukunftSchule (2018)
	Vienna MA31	Perennial/climbers	$500\,L\,yr^{-1}$	Pelko (2018)
Wall-based	Vienna Kandlgasse	Perennial	$750\,L\,yr^{-1}$	GrünPlusSchule (2018)
	Vienna Diefenbachg.	Perennial	$580\,L\,yr^{-1}$	GrüneZukunftSchule (2018)
	Mexico	Perennial/climbers	$615\,L\,yr^{-1}$	Sánchez-Reséndiz et al. (2018)
	Eindhoven	Perennial	$630\,L\,yr^{-1}$	Van de Wouw et al (2017)
	Delft	Perennial	$3\,L\,d^{-1}$	Ottelé et al. (2011)
	Spain (multiple systems)	Perennial	3.7 to $8.8\,L\,d^{-1}$	Pérez-Urrestarazu (2021)
Ground-based	Hong Kong	Perennial	$100\,L\,mon^{-1}$	Pan and Chu (2016)
	Vienna, St. Anna	Climbers	$140\,L\,yr^{-1}$	Prenner (2020)
	Berlin	Climbers (*Fallopia b.*)	$0.5\,L\,d^{-1*}$	Hoelscher (2016)
	Berlin	Climbers (*Hedera helix*)	$0.5\,L\,d^{-1*}$	Hoelscher (2016)
	Berlin	Climbers (*Parthenocissus tricuspidata*)	$0.5\,L\,d^{-1*}$	Hoelscher (2016)
	Berlin	*Wisteria sinensis*	$8\,L\,d^{-1}$	Schmidt (2010)
	Basel	*Hedera helix*	$0.35\,L\,d^{-1*}$	Leuzinger et al. (2011)

* Water demand per unit leaf area

A full-scale multifunctional pot-based green facade was investigated in the VG 2.0 project to contribute to the development process (Pucher et al., 2020). Details about this study are presented in the following sections.

3.1 Water consumption of VGS

Generally, a distinction between water demand and water consumption needs to be made. Water demand, especially when calculated as potential evapotranspiration can be defined as the water needed to support plant production under optimal conditions. Water consumption is the actual amount of water provided to the system and taken up by plants (actual evapotranspiration). This parameter is easy to measure (e.g., water meters) and is, therefore, mostly reported in the literature.

Table IV.1 lists the water consumption per m^2 of the vertical area from different systems around the world. A general difference in the water consumption of pot-based (280–500 $L\,yr^{-1}$) and wall-based systems (580–6,150 $L\,yr^{-1}$) can be found. Wall-based systems tend to have a higher water consumption as the substrate volume fully covers the greened vertical area, and as water moves down by gravity.

Pérez-Urrestarazu (2021) investigated the water consumption of multiple wall-based systems in Spain. Water use mainly depends on the position of the system and the incoming radiation. Drainage losses were found to be significant for these systems.

Therefore, recirculation of excess water should be applied. From a design perspective, modules can be used to limit water movement.

For pot-based systems, each pot can be regarded as a closed unit with a dedicated irrigation system (e.g. number of drippers per area). Therefore, a drainage system is not necessary. In addition, an impounded bottom for water storage is often used to utilize the irrigated water efficiently. Ground-based systems can have varying water consumption as the vertical extent, and the substrate or soil and the horizontal area are highly influential.

While the VGS type can be an indicator of water consumption, the irrigation technique and intervals are also critical. It is advisable to irrigate more often with a reduced flow volume and for a short time period. This is based on the soil hydraulic behavior of moist substrates, where water can move more easily, resulting in a uniform water distribution compared to less often, high-volume irrigation strategies. When excess water is collected and reused, higher flow volumes can be used to generate moist conditions without wasting water (Pérez-Urrestarazu et al., 2014; Segovia-Cardozo et al., 2019; Kaltsidi et al., 2020).

For ground-based systems, little data exist on their water consumption. Leuzinger (2011) quantified the transpiration rates of *Hedera helix* in a forest environment near Basel, Switzerland, using a potometer and sap flow measurements. In the period from 01.04.–24.04.2004, peak transpiration rates of $13.5\,\mathrm{mL\,min^{-1}}$ (= $0.81\,\mathrm{L\,h^{-1}}$) for the whole plant were detected, and average transpiration rates per unit leaf area of $0.23\,\mathrm{mmol\,m^{-2}\,s^{-1}}$ (= $0.015\,\mathrm{L\,m^{-2}\,h^{-1}}$). Hoelscher et al. (2016) measured transpiration rates of *Parthenocissus tricuspidata* and *Hedera helix* in an urban environment from 16.08.–19.08.2013 and 01.08.–06.08.2014, respectively, using sap flow gauges. Mean transpiration rates were found to account for $0.5\,\mathrm{L\,m^{-2}}$ per day (per leaf area) for both *Parthenocissus tricuspidata* and *Hedera helix*. In the same study, water consumption of *Fallopia baldschuanica* planted in a container accounted for $0.5\,\mathrm{L\,m^{-2}\,d^{-1}}$ (per leaf area).

3.2 Case study TUB

When implementing VGS, the water demand throughout the vegetation period is needed in order to maintain plant health and make use of the VGS for urban water management. Yet, little long-term data exists on the water demand of the different systems.

At the Berlin study site, the water consumption of four ground-based green facades planted with *Humulus lupulus*, *Phaseolus coccineus*, *Vitis vinifera*, and *Fallopia baldschuanica* was monitored during the vegetation period of 2021 (Figure IV.8). The site is a western-oriented wall located on the TU campus in an inner-city area in Berlin, Germany. The investigated plants were placed in front of the wall in plant containers each of 1 m³ volume. Each container was filled with a 25 cm layer of broken bricks as a drainage layer covered with a root barrier membrane, a 10 cm sand layer, and a 35 cm layer of topsoil. In addition, outflow was enabled in the upper part of the drainage layer. Thus, each container was provided with a potential storage volume of 0.275 m³ of water. Excess water was detected with a tipping bucket combined with bending beams (ME-Systeme LCB130, G3) every second.

Figure IV.8: Experimental site TU Berlin (image by TUB)

The plant containers were placed on weighing cells (ME-Systeme KR80, 0.5 t), and the load of the plant containers was measured every minute. During the vegetation period (April – September), three different irrigation frequencies were tested (manual irrigation once per week (23.04.–14.06.), automatic irrigation once per day (14.06.–10.08.), automatic irrigation twice per day (10.08.–21.09.)). The irrigation was conducted above ground with an irrigation hose. Figure IV.9 shows the change in mass of the plant container for *Fallopia baldschuanica* during the first two weeks of May 2021.

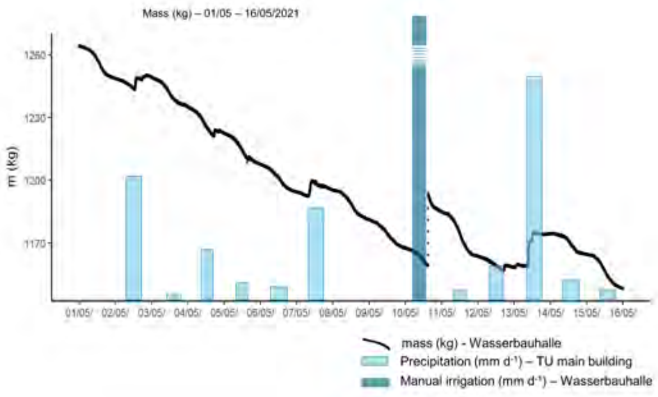

Figure IV.9: Mass of the plant container of *Fallopia baldschuanica* (kg) and irrigation (mm) 01.05.–16.05.2021

The dynamic water flows in and out of the container were filtered with the AWAT filter (Peters et al., 2016), resulting in gains and losses due to precipitation and evapotranspiration (ET) of the system (Figure IV.10). Comparing the course of ET with the course of air temperature and solar energy yield on the plant, an optimal water supply and therefore potential ET after manual irrigation can be assumed.

3.3 Case study BOKU

The experimental pot-based system implemented at the BOKU is fully described in chapter III. The following results refer to systems of 10 pots altogether providing a substrate volume of 0.54 m^3 and a substrate surface of 3 m^2.

Investigation of irrigation strategies

The main objectives of the investigation include the comparison of three different water supply patterns: (i) minimum water supply, (ii) sufficient water (and GW) supply, and (iii) excess water (and GW) supply. The latter regarded as a treatment of GW. The duration of this experiment comprised the growing period from April to August 2021 (the system has been in operation since March 2020; hence, steady-state conditions can be assumed).

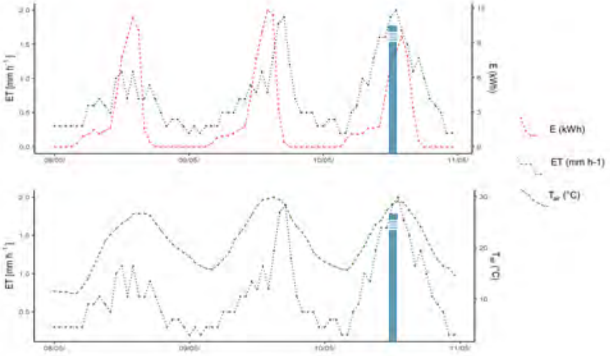

Figure IV.10: Evapotranspiration (black) versus solar energy (red, top) and air temperature (green, bottom) on the TUB test site between 08.–11.05.2021; manual irrigation on 10.05.

Raw GW was prepared following a protocol using common personal care products and cleaning agents (Pucher et al., 2020).

1. Minimum water supply (Wall 1): The irrigation scheme was adapted based on local climate conditions to prevent plant damage. Irrigation started once a week, changed to twice, and then to three times per week.
2. Sufficient water supply: This group was irrigated daily with 8.3 mm. One system used tap water (Wall 2) and another used raw GW (Wall 3)
3. Excess water supply: This group is also referred to as the GW treatment unit and received 30 mm of raw GW per day (Wall 4).

Irrigation for Wall 1 and Wall 2 was performed using an irrigation computer and tap water. Wall 3 and Wall 4 were irrigated using submerged pumps installed in a 2 m^3 tank. This practice led to a more varying irrigation volume than for Wall 1 and Wall 2. Table IV.2 lists the daily irrigation amounts and information on the irrigation intervals.

Table IV.2: Irrigation design for the experimental system at BOKU University. The experiment started in August 2021

Wall	Daily Sum	Irrigation Interval
Wall 1	25 L	Weekly, from June bi-weekly, followed by three times a week
Wall 2	25 L	Daily
Wall 3	25 L	Daily
Wall 4	90 L	Every 2 h

For Walls 1 to 3, the inflow and outflow were monitored, whereas for Wall 4, only the inflow was recorded. Based on manual measurement and the irrigation interval, it was assumed that for Wall 4, the inflow equals the outflow. From the measured inflow and outflow in Wall 1, Wall 2, and Wall 3, the daily ET of each wall was calculated. To compare all three walls, the weekly sum of ET was calculated. This was needed, as for Wall 1 only weekly data are available. As illustrated in Figure IV.11, a distinctive pattern over the 20-week duration is observed. This can be explained by the temperature over the experimental duration (Figure IV.12). In June, the highest temperatures were reached, whereas in July the temperature decreased. In August, an increase in temperature led to an increase in ET. The influence of irrigation can be observed even better when comparing the total biomass in the walls with different irrigations.

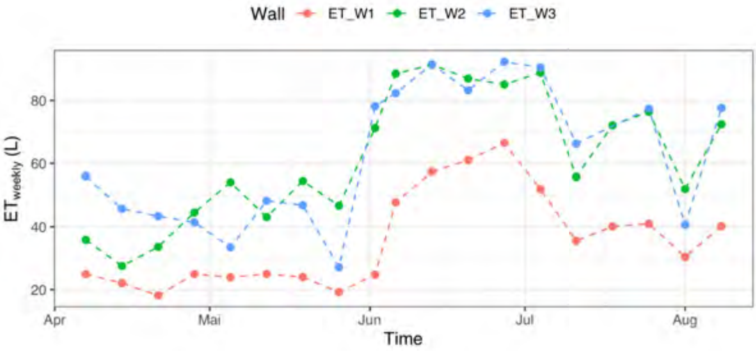

Figure IV.11: Weekly sum of evapotranspiration for Walls 1, 2, and 3

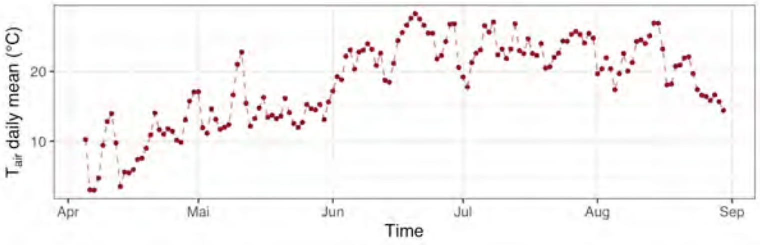

Figure IV.12: Mean daily temperature over the experimental period

Every pot-based system in the demonstrator at BOKU covers a wall area of 5 m². Wall 1 with low irrigation (1–2 times a week) produced a total dry plant biomass of 363 g. The total biomass in Wall 2 and Wall 3 with sufficient irrigation (once per day) was 657 g and 676 g, respectively. In Wall 4, which was irrigated every hour, the total dry biomass was 1,115 g (three times as much as the biomass in Wall 1) (Braunegger 2022). Based on the results (Figure IV.13), the following conclusions can be drawn:

- The amount of irrigation water influences biomass development.
- The water sources, namely tap water and raw GW, show no difference in biomass development.

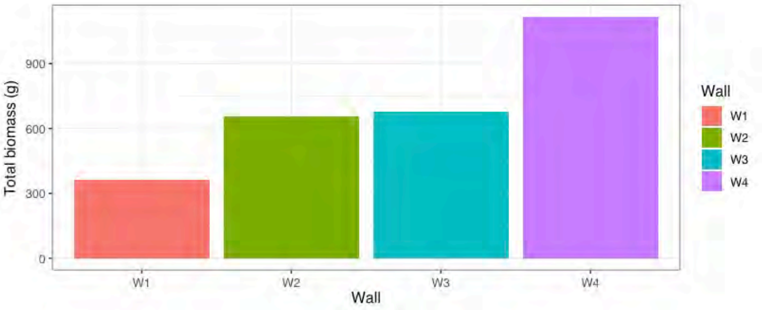

Figure IV.13: Total dry biomass for each wall after complete harvest

Investigation of greywater treatment performance

As stated earlier, a sufficient water supply is needed for a VGS to provide possible co-benefits (section 4). In this project, one investigation was related to the treatment and use of GW for irrigation purposes. Generally, a treatment step is necessary before reuse to comply with water reuse regulations and guidelines (Boano et al., 2020). With the introduction of VGS as a GW treatment technology, a multifunctional system can be described using the raw GW for irrigation purposes and at the same time acting as a treatment system providing excess water for reuse purposes. In this sense, the VGS performs as a vertically installed treatment wetland (e.g., Masi et al., 2016; VertEco, 2021). For the investigation, Wall 4 was split into two systems: horizontal flow (HF) and a semi-vertical flow system (sVF), each consisting of five planter boxes. The HF system represents the described VGS, whereas the sVF system has alternating one and two openings. Each system was irrigated every 2 h with a daily volume of 90 L, representing the GW volume of one person. Figure IV.14 illustrates the water quality parameters analyzed for the two treatment units, namely HF and sVF, as well as Wall 3 (representing the system irrigated with raw GW). Concerning Wall 3, an excellent treatment performance for all parameters was observed. We conclude that the excess water in this system was highly treated and could be further utilized for different reuse purposes. Comparing the treatment systems HF and sVF, a better treatment performance for HF could be observed for all parameters.

Possibilities of a multifunctional design

The results of both experiments (water supply, biomass production, and GW treatment) indicate a sufficient performance of the proposed low-tech design and multifunctional behavior of the system. Different water supply patterns indicate a direct relation to biomass production and ET capacity. Based on the operational observations over the two-year period, Wall 1, Wall 2, and Wall 3 did not experience any malfunctions. The GW treatment systems showed signs of clogging in the planter boxes in the second year of operation. After a resting period of one week, the systems were free again. The reasons were identified as a combination of biofilm development, root development, high organic and hydraulic loading, and maturation of the substrate (for details see section 4). This reduced the porosity and hydraulic conductivity of each planter box. As this was observed in all boxes, biofilm development cannot be solely responsible, as, in the last box, the organic matter content was already highly reduced.

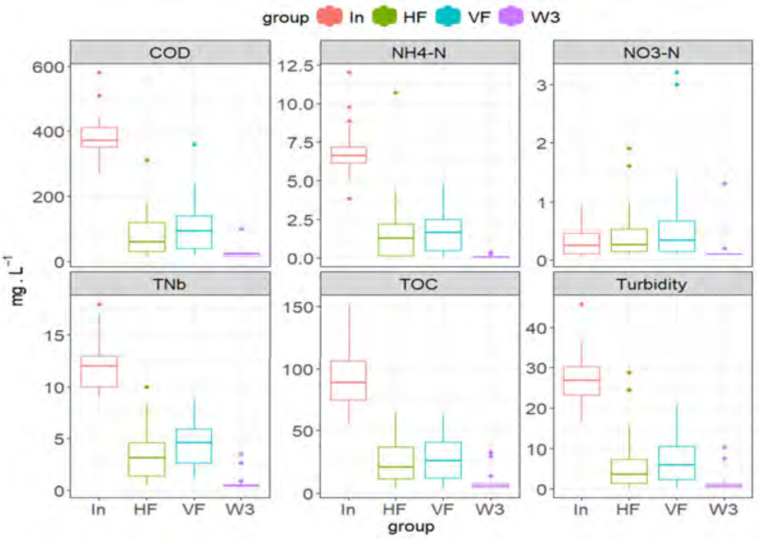

Figure IV.14: Boxplot of influent and effluent concentrations of the main quality parameters for each system (HF = horizontal flow, VF = semi vertical flow, W3 = Wall 3)

To further develop a VGS GW treatment system, an investigation of the longterm behavior of the substrate and the pore volume change due to root development should be carried out.

3.4 Modeling and simulating water demand for VGS

For horizontal surfaces, the water demand of plants can be calculated as potential ET with empirical (e.g., Haude (1955), Thornthwaite (1957), and Turc (1961)) or physical approaches (e.g. Monteith 1965). Based on the Penman-Monteith approach, Allen et al. (1994) developed the grass reference method recommended by the Food and Agriculture Organization of the United Nations (FAO report 56). The grass reference method calculates ET 0 for a horizontal surface covered with grass at sufficient water supply and with a crop height of 0.12 m. To quantify ET for different plant species and crop heights, the grass reference ET0 is multiplied with an individual crop factor kc which is dynamic throughout the vegetation period (DVWK 1996).

In the case of VGS, plants can cover large vertical surfaces using a small area on the horizontal plane.

For the vertical plane in the urban environment, ET is influenced by the building morphology and exposition with implications for the relevant meteorological parameters and a different selection of plant species. In numerous studies investigating the thermal performance of VGS, the Penman-Monteith equation or the grass reference equation has been applied, mostly with on-site measured or transformed data originating from remote climate station data.

The availability of such special input data limits the use of water demand models for urban planning. Saad (2020) analyzed the suitability of ET modelling approaches for VGS, the availability of their input parameters, and the accuracy of the model outputs using test site data from TUB. When comparing simulated water demand derived from a remote climate station versus on-site data, radiation and wind speed were found to be the most sensitive parameters. Relative humidity and air temperature could be used from remote climate stations, even though the accuracy of the simulated output could be improved with an empirical factor for air temperature (inthe case of the test site at TUB, this factor was found to be 1.071 for the study period). One possibility to adapt remote radiation data to site conditions is to model with Ray-Man (Matzarakis, 2000) using a Digital Elevation Model (DEM). Owing to its heterogeneity in the urban environment, wind speed has been shown to be the most difficult to derive from remote data and is recommended to be measured on-site for at least several months to derive empirical factors for adaptation. For the ground-based green facade model, results of water demand could be improved slightly by considering the variability of radiation and wind speed over height (Nash-Sutcliffe model Efficiency coefficient (NSE) of 0.38 for ET (height dependant) compared to NSE of 0.29 for ET (non-height dependant) (Saad, 2020).

When using the Penman-Monteith approach on a building scale, the calculated water demand can be balanced against water availability from precipitation and GW production, as shown in Pearlmutter et al. (2021), in which VGS was included in runoff and GW management strategies for a set of case study cities and typical buildings.

The study demonstrated that climatic conditions shape the overall water management potential as drivers for ET and runoff provision. However, architecture and inhabitants equally determine the amount of water that can be processed and the greenable area on the building. They are key factors for providing space to collect runoff and implement building greenery and for GW production. The greywater produced on-site can balance precipitation shortages during the year and increase the greenable area irrigated with local water sources. In an urban environment, VGS can help optimize decentral water management on the building and district scale (Pearlmutter et al., 2021).

Table IV.3: Processes and influencing factors of the conceptual model for rainwater use in irrigation (reused with the permission of the author Prenner et al., 2021)

	1: Atmosphere	2: Hydraulic	3: Quality	4: RWH	5: VGS
Processes	Precipitation	Runoff formation	Pollutant absorption	Runoff storage	Evapotranspiration
				Runoff distribution	Drainage
					Overflow
Influencing factors	Radiation intensity	Catchment area	Pollutant load	Tank size	Vegetation
	Wind	Surface type	Runoff treatment	Tank material	PGM
	Air temperature	Runoff coefficient		Tank position	Plant containers
	Weather	Built environment		Tank design	Irrigation system
				Conveyance system	Quality requirements

3.5 Conceptual model for rainwater use in VGS

The use of rainwater for the irrigation of VGS is often mentioned as a sustainable alternative compared to the use of piped drinking water in the literature. However, the practical details of such systems (e.g., runoff areas, quality, technical design) are not well studied (Prenner et al., 2021). A conceptual model was developed within this project to provide a detailed description of the processes involved and influencing factors so that the knowledge gap disappears. Table IV.3 presents the five sub-modules, their main processes, and influencing factors (Prenner et al., 2021).

Atmosphere

As described by Prenner et al. (2021), the atmospheric sub-module includes the radiation intensity, air temperature, wind, precipitation, and weather conditions. The growth of plants in the urban environment is influenced by changing atmospheric conditions such as incoming radiation, prevailing wind, air temperature conditions, precipitation patterns, and generally the weather conditions (Hunter et al., 2014; González-Méndez and Chávez-García, 2020).

The precipitation patterns and the time resolution of the available data are essential, as they influence the required storage capacity (ÖNORM EN 16941-1, 2018; Zabidi et al., 2020). Generally, daily data are advised to include short dry periods and extreme storm events (Riley, 2017). Wind conditions in urban environments are influenced by surrounding buildings and can lead to locally strong winds. This influences plant development and can lead to mechanical damage. Different wind conditions also directly affect humidity and vapor pressure.

Low levels of relative humidity decrease transpiration as plants protect themselves from drying out, while high levels of humidity increase transpiration (Susorova et al., 2013, Prenner et al., 2021).

Another critical factor influencing the ET rate is the radiation intensity (Dingman, 2015; Lee and Jim, 2017). In addition to the general atmospheric conditions, namely cloud development and movement of the sun, reflections by surrounding buildings, as well as the actual height of the VGS, can affect the local radiation intensity (Hunter et al., 2014; Riley, 2017; Hoelscher, 2018).

Another atmospheric parameter is the air temperature, directly related to the vapor pressure. An increase in air temperature leads to an increase in vapor pressure deficits, causing higher ET from VGS. The actual water demand increases (Jim and He, 2011; Pérez-Urrestarazu et al., 2014; Dingman, 2015). In pot-based systems, high temperatures can harm root health and development. This can be observed in non-isolated pots (Mathers et al., 2007; Hunter et al., 2014).

Hydraulics

The hydraulics sub-module describes the runoff formation, which is influenced by the area connected, the runoff coefficient, the surface type, and the surrounding built environment. A primary distinction can be made between the runoff from the roof and runoff at the ground level (e.g., streets, parking lots, courtyards). Mostly, the roof runoff is used as the collection is generally done by design. If the amount is not sufficient, the ground-level runoff can be collected as well (Nolde, 2007). The available runoff yield can be calculated using the following equation (Farreny et al., 2011; ÖNORM EN 16941-1, 2018):

$$Y_t = Ah_t \cdot RC\eta \tag{IV.1}$$

where Y_t is the runoff yield per day (L per day), A is the runoff area (m^2), h_t is the precipitation height per day (L per day), RC is the runoff coefficient (-), and η is the hydraulic treatment efficiency coefficient (-). The RC is dependent on the surface type, the material used, and the slope. While a constant value for a particulate area and type is used, Nehls et al. (2020) identified a dependency of RC on rainfall intensity. The hydraulic treatment coefficient is the linkage point to the next sub-model "Water Quality." It describes the ratio of the collected runoff yield as the influent to the treatment unit and the effluent volume. This accounts for water loss within a particular infrastructure (ÖNORM EN 16941-1, 2018).

Water quality

Depending on the area of runoff generation, contamination with different types of pollutants in variable quantities can occur. Generally, the following pollutants are essential: heavy metals, suspended solids, organic carbon, bacteria, and chlorides (Nolde, 2007; Ingvertsen et al., 2011). Emerging pollutants from urban runoff are especially critical. These include pesticides used for gardening as well as in building materials, hydrocarbons (e.g., oil spills, fuel, and vehicle emissions), alkylphenols from roads and building material runoff, phthalates mainly from traffic surfaces, per- and polyfluorinated alkyl substances from street and roof runoff, and polychlorinated biphenyls from lubricants, hydraulic oils, and house facades (Prenner et al., 2021; Tondera et al., 2018). As the runoff from traffic areas is often more polluted than the roof runoff, only the latter is mainly used for rainwater harvesting (RWH) (Angrill et al., 2017; Leong et al., 2017; Nolde, 2007; Zabidi et al., 2020).

Depending on the pollutant, various treatment strategies can be applied. Generally, a mechanical pre-treatment to remove the larger particles and settle the organic matter is applied to avoid accumulation in the storage tank. For reuse purposes, further treatments such as filtration and disinfection are advisable. High temperatures in storage containers can lead to quality degradation as bacterial growth is enhanced (Leong et al., 2017). As the pollutants accumulate during dry periods the so-called "first flush," namely the wash-off of those pollutants with the first rainfall, can be diverted into the sewer system to prevent high pollutants load in the RWH system (Leong et al., 2017; Zabidi et al., 2020). In addition, the VGS itself can act as a treatment unit, as processes equally to treatment wetlands occur.

Rainwater-harvesting

The RWH system is influenced by the precipitation pattern and irrigation water demand of the VGS unit. Therefore, the timescale of available precipitation data is critical. Prenner et al. (2021) described two main approaches for the sizing of the storage unit. The basic approach uses the mean daily water demand and the expected days of a general dry period. Based on ÖNROM EN 16941-2 (2018), a value of 21 days for German-speaking countries was used. The detailed approach uses daily data and an algorithm to calculate the storage size to respect irregularities in the required irrigation demand. Based on an input-output simulation, the overflow and required backup water for the system were calculated. The optimal storage size was then chosen by the planer, balancing the optimal tank size between the backup and overflow (ÖNORM EN 16941-1, 2018). For further details, please refer to Prenner et al. (2021).

The implementation of the RWH systems depends on multiple factors. Generally, either rooftop or underground storage is used. Collecting tanks and pumping wells are required when street runoff is collected (Nolde et al., 2007).

Vertical Greening System

In the VGS, the following processes are essential: evapotranspiration (ET), drainage, and overflow. These processes are influenced by the type of vegetation, the design of the planter box, including the plant growing media (PGM), and the irrigation system. Irrigation water can be applied either at the top or at the bottom of the VGS. In the latter case, an impounded area was used for water storage. In both cases, the soil hydraulic parameters of the PGM, namely the hydraulic conductivity and porosity, determine the water flow behavior. In addition, the capillary rise behavior is vital for systems with impounded areas. Furthermore, PGM influences root growth, plant health, water, and pollutant retention (Gonzales-Mendes and Chavez-Garzia, 2020).

Overflow can occur when the PGM is saturated, or irrigation water cannot sufficiently infiltrate. As overflowing conditions can affect the environment around the VGS, this should be prevented and overflowing water should be drained into a storage tank for further use or discharged into the sewer system.

In addition to overflow conditions, excess water from a drainage system, as often applied in wall-based systems, should be collected and reused for sustainable irrigation practice. In the case of applied fertigation, access water can contain nutrients and should be specifically discharged. Storage for reuse over a more extended period can lead to biofilm development and needs to be respected for a system with water reuse practice. Sufficient water is available in the planter box to provide optimal conditions for evapotranspiration. Furthermore, the choice of plant species should be based on local conditions, considering climate and built density. For a detailed mathematical description, readers are referred to Prenner et al. (2021). The presented model provides a clear understanding of important processes and influencing factors that promote RWH practices. Based on the included sub-models, it is possible to identify the potential irrigation provided by rainwater. The main limiting factor is the catchment area (sub-model RWH). While the rooftop area is always included, street runoff is not respected due to pollution. In a case study from Berlin, Nolde et al. (2007) presented a solution for including street runoff in their water reuse system. As water quality is an important aspect, a specific sub-module is available that provides treatment recommendations based on the pollutant level.

The implementation of rainwater use contributes to sustainability and circularity in urban water management. Therefore, the conceptual model should be used to analyze the possibilities and extent of rainwater use for irrigation.

4 Energy

4.1 Monitoring cooling effects of Vertical Greening Systems

In the past, the cooling potential of VGS was experimentally quantified for different systems and climates (Table IV.4). In summer days, temperature reductions of the wall surface are caused by shading, transpiration, and insulation (Hoelscher et al., 2016) and directly impact outdoor and indoor wall surface temperatures. The most commonly monitored indicator for the cooling potential of VGS in research is the exterior wall surface temperature, which can be reduced by more than 10 ℃ for different climates (see Table IV.4). Less frequently, the interior wall surface temperatures or the indoor air temperatures are measured. Both highly depend on the wall configuration, the given indoor air volume, and the amount of opaque versus window areas and the user behavior. Thus, both cannot be generalized to a wide range of building types. Simulation tools can be used to transfer experimental findings to a set of buildings (see subsection 4.2). As experimental research focuses on the cooling potential of VGS, the impact of VGS on the built environment during the night or in winter is still poorly investigated. findings from Mazzali (2013) and Hoelscher et al. (2016) suggest that wall-based and ground-based green facades have adverse effects on the ability of a building to release excess heat to its environment during the night. In conclusion, an energy-oriented design of VGS needs to consider static boundary conditions, such as urban morphology and wall configurations, but also daily, seasonal, yearly and long-term dynamics (e.g. climate change) in process variables and drivers.

TUB test site

In 2020 and 2021, the thermal effects of four different ground-based green facades were monitored on a test site at the campus of the Technische Universität Berlin in Charlottenburg (52.5136 N, 13.3243 E). On the interior and exterior wall surface of a western-oriented test wall of an industrial hall, temperature sensors (Pt100, Innovative sensor technology, IST-AG) were installed on three different heights (2.8 m, 6.2 m, and 9.6 m) on the bare wall and behind the ground-based green facade compartments greened with *Humulus lupulus*, *Phaseolus coccineus*, *Vitis vinifera*, and *Fallopia baldschuanica*. In addition, shortwave and longwave radiation sensors were installed behind the greenery (height 4.4 m), on the bare wall (height 4.4 m and 6.8 m), and the horizontal roof surface (height 12 m).

Table IV.4: Experimental studies on thermal effects of VGS

Type of VGS	Plant species	Location	Study description	Effect	Reference
Ground-based	*Pyrostegia venusta* planter box placed on the ground	Guangzhou, China (subtrop.)	Measurements of indoor and outdoor wall surface temperatures, indoor air temperatures, heat fluxes 30.09., 01.10., 14.–15.09.2018	Max. $T_{s,out}$ reductions of greened wall: 14.2 ℃; $T_{a,in}$ reductions in a greened room up to 3.5 ℃; Mean $T_{a,in}$ reductions in a greened room of 1.5 ℃	Zhang (2019)
	Climber plants	Singapore (trop.)	Temperature reductions on a single standing wall surface	Max. $T_{s,out}$ reductions of a greened wall: 4.36 ℃	Wong (2010)
	Parthenocissus tricuspidata	South-west facade; Berlin, Germany	Meteorological parameters, among them wall and plant surface and bare wall temperatures from 19.07.–16.08.2013	Max. $T_{s,out}$ reductions of a greened wall: 0.1–11.3 ℃	Hoelscher (2016)
	Hedera helix	East facade; Berlin, Germany	Meteorological parameters, among them wall and plant surface and bare wall temperatures measured from 01.–06.08.2014	Max. $T_{s,out}$ reductions of a greened wall: up to 12.3 ℃	Hoelscher (2016)
	Fallopia baldschuanica	West facade, Berlin Germany	Meteorological parameters, among them wall and plant surface and bare wall temperatures measured in the summer of 2014	Max. $T_{s,out}$ reductions of a greened wall: up to -0.8–6.6 ℃	Hoelscher (2016)
	Thunbergia grandiflora	Johor Skudai campus Malaysia (trop.)	Measurements on three sunny days in summer 2013	$T_{a,in}$ reductions of 3.0 ℃, $T_{a,cav}$ reductions on the hottest time of day of 6.5 ℃	Safikhani (2014)
Wall-based	Not specified	Al-Ain, United Arab Emirates, scorching, dry climate	Measurements of indoor and outdoor air and wall surface temperatures between 01.07.–01.08. on an eastern oriented facade	$T_{s,out}$ consistently 5 ℃ lower on greened wall; $T_{s,out,max}$ = 13 ℃	Haggag (2014)
	Juniperus communis Sedum spurium, *Geranium sanguineum*, *Geranium Johnson's blue*, *Anemone sp.*, *Viva minor*, *Parthenocissus tricuspidata*, *Heuchera micrantha* Palace Purple, *Salvia nemorosa*, *Lonicera pileata*, *Pittosporum tobira*, *Rosmarinus officinalis*, *Alchemilla mollis*, *Bergenia cordifolia*, *Oenothera missouriensis*, *Plumbago capensi*	North Italy Lonigo, south-west oriented wall	Two days (with highest and lowest solar energy input = 06.07.–21.09.2011; measurements of wall surface temperatures, indoor and outdoor air temperature, and rH, wind speed, heat flux, solar radiation	Height dependency of surface temperatures not significant; $T_{s,out}$ 12–20 ℃ lower on a greened wall on sunny days; $T_{s,out}$ 5 ℃ lower on a greened wall on cloudy days; In the night, $T_{s,out}$ of bare 2–3 ℃ lower than a greened wall	Mazzali (2013)
	grass	North Italy, Venice; south-west oriented wall		During the daytime, $T_{s,out}$ on greened wall up to 16 ℃ cooler than on bare wall; in the night $T_{s,out}$ on bare wall is up to 6 ℃ cooler than on a greened wall	Mazzali (2013)
	Zoysia matrella 'Zeon', *Zoysia tenuifolia*, *Zoysia japonica* 'El Toro', *Cynodon dactylon X Cynodon trasvalensis* 'Patriot', *Stenotaphrum secondatum*, *Dicondra*, *Paspalum vaginatum*, *Cynodon transvalensis*	North Italy, Pisa	Two days (with highest and lowest solar energy input (10.09.–01.10.2009)); measurements of wall surface temperatures, indoor and outdoor air temperature and rH, wind speed, heat flux, solar radiation	During the daytime, $T_{s,out}$ on greened wall is up to 12 ℃ cooler than $T_{s,out}$ on bare wall; in the night, $T_{s,out}$ on bare wall up to 3 ℃ cooler than on a greened wall	Mazzali (2013)
	A: *Piper sarmentosum*, *Philodendron*, *Cordyline terminalis*, *Schefflera* B: *Hemigraphis alternata*, *Portulaca grandiflora*, *Nephrolepis acutifolia*	National University of Singapore (trop.)	Air, wall surface, and radiant temperature measurements for five days (A) and nine days (B) in Oct–Nov 2011 and Jan–Mar 2012	In periods of high solar radiation input, the greenery can lower radiant temperature as far as 1 m in front of the wall	Tan (2014)
Ground/wall-based	Ground-based (*Hedera helix*), wall-based (different evergreen species)	Delft, Rotterdam, Benthuizen (all < 20 km apart), Netherlands	Air and surface temperature and wind speed measurements in front of, in, and behind the facade greenery	Optimal wind speed reductions in smaller air cavities (4–6 cm suggested); $T_{s,out}$ reductions measured; air temperature and wind speed profiles constant between foliage and 1 m distance to the wall	Perini (2011)

Figure IV.15 exemplarily shows temperature reductions as the difference between surface temperatures of the greened and bare wall (greened – bare) in two weeks of June, July and August 2020 for three plant species.

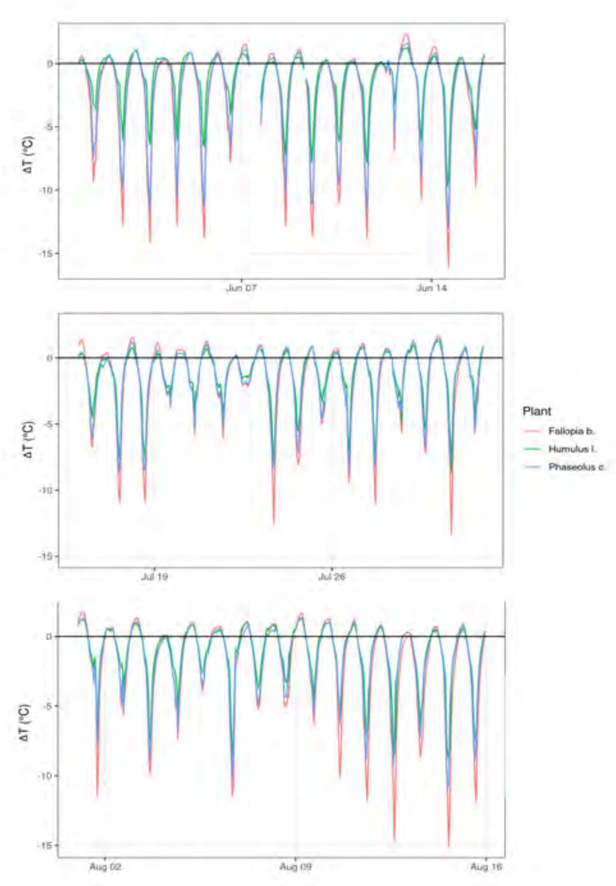

Figure IV.15: Differences in exterior wall surface temperatures (greened – bare) (hourly values) for ground-based green facade of *Fallopia baldschuanica* (red), *Humulus lupulus* (green), and *Phaseolus coccineus* (blue), at the TUB test site in 2.8 m height. Top: 01.06.–15.06.2020; middle: 16.07.–31.07.2020; bottom: 01.08.–15.08.2020

During the day, observed reductions reached up to −10.1 ℃, −13.0 ℃, and −16.1 ℃ for *Humulus lupulus*, *Phaseolus coccineus*, and *Fallopia baldschuanica*, respectively. The height did not have a considerable impact on the peak surface temperature reductions in the given setting.

BOKU test site

The air temperature was measured in front of the VGS in six positions, namely in the middle of each wall and on top and at the bottom of Wall 3. In addition, the temperature of the bare wall was measured (bare-wall). A comparison of the mean monthly temperature in front of the VGS (mean of daily values of all probes) and the bare wall is illustrated in Figure IV.16 . Generally, a lower mean value for the VGS can be observed. The temperature difference increased with increasing overall air temperature (Figure IV.17). The daily mean difference between the VGS and bare-Wall is calculated and illustrated by the histogram in Figure IV.18 to quantify the influence of the VGS on the local air tem- perature.

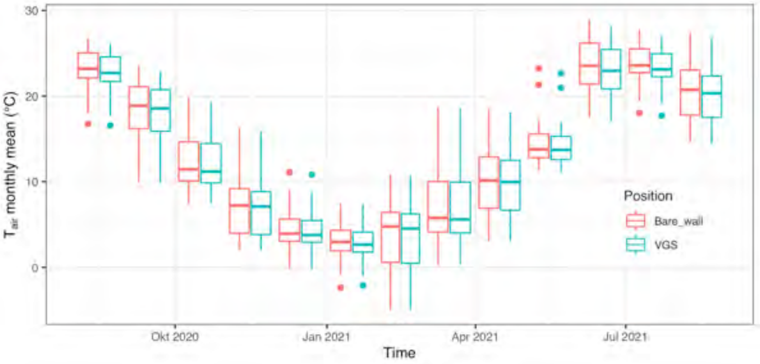

Figure IV.16: Monthly mean air temperatures for the greened (VGS) and bare wall

Out of the total recorded 390 days during 76 days, the mean daily difference was 0.5 ℃ or higher. On ten days, the mean daily temperature difference was between 0.8 and 0.9 ℃. A comparison of the measured mean daily temperature of each wall was performed to identify the effect of the irrigation practice on the local temperature. The Austrian Agency for Climate Research (ZAMG) defines a heat day with a maximum temperature higher than 30 ℃.

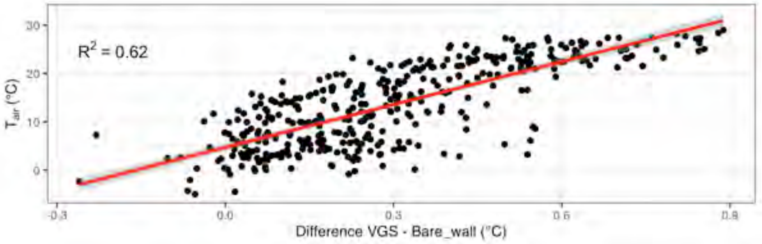

Figure IV.17: Scatterplot and fitted linear regression for the mean air temperature and the measured difference of the bare wall and the VGS (including the 95 % confidence interval)

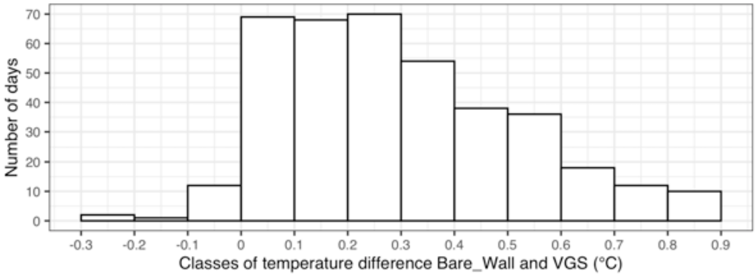

Figure IV.18: Histogram for the temperature difference of the bare wall and the VGS based on daily mean values. The bins have a range of 0.1 °C

The data were filtered for the maximum daily value higher than 30 °C, and the longest continuous timespan was extracted. Figure IV.19 and Figure IV.20 show the main heat-day-related measurements for each wall. As previously indicated, a higher air temperature leads to a higher difference between the VGS (here, Wall 1 to Wall 4) and the bare wall. When comparing the mean temperature of each VGS wall, a lower mean temperature for Wall 4 over Wall 1 can be observed. This result implies that the amount of water supply can have an impact on the local cooling effect. This also fits the conclusion by Gräf et al. (2021), namely that water-stressed plants show a limited cooling effect.

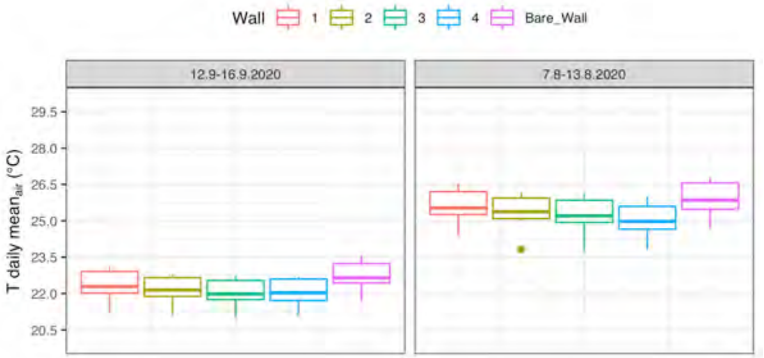

Figure IV.19: Mean daily temperature measurement for each individual wall as a boxplot for consecutive days with a maximum temperature over 30 °C for August and September 2020

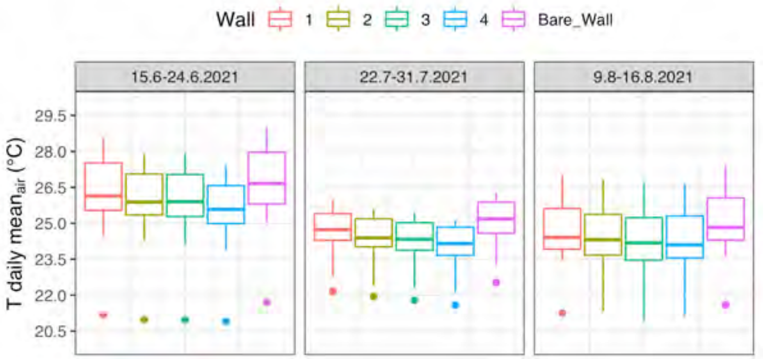

Figure IV.20: Mean daily temperature measurement for each wall as a boxplot for continuous days with a maximum temperature over 30 °C for June, July, and August

4.2 Modelling and simulating cooling effects of Vertical Greening Systems

The cooling and energy-saving potential of VGS depends on different factors such as the given greenery system, its design and maintenance status, local climatic conditions, building structure and orientation, and construction materials.

Table IV.5: Selection of simulation studies referring to energy transfer between facade greenery and buildings

Type of VGS	Type of Model	Study design	Findings	Reference
Pot-based	Self-developed model	Modeling and simulations of a double skin facade with front glass and plants vs. blinds placed in the cavity	Better cooling performance of plants compared to blinds; peak. temperatures of 35 ℃ (plants) vs. 55 ℃ (blinds) in the cavity	Stec (2005)
Wall-based	ENVI-met green facade module and EnergyPlus	Energy savings for six idealized urban blocks	Daily energy savings of 123–347 $Wh\ m^{-2}$ / summerly cooling energy saving reduction of 11–31 $kWh\ m^{-2}$	Peng (2020)
	Self-developed add-on to TRNSYS	Two buildings with east and west orientation located in La Rochelle (France, oceanic climate) and Athens (Greece, Mediterranean climate)	Heat load reduction of 11.9 % (La Rochelle) and 8.7 % (Athens); cooling load reductions of 50.6 % (La Rochelle) and 37.3 % (Athens)	Djedjig (2015)
	VGS model based on green roof model in EnergyPlus	Calculations for one day in summer and one in winter for Hong Kong and Wuhan	max exterior wall surface reduction of 26 ℃, 3 % reduction in annual cooling energy consumption; potential increase in heating load in winter	Dahanayake Chow (2017)
	Green roof module in EnergyPlus	Simulations for two wall types during winter in Braganca, Portugal (Mediterranean climate), U-values: 2.15 $W\ m^{-2}\ °C^{-2}$ and 3.25 $W\ m^{-2}\ °C^{-2}$	In winter, shadowing by plants can block sunlight, thus preventing heating through solar radiation (especially for the southern wall); plants insulate a wall area with low solar radiation input	Carlos (2015)
Ground-based	Self-developed model	Two-layered facade greening in front of a well-insulated, moderately insulated, and a non-insulated building	Reduction of peak heat fluxes to the interior space of 77 % with a two-layered facade greening; cooling effects higher for less thermally insulated facades	Šuklje (2016)
	Self-developed model	Greened test wall in Thessaloniki (Greece) with varying plant cover (0–100 %) and four orientations (N-E-S-W)	Higher cooling effects for E and W oriented facades; recommendation of greenery implementation on low insulated walls	Kontoleon and Emorfoupolou (2010)

The consideration of VGS in urban planning requires tools for cooling and energy-saving potential assessments. In recent years, several computational tools have been developed to simulate the energy transfer between the outdoor environment, VGS, building envelope, and indoor space. These tools are often developed for this purpose (Šuklje, 2016; Stec, 2005; Kontoleon and Emorfoupoulou, 2010) or existing energy transfer models are adapted or modified (Djedjig, 2015, Dahanayake and Chow, 2017, Carlos, 2015). Examples of adapted, or integrated existing models are EnergyPlus (DOE, 2015), TRNSYS (TRNSYS, 1975), or ENVI-met (ENVI-met, 2021). Most simulation studies refer to wall-based green facades, but ground-based systems and less often pot-based green facades are assessed in simulation studies. Table IV.5 gives an overview of selected simulation studies on the thermal effect of VGS. The target parameters are usually wall surface temperatures or wall heat fluxes, which are often regarded separately for the summer and winter cases. Accordingly, reductions in cooling or heating loads for the buildings and related energy savings are commonly addressed.

Meteorological input data preparation

The reliability of building energy simulations is highly dependent on the quality of meteorological input data. Available data (e.g., DWD, 2021) are usually collected for the horizontal plane at remote climate stations. For energy analysis on vertical surfaces, meteorological parameters should be adjusted to the vertical site or measured directly on-site, at least for wind speed and radiation (Saad, 2020). Owing to the wall orientation and neighboring buildings, there is a shift in the daily course of radiation on the vertical plane. In addition, different areas on the wall can have different shadow patterns or reflections from adjacent obstacles during the course of the day. An alternative to on-site measurements is the simulation of input parameters, such as radiation data. Solar radiation can be simulated with remotely measured data from the next climate station and a DEM, representing a 3D model of the area of interest. There are commercial providers such as Meteonorm (Meteonorm, 2020) or openly available tools (e.g., RayMan or SEBE (Lindberg et al., 2018)) to gather or process simulated on-site data. A comparison of daily solar radiation measured on-site with simulated data from RayMan and SEBE was provided by Saad (2020, Master's thesis, Figure IV.21).

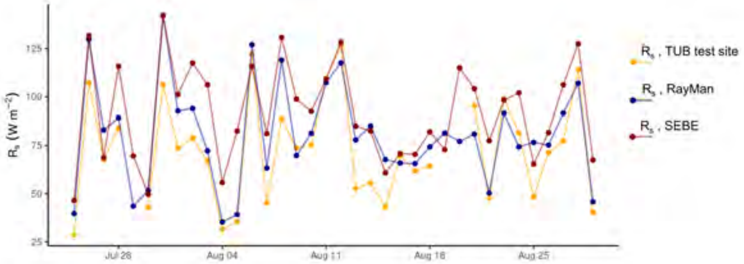

Figure IV.21: Comparison of solar radiation measured on-site and simulated with RayMan and SEBE, 25.07.–29.08.2014 (Saad 2020, Master's thesis)

For the SEBE model, a plugin to the geoinformation system QGIS (QGIS Development Team 2019), the accuracy of solar irradiance input to the building surface can be improved by adjusting the transmissivity of local urban vegetation, as suggested by Dienes (2019, Master's thesis). By incorporating foliation dynamics of prevalent tree genera in Berlin, incoming solar energy patterns could be adjusted in terms of the amount and seasonal variation. Figure IV.22 shows the different solar irradiance patterns on a test wall when the selected tree species are integrated into the model.

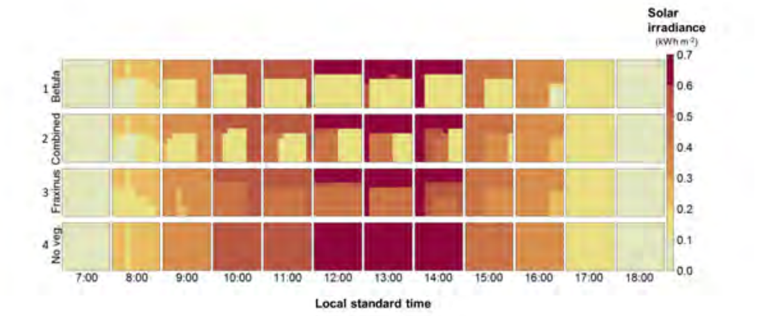

Figure IV.22: Hourly solar irradiance in the shade of the selected genera: (1) *Betula pendula*, (2) *Betula pendula* + *Fraxinus excelsior* combined, (3) *Fraxinus excelsior*, (4) no vegetation (Dienes, 2019))

Simulation tool and scenario analysis developed in the project

In the course of this project, the cooling energy saving potential for a set of relevant buildings from Berlin and Ljubljana should have been analyzed. Thereby we wanted to answer the often upbrought question, if insulated bulidings can profit from facade greenery in the same way as non-insulated buildings. To answer the questions, a one-dimensional heat transfer model, developed by Šuklje (2016) has been adapted. The calculation tool is available in the R (R Core team, 2018) programming language (link, see Hoffmann et al., 2021 for details). A set of relevant buildings has been identified and parameterized by the thickness, material density, thermal conductivity, specific heat capacity and thermal mass of each individual wall layer. The selected buildings differ in their wall structures, thermal insulation, and functions.

Figure IV.23: top left: Wilhelmine building, Prenzlauer Berg, Berlin, Germany; bottom left: test hall at TU campus, Berlin, Germany; right: pre-fabricated panel building, Berlin, Germany (images by Karin A. Hoffmann)

Figure IV.23 shows three of the selected buildings from Berlin. The energy-saving potentials have been simulated for a ground-based green facade consisting of a one-layer climber plant with a transmission of 0.17 ± 0.02 . We simulated the behaviour in the summer period (June 1 to September 30) for a typical reference year (20-year average using the Meteonorm dataset for Berlin and Ljubljana. Here, one can extract the incoming radiation for a tilted surface. Given a optimal water availability for potential evaporation of the plants, evapotranspiration was considered using the Penman-Monteith equation in the model. We found the highest cooling energy-saving potential for a commercial hall (built in 1954) and a pre-fabricated panel building (built after 1950). Compared to the other wall structures, these two have moderate thermal insulation and moderate to low thermal mass. Surprisingly, the retrofit version of the pre-fabricated panel building (with added insulation and high thermal insulation) had a higher cooling energy-saving potential than the two buildings with lower thermal insulation (namely the Wilhelmine building and a residential building from 1932). The findings suggest that the selection of priority buildings for VGS implementation as an energy-saving measure should be case-specific, taking into account the thermal insulation and thermal mass, arrangement of the material layers, and local climatic dynamics.

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Chapter V

CHALLENGES IN THE PLANNING, GOVERNANCE, AND FINANCING OF URBAN VERTICAL GREENING

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This part of the book addresses various aspects of and possibilities for including vertical greening (VG) content in planning and governance at various levels, which can have a significant impact on the development and implementation of VG in practice. The first section (section 1) – understanding planning and governance for vertical greening – explains our understanding of the general issues and relationship between the concept of VG and spatial planning as part of urban governance.

The second section (section 2) presents a report on a survey on the current situation regarding the inclusion of VG topics in planning and governance for sustainable and socially responsible urban development in Austria, Germany, Slovenia, and Taiwan and in the cities of Vienna, Berlin, Ljubljana (and Taipei) in particular. We rely on data, information and documents obtained in the analysis of the status quo and case study cities of Berlin, Vienna, Ljubljana, and Taipei and other project activities such as workshops and interviews with stakeholders and online surveys. All four groups were asked about their viewpoints regarding benefits and barriers and their experiences with VG.

In the third section (section 3), we discuss the practical challenges of VG planning at the city level. In doing so, we try to present and justify why it is necessary to approach VG planning systematically and strategically.

In section 4, we present some outcomes of the project that can support the planning process and governance decisions for VG development in urban areas. These outcomes include the following: (1) the approach for developing a catalog of city structure types as a tool for evaluating city morphology for better decision-making in VG implementation; (2) the identification of cultural heritage issues in VG; (3) an explanation of how Urban Atlas can be used for urban structure analysis; and (4) a geoinformation decision support system for determining green infrastructure deficit in urban areas as a step toward defining of the priority areas for VG implementation on a city level.

The last section (section 5) is dedicated to financing issues related to the nature-based solution (NBS) concept, explaining possible financing systems and models used for VG as NBS.

1 Understanding planning and governance for Vertical Green

The greening of facades and other vertical surfaces to improve the living and natural environment of cities is a relatively new approach in the planning and governance of modern cities, although vegetation-covered facades and walls has a long history (see chapter I). However, awareness of the functional and aesthetic benefits of VG has generally been lost over time, and the use of green facades eventually became merely a personal preference of the owner or part of the architect's design style. Only in recent decades has the greening of buildings been reinvented and become a new trend following the environmental movement, raising awareness of the necessity of bringing more vegetation into cities to better mitigate climate change and to improve the urban environment and living conditions. The finding that more vegetation needs to be introduced into urban spaces to sustainably develop cities and increase their resilience and livability has been especially important. However, the mere presence or increase in the amount of vegetation is not enough. To actually improve quality of life in city environments through all possible benefits of green areas and vegetation in the urban environment, it is necessary to ensure systematic, integrated, and comprehensive planning regarding such greenery.

Green walls and green roofs were recognized as important green elements in urban areas early in the development of the concept of green infrastructure (GI), a relatively new urban green space planning approach aimed at providing and connecting vital ecosystem services that contribute to or enhance urban sustainability and the natural environment. Green infrastructure is also described as a network of green spaces and water systems that deliver multiple types of environmental, economic, and social value and benefits for sustainable urban development. The term refers to any vegetative infrastructure system that enhances the natural environment through direct or indirect means and includes green roofs, living walls, parks and reserves, backyards and gardens, waterways and wetlands, streets and transport corridors, pathways and green corridors, squares and plazas, sports fields, and cemeteries (World Green Infrastructure Network, 2021).

However, in practice, many important questions related to the planning, governance, and financing of green walls (and green roofs) are still unanswered. GI is still more of a concept than a well-developed planning approach, especially when in relation to urban green space planning.

Based on principles from landscape ecology, GI emerged in the 1990s as a response to problems with urban sprawl but still carries a significant degree of ambiguity, having been employed differently in different scientifical disciplines, policies, and planning initiatives in different countries. It has high-level international policy support and attention, but there are still debates regarding whether GI should have an ecological focus that prioritizes biodiversity conservation or one that focuses on sociocultural and economic aspects (Hansen, R. et al., 2021). In the European Union, GI became known as a “strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services”.

The document Green Infrastructure (GI) — Enhancing Europe’s Natural Capital (European Commission, 2013) set a new priority goal of European strategic programs and development policies for the period 2014–2020; the document is one of the most important and successful tools for understanding the value of the ecological, economic, and social benefits that human society may obtain from the natural environment and for appropriately claiming these benefits (ecosystem services). However, there has been no systematic overview of how the concept has been taken up in planning practice in different European countries over the last ten years (Hansen, R. et al., 2021).

Different EU countries have different interpretations and approaches toward GI planning implementation in national planning documents and practice. Furthermore, similar approaches, such as green space strategy planning, green system planning, and other comprehensive landscape planning approaches, have been well developed and successfully implemented in many countries and are part of their regular, statutory spatial planning processes and legislation for green space development in urban areas. From the point of view of the comprehensive planning of green areas, it is important to clearly define all types of green spaces and water bodies that are relevant in the planned area because only in this way is it possible to achieve an appropriate transfer of strategic decisions, solutions and guidelines for planning and designing different green space implementation through regional, municipal, or other local spatial plans.

At the same time such a typology lays the foundation for the analysis and assessment of an area's supply in terms of various aspects of green areas and the determination of needs, potentials, goals, and development guidelines for improvement.

VG (such as ground-based, wall-based, pot-based green facades, see subsection 1.1) and green roofs are very special elements and types of green areas that differ greatly from other types in that they actually form part of buildings. This means that these types of green spaces require different approaches in both planning and governance than conventional green areas do. Being at the same time a type of green space in a city or town with very important associated characteristics, benefits, and limitations related to natural characteristics but also inseparable parts of buildings gives these spaces a dual character in all stages of their development process. This should be taken into consideration at all steps and levels, including in initiating, decision-making, evaluating, planning, designing, financing, implementing, and managing activities, as well as in the definition of stakeholders.

This point raises the questions about when and how the requirements and guidelines for the implementation of VG should be addressed in the process of urban planning to benefit the city as well as the owners and inhabitants of the building. Is such greenery part of building regulations, green and open space planning, climate adaptation plans, green infrastructure plans, local green development plans, and detailed urban design projects? Does it need to be planned at all, or is it just better to support investors who are willing to implement vertical green elements? How can we evaluate and achieve all possible benefits of VG and on what level can we do so? Who should finance VG, given that if benefits the neighboring urban area and the city? Who should take over and finance the management of VG after construction is complete?

As we have presented and substantiated in previous chapters, the impacts and benefits of VG are much broader than the direct impact on the building itself. Much more than a classic built facade, green facades affect not only their own buildings but also their immediate and wider surroundings. If carried out on a large enough scale to have cumulative benefits and in appropriate locations, these facades can also have a positive impact on the city as a whole.

As presented in chapter II, the planning, implementation, and management of VG involve different sectors and stakeholders.

Related to this are several challenges in the context of providing appropriate conditions for the desired development of VG at the level of cities, their areas, and individual buildings. The values, opinions, and motivations of stakeholders have a very strong impact on urban governance issues, including how to establish appropriate links and synergies among the various activities of different sectors, planning levels, and document topics as well as within the decisionmaking, financing, and management of VG.

From practice, we know that green roofs are a much more developed area than VG and are therefore also better and more frequently included in the spatial planning systems, legislation, and planning documents at different levels. Given the abovementioned common features arising from the dual nature of these two interventions, the experience and approaches we have regarding green roofs can be used as a model when examining and seeking to understand aspects of planning, management, and governance related to VG.

However, there is one important distinction we should take into consideration. Being horizontal, green roofs have much greater potential to be designed as publicly (or privately) accessible green spaces than VG, making it much easier to fulfill various social functions and multi-use possibilities of green spaces. Being vertical, VG is much more demanding and complicated to design, finance and manage as a multifunctional and multiuse space. This should be taken into consideration when considering VG as a possible compensation approach for building accessible green or other open public spaces. Vertical green elements cannot fully replace other urban green spaces, especially those intended for public use. Of course, there are ways to design privately (or even publicly) accessible VG interventions, such as the Bosco Verticale in Milan and similar buildings with privately or publicly accessible green terraces and balconies that compose the vertical greening element of the building, but this is not yet common practice. The green facade of the IKEA building in Vienna, for example, was designed to be publicly accessible, but in practice, this access has not (yet) been realized.

Therefore, we want to point out that VG, as a type of urban green space, is especially important in certain urban environments and circumstances where no other types of green spaces are feasible to improve the environmental problems and quality of living conditions. These are usually existing, very densely built-up urban areas or urban areas that according to strategic green space planning, need to be kept greener, because they are parts of green wedges and corridors.

Moreover, VG as a green space is important primarily as an additional improvement measure and sustainable planning and design approach for regenerating or initiating new development in cities and other built-up areas.

2 Planning and governance of Vertical Green in Vienna, Berlin, Ljubljana and Taipei

A survey of the status quo of formal and informal types of planning and governance was conducted by the UIRS expert group with the help of partners from all four participating cities and countries. The aim of the survey was to gain insights into governance practices and documents to support the implementation and management of vertical greening in the participating cities. Deeper insights into different planning and governance practices related to vertical greening implementation in Austria (with a particular focus on Vienna), Germany (Berlin), Slovenia (Ljubljana), and Taiwan (Taipei) are presented below.

Although all the participating cities are capital cities, they are very diverse in terms of their size, climate situation, urban structure, ratio of green space to urban area, and ratio of green space per inhabitant, so no direct comparison is possible between them. It was also known in advance that the countries and cities in question differ greatly in terms of the level of existing implementation of green walls in current urban practice, especially in terms of modern forms of vertical greening of multiapartment and public buildings. Nevertheless, we predicted that more in-depth insights into VG-related planning and governance situations can offer a better understanding of process development. By analyzing individual situations and contexts, we also identified examples and experiences that could be useful for different cities.

We opted for a methodologically unified approach in order to obtain similar insights into these different situations. Therefore, we prepared a common framework for analysis with several sets of questions related to the inclusion of VG content in established forms of formal and informal planning, in legislation and in some other relevant aspects of governance that we identified as particularly important in this context. In that way, we obtained a comparative overview of different planning and governance approaches at the national, city and local levels for all four cases. The content of this survey was previously reviewed and agreed upon by all the project partners, who then answered the questions for their respective countries and cities. The survey consisted of several thematic sections with an extensive set of questions addressing planning and governance issues, the answers to which were intended to help their partners completing the document better understand such complex content.

In addition to legislation and planning issues, stakeholders' roles, involvement, and opinions were defined as key factors of urban governance related to VG. The city or municipal government of elected representatives and city administration were identified as the largest and most visible actor in urban governance. Their most important task is to carry out or ensure the necessary communication, inclusion, and cooperation with all other stakeholders, such as inhabitants, private owners, businesses, NGOs, research and planning agencies, and other public actors that may have a strong influence on urban development. Being profoundly political, governance depends not only on political, economic, and planning systems and legislation but also on government institutions' capacity and knowledge in recognizing, making decisions about and supporting new urban development concepts. Furthermore, governance is often strongly influenced by the values, attitudes, and motivations of the different stakeholders involved.

In addition to the findings from the research on planning and governance, we also used information, data and findings from the Future workshop that was held in Berlin. It involved representatives of stakeholders from all 3 participating European cities and helped us better understand how different stakeholders view the obstacles, problems, and benefits of VG and what kind of solutions and activities they would need for future VG implementation on a city level.

In-depth interviews and workshops with stakeholders and representatives of city services in Ljubljana provided a better understanding of the interdepartmental cooperation and development steps that are necessary within the city's administration for the successful development of VG from beginning to end and into the continued management activities. Additional insights into different stakeholders' opinions were obtained from the answers to the online questionnaire conducted in Slovenia, Berlin and Vienna that was prepared for 4 different groups of stakeholders (more information about this in chapter II).

2.1 Planning

The survey addressed how VG is included in the statutory, formal, and legally binding strategizing, implementation, and planning practices at the national, regional, and city/local levels. The survey also investigated whether and how VG is included in informal, non-statutory planning at the city and local levels (which is supported by city or state administrations or other stakeholders in different ways but is not officially biding). Furthermore, the survey checked which international guidelines and documents are considered in the planning and legislation systems of different countries and cities, as well if vertical greening is already addressed as a nature-based solution in various national documents and legislative acts.

Statutory, formal planning

By formal, statutory planning, we mean the production of legally binding, obligatory development and protection documents, acts, rules, and regulations. The research question focuses on how VG implementation is included in legal documents and their recommendations or guidelines. The situation has been investigated through two main types of documents – strategic and implementation documents – and on three relevant planning and development levels: national, regional, and urban. We concluded that the regional level is not relevant in the current survey context because in Slovenia, there is no statutory regional-level planning, while Vienna is defined as both a regional and city entity, and Berlin is a city-state.

In Taiwan, VG is not formally included in the strategic planning system on any level.

Strategic documents on a national level

The data obtained in the research show that VG as a topic is rarely directly included in any strategic document at the national or regional level but is more often indirectly included in the goals and visions of various national strategic documents that refer to different European strategy papers and directives such as the EU Biodiversity Strategy for 2030, EU Adaptation Strategy Blueprint, EU Strategy on Green Infrastructure, and the Directive on the Energy Performance of Buildings. VG is generally listed among examples of how to achieve the vision or goal of increasing the amount of green within urban areas to improve biodiversity and mitigate climate change.

In Austria, VG is indirectly integrated through the requirement to implement in national strategies international (EC) documents such as Green Infrastructure (GI) — Enhancing Europe's Natural Capital (European Commission, 2013), which recognizes green facades as an important element of GI, and the Directive on the Energy Performance of Buildings, which, "among others, promote[s] green infrastructure solutions such as green roofs and walls to help to reduce GHG emissions."

In Germany, VG is listed among the measures for achieving the goals of transforming urban landscapes into green settlements and increasing the amount of green in the direct surroundings of residential areas; these goals were set in the National Strategy for Biological Diversity 2007 (BMUB, 2007), the Urban Natural Master Plan of the BMU (2019), and the White Paper: 'Green Spaces in the City' provided by BMUB (2017). The regional Strategy – City Development Plan Climate 2011 (Stadt Berlin, 2011) for Berlin dictates that Berlin needs to restore its building stock in a climate resilient manner and, green facades should be used wherever possible.

In Slovenia, VG is indirectly mentioned in the Development strategy of Slovenia 2030 and the Spatial Development Strategy of Slovenia 2050 (draft) in the content covering of green infrastructure, heat island mitigation and green systems.

In Taiwan, VG is not formally included in the strategic planning system on any level.

Strategic documents on the city level

Similarly, at the national and regional levels, VG implementation at the city level is part of the vision and goals of different city development plans in all participating European cities. From the survey answers, we can conclude that VG is particularly related to climate problems, but only in Vienna and Berlin are VG guidelines also prepared as part of city development plans.

In Vienna, greened facades are seen as a measure to combat urban heat island effects and are addressed in legally binding documents at the city level within the Smart City Strategy, Urban Heat Island Strategy, Coalition Program of the Government of Vienna, and Urban Development Plan Vienna (Stadt Wien, 2015) more details are provided in the thematic document 'Thematic Concept Green and Open Spaces'. VG is included under different topics in city development plans. Guidelines are prepared for specific urban areas only and are related to land use plans and apply only to new or rebuilt buildings. Vienna also has a VG-related building regulation dictating that "on new buildings of a specific height, 20% of the street facing facades have to be constructed as vertical green."

Step 2025 Thematic Concept Green and Open Spaces defines vertical greening implementation as one of the measures for developing *Type 01: Lively streetscapes and pedestrian zones.* It is one of the 12 types of zones defined as green and open space in city planning, providing a uniform tool for use by expert departments, planning offices and politicians in green and open space planning in **Vienna**.
Type description: Street spaces and pedestrian zones with exercising and resting zones for pedestrians and cyclists, contiguous space that allows for crossing traffic surfaces without risk
Examples: Mariahilfer Straße, Stephansplatz, Rotenturmstraße
Functions: Functions for everyday life and recreation (especially for pedestrians and cyclists, resting, encounter, communication, and consumption); Potential function for the structuring of the urban fabric (urban networking/ connections)
Strategies: Improving and ensuring the possibility for passing for non-motorised traffic.

Tasks: Development of high-quality tree locations, use of micro open spaces, creation of resting zones without commercial activities, promotion of facade greenings, front gardens and P side-walk café gardens.
VG justification: Plants and facade greenings increasingly contribute to a pleasant atmosphere of these open spaces and a significantly lower share of motorized individual traffic brings about a certain reduction of conflicts regarding their use, although there is still great space demand for traffic purposes. Especially this open space type should be planned in close connection to the ground-floor zone. Flexible possibilities of adoption increase diversity and reduce costs for maintenance. [...] Facade greening, front gardens and side-walk café gardens motivate local residents to increasingly assume responsibility for open spaces.

In Berlin, the goals that mention VG are related to the climate situation. VG is part of the 'City Development Plan Climate', which is a separate document from the 'City Development Plan Housing 2030', 'City Development Plan Economy 2030', 'City Development Plan Mobility and traffic' and 'City Development Plan Centres'. VG implementation is part of various criteria , and there is VG-related guidance in 'Planning Advice – urban climate 2015', which was prepared for the city as a whole, for different land use types and specific urban areas but not for specific types of buildings. The measure is considered a priority because of its effects related to the human bioclimate and multi-effectivity, which refers to

- The potential for VG implementation, especially in settlement areas with high thermal loads
- FLL 2000 for the technical design and maintenance of VG
- responsibility for VG systems resting with the house owners

In Berlin, city development plans include recommendations for further planning and are developed as concepts in accordance with the National Building Code (§1 Abs. 6 Nr. 11 BauGB). In this respect, it is a particularly interesting practice to secure 'green qualities' for the city center of Berlin through the use of the 'biotope area factor' (BAF) (Biotopflächenfaktor/BFF, Land Berlin, 2021).

The **BAF** expresses the ratio of the ecologically effective surface area to the total land area. Examples of natural environmental effective land use include non-sealed surfaces, open bodies of water, and roof and facade greening. BAF is a measure of the Berlin's landscape program that formulates basic goals and measures to promote high quality urban development with respect to the ecosystem, protection of biotopes and species, the appearance of the landscape, and recreational use. As part of the landscape plan BAF is established as an ordinance. However, according to §50 NatSchG Bln , the expenditures of the property owners for the measures should be "within reason", which is why the implementation of the measures should always be reinforced in cooperation with the property owners and developers.

The BAF expresses the ratio of the ecologically effective surface area to the total land area.

In this calculation, the individual parts of a plot of land are weighted according to their "ecological value". Among the types of surfaces and weighting factors per m^2 are also the following types of VG:

- Vertical greenery with connection to the ground (direct connection of the vertical greenery with the soil, supply with nutrients and water directly over the roots in the soil) has a weighting factor of 0.5 m^2
- Vertical greenery without connection to the ground (vertical or horizontal vegetation on a wall without direct connection to the soil on the ground, permanent planters supplying the vegetation, with artificial irrigation) has a weighting factor of 0.7 per m^2 .

In Ljubljana, VG implementation issues are related to objectives in the field of environmental quality that aim to reduce the impact of urbanization on climate change, to adapt to climate change, to protect the production potential of the soil, and to promote various forms of food production for local self-sufficiency, including production on roofs and terraces (Municipal Spatial Plan of the City of Ljubljana: strategic part. Folder 1, Ordinance on the Strategic Plan of the City of Ljubljana, Annexes to the Municipal Spatial Plan).

In addition, in the strategic and executive section of its ‘Sustainable Urban Development Strategy’ document, Ljubljana City committed to contributing to the improvement oftransport/mobility by developing green infrastructure and the use of ‘nature-based solutions’, as this is a recognized way to improving climate conditions at the regional level. Among other sections, the strategic part defines the following priority objectives for green areas:

- The construction of new green elements (green roofs, walls, “green living rooms”, etc.) in defined areas by 2016. This objective is linked to Ljubljana’s Green Capital of Europe 2016 initiative.
- The construction of new green elements (green roofs, walls, “green living rooms”, etc.) in additional defined areas by 2020.
- The construction of green areas, city tree-lined avenues, green parking lots, green roofs and walls, etc. by 2050 to help mitigate and adapt to climate change and regulate the urban microclimate to prevent overheating.

Mapping VG

Answers to questions about the graphical representations of the areas with planned VG within the planning documents showed that none of the urban plans included maps that directly presented the areas planned for VG implementation. This is not surprising given the two-dimensional nature of the graphical representations on the maps and the vertical character of VG. However, in the city development document for Berlin, ‘Planning advice map urban climate 2015’ (Land Berlin, 2015), which accompanies the online version of the ‘Atlas of Berlin Urban Development and its Environment’, there is already a map presenting thermally polluted settlement areas where green facades are recommended and defined as a priority measure because of their multiple effects on the human bioclimate (see Figure V.1).

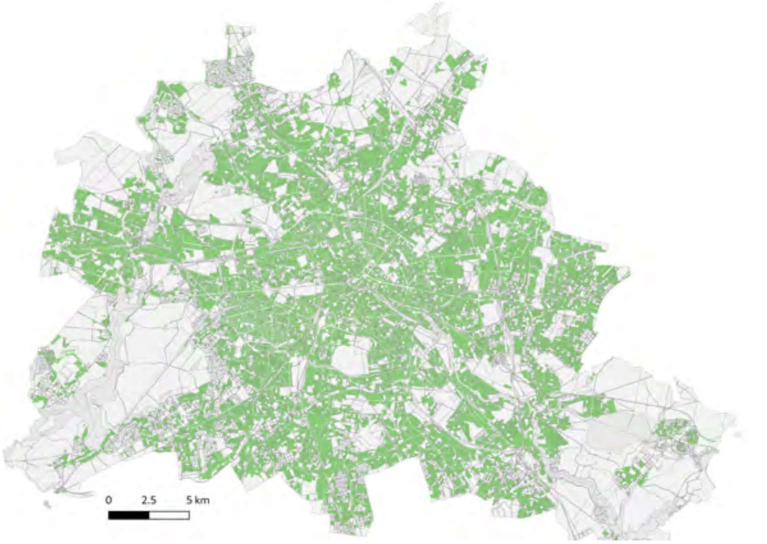


Figure V.1: Urban areas – recommendations for measure 15 – Facade greening https://www.berlin.de/umweltatlas/

Furthermore, we noticed that VG is sometimes indirectly included in maps via different open and green space planning typologies as a measure of open space development. For example, in 'Vienna Step 2025 Green and Open Spaces' (Stadt Wien, 2015), vertical greening is defined as a measure of Type 01: Lively streetscapes and pedestrian zones green space. This linear and urban open space typology is presented on a map titled Schematic illustration of the green and open space network (see below, Figure V.2).

Another indirect VG mapping example is the 'Ljubljana green system plan' with a map presenting green wedges where green roof (and VG) implementation is included as a planning guideline (see Figure V.3).

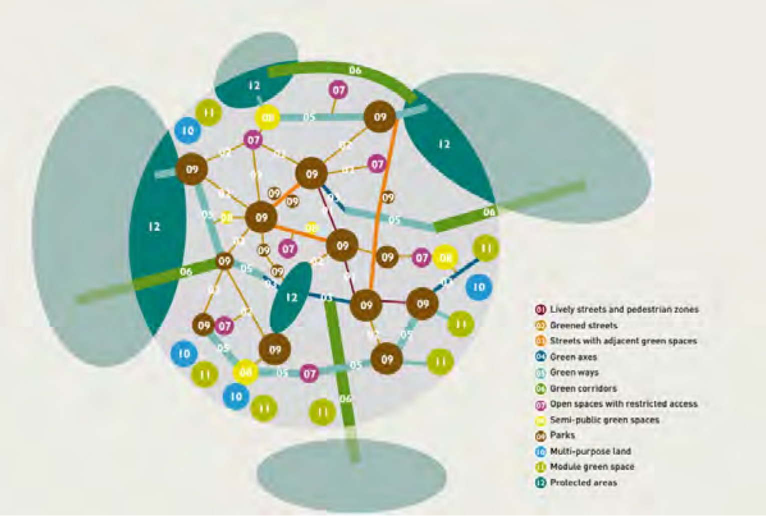


Figure V.2: Schematic illustration of the green and open space network including Type 01: Lively streetscapes and pedestrian zones, which VG is proposed as a measure of (Stadt Wien, 2015)

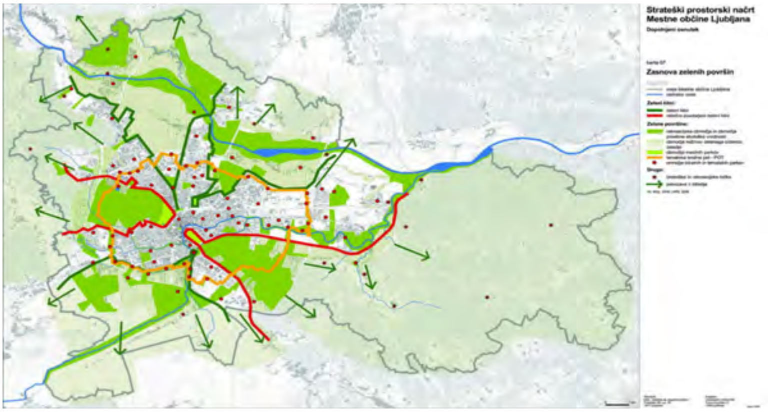


Figure V.3: Strategic plan of the Municipality of Ljubljana – Green System plan map

Design and implementation documents

In this part of the research survey, we checked whether there were any VG standards, recommendations or guidelines set at the national or city levels (municipality plan or ordinance) in each participating country in three aspects: VG design, VG implementation and VG maintenance.

In 2021, a new standard for vertical greening (ÖNORM L 1136, 2021) was adopted in Austria. The standard defines principles and requirements for the vertical greening of buildings and applies to the planning, execution, and maintenance of perennial green walls and outdoor building surfaces. This also includes wall greening with plant troughs, which are set up or hung on the walls. ÖNORM can be used for the greening of pergolas, dry stone walls, gabions, noise barriers and self-supporting structures. It also applies to walls with slopes of 30° to 150°, where greenery can generally be planted.

In Berlin, the recommendations and guidelines for VG design, implementation and maintenance are part of 'Planning advice – urban climate Berlin 2015'. This document refers to the FLL 2000 guideline addressing the functions and impact of VG, legal building requirements, the choice of plants, climbing aids, limitations on greening and maintenance. Vertical green is also recognized as an option to meet the biotope area factor (BAF) and improve the situation in the area. In Berlin, almost 50 % of all "landscape plans" contain BAF as a planning target.

Landscape plans ("Landschaftspläne") are developed on a municipal level and define spatial features and measures based on the goals and principles of nature conservation and landscape management (§1 and §2 BNatSchG).

Parts of a landscape plan are usually **'Purposes of open spaces', 'Extent of settlement areas', 'Development goals for landscape and nature', and 'Priority zones for nature conservation**.

Landscape plans refer to a planning period of 10 to 15 years and are updated according to current developments. In 2017, the following districts implemented landscape plans included the BAF: Charlottenburg-Wilmersdorf, Friedrichshain-Kreuzberg, Lichtenberg, Marzahn-Hellersdorf, Mitte, Neukölln, Pankow, Reinickendorf, Spandau, Steglitz-Zehlendorf, Tempelhof-Schöneberg und Treptow-Köpenick.

Non-statutory, informal planning

In the survey, we also addressed non statutory, informal planning that is supported by city or state administration or other stakeholders in different ways but is not officially biding. Usually, the documents produced are the result of development guidelines, public information websites, calls for projects and funding and different bottom-up initiatives. In the survey, we asked if vertical greening was addressed by the following:

- Action planning on a city level
- Action planning on a local level
- National/regional government-supported interventions on a local level
- City-supported interventions on a local level
- Public-private partnerships on a building level
- The possibility of adding and describing other options known to the city partners.

Action planning at the national, regional and city levels

From the answers and documents, we can conclude that action planning at the city level is a well-established practice in Vienna and Berlin. The capital city and state of Vienna have also developed guidelines and recommendations for VG design, implementation and maintenance for public use across Austria, but these guidelines are not mandatory (Stadt Wien, 2019). The facade greening is a topic of the 'Environmental Atlas of the City of Vienna'. Among its publicly accessible collection of maps and plans on various topics and projects of the Vienna Environmental Protection Department (MA 22) also the inventory of facade greening is presented (Stadt Wien, 2021b). It is classified into 3 types: ground-based greening, facade greenery and mixed systems. Each of these types is presented alongside photos of the location of the facade; an explanation of the name, address, use, and construction date of the building; and a description of the green facade type, the plants used, the size of its surface area and its public visibility.

Each informative box also links to an explanation of the types of facade greening and best practice examples, good reasons for using green walls, their advantages, relevant advice, and funding sources for facade greening with links to free consultation and application forms for obtaining building permits. There is also information on available grants for funding with links. Building greening – advice and subsidies is also one of the subject areas of the Spatial Development section of the Environment and Climate Protection of the City of Vienna website. To support VG implementation, there is guideline for administrative steps and permissions needed for VG presented as a checklist addressing facade greening on private property or other areas that are not public good as well as for facades accessed from (public good) areas such as sidewalks (Stadt Wien, 2021c). Action planning is also established on a local level in the form of district projects such as 50 Green Houses (50 GH, 2019). In Germany, national-level recommendations and guidelines are set for all 3 relevant aspects of VG development, design, implementation, and maintenance, including plant requirements (FLL 2018). Furthermore, the NGO "Grüne Liga Berlin" offers consultations for courtyard greening and runs competitions for the most aesthetically pleasing courtyard and best courtyard for socializing.

In Slovenia, VG is included as a type of green space in the national guideline Green Systems in Cities and Settlements: Directing the Development of Green Areas, which is part of the National Spatial Order and as such, the official guiding document for Slovenian municipalities. Recently, in 2021, the Slovenian Ministry for Environment and Spatial Planning also published recommendations for greening roofs and vertical surfaces (Čufer and Ribič, 2021). Additionally, in the Taipei (Taiwan) city/municipality plan, there are recommendations and guidelines for VG design, implementation and maintenance.

Public administration support

Public administration support for such interventions comes from national or regional governments or the cities themselves. Among the city administrations involved in this study, the most supportive is the city of Vienna. It supports the implementation of VG on private and public buildings through different programs and calls for VG implementation, and it supports bottom-up initiatives.

There are different local-level action planning projects, such as 50 Green Houses. National and regional support for such projects comes from the Austrian Research Agency or Klimafond.

In Berlin, there was an extensive program between 1983 and 1995 funding courtyard greening, including vertical green. The program financed 1,643 projects and helped green 740,000 m^2 of courtyards and facades as well as 65,000 m^2 of roofs in Berlin. Today, there is a program for roof greening in Berlin called "1000 Grüne Dächer" (1000 Green Roofs program). An initiative of the Berlin senate and the Berlin water agency, the "Berliner Regenwasseragentur" is offering consulting on rainwater use in roof greening. The coalition agreement of the Berlin state government (after the state elections of 26 September 2021) mentions an extension of roof greening programs to include facade greening as well.

Example from Berlin: "Klimaanpassung in sozialen Einrichtungen" program (2020–2023): Funding for strategic consulting, conceptualization and implementation as well as information campaigns and educational programs for adapting to climate change in social facilities; among others, roof and vertical greening implementation are suggested as measures on building sites. It is funded by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection between 2020–2023)
According to a market report 2020 by BuGG (Federal Association of Building Greening, BuGG, 2020), of the 191 German cities with a population > 50,000 included in the report, 45 provide financial support for VG implementation.

In Ljubljana, there are no notable examples of projects supporting green walls, but there have been some successful initiatives and projects for green roofs. However, the UIRS team conducted a series of in-depth interviews and a workshop on the potential for VG implementation in the city of Ljubljana with representatives of all relevant departments and services of the city administration. Interviews with municipal officers from several departments in Ljubljana City Municipality revealed that the municipality supports and encourages VG implementation if there is any initiative from investors from their point of view, and public-private partnerships are the most promising form of cooperation.

Schools, retirement homes and other public buildings are considered most appropriate for the implementation of VG that is publicly funded. However, no formal cooperation (calls, programs, etc.) or funding was provided by the public administration at the time of writing.

When we examined public administration support at the city level in more detail and found that in the public administration of all the surveyed cities:

- Responsibilities for VG implementation are not clearly defined
- There are no procurement methods for VG implementation
- The management of VG is not a part of regular public urban management

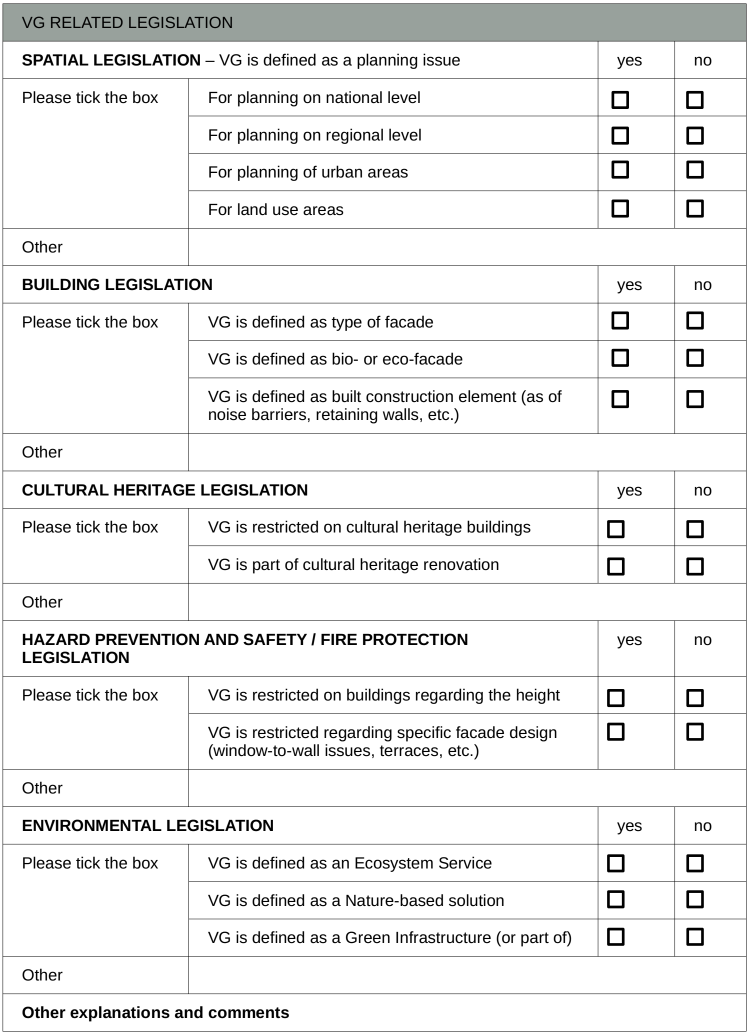
As public–private partnership on a building level

In Vienna, there are many different forms and examples of public–private partnerships for VG implementation on a building level, such as Cooperation of House owners maintaining the facade with the costs for VG funded by the Austrian Research Agency. The government of the City of Vienna is also using its own buildings as lighthouse projects for VG and has many good examples, such as MA 48, MA 31, and various school buildings.

In Ljubljana, there is a small-scale partnership between the municipality and the child care service, Mala Ulica, and there are cases of private company action in the BTC city shopping district where smaller green walls were implemented on some buildings as a compensation measure to meet the green space factor.

2.2 VG-related legislation

As part of the vertical green-related planning and governance aspects, the survey addressed the status quo of the legislation related to VG issues in different sectors, including spatial legislation, building legislation, cultural heritage legislation, hazardprevention and safety/ fire protection legislation and environmental legislation. The questions used are presented below (see Figure V.4).



VG RELATED LEGISLATION			
SPATIAL LEGISLATION – VG is defined as a planning issue		yes	no
Please tick the box	For planning on national level	☐	☐
	For planning on regional level	☐	☐
	For planning of urban areas	☐	☐
	For land use areas	☐	☐
Other			
BUILDING LEGISLATION		yes	no
Please tick the box	VG is defined as type of facade	☐	☐
	VG is defined as bio- or eco-facade	☐	☐
	VG is defined as built construction element (as of noise barriers, retaining walls, etc.)	☐	☐
Other			
CULTURAL HERITAGE LEGISLATION		yes	no
Please tick the box	VG is restricted on cultural heritage buildings	☐	☐
	VG is part of cultural heritage renovation	☐	☐
Other			
HAZARD PREVENTION AND SAFETY / FIRE PROTECTION LEGISLATION		yes	no
Please tick the box	VG is restricted on buildings regarding the height	☐	☐
	VG is restricted regarding specific facade design (window-to-wall issues, terraces, etc.)	☐	☐
Other			
ENVIRONMENTAL LEGISLATION		yes	no
Please tick the box	VG is defined as an Ecosystem Service	☐	☐
	VG is defined as a Nature-based solution	☐	☐
	VG is defined as a Green Infrastructure (or part of)	☐	☐
Other			
Other explanations and comments			

Figure V.4: Questions used to research the state of vertical green-related legislation

We can conclude that this topic is not (yet) recognized in this area of governance. At the time of writing, in none of the participating countries in the VG 2.0 project, environmental legislation has not defined VG as a nature-based solution, nor as an ecosystem service or element of green infrastructure. However, certain VG contents are directly or indirectly included in the spatial or construction legislation, fire and lightning protection legislation, and cultural heritage legislation in Austria and Germany and at regional level legislation in Vienna and Berlin.

In Germany, VG is legally defined as a planning issue and included in spatial planning legislation at the regional level. The Federal Association of Building Greening's (BuGG) Market Report 2020 (BuGG, 2020) shows that of the 191 German cities with a population > 50,000 included in the report, 41 % included VG in local legally binding development plans. VG is also partly addressed by the Federal Nature Conservation Act ("Bundesnaturschutzgesetz, BNatSchG") in terms of the introduction of invasive plant species or the protection of endangered species (relevant for maintenance) or as a compensation measure for construction projects (examples can be found in the Compensation Information System Berlin).

In Austria, VG is more related to spatial planning legislation for urban areas and building regulations. As already mentioned above, a new standard for vertical greening (ÖNORM L 1136, 2021) was adopted in Austria in 2021. The topic of vertical greening is also a part of Vienna building regulations §5 Abs. 4 lit k/§83, which include the requirement that "for 7.5–26 m street-side facades in newly built areas, 20 % of the facade must be constructed as VG".

Furthermore, there have been some measurements adopted concerning restrictions on VG, related mostly in legislation concerning cultural heritage and hazard prevention. In Vienna, for example, it is necessary to check the suitability of VG for the facades of cultural heritage buildings, and the standard *object security tests for residential buildings – Regular test routines as part of visual inspections and non-destructive assessments* (ÖNORM B 3800-5, 2013) define requirements for VG higher than 3 floors. In these cases, an empty space 1 m above the window and 20 cm on either side is required between the floors of residential buildings.

In Berlin and elsewhere in Germany, for buildings/ ensembles listed as heritage site, a permit for VG implementation must be issued individually by the Local Monument Authority, as stated in the Facade Greening Guidelines (FLL, 2018).

This document also describes the requirements of fire safety in terms of various facade parts and materials. The requirements are indicated as national norms and vary depending on the morphology and function of the building. However, these requirements are defined for a variety of materials, not just for VG. If parts of the VG are electric conductors, they must be connected to the lightning protection of the building according to DIN EN 62305 (2011).

2.3 Other relevant aspects of VG-related governance

In deciding which other aspects of governance make sense to address in connection with vertical greening, we proceeded from the fact that it is a new concept of modern urban development. Therefore, we decided to examine two main aspects, namely, how the content is visible and recognized by various stakeholders and what kind of support from public administration is already available to those interested in VG implementation.

To assess the recognition and visibility of VG among different stakeholders in the context of a particular country and city, different questions and statements were included in the survey; these could be answered with yes, no, or partly agree, as presented below.

- How commonly is VG recognized as an important topic in society
- There is information from news articles or other public media on this topic on a regular basis
- There are different books and publications on the topic available for purchase
- There is information on vertical greening examples in public media
- There are bottom-up initiatives for VG implementation
- There are public discussions on VG-related topics
- There are NGOs and associations supporting VG implementation
- VG is recognized as an important topic by experts such as spatial planning/urban planning professionals, landscape architects, architects, civil engineers, and environmentalists

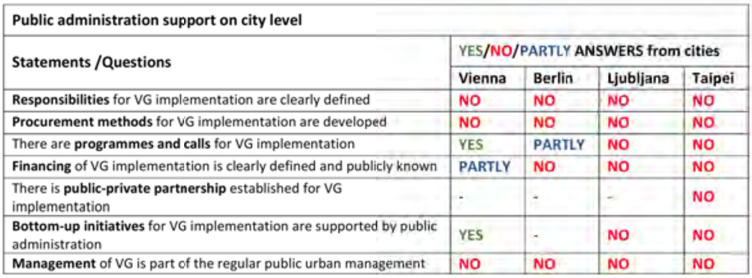
- VG is recognized as an important topic by those involved in research and education
- VG is recognized as an important topic by city administration
- VG is recognized as an important topic by regional administration
- VG is recognized as an important topic by state administration

From the answers to these questions, we can conclude that stakeholders in Austria (Vienna) and Germany (Berlin), are much more familiar with the VG topic and have more experience with green walls than those in Slovenia (Ljubljana) and Taiwan (Taipei). There are articles and other media reports on VG topics on a regular basis, and different books and examples of VG have been published. In addition, there are bottom-up initiatives or public discussions, and different NGO's and associations support VG implementation in Berlin in Vienna, although in Ljubljana and Taipei, this support is absent or rare. This is also in line with the actual situation of green facades in the cities in question, which suggests that personal experience with real-life examples may be particularly important for these aspects of governance.

Vertical greening is increasingly recognized as an important topic within research and education areas and by experts in all countries, especially landscape architects, architects, and urban planners. In Germany also by environmentalists and civil engineers, and in Slovenia by sanitary engineers.

What is particularly encouraging is that VG is at least partly recognized as an important topic by the city administrations of all the cities in question. However, as expected, only in Austria and Germany is there at least partial recognition of the importance of VG in regional and state administrations.

With the additional questions related to public administration support (which is presented for the relevant cities in Figure 2.1 – Non-statutory, informal planning) we examined in more detail what types of support for VG were common in different cities at the time of this research. The answers to the questions or statements (see Figure V.5 below) show that the actual support of city administrations, even in Berlin and Vienna, is still very weak, and there are still many untapped opportunities in all these cities to strengthen governance in this area.



Public administration support on city level

Statements /Questions	YES/NO/PARTLY ANSWERS from cities			
	Vienna	Berlin	Ljubljana	Taipei
Responsibilities for VG implementation are clearly defined	NO	NO	NO	NO
Procurement methods for VG implementation are developed	NO	NO	NO	NO
There are **programmes and calls** for VG implementation	YES	PARTLY	NO	NO
Financing of VG implementation is clearly defined and publicly known	PARTLY	NO	NO	NO
There is **public-private partnership** established for VG implementation	-	-	-	NO
Bottom-up initiatives for VG implementation are supported by public administration	YES	-	NO	NO
Management of VG is part of the regular public urban management	NO	NO	NO	NO

Figure V.5: Answers from the VG 2.0 survey to the statements on public administration support for VG implementation on a city level

3 Challenges in VG planning at the city level

The issues and challenges in rseaping the benefits of facade greening at the city level are very complex. Not only are these measures not widely used, despite being recognized as beneficial, but they are seldom tested within larger spatial arrangements, as they are very specific as type of urban green. These elements of green infrastructure require a different, innovative approach in terms of planning and management. Because VG are vertical surfaces and actually part of the building or other constructed elements, the challenges in addressing these elements derive not only from their natural "green space" characteristics but also from their physical and system structure at the building level. The question thus arises whether we need to plan vertical greening in strategic and systematic ways, as we do with other green infrastructure elements in urban planning, taking into consideration the benefits on the wider city level, or whether the decision to implement VG is primarily related to benefits on the building scale and is made for each specific construction project.

In this chapter, we address some specific issues and challenges in VG planning that are connected to the planning system in general. In the first part, the chapter examines VG as a specific type of urban green space at different planning levels, from strategic urban planning to urban design.

Vertical greening-related aspects and Urban planning and evaluating potentials of VG are part of the PhD research of one of the authors at the University of Ljubljana, Faculty of Architecture, (PhD candidate Jana Kozamernik), that focuses on a more detailed definition of the criteria for the evaluation of urban ambience in terms of the impact on perception and urban microclimate.

One of the key issues encountered in the project was the necessity, detail, and level of VG guidelines and regulations in city planning and design. The survey of Vienna and Berlin planning and governance approaches and examples revealed far more developed situations of VG implementation in these cities than in Ljubljana and Taipei. Data from the analysis show that this can be attributed to better support from national and regional legislation as well as the already established regulations and guidelines for VG implementation on buildings. When support for VG on the general level is present and supplementary information is available, implementation projects can follow examples of best practices. The need for the regulation of VG implementation at the strategic planning level was also clearly expressed in the in-depth interviews and workshops with city administration personnel of the Ljubljana municipality. Furthermore, we noticed that EU directives, strategies and guidelines are important for encouraging and supporting the adoption of such approaches on all levels. In Austria, Germany, and Slovenia (but not in Taiwan), VG is at least indirectly (as a measure) included in the goals and visions of various national, regional and city strategic documents that refer to different European strategy papers and directives, e.g., the EU Biodiversity Strategy for 2030 (European Commission, 2020a), EU Adaptation Strategy Blueprint (European Commission, 2020b), EU Strategy on Green Infrastructure (European Commission, 2013), and Directive on the Energy Performance of Buildings (European Commission, 2010).

Another important question is whether VG planning at the city level is truly justified and why. The vertical greening inventory in the Ljubljana urban area showed that most of the VG is located within areas that are already quite green, such as areas with individual houses that have gardens. The decision to adopt green facades seems to arise out of the personal preferences of people who prefer contact with nature rather than out of environmental or quality-of-life problems. A similar insight was obtained from site visits in Vienna, where in some parts of the city, a great number of individual houses have facades greened in a traditional way with climbers.

We also observed another recent trend in VG implementation that is widely researched: greening the facades of large, multistory luxury corporate or residential buildings. In many of these cases, VG is declared to be a way to promote green, sustainable development but is more of a way for the building design to promote the identity and prestige of the occupants. Although often declared to arise out of environmental consciousness, most of these interventions are a form of advertisement. In some cases, this is considered greenwashing, which seeks to conceal real problems with controversial investments and interventions, for example when green marketing is used to convince people that a building is environmentally friendly despite its unsustainable design and maintenance, e.g. high material consumption (e.g. frequent replacement of plants), unsustainable materials of fixing systems or panels, etc. Therefore, we strongly believe that it is necessary to open and expand the discussion not only about the benefits and problems of VG and question its use but also about the need for a systematic and integral approach to planning for the benefit of the city and its inhabitants. It is important to understand that VG is a specific type of urban green space with functions that are important for urban areas where the effects connected to VG, such as NBS, may be welcome. These factors are related to biodiversity, the mitigation of and adaptation to climate change, and the regulation of the urban microclimate as well as other benefits, such as the energy performance of the building (see chapter I). It is therefore particularly important to identify and take into account a common assessment of all these benefits.

3.1 Planning levels – from city to building scale

VG is a special type of green space because it consists of living elements and is considered an NBS similar to other green spaces, but it is, at the same time, a vertical part of the building. As such, it is part of the building construction and design as well as comprehensive green space planning on the city level, such as green infrastructure plans, green space strategies, green system plans, or similar planning documents. However, the recognition of VG in spatial development and planning is still very weak and very general in most countries and cities. On the EU level, there are some relevant documents that directly and indirectly support VG green implementation.

However, the recognition of VG in spatial development and planning is still very weak and very general. As presented in the previous chapter, both strategic planning at different levels and the inclusion of VG in regulation and implementation documents at the local and building levels are necessary to boost more systemic VG development. However, VG implementation can be supported from the bottom-up as well. In Taiwan, for example, VG is not recognized at any level of strategic national, regional or city planning, but it is part of the solutions and guidelines provided at the city and local levels.

On the urban scale, important issues are connected, especially those involving buildings in specific urban environments, the influential area of buildings (building impact on the surrounding area), the morphological structure, the location of buildings, environmental problems in the area (such as urban heat islands, air quality, noise levels, floods, imperviousness, etc.), the dimensions of buildings, building typologies, land use, the share of green spaces in the area, in-between spaces and voids in built structures, urban cover and surfaces in areas, and the use of outdoor space, accessibility, private and public open spaces, floor connections, walkability, etc.

At the building level, the most important issues related to VG implementation are the building's typology, uses, and age and the spatial and volumetric proportions of the building, its walls, and its facade – including the composition, height, width, orientation, shadowing, window-to wall ratio, texture, and colors, of these elements; also included are the accessibility of facades (from the inside or outside of the building) and special regulations regarding urban areas and buildings, such as conservation or other restrictions (e.g., cultural heritage protection, see cultural heritage issues for vertical green).

3.2 Vertical green-related aspects

In general, VG can be addressed from different aspects related to functions and different interlinking issues. These can relate to the climate, environmental impact, design, technical issues, social and psychological perspectives, financial issues and the economy, and management in general. Vertical greenery systems are biotechnical systems with vegetation that appear to be an integral part of the building's envelope.

These systems can be defined as vegetation systems, energy systems, water systems, NBS systems, as well as facade systems, technological systems, construction systems, etc. The vegetation and the system itself define the appearance and multifunctionality of VG, and different systems and forms can be used and adopted to meet the needs of individual situations.

In terms of microclimates, VG can act as a shading system. Vegetation plays a crucial role in establishing microclimatic conditions in urban areas and has beneficial impacts on environmental issues, including water systems, acoustic characteristics, wind, the absorption of pollutants, and biodiversity, which is why VG systems are considered multifunctional.

There are also different social and psychological aspects related to green walls, such as the perception, experience and use of space. The design function of VG is prominent when VG is used for artistic expression or as an identity element of the building. The technical and architectural aspects highlight the potential of sustainable solutions related to the complexity of systems, the use of materials, technical performance, safety, and the integrated renovation of the building (energy). VG can be used for food or biomass production. VG management and maintenance are crucial, as the full performance of the system can be achieved only with quality design and the maintenance of green vertical surfaces. The whole spectrum of diverse aspects associated with green walls in urban space shows the complexity of the topic in urban design (see Figure V.6).

Figure V.6: Interlinking aspects related to vertical greening (Kozamernik, 2020)

3.3 Urban planning and evaluation potential of VG

The evaluation of the potential impact of VG on urban space is complex, as diverse aspects and urban situations must be taken into consideration. Focusing on the possible impact of VG on the surrounding space, VG evaluation includes urban planning topics, such as the social environment, urban structure, urban systems, and environmental conditions. These topics are the most important areas of analysis at the city scale as well for defining evaluation criteria for the potential use of VG. In the VG2.0 analysis of urban situations, some of these topics were investigated, with a particular focus on analyses regarding the lack of green infrastructure in cities and the types of built tissue focused on improving urban space or solving different problems in urban areas. In the case of the social environment, urban structure, urban systems, and environmental conditions, the following detailed issues are addressed on different scales, which can be transformed to a list of evaluation criteria:

Social environment

Topics such as population density and ownership are crucial for the evaluation of VG's potential impacts on the social environment. Population density in terms of the distribution of people in the city, which shows where in the city the VG benefits for the quality of the environment (as an impact factor on population) will be felt, improving the quality of life and working quality. In addition to considering citizens, we should also look at the working population, educational facility users, areas for temporary accommodation (nursing homes, hospitals, etc.), and similar elements. In terms of ownership criteria, we provide insights into challenges related to management and financing, stakeholder structure and responsibilities, and the use of buildings and their surroundings – open space. The ratio of private to public ownership may have a strong impact on planning, implementation, and management issues.

Urban structure

The topics addressed in the field of urban structure are

- Morphology,
- Building envelope, and
- Building quality.

Regarding morphology, the building patterns, scale of buildings, and in-between spaces need to be considered. Building patterns/types with different built forms, including build volumes, open or closed forms and their characteristics, are addressed. The scale of the building and the dimensions of the facade surfaces are an important criterion in terms of their potential use for VG (size of the areas, physical connection, accessibility on different floors, etc.). Street widths and in-between spaces define the relevant morphological and environmental conditions (thermal, wind, etc.). The orientation of the building facades (exposure) and shading (e.g. tall surrounding buildings) are important. Regarding facade size, the potential of smaller/larger facade areas and the use of various types of green walls as well as the adoption of safety regulations can be evaluated. The spatial exposure of buildings (visual exposure) is an important factor. Regarding building quality, detailed information needs to be obtained on buildings, especially regarding their construction and energy consumption. In terms of renovation plans for specific buildings, green facades can also be considered as a possibility.

Urban systems

In the field of urban systems, some spatial planning issues are listed that are important for the evaluation of the potential of VG, such as programs involving space (land use), public infrastructure, green systems or green infrastructure, or cultural heritage. The analysis of programs involving space considers dominant functions in area – functional areas, uses of space, activities, the movement of pedestrians, etc. The presence of infrastructure is important (traffic system, services), as is the connectivity of streets and paths (use) and other construction that can affect VG system implementations – for example underground infrastructure along facades.

For urban green and open spaces, a green system is both a planning concept or plan and an urban system interlinking all relevant spaces into a multifunctional network including the green infrastructure. A green system plan also defines urban areas in need of greening and ways to connect different types of green and open spaces. Such plans also address areas that are usually treated under special regimes (zones with a need for a larger share of green areas than other zones need). Another topic connected to urban planning that also affects building envelopes is cultural heritage regimes for protected buildings and urban areas, as these affect the possibilities for implementing VG (the existence of restrictions in renovation, etc.).

Environmental conditions

The spectrum of environmental issues related to the evaluation of VG potential is very broad. Topics such as the situation of urban cover/ surfaces and environmental problems are addressed here. Urban cover and surfaces concern permeability (sealed/permeable surfaces), the presence of green spaces, tree coverage and the location of development areas (future built areas). The permeability of surfaces strongly influences environmental conditions; therefore, VG can be an important measure for improving the capacity to retain and use stormwater in areas with impermeable soil. Furthermore, another important factor is the presence (and type) of green spaces in different urban areas. Green system analysis and plans will point out city areas that need additional greenery. The analysis of tree coverage is important, as trees provide shading, have an impact on all environmental aspects and are the most effective green element for regulating microclimate conditions. Another topic is the future development of gray zones or brownfields, which can incorporate larger shares of NBS. By addressing environmental problem issues such as urban heat islands (UHIs), air pollution, noise pollution and water conditions (water overload or shortages), areas with high heat loads in summer can be evaluated for the possible use of additional vegetation. Greening implementation could also benefit areas with increased concentrations of air pollution (small particle values), increased noise levels (where the possibility of using barriers such as VG can be considered) and the use of rainwater or groundwater (flood issues, possible irrigation networks, etc.).

3.4 Integration of VG topics in urban planning

To bring nature back to cities and reward community action, the European Commission has called on European cities with at least 20,000 inhabitants to develop ambitious Urban Greening Plans by the end of 2021 (EU Biodiversity strategy for 2030, European Commission, 2020a). Such plans should help improve connections among green spaces, eliminate the use of pesticides, limit the excessive mowing of urban green spaces and other harmful biodiversity practices and mobilize policy, regulatory and financial tools. Among the proposed measures for different green spaces are green roofs and walls, which should be taken into consideration in future urban development. From the analysis of the cities in the VG 2.0 project, we can conclude that vertical greening is already recognized as important; if not yet a specific element in planning, it is at least seen as a measure for achieving the visions and goals of urban development strategies. However, the implementation of the VG is still more dependent on individual initiatives and informal planning activities, thus missing out on its full potential to achieve systemically defined, comprehensive benefits for wider urban spaces. We believe that the reasons for this should also be determined in established spatial planning approaches; these approaches rely heavily on aspects of land use definition, which is unsatisfactory and less appropriate for green space planning in general but even more so for vertical green planning. When planning green spaces, it is important to keep in mind that many types of extensive urban green areas that are very important for sustainable and resilient urban development are not part of green space land use but are part of other land use, such as residential or agriculture, or forestry uses, or part of water bodies, swamps and similar areas. Therefore, a comprehensive and integral green space strategy with guidelines for all types of green spaces in implementation is a necessary part of any urban plan.

Green infrastructure planning and other similar contemporary strategic urban green space planning approaches (green space strategies, urban green systems) represent an important shift toward more suitable urban planning that also considers aspects of co-use, multifunctionality and co-management. However, planning VG as a special type of green space represents an additional, new challenge. As already mentioned, facades and vertical surfaces should be addressed differently than other green spaces.

Not only can VG, given its vertical character, not be defined as land use or even presented on other usual spatial planning maps, but it also has a dual character, merging natural elements with built structures. Furthermore, it is important to take into consideration the type of VG system used. Some systems mainly exploit the natural features of vegetation (e.g., climbing) and are connected to the ground, so they can be understood as essentially naturally established ecosystems; on the other hand, there has recently been a much greater emphasis on and expansion of manufactured vertical (eco-)systems. These may be composed of different vegetation and forms of growing media that should also be part of the calculations involving the various factors that are important in urban planning, such as green space factors or other factors that are related to different aspects of environmental benefits, ecosystem services, and biodiversity. It is important that the greening of facades and other vertical surfaces is addressed from different aspects and on different scales at the same time. Some interesting practices and examples already exist in this area:

Biotope Area Factor (BAF) is a planning instrument developed by the city of Berlin. Like the urban planning parameters used in development planning, such as the gross floor area, the site occupancy index, and the floor space index, which regulate the dimensions of use structures, the BAF expresses the proportion of a plot of land that serves as a location for plants or assumes other functions within the ecosystem. The BAF thereby helps standardize and concretize the following environmental quality goals:

- Safeguarding and improving the microclimate and atmospheric hygiene,
- Safeguarding and developing soil function and water balance,
- Creating and enhancing the quality of the plant and animal habitat,
- Improving the residential environment.

The BAF can be established with a binding force in landscape plans for selected, similarly structured parts of the city. The BAF covers urban forms of use – residential, commercial, and infrastructural – and formulates ecological minimum standards for structural changes and new development.

All potential green areas, such as courtyards, roofs, walls, and fire walls, are included in the BAF, which can be used in landscape plans (in a zoning plan) or as an ordinance. The BAF values are listed in the table below and are applicable to various development and use structures.

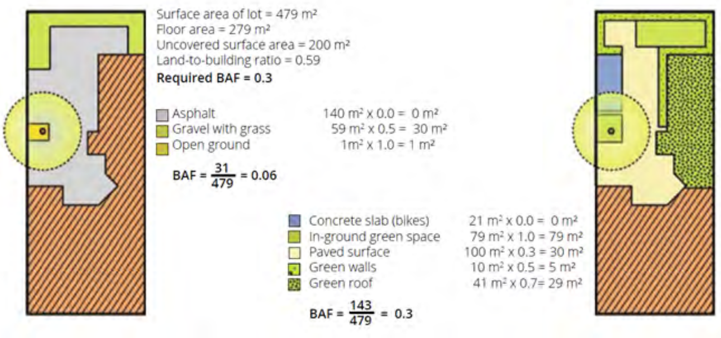


Figure V.7: Application of the Biotope Area Factor (ParticipatoryPlanning, 2019)

Ring et al. (2021) propose a new calculation method called "Open Space Factor Vienna" in order to improve microclimatic impacts as compensation for ongoing climate change at the plot level. The novelty of this method is that it takes into consideration different reference areas, such as facade greening (FG), the facade area (FA), the roof area (RA), ground level greening (GG), plot size (PS), outdoor area (OA) and building footprint (FP) (Ring et al., 2021).

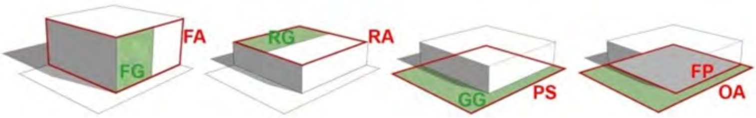


Figure V.8: Composition of GFF-V and the different reference areas. FG: facade greening, FA: facade area, RG: roof greening, RA: roof area, GG: ground level greening, PS: plot size, OA: outdoor area, FP: building footprint. (Ring et al., 2021)

In general, awareness of the benefits of VG increases with the promotion of best practices, but there are still many fears and preconceptions about VG (see chapter II). Although VG systems are not widely implemented in European cities, especially those in temperate climate zones, guidelines are already available in some countries. In addition, there are several building regulations that touch on the greening envelope topic – including vertical greening and green roofs.

VG as an Urban Green Infrastructure element

Due to climate change, rainwater retention and heat island mitigation are becoming key challenges in integral approaches to future urban development that seeks to ensure quality of life, sustainability, and resilience. To address climate change problems, systematic greening, especially in condensed urban zones, is increasingly recognized as an important function of urban green spaces, alongside their public health and recreational values. One of the contemporary ways to meet these challenges is a green infrastructure approach that has strengthened some very important aspects of green space planning by, for example, considering the integrity of VG benefits (ecosystem services), nature-based solutions, more discussions of motivation and increased cooperation, which represent an important shift toward comprehensiveness, integrity and cross-sectoral synergies in urban development. Green infrastructure as a concept originates from landscape ecology and is still quite differently understood by different sectors and professionals; however, during its development (in order to be effectively put into practice), it adapted to spatial planning challenges and adopted many parts of already established strategic approaches to green space planning in cities and settlements (green space strategy, urban green system). In some countries, green infrastructure is adopted instead of previously used concepts, is added as an additional level of action, or is adopted at different scales and in different areas (urban, rural, etc.).

In any case, green infrastructure planning is becoming an increasingly important part of the urban master plan of each city targeting different green infrastructure measures (urban, spatial and landscape planning measures such as soil desealing and the ventilation of the city) and architectural measures (choice of materials, greened roofscapes and facades, shading elements, etc.).

For this reason, one of the important evaluation measures for cities will become thermal imaging (heat island registers), which identifies overheated spots and thus accelerates the implementation of targeted actions that are closely related to green infrastructure implementation on a city level. Due to the functions provided by natural material used in the VG system applied, VG is already a recognized element of green infrastructure, but there are still open questions because of its dual character, which distinguishes this type of green space from other ground-based GI elements. The key issues are how to approach the planning and design of GI elements that are not only green and thus able to provide ecosystem services but are also vertical and part of the building and how to adequately integrate these elements into the general GI planning approach while still achieving the targeted city-level benefits. However, the analysis of planning documents in countries involved in the project showed that those new concepts are not yet widely used or related to VG in official documents. For example, NBS was officially part of strategic planning only in Germany at the time of writing.

Green Infrastructure planning on a strategic level

Modern urban planning approaches must incorporate green infrastructure in general/strategic plans as part of their usual thematic documents, such as green space strategy, urban open space strategies or green systems or as a comprehensive green infrastructure strategy, which includes all the functions and aspects of urban green space development. If a GI plan is used instead of other strategic urban green plans on a city (or other) level, green infrastructure planning should follow the same principles as those developed for urban green space strategies, for example as done within the GreenKeys project (Smaniotto Costa et al., 2008) and should include at least 4 main parts (see Figure V.9):

- vision and mission of the strategy with strategic aims and priorities (adapted to each city's situation),
- an analytical section,
- a green space plan,
- the strategic action plan.

It is also important that analytical and evaluation activities and guidelines for the action section be adapted to different GI element types as defined within specific topics if necessary.

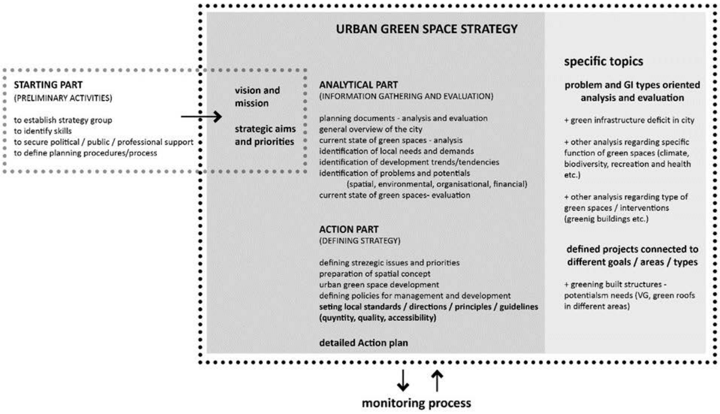


Figure V.9: The urban green space strategy concept (left part, adapted from Smaniotto Costa, C. et al., 2008) can stress specific green space elements and GI types (right part)

Recommendations on VGS in strategic planning level

Vertical Greening Systems (VGS) should be defined as Green Infrastructure (GI) connected to buildings. Depending on its extent it is defined as small- or middle-scale measure, significant on micro urban scale, which can be stressed especially in defining area-based guidelines. Analysis of potentials and needs for implementation of VG can be done from different approaches. On a strategic level the recommendations on possible greening of buildings in certain areas or of certain types of buildings, which can be set as priorities. VG and green roofs should be defined as NBS with respect to sustainability and quality aspects of urban areas.

Establishment of green space monitoring as well as VG inventory should be an ongoing and active process in the strategic action part as it has an important role as comprehensive overview of the extension, development and status of various green space types and is most important instrument of green space surveillance and also serves as an essential information basis for future urban GI planning.

Guidelines for specific types

Guidelines and detailed recommendations for planning of different types of green spaces are intended primarily for defining planning provisions at the implementation level of municipal spatial plans. They are directly related to the strategic provisions of the green infrastructure strategy goals and prepared according to the local socio-economic and spatial context. General guidelines to achieve the objectives of the strategy by taking into account the different aspects of green infrastructure at city level: connectivity of green spaces, quantity of vegetation, quality, provision of visual and accessible green spaces, water retention, biodiversity, etc. Guidelines and more detailed rules for green areas appearing in connection with buildings shall include

- total share of green areas in relation to the total area where the minimum is defined according to the area functions, use, building type, urban design, green system, and local context, definition of functions, content, and quality of arrangements, expected spatial characteristics, design quality
- ratio of open living space and the total area of a building plot intended for the construction (for residential areas)
- ratio between green areas on the permeable terrain and the total area of the building plot is determined, which is expressed as a factor of green areas or the minimum share of overgrown terrain, which ensures free outflow of rainwater (for areas of non-residential buildings)
- tree canopy coverage
- guidelines for ensuring accessibility – the connection between the building and the associated green area and accessibility guidelines

- guidelines for ensuring the quality of landscaping and maintenance of individual types of green areas.
- level of equipment – the areas with high, medium, low, and minimum level of equipment according to the function and use of these areas.
- level of maintenance – the areas with very intensive, intensive, less intensive, and minimal maintenance according to the function and use of these surfaces.

One of the basic parameters in the spatial plans is the proportion of green space per building plot, depending on the land use of the area. Different factors can be used for measurement of the degree of green space in urban area. On the basis of strategies or policies, the biotope or green area factor can be included in regulation. It defines the inclusion of a minimum coefficient in an urban plan. Besides basic parameter of green area ratio it introduces the factor which can also measure the properties of a surface. It can be used to determine the required future condition for the renovation of densely built-up areas. These factors are usually calculations on climate, biodiversity, and well-being components, including the accessibility and different types of open spaces. They could represent the evaluation tool taking into consideration different green implementations on building plot (roof area, facade area, ground floor level). Similar factors are already used in Vienna (Green and open space factor Vienna), Berlin (Green Area Factor, Green Space Factor and Biotope Area Factor), used on the level of building plots.

Recommendations on Green Roofs and vertical surfaces

Green roofs and vertical green are a type of vegetative element that are a part of a building (or other built structure). Green roofs are extensive and intensively used and can also be arranged as public green open spaces or living areas. The implementation of a green roof is otherwise recommended on all buildings with a flat roof in cities. Guidelines for implementation and level of maintenance for vertical green are determined in the framework of building design. Priority to the design of buildings with green roofs and vertical green is in all areas with a stressed need for GI implementation and in accordance with spatial planning documents.

The implementation permissions on VG implementation differ depending on the country, area, the layout and the ownership and public accessibility of the building. In cases of large vertical surfaces usually obtaining a certificate from the city's department of spatial planning regarding the impact on the local environment, with the submission of documentation of the envisaged implementation of the green facade is needed. For greening facades on private property, the written consent of all the owners and the neighbours should be signed in advance as well the fire safety evaluated.

In implementing/installing green facade adjacent to public property (or on public property) usually the administrative procedure is required. If the installation of a structure requiring fixing to the facade or to the ground is foreseen, information regarding the building permit is required, the statics of the building and the facade structure must be taken into account, also in the case of listed buildings. The documents must be submitted, such as the consent of the owners of the premises in the building and of the competent authorities if the facade is adjacent to a public area, as well as technical illustrations of the greening (construction, planting, plant climbing), static assessment, fire protection and protection of public areas (if necessary) and additional information on traffic safety (pavements, roads), compatibility of the proposed solution with underground lines, etc. If the intervention is public property, the implementation, construction, financing, responsibilities, stakeholders, deadlines, etc. are usually also communicated in public.

4 Project outcomes for supporting VG planning and governance

Planning approaches that guide the development of green spaces, their networks and interconnectivity are also the basis for the inclusion of VG and green roof planning at the city level. To recognize the needs for GI implementation at the city level on the one hand and possibilities to include VGs at the building scale on the other, different approaches can be used to address specific topics. Combining different approaches may result in forming specific actions to be proposed as activities or projects in a city's green action plan (see section 3 Challenges in VG Planning at the City Level). Different approaches and thematic analysis in project VG 2.0 are addressed by subchapters:

- Urban morphology and structure types of Berlin, Vienna and Ljubljana – city structure type catalogue (see subsection 4.1)
- Cultural heritage issues for vertical green – monument protection as a limiting factor for large-scale facade greenery implementation to counteract indoor heat stress – a GIS-based analysis for Berlin (see subsection 4.2)
- Urban Atlas-based typology – a GIS-based urban structure analysis for Berlin, Vienna and Ljubljana (see subsection 4.3)
- Geoinformation decision support system for determining green infrastructure deficit in urban areas – a GIS-based analysis for Berlin, Vienna and Ljubljana (see subsection 4.4)

4.1 Urban morphology and structure types of Berlin, Vienna and Ljubljana – City structure type catalogue

The city is a complex social and spatial phenomenon. It is a result of historical development, and its tissue is a combination of buildings and open spaces. The aim of the city structure type catalogue was to obtain an overview of the cities and to understand each city's built tissue, which can be evaluated from different perspectives.

The approach consists of a review of the city's planning documents and descriptions of different areas, morphologies, environmental and natural characteristics, etc. of Berlin, Vienna, and Ljubljana.

Combined with other analyses using environmental data, the evaluation of specific areas in cities and possibilities for using VG as NBS can be addressed. On city-scale studies, the large-scale level can be presented, and evaluation can be done on a general level. On the city scale, most environmental and climate-related aspects can be addressed, as well as urban structure with consideration of population density and urban flows. Other aspects are likely to be analyzed in more detail – at the micro urban level. Analysis of living conditions with respect to green areas is important, especially in areas of population density. The elements of morphological structure that have been investigated for the purpose of the structure type analysis are building characteristics such as age, massing, number of dwelling units, form and building material, urban floor plan, relationship between built-up areas and urban open space, the enclosure of the built-up area, the position of the buildings in relation to the streets, and the arrangement of the buildings.

The elements of the morphological structure in cities are therefore quite diverse, and the typification (procedures of subdivision into homogeneous morphological types) and typologies (results of subdivision) also differ from city to city and in different countries.

Berlin

Berlin is divided into 52 different area types, which are described based on their typical use, historical development and the structure of buildings and open spaces. In the map Urban Structure (Umweltatlas, 2021), these area types are grouped into 16 overarching structure types. There are 11 structure types with primarily residential use differentiated on the basis of the structure of buildings and open spaces and of their building age. The types of primarily residential use occupy approx. half of the built-up areas of Berlin. The category 'Low buildings with yards' occupies 46 %, by far the largest portion of residential areas, followed by 'Post-war high-rise development', with 10 %. 'Village-like development' has the lowest share of the area, at 2 % (see Figure V.10).

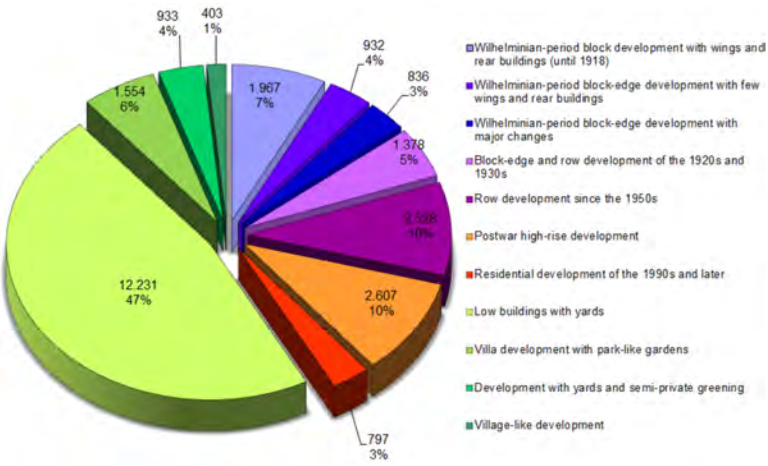


Figure V.10: The 11 structure types of primarily residential use occupy approx. half of the built-up areas of Berlin (link)

Areas of dense residential development, such as ‘Closed rear courtyard’ and ‘Closed block development and rear courtyard areas’, must be taken into consideration, as these types are characterized by close blocks of buildings with several courtyards, usually entirely surrounded by buildings and sometimes completely impervious space. Dense block construction with closed courtyards is also the most densely inhabited area type. Regarding the structure types, these areas are Wilhelminian-period block development with wings and rear buildings (built until 1918). As some have historical value, the implementation of VG has to be considered/evaluated case-to-case. The implementation of green spaces or green elements is also crucial in postwar high-rise development structure types where courtyard areas and their open areas usually serve as car parking spaces. There is also a need for green spaces in areas of densification where the pressure of building construction resulted in shrinking surrounding green spaces.

The core commercial, service use, small business and industrial areas are nonresidential areas of high use intensity and density, where urban density and imperviousness are common. Structurally, the spectrum in Berlin extends from Wilhelminian-period block construction to more recent high-rise construction.

Vienna

Building typology in Vienna defines the types with buildings classified according to their type (e.g., palaces, houses with a central courtyard, etc.), their use (e.g., hospitals, hotels, shopping centers, etc.) and their open spaces (gaps between buildings, gardens, etc.). The official typology includes 31 types and primarily does not focus on age or heritage evaluation.

In 2016, the MA 18 Urban Development and Urban Planning published Vienna residential area types, the purpose of which was to compare residential environments in the city.

The typology developed as an upgrade of so-called urban area types (made in 2010), and the aim was to group areas similar in terms of construction and social structure. It specifically addresses building density and population density in residential structures and is specific for the Vienna case. The aim of typology was also to show more clearly the spatial expansion of the city – especially in the growth phase from 2001 onward.

The highest percentage of the population in Vienna lives in areas of (3) Gründerzeit: high building density and population density above average (20.5 %), (10) mixed building age, period from 1961 dominated (16 %) and area (4) Gründerzeit and old town: high building density and population density below average (15.4 %).

Ljubljana

Ljubljana has a specific morphology, and the individual morphological zones are rather small and spatially fragmented, usually a mix of building types. The classification of the Ljubljana built structure was made for purposes of a spatial development plan and is based on age, function and built form. Dimitrovska Andrews et al. (2001) identified 15 distinctive homogeneous urban areas that give the city its identity. The classification is based on historical periods of urban development but does not cover the whole city, as only the typical urban areas that have distinct urban designs and architectural qualities were identified.

In 2016, the morphological typology of residential areas in Ljubljana was published (Tiran, 2016). Sixteen types of residential areas were identified and classified into 4 groups according to the number of residential units: single house areas, multiple dwelling house areas, mixed single and multiple house areas and areas of block of flats. The analysis shows that in 2016, the largest share of the population (25 %) lived in block residential neighborhoods, while in total, slightly less than half of Ljubljana's population lived in areas of blocks of flats. Approximately 20 % of the population lives in the newer type of single-family house areas, with smaller numbers of populations in the other morphological types. The concept of the block residential neighborhood became the basic form of building after 1965. The basis is the division of the neighborhood into quarters with the development of different building types: high-rise towers, lower free-standing blocks and a row of apartment blocks. Block-type residential neighborhoods are characterised by a higher quality of living environment compared to postwar block-building, which appear as blocks of flats or tower blocks located with and without urban concepts. Modern blocks of buildings are different morphological types – the most common villa blocks. The newer areas of single-family houses are a widespread type in Ljubljana. This type was developed during the period of accelerated urbanization.

4.2 Cultural heritage issues for Vertical Green

Listed buildings (i.e., buildings protected as cultural heritage) as well as other buildings with quality exterior elements are a special category when considering altering their exterior with implementing vertical green. Certain limitations are in place, which are designated for the exact building or cultural monument and are usually not generalized. However, most countries have also general documents considering the renovation of cultural heritage buildings to help owners take the right steps in the process of renovation (BDA, 2011; Ministrstvo za infrastrukturo Republike Slovenije, 2016; English heritage, 2018). There is also a difference in the type of vertical green considered. Some buildings were traditionally covered with climbers, and in such cases, reconstruction and renovation usually suggest the preservation of wall greening after renovation.

Figure V.11: Plečnik house in Ljubljana, where greened wall (*Parthenocissus tricuspidata*) as a part of original design was preserved after renovation in 2015 (image by Damjana Gantar)

The following subchapters present general opinion on facade altering in case of building renovation and cultural heritage issues, short overview of selected cases of guidance documents and, in conclusion, a GIS-based analysis for Berlin, Germany on Monument protection as a limiting factor for large-scale facade greenery implementation to counteract indoor heat stress.

Possibilities to green one of most protected elements of the building – facades

The facade is one of the most important and usually most protected elements of the built heritage – if the building is protected due to its quality exterior design, as it gives the building its character and significance. The building usually has four external walls or facades, in a compact street line of only two. The main facade is public, placed in a street line, from which only piers, loggias, balconies, and eaves extend and is usually more protected due to its better-quality design.

The main facade is also a kind of face of the building, which, especially when we talk about historic buildings, with its composition, design of building elements, richness of decoration and facade cladding tells us what is inside the building, who is/was the owner and what was their social status. The courtyard facade is private, especially in cities where it was often changed, rebuilt or extended, so it is usually less protected. In the modernist architecture of the 1920s and 1930s, which sought to build residential houses in greenery, the type of freestanding block in greenery became established, where there is no longer a distinction between street and courtyard facades, but both facades are equivalent. Such a principle is also characteristic of new housing estates built after the Second World War, as well as of some public buildings in cities.

The composition of the facade, which usually corresponds to a certain art style, is reflected in the basic vertical and horizontal articulation, in the proportions between the whole and the parts, in the arrangement and rhythm of the window and door openings. All these elements determine the character of the facade and indirectly determine the character of the building as a whole. Facades are often decorated with rich sculptural decoration, reliefs, colored plasters and decoration in various techniques. Therefore, renovating the exteriors of the facades of historic buildings is a difficult task. Changing the facade composition during renovation for any reason is risky, as it changes the architectural character of the building and is justified only if required by very strong arguments (changed purpose of the building, adaptation to new standards, access for people with disabilities, etc.). Even in this case, interventions must be carried out to minimize the impact on the essential features of the facade.

The preservation of the original design, especially for front facades, is usually most strictly defined. Guidelines for interventions for built heritage in Slovenia, for example (ZVKDS, 2015), determine the research by diagnostics of facade layers. Based on the results, a color study is prepared by the competent service. It is recommended to use traditional materials when renovating. Partial interventions on the facade are not acceptable in principle. Facade decoration as an integral part of the facade must be preserved and renovated in accordance with the principles of restoration. If it is damaged or destroyed, it must be restored or reconstructed (as a pure replica), according to documentation.

In Slovenia, renovation of listed buildings must follow cultural protection conditions, which are prepared by the responsible (territorial) unit of *The Institute for the protection of Cultural Heritage of Slovenia*, case specifically for expressed intention of renovation in accordance with defined protection regime.

There are also general guidelines for the energy renovation of cultural heritage buildings (Ministrstvo za infrastrukturo Republike Slovenije, 2016), which determine the preservation of street facades when buildings are protected for their own value or as part of the settlement. Guidelines also describe measures for improving the thermal insulation of buildings. The external insulation of walls is classified as a measure with unacceptable impact (on a five-point scale); however, it is also pointed out that rejection of this measure in principle is not justified. From construction physics, this is the most suitable measure to improve the thermal performance of the building and should be recommended for facades with simple design, very dilapidated and damaged facades, facades facing backyards or side facades, etc. Guidelines (ibid, 2016) do not mention any type of vertical green. Similarly, Austrian guidelines (BDA, 2011) list measures for energy renovation in three groups (green, yellow, red) of acceptability from a cultural protection view. In principle, altering the exterior facade with thermal insulation is not recommended. Exceptions are only possible for parts of the facade that were not originally intended to be visible (e.g., firewalls), and even in this case, only when the insulating effect cannot be achieved by alternative measures.

Adding vertical green on the facade can be seen as a similar measure as adding insulation; it alters the building's external envelope. The implementation of VG alters the facade appearance more. Nonetheless, it can be designed building specifically with the consent of the relevant consultants and experts. An interdisciplinary team can determine which parts of the building exterior can be altered. Inner courtyards, blind facades, external staircases, or other extensions might be the proper environment to add some contemporary and green elements to heritage buildings. Adding vertical green can also be performed in a way that the appearance of the building hardly changes o changes only temporarily (e.g. annual plants or ropes).

Monument protection as a limiting factor for large-scale Facade Greenery implementation to counteract indoor heat stress – a GIS-based analysis for Berlin

The following study presents the question of how monument protection limits the implementation of facade greenery, which is one of the strategies of adaptation to heat stress, in Berlin. The number of 'summer days' (max. air temperature 25° C) and of 'hot days' (max. air temperature 30° C) in Berlin, Germany rose significantly from 1960, and the area of distribution of 'tropical nights' (min. air temperature 20° C), which can be attributed to climate change and the urban heat island effect (SenUVK, 2016, 2018). High summer temperatures can cause working productivity loss (Lundgren et al. 2013) and raise morbidity and mortality, especially for the elderly population (Oudin Åström et al., 2011). Buchin et al. (2016) found the highest risks for indoor heat stress. Facade greenery, as a proven strategy for adaptation to heat stress, is prohibited for monumentprotected buildings and facades. To what extent monument protection effectively limits the implementation of facade greenery in heat stress-affected city centers has not yet been quantified.

In Roesch et al. (accepted), the ratio of buildings under monument protection was quantified for Berlin, using a GIS analysis. It was done for the entire city, the inner-city area and at the block scale. To calculate the monument protection ratios, maps of Berlin buildings, monuments, blocks and horizontal urban green areas were processed. The ratio of buildings under monument protection was calculated for each block of Berlin. To avoid deforming the outcome, urban green areas were left out. Additionally, the heat stress vulnerability data of Dugord et al. (2014) were compared to the monument protection block-level map (Figure V.12). Areas combining potential vulnerability and monument protection ratios of 50 % and more were identified (Figure V.13). Inside the 80 km^2 city center of Berlin, which is severely affected by heat stress, monument protection prohibits facade greenery on 0–100 % of the buildings in the individual blocks. However, a mean of 25.4 % of the building facades in the city center and 16.2 % for all of Berlin are protected and therefore cannot be greened.

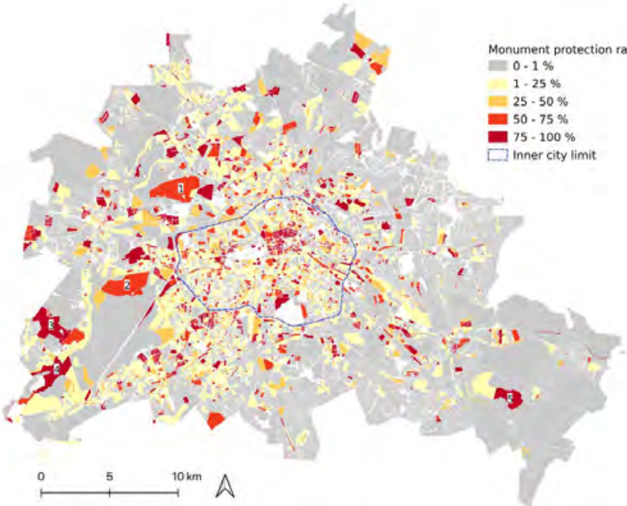


Figure V.12: Preliminary map of protected monuments and potential heat vulnerability (image by Emil Roesch)

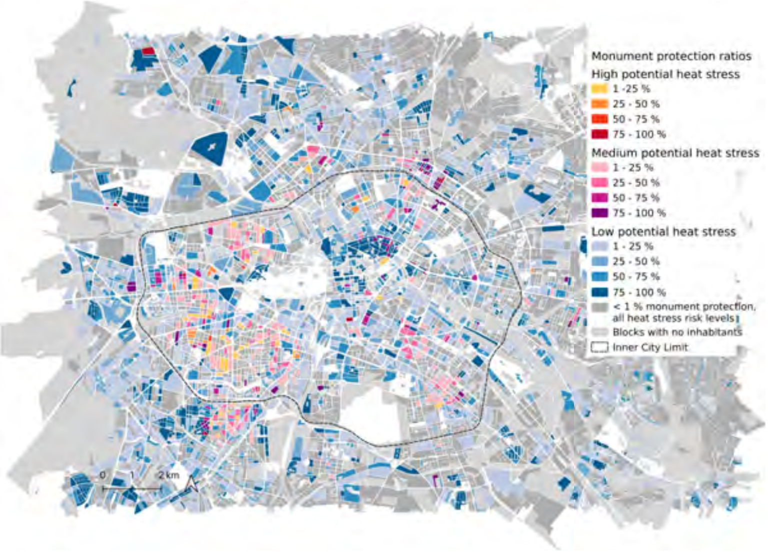


Figure V.13: Zoomed map (image by Emil Roesch)

Compared to other restricting factors, monument protection does not generally hinder large-scale facade greenery in Berlin, although there are 102 heat stress vulnerable blocks inhabited by 48,122 people, where almost no greenery is possible (> 50 % monument protection, Table V.1).

Table V.1: Number of blocks and inhabitants affected by monument protection and heat vulnerability, respectively

Monument protection	No - very low potential heat vulnerability		Low - Medium potential heat vulnerability		High - extremely high potential heat vulnerability	
	Blocks	Inhabitants	Blocks	Inhabitants	Blocks	Inhabitants
<1 %	9,295	1,940,621	302	180,928	100	49,546
1-25 %	1,845	647,371	161	120,337	46	33,855
25-50 %	738	244,006	72	47,026	13	8,009
50-75 %	409	122,316	27	16,424	3	1,289
75-100 %	845	176,174	59	25,383	13	5,026

This demonstrates that facade greenery should be discussed as an exception to monument protection for specific cases, justified by a predominant public interest, which overrules monument protection (DSchG Bln 1995). It also points to the need for minimally invasive and mobile greenery technologies, which would enable heritage protection conforming greening.

4.3 Urban Atlas-based urban typology – urban structure analysis for Berlin, Vienna and Ljubljana

The Urban Atlas (UA) provides pan-European comparable land cover and land use data for Functional Urban Areas (FUA) (Urban atlas, 2021). It offers high-resolution land use maps as well as other data related to spatial characteristics extracted from different sources and can be used for the analysis and comparison of larger urban areas – European cities with at least 100,000 inhabitants.

The UA classification of urban surfaces derives from CORINE Land Cover and is composed of 27 classes distributed among 5 thematic groups: artificial surfaces, which are defined as surfaces with dominant human influence and without agricultural land use, agricultural areas, forest and semi-natural areas, wetlands and water bodies. Furthermore, artificial surfaces are classified into urban fabrics, consisting of built-up areas and their associated land, such as gardens, parks, planted areas and non-surfaced public areas, and infrastructure, distinguished by their pattern of continuity and degree of soil sealing but not by their type of buildings and function. Urban fabric consists of predominantly residential areas but also downtown areas and city centers, including the Central Business Districts (CBD) and areas of partial residential use. However, for VG implementation at the city level, other UA classes of artificial surfaces are very relevant, especially industrial, commercial, public, military and private units of buildings with large surfaces and often extensive areas of blind facades.

Green urban areas are classified under urban fabric/artificial nonagricultural vegetated areas, together with sports and leisure facilities. However, large areas of urban green that are part of the urban structure and significantly affect the needs for VG implementation are part of the UA data within other key classification groups, natural and seminatural areas, wetlands, water and agricultural areas. This should be taken into consideration together with all associated gardens, parks and other green areas and infrastructure that are part of urban fabric areas, especially when focusing on potentials for small-scale GI elements such as VG.

Urban Atlas data for evaluation of urban areas

The aim of the project was to analyze the urban structure of three cities – Berlin, Vienna and Ljubljana – using a single comparable dataset and focusing on the evaluation potential for vertical greening as a building component – hence the use of the Urban Atlas – as available open source data. As UA urban fabric includes data on building heights and built-up areas according to functional land use, it was used as one of possible approaches addressing urban typology that is relevant for VG implementation.

To evaluate the environmental state of urban areas and the need for an additional greening urban atlas offers another important dataset, that is, the imperviousness of surfaces. The approach of this UA-based analysis is to combine data on building heights with area functions – the built density and uses in the area. Different height levels are one of the curtail data for VG implementation decisions – especially because of different conditions and possible use of different VG systems on buildings regarding heights. For instance, when using VG on a street level, physical contact with the wall should be taken into consideration, and when in heights, the safety issues and implementation of VG are usually more complicated. Imperviousness is another indicator of urban areas with potential problems related to storm water, summer overheating and lack of green infrastructure – which can also be addressed through VG solutions.

The analysis for VG-related urban typology focused on two groups of artificial surfaces – urban fabric and industrial, commercial, public, military, and private units. The nomenclature of urban fabric areas is made according to 3 parameters defined in UA:

- continuity (continuous/discontinuous),
- built height (low-, mid- and high-rise) and
- density (5 levels from very low density to high density urban fabric, depending on the percentage of soil sealing).

The UA classification approach is related to the density and imperviousness of surfaces, classifying areas into 5 classes of urban fabric. The continuous layer, for example, represents all areas with predominantly residential and mixed-use areas with > 80 % soil sealing, while the other (less than 80 % soil sealing) are areas of discontinuous areas.

However, the urban fabric layer does not include other buildings or structures suitable for VG, which are defined in the industrial, commercial, public, military, and private (and transport) unit layers. These types of UA artificial surfaces are not further classified according to soil sealing (imperviousness parameter). Therefore, these areas (industrial, commercial, public, military, and private units) and their associated surfaces were included in the analysis without further reclassification, but in practice, further adaptation of data is possible (as presented in the case of Ljubljana).

The building height was recognized as one of the key factors for urban typology analysis because it determines the opportunities for VG, and its typology is one of crucial criteria for the evaluation of VG in urban space. In the analysis, the average building heights from the Urban Atlas raster layer (Building Height 2012 layer (2012)) and Imperviousness Density 2018 (2018) were merged with Urban atlas 2018 polygons. The results are presented in average building height classes (1–7 m, 7–15 m, 15–30 m, 30–50 m, 50–100 m) and soil sealing (< 10 %, 10–30 %, 30–50 %, 50–80 %, > 80 %) for urbanized areas. The density parameter is related to the data on soil sealing, which is a very important aspect for decisions on GI implementation needs.

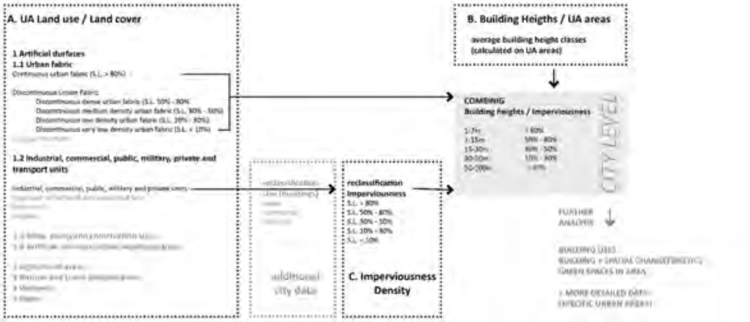


Figure V.14: Scheme of combining open source data (Copernicus) – the EA land use, building height in and imperviousness of the analysis of three cities (image by Jana Kozamernik)

Analysis of types of urban areas for three cities

In the analysis of all three cities, soil sealing data and building heights of different classes were combined and calculated on the UA units (polygons). From that, maps with average building heights and imperviousness were prepared for Belin, Vienna, and Ljubljana. Maps show areas where both high buildings and a high ratio of soil sealing parameters are present.

With a higher number of buildings and a higher ratio of soil sealing, the potential for VGs to be among priority measures and NBSs for the improvement of environmental conditions is also high (see Figure V.15).

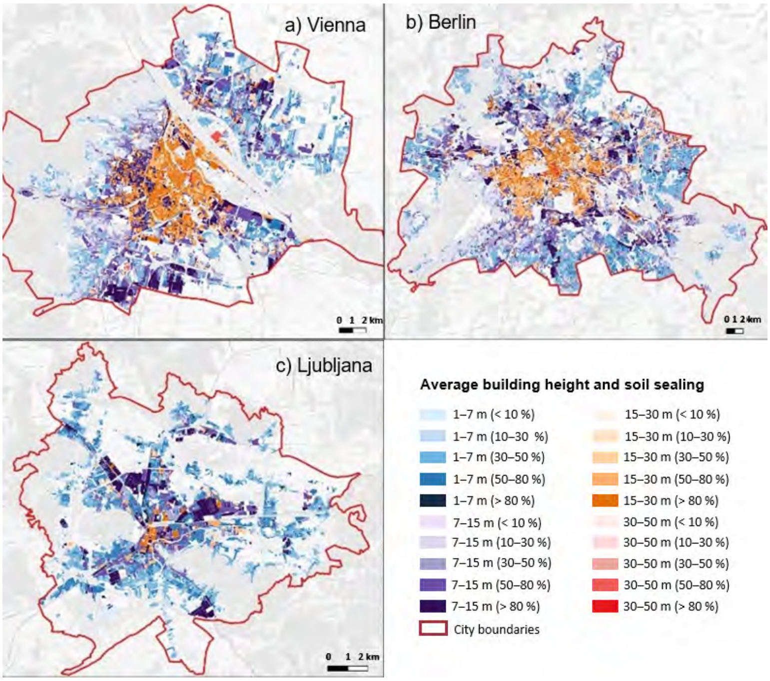


Figure V.15: Vienna (a), Berlin (b) and Ljubljana (c): UA units with different average building heights and imperviousness ratios. Different colors show average building heights (blue: units with average buildings height 1–7 m; violet: units with average building height 7–15 m, orange: units with average building height 15–30 m, red: units with average building height 30–50 m) and different percent of sealed space, darkest colors show most sealed areas (> 80 % sealed surface) (image by Simon Koblar)

The reason is that in areas of very high density (and soil sealing ratio), there is usually a low potential for other green space types of implementations, and higher buildings have larger facade surfaces; therefore, more VG could be potentially implemented on them than on lower buildings. The impact of VG could be beneficial in such areas. For further detailed analysis, however, other investigations at the building and ambience levels need to be done, especially regarding the possible implementation of VG on the facade surface (window-to wall ratio, etc.).

As general analysis is made at the city level, further and more specific analysis for smaller areas is possible. The potential also underlies this general result on the potential for VG regarding built structures with UA land use layers on artificial surfaces where areas with residential or other functions can be identified. The areas with ptential of VG (regarding problems with sealed areas and the potential of large facade surfaces) can be addressed through their urban function. On the other hand, there are specific types of buildings – such as commercial buildings – that usually have larger window surfaces, so the potential for implementation of VG is questionable. Therefore, it is important to consider the greening of facades at an early stage in the design of a building.

As the Urban Atlas provides only a general distinction between residential areas, additional analysis can be performed for other surfaces. Regarding UA classification, industrial, commercial, public and military units are one category, and reclassification or division is needed to separate the public (education, health care, cultural, etc.), commercial and industrial and other units. The areas in one UA type can be divided into these sublayers. In this manner, potential users and stakeholders can be identified, which leads to estimation of different management and maintenance possibilities as well as possible functions or aspects VG can provide (for instance, climate/rainwater management/educational function in "public – educational" subunits). The important aspect to take into consideration for the more detailed classification in this unit is also the expected type of facade for the function of the buildings in terms of whether openings (windows) are required on the facade. For several subcategories in this class, such as shopping centers, industrial facilities, warehouses, etc., large blind facades are typically used and can be considered as the potential for VG. As analysis for three cities was performed without subdivisions and additional classification, the aim was to test Urban Atlas data that are accessible for all major cities, and the results can therefore be compared.

The detailed analysis divided the Ljubljana subunits into subunits, with an initial question on implementing VG in connection to larger public buildings or commercial areas. The analysis showed that the model can be updated and overlaid with different – more accurate or more detailed data – which can provide more accurate results for specific areas/urban units. The results of the analysis show clear differences between the three cities regarding built structure and density. Vienna and Berlin are large-scale metropolises as condensed cities with densely built central parts and higher buildings as Ljubljana, smaller in scale and considering built structures.

4.4 Geoinformation decision support system for determining Green Infrastructure deficit in urban areas

Mapping the different spatial characteristics at the city level is essential in all spatial planning processes, both at the level of analysis and evaluation and at the level of final plans. With the growing awareness of the importance of natural elements in modern cities, the need for measures to implement a green space strategy (including green infrastructure) is crucial, taking into account the different aspects that define the quality of urban space at a broader level. The analysis undertaken in this project has attempted to identify areas in need of more green infrastructure (GI), taking into account the effects of GI on urban space.

The aim of the Geoinformation decision support system for determining green infrastructure deficits in urban areas is to identify areas with major GI deficiencies. Combining different types of analysis on city and detailed urban scales, the potentials for different GI types can be further evaluated. In GIS data, different types of GI can be mapped as basic data on land use, but as the planning tool for analysis, it cannot determine what kind of green infrastructure elements are appropriate in different areas (e.g., classic green areas, vertical greenery, green roofs). The limitations of GIS as a tool, its accuracy and its applicability to scale must be taken into account. Therefore, detailed urban design issues such as the type of GI must be determined at a later stage with the use of more precise data as well as local context evaluation and other expert analyses. The aim of the presented GIS analysis is to investigate possibilities for forming a comparable basis for cities on a broader scale in setting priority zones for GI.

Integrating social and environmental aspects on a city scale

In a GIS-based analysis for evaluating green infrastructure deficit in urban areas, a homocentric indicator was developed that shows in which areas it would make sense to introduce green infrastructure for its potential benefits on people, taking into account how much green infrastructure is already present in urban space and the intensity of the urban heat island as heat load in summertime. The GI deficit areas or priority areas for future GI implementation would potentially be those with more people present in outdoor space, higher urban heat island intensity and less existing green infrastructure and vice versa.

The categories of indicators – people, environment and climate – were chosen for analysis based on expected effects of green infrastructure, taking into account availability and accuracy of data on city scale to be used. Regarding people, the homocentric indicator assumes that more people who are present at the specific location in the city, higher the benefits of additional GI. Nevertheless, in the case of many green spaces in specific areas, the effects of implementing a new GI will be small. On the other hand, in areas with little or no green spaces, even a small GI installation (like green facades) will have noticeable positive effects. Additionally, the urban heat island was included in the model in the scope of climate change and urban planning focus with adaptation to climate change.

Environmental issues were first addressed by usual environmental and spatial quality aspects related to GI, as are existing different types of green spaces and elements (regardless the land use typology). However, analyzing available data, we recognized that it was a very similar and simpler approach to use the data on imperviousness density showing the degree of soil sealing, which is often decisively comparable to the presence of green spaces. This is particularly important for identifying GI deficits, as it can also capture data on green areas that were otherwise not provided by spatial data. To address the issue as much in detail as possible, we added the data from the UA street tree layer. A special focus was placed on climate change problems in urban areas, especially heat island problems, which are one of the key problems that can also be addressed by VG as an improvement measure.

Input data to identify potential areas where GI (including vertical green) could be an improvement measure we have thus used were:

- number of inhabitants,
- locations of long stay activities and short term activities – as people's aspect of being in space;
- environmental data of the soil sealing and street tree layer and
- climate related data on urban heat island.

An indicator that shows a lack of GI was calculated for three case study areas – Ljubljana, Vienna and Berlin. The goal was to use the same publicly available input data for all three cities to enable comparisons between cities and future use of the methodology for other cities. However, this decision forced us to use lower resolution data and omit some potentially valuable data sources that are only available in some cities.

Index calculation

One of the challenges has been to combine data that are on different scales. Therefore, the solution was to perform standardization, where raw values were converted to a statistical z-score, showing standard deviation from mean values. All input data were either in raster format or converted to raster prior to z score calculation. The z-score was calculated for urbanized areas inside cities, and larger green areas were excluded from the area of interest. To map the border of interest area, artificial surfaces from the Urban Atlas 2018 were used as the basic layer (Forslund, 2020b) and buffered by 50 m to include the closest surrounding areas. Areas covered by these categories were clipped by a city area, determined by the NUTS 3 region for Vienna and Berlin and by the settlement border for Ljubljana. In the Ljubljana case, the NUTS 3 region also includes small neighboring settlements, so the area was clipped only to the city area. The final analysis area for each city was adjusted according to the temperature map data. Detailed information about data used in GIS analysis and preparation for further calculations:

1. People
   1.1. No. of Inhabitants – Global human settlement raster layer for 2015 at a resolution of 250 m (Pesaresi et al., 2019).
   2.2. Long stay activities – locations of health care facilities, education facilities and nursing homes, extracted from OpenStreetMap. We converted extracted features to point data and generated a heatmap using the QGIS 3.16 tool "Heatmap (kernel density estimation)"(QGIS 3.16, 2021), with a search radius of 200 m. Null values were converted to 0, thus enabling z-score calculation.
   3.3. Short-term activities – shop, restaurants, cafe's form OpenStreetMap. Data processing was the same as for long stay activities.
2. Environment
   1.1. degree of soil sealing was retrieved from the Imperviousness Density raster layer with 10 m resolution ('Imperviousness Density 2018 – Copernicus Land Monitoring Service', 2021).
   2.2. Street tree layer – part of Urban Atlas was used (Forslund, 2020a). Areas were converted to points with a density of 10 m. This point layer was later converted to a heatmap (same as point 1.2).
3. Climate
   1. Urban heat island raster data for July 2017 for each city were used (European Commission, 2020c). We calculated the mean monthly temperature from the layer containing measurements in 1-hour intervals.

The steps of combining data in calculating the green infrastructure deficit index are shown in Figure V.16. Basic input data (1.1, 1.2, 1.3, 2.1., 2.2., 3.1) were first standardized to z-score. Each connection represents the process of summing data from the previous step and calculating the z-score of the combined layer.

The exception was made for the street tree layer, where the z-score was subtracted from the degree of soil sealing. Positive values in the combined layer "environment" thus represent areas with more soil sealing and lower tree density. The z-score of climate (UHI value) was included directly as an equivalent part of the calculation.

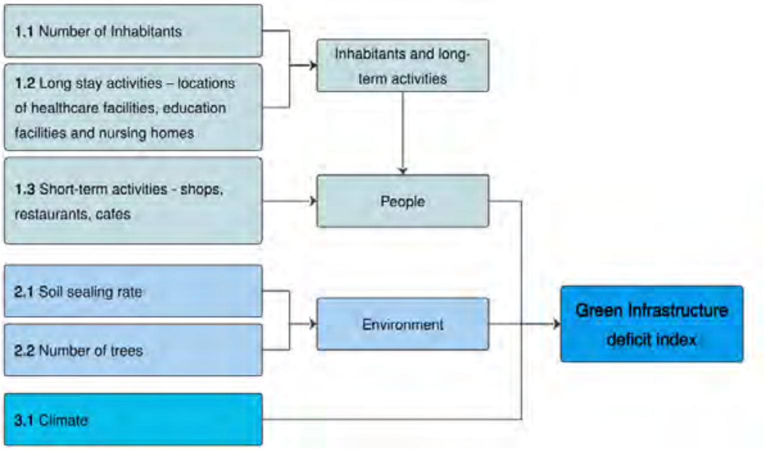


Figure V.16: Steps used and the process of combining data to calculate the green infrastructure deficit index

Mapping GI deficit

The calculations of the index – the z-scores of all combined layers – are presented on Figure V.17 in the city analysis area, showing deviations from mean values. The deficit index, which expands from lover to higher values, indicates the need for implementing green infrastructure taking into consideration the model data – people's presence in locations, selected environmental data and summer temperature characteristics. The values calculated in the model are presented with a color scale.

Blue areas show negative values (= less need for new GI interventions), and red values indicate positive values – the locations with a higher need for green infrastructure implementation according to the recognized benefits of green infrastructure – on the scope of selected aspects. The maps show the concentration of high values (the need for GI) in densely built areas; in the Berlin and Vienna cases, the red areas highlight the junctions in open space, and in the Ljubljana case, areas with high imperviousness and UHIs are more stressed. These results however show the areas and not focusing on the specific types of green spaces. The evaluation of the potential to use specific types (green spaces, building greening) is a following step, which should be done on a more detailed scale. Evaluations regarding the specific micro urban conditions and expert analyses are needed.

5 How to address VG financial issues through NBS financing approach

Cities are under very high pressure to address climate change challenges. Society is faced by rapid urbanization and population growth, degradation and loss of natural capital and associated ecosystem services. Nature-based solutions (NBS) can tackle some of the most pressing ones such as urban heat islands, air and water quality pollution through purification and filtering, fostering adaptation to climate change through cooling effects and water retention, halting biodiversity loss, but also promoting public health, food security and even social cohesion, beyond others (see for example Eklipse Working Group 2017 for so called economic, social as well as environmental co-benefits of NBS) (Raymond et al., 2017). The EC are thus proposing Nature-Based Solutions (NBS) as a multidimensional and cost-effective way of addressing climate change. Although there is a great demand for NBS worldwide, NBS have not yet been applied efficiently enough on a larger scale, partly due to economic viability. It is therefore necessary to examine the structure and framework of NBS funding in more detail.

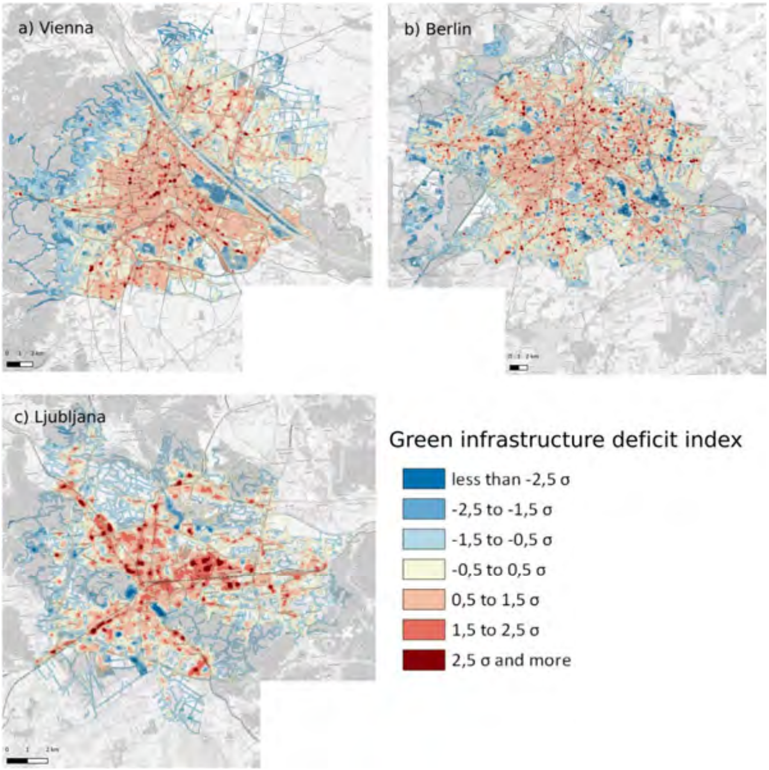


Figure V.17: Map of the Green infrastructure deficit index for Vienna (a), Berlin (b), and Ljubljana (c) (image by Simon Koblar, UIRS; own calculation after OpenStreetMap contributors)

Most NBS funding comes from the public sector and is mostly targeted at smaller projects. According to the Naturvation Atlas, up to 75 % of NBS are financed exclusively from public sources (via the public budget, direct funding, or subsidies). Typically, NBS are multifunctional and investment in them yields benefits to multiple sectors and beneficiaries.

Private investors are most likely to favour NBS investments when the direct benefits to the company itself exceed the investment costs. As a result, NBS still relies exclusively on public investment in most cases. However, the pressure on public finances is high in most cases.

The question is whether investing in NBS is worthwhile compared to other competing public sector priorities. What return on investment can NBS offer to attract alternative sources of investment? How should the return on investment be measured – in monetary terms or taking into account the values from environmental and social benefits that accrue?

The pressure on public finances is not the only reason why innovations in financing and business models for NBS are needed. Engaging the wider community and creating ownership are other necessary innovations that could be enabled through financial instruments. These include the potential for public-private partnerships (PPPs), payments for ecosystem services (PES), the importance and challenge of assessing the value of NBS for investors and society, and the potential for innovative financing instruments.

To better understand the issue of financing NBS and to be able to distinguish between the different options, financing possibilities for NBS as it is seen today, will be examined in a first step, following the H2020 clever cities project topology (www.clevercities.eu). Thereafter, innovative financing options for NBS and VG financing possibilities – being relevant part of urban NBS at scale – will be discussed.

5.1 Financing possibilities for NBS

To innovate on financing options for a broader stakeholder, it is key to measure the co-benefits of NBS solutions. Based on the European network projects on NBS, which further elaborated benefits and impacts within the framework of the H2020 program, a handbook was published in 2021 (European Commission, 2021), which presents the impact in a measurable way based on indicators, on which NBS can or should have a direct or indirect influence and can thus generate corresponding benefits. For example, NBS as capable of contributing to resilience of urban areasthrough the provision of ecosystem services, and by enhancing social awareness and actions to combat climate change. The co-benefits delivered by NBS particularly in urban areas support climate change mitigation and adaptation efforts, and contributing to the liveability of cities. Indicators in the Climate Resilience challenge area primarily address:

- Direct impacts of NBS on greenhouse gas emissions via carbon storage and sequestration in vegetation and soil;
- Indirect impacts of NBS on avoided greenhouse gas emissions from various activities, through the provision of passive cooling, insulating and/or water treatment; and,
- Impacts of NBS on temperature and human comfort

Financial and commercial incentives

When it comes to financing NBS, attention must also be paid to financial or commercial incentives. As the financing of NBS needs to be reinforced to be implemented in larger share. In some cases, NBS can also offer financial benefits, e.g. profitable and revenue-generating proceeds when directly interlinked with cost-saving benefits of NBS (see for example Case Study DC Water Impact Bonds, Goldman Sachs, 2021). If there is a commercial benefit to financing NBS, financially motivated investors – such as largescale investors (commercial investors), social investors, real estate developers, utilities and even municipalities – may see this as an additional incentive to finance an NBS project.

For example, in the very well-known DC Water Impact Bond case study (see below), investors (commercial and social) and the Washington DC Municipal Water Authority came together to fund NBS for water management services. The investors paid to reduce stormwater runoff by implementing green infrastructure that absorbs stormwater. In this case, the water authority had the financial advantage by saving costs due to low sewage overflows. The investors received USD 3.3 million in interest as profit from the loan.

DC WATER IMPACT BOND CASE STUDY

Financing Instrument
Environmental Impact Bonds (Blended Finance) USD 25 million of 30-year tax-exempt municipal bonds with an initial coupon rate of 3.43

Outcomepayer
DC Water

Upfront Investors
Goldman Sachs, Calvert Foundation

How does it work?
The tax-exempt Environmental impact Bond (EIB), valued at USD 25 million, was sold in 2016 in a private placement to Goldman Sachs Urban Investment Group and Calvert Impact Capital. Revenues from the EIB provided the upfront capital needed to build the first green infrastructure project under the DC Clean Rivers Project, a USD 2.8 billion program to control stormwater runoff and improve the District's water quality. The 25-acre green infrastructure facility is designed to copy natural processes to absorb and slow stormwater flows during heavy rains, reducing the frequency and volume of combined sewer overflows that pollute the District's waterways.

In March 2019, DC Water announced the success of the EIB and the full repayment of the EIB loan was made after a robust assessment of the project results confirmed the effectiveness of the green infrastructure in the district. As a result, the project met the targets set in 2016 and reduced runoff into Rock Creek by almost 20 %.

In doing so, DC Water conducted a rigorous, three-stage program evaluation of the effectiveness of green infrastructure in managing stormwater runoff.

Funders

The most common way to finance NBS in urban environments remains direct funding from local and central authorities at district, city, state, or federal level. As the scope of NBS and the awareness and need for the benefits of NBS grow, other investors have emerged over time. This is very relevant specifically for the implementation of vertical green since most of the potential buildings are often in the hands of private owners. The main types of investors to be considered at least when implementing NBS are shown in Table V.2.

Table V.2: Funders of NBS

Funders	Short description
Districts/Local Authorities	Municipal funding of NBS, usually through grants or direct contribution
Central Authorities	Funding from central government, usually in the form of grants or direct contributions
Non-Profit	Philantropic and charitable foundations. Funding often via grants
Large scale investors/Commercial investors	Large scale investors are private investors (e.g. pension funds etc.) who invest in the implementation of NBS in expectation of a positive financial return. In recent years, a dynamic towards 'green' risk, so-called "impact investment" has been developing. Large scale investors are only interested in large capital investments, for example from 10 million upwards.
Small scale investors	Small scale investors are private natural persons, for example citizens, who are interested to invest in their local area. Small scale investors expect a positive financial and social return.
Social investors	Social investors investing in large scale or small scale NBS expect a positive financial and/or social return.

In accordance with their interests, funders usually invest in business models that are typical for them. In principle, therefore, the funders must be considered together with their associated business models (see different types of business models in Table V.3.

Table V.3: Funders of NBS

Business models	Description	Typical Funders
Risk Reduction	Pre-investments in urban NBS are made to preventively reduce the high costs expected in the future due to extreme weather events such as heat or flooding.	**Central and local authorities.** This business model is attractive for central and local authorities as they invest in the long-term benefits of NBS. The positive effect is the reduction of the risk of extreme weather events and thus lower costs due to less damage. **Other investors: Insurance carriers.** Insurance companies find it attractive to invest in NBS that have the benefit of reducing extreme weather events that are costly in terms of claims. This seems to be particularly interesting for reinsurers. **Philanthropy/charity and social investors.** Philanthropists and social investors are more willing to invest in positive impacts of NBS under this business model. This is because there is the possibility of a financial return, e.g. by reducing flood costs (see DC Water Environment Impact Bond).
Real-Estate Value Increase	The integration of NBS into urban real estate development brings the advantage of increasing the quality of life in the space and thus the value of the property. The costs of creating and maintaining NBS are integrated into the business model and are "absorbed" by property value and economic growth.	**Local authorities and developers** (e.g. housing associations). Investors in new housing developments are the parties most likely to fund this model. Incentives include higher property values, potentially lower maintenance/operating costs (e.g. lower heating/cooling costs for green roofs and facades) and a positive public image. **Commercial investors.** Commercial investors also have an incentive to invest in green infrastructure if there is a positive financial return (e.g. through rising property prices or secure long-term rental income, as for example in BID).
NET Profit Model	Most real estate and infrastructure developments are accompanied by the loss of green space. This provides incentives to promote compensatory investments in urban NBS. There are also models in terms of urban development contracts via a PPP with private developers who are allowed to build more but then have to create green spaces, e.g. to maintain the microclimate.	**Commercial investors and other investors.** This business model is often developed and/or enforced by planning authorities, usually local governments, to maintain and develop green infrastructure in an urban area. As a result, the investors are usually real estate developers. A recent and popular example in Vienna is the Biotope City https://biotope-city.net/
Improvement of local environment/ neighbourhood	Citizens value local NBS projects and are willing to promote nature in their neighbourhood because they get a direct benefit from it. For example, for growing food for the community or for energy production, etc.	**Local authorities, philanthropy/ social investors and citizens.** This is a locally based business model most likely to be funded by organisations with a local connection: Local Authorities/Districts, Foundations and Citizens (through crowdfunding). However, it is currently unlikely that there will be a revenue stream for value creation and it is therefore questionable whether social or commercial investors will fund this business model.
Health Model	The therapeutic and health value of NBS is recognised and used as a driver for NBS funding.	C**entral and local authorities.** Funders who are responsible for health spending in general and have incentives to improve population health and well-being and reduce future health spending are most likely to be interested in funding NBS. These tend to be central and local health departments, including public health. **Philanthropy / charities and social investors.** Charities and social investors whose mission is to improve health and well-being will also value health benefits and therefore fund health-focused NBS. For social investors, there must be an income stream or non-cash savings to repay the capital invested.

Financing types

There are different types of funding for NBS (see Table V.4). These can be repayable (e.g., investments such as debt or equity and payments that support NBS upfront), or non-repayable sources (e.g., grants).

Table V.4: Financing Types of NBS

Financing Type	Repayable	Description
Direct funding / grant	NO	Investors pay directly for NBS or pay a non-repayable grant to a beneficiary to invest directly in NBS. This type of financing includes public subsidies, i.e. public funds to cover the costs.
Debt capital / credits	YES	Donors lend capital (upfront funds) to pay for NBS; the recipient repays the money over time with additional interest charges
Equity	YES	Donors invest funds in an NBS and take a percentage of ownership. The repayment to the donors depends on the value of the NBS and its value

For repayable types of funding, revenue must be generated from the business model, including non-repayable sources of financing, for the repayable funds to be returned to the investor.

Three main types of financing can be classified. They can be used independently and in combination to create NBS financing mechanisms (e.g., loans, crowdfunding, grant funds, earned income models and public-private partnerships).

These three types of financing listed in the table above are part of the commercial spectrum. This spectrum distinguishes between repayable and non-repayable financing and shows that there can be financing within a range of expected returns. In commercial financing, a return in line with the market is usually expected, which – the higher the risk of capital repayment for the investor – is also increased accordingly. The risk level depends on the business model for each funder, and how likely the repayment is.

As of today, the most frequent business model for commercial financing is the increase of Real Estate Value. Debt and equity are the main types of conventional financing. Direct financing/grants are examples of concessional financing where a lower than market or exceptionally low financial rate of return is usually expected. Debt can also be offered as concessional finance on concessional terms – e.g. a social investment loan for climate adaptation where the interest rate offered is reduced due to the expected positive NBS benefits.

Projects often require different types of financing, depending on their financial profile. Projects that cannot achieve a financial return require non-repayable financing. Projects that generate some return but not enough to cover costs need concessional support. This could be, for example, a mixed approach such as a loan plus grant funding. High social impact projects that achieve some financial return but may not be able to achieve market returns on debt or equity may look for social investors or repayable government investment. finally, projects that provide a return on commercial investment may access mainstream market investors or seek social investors or state investors as funders.

A variety of investors are willing to finance NBS with one or more direct financing/grants, debt or equity financing. The form in which an investor's money is disbursed depends not only on the financial return, but also on the goals of the funder. For example, social investors may be able to offer reduced interest rates but need to achieve a monetary return on the funds they use for NBS and therefore require revenue-generating types of financing, such as debt or equity.

Funding mechanisms

The following paragraph summarizes various mechanisms and instruments from the projects and interviews mentioned above and illustrates them with examples.

Bundling of different budgets (pooling)

In general, local governments often bear costs for NBS projects in public open space; however, environmental budgets are not sufficient in most cases. Pooling funds from different ministry departments can be an innovative solution in such cases. These can include:

- Public health budgets
- Public safety
- Education budgets
- Decentralized budget

This is because the added value regarding health conditions if more NBS in the city is realized, e.g. reduction of UHI and thereby reduction of excess mortality due to heat stress, is now better researched and therefore funds can be co-generated from the public health budget. In addition, a growing evidence shows the impact of well-designed and maintained green infrastructure on crime reduction. Therefore, funds can be sourced from public safety / police budgets. Interventions for a specific location or group such as schools and students have a high chance of receiving part of the funding from the education budget. For effective bundling of different budgets, different sectors can be screened for potential direct or indirect benefits of NBS and financial resources can be provided in different forms.

Green debt

- Loans: from private or public financial institutions or government funds.
- Concessional finance (soft loans): earmarked loans with favourable interest rates (below market rate), long maturities and grace period

- Green bonds: Instrument for raising capital via debt capital with a commitment to environmentally friendly projects. A fixed amount of capital is lent to the debtor by creditors. When the maturity of the bond is reached in a defined period of time, the capital and additionally an agreed amount of interest is paid back to the creditors. Green bond investors are usually commercial and social investors.
- Crowdinvesting: can be used to raise debt at a fixed rate of return that is at or below market prices
- Natural Capital financing Facility (NCFF): financing facility promoted by the European Commission and the European Investment Bank to finance natural capital projects

Green equity

- Equity financing: equity from public or private funding, also through crowdfunding
- European Structural and Investment Funds (ESIF): grants from the EU through Cohesion Funds and European Regional Development Funds.
- EU financial Instrument for the Environment (LIFE): co-financing of environmental projects, adaptation to climate change and mitigation of climate change
- Horizon Europe: the EU's Framework Programme for Research and Innovation supports NBS projects involving these components
- Philanthropic contributions: these include charities, private and public foundations, citizens private funders, etc. They are unpredictable yet valuable sources of funding. Generally, donations are site-specific.
- Crowdfunding: Some participants invest a certain amount of money in a project. As this form of funding is an unpredictable source, because crowdfunding campaigns cannot be planned in advance to secure funding commitments, it may require additional sources of funding for a project.

Revenue generating instruments

Mechanisms are listed here that relate to revenue generation from projects. This provides the opportunity to secure long-term financing for the maintenance, improvement and development of an NBS.

- Land sales / leases: Capital can be generated from land sales and leases of governmentowned land.
- Taxes: Taxes under local government or redistributed taxes from other levels can be a source of revenue and invested in NBS.
- Tax transfer: the redistribution of tax revenues at government level for environmental indicators.
- User fees: revenue from entrance fees, user fees for activities on sports fields or rental for events can generate budget for green space maintenance.
- Residents' contributions: one-off fee that the developer has to pay in order to obtain permission for a real estate project.
- Improvement charges: a form of tax or fee levied on land that has increased in value as a result of public infrastructure investment.
- Voluntary contributions from beneficiaries: private individuals who benefit from public developments pay a negotiated amount to cover some project costs
- Funds combined with offset/compensation requirements: Offset fees are required for construction projects that have a negative impact on nature. These fees can serve projects that aim to improve the natural environment

Market-based instruments

- Reduction of user fees: e.g. user fees for grey infrastructure (sewage fees) are reduced if environmentally friendly alternatives (sustainable drainage systems) are implemented. Or fees are reduced for developers if they integrate NBS.

- Tax relief: for the installation of NBS.
- Subsidies: Government can provide subsidies to cover (part of) the cost of installing NBS on private property.
- Tax concessions: tax concessions provide incentives for private individuals to manage green spaces.
- Compensation payments: Regulations to compensate for developments that harm nature.
- Payments for ecosystem services: Payments from interested parties to the landowner for ecosystem services.

Revolving funds

Investment funds, where the proceeds from previous investments provide a revolving flow of capital to replenish the fund and finance further projects. They can be held at different levels of government to serve as gap funding and promote development. This instrument might be specifically interesting for small scale investments at local level, having a business model at its background (for example rainwater management or food production).

Public-private Partnerships (PPP)

A PPP is a contractual collaboration between the public sector and private sector companies. Private parties are committed to provide public assets or services on a long-term basis; they bear the responsibility for management and risk.

Social or Environmental Impact Bonds

Refer to a results-based contract. Private investments are used upfront to finance NBS and then repaid by public entities when pre-determined results are achieved. If the planned results are not achieved, the full amount does not have to be repaid. Thus, there is risk sharing for the investors. In particular, this aspect has been used in the social sector so far.

Business improvement districts

Businesses in a certain area join together to set up their own governing body, which decides on funding improvements and generates revenue through various instruments.

5.2 Financing models for VG 2.0

The product vertical greening (VG) is getting more and more attention due to its presence in the media and climate change. This type of greening is a young discipline that – unlike roof greening – has not yet been exhaustively developed in Europe. Accordingly, this market is not yet saturated, and some market niches are still open for new, innovative ideas on systems and models.

Above all, providers of wall-bound greenery address mainly developers of public and semi-public projects due to their high price. The offer for these customer segments is diverse. The sales market for private customers, on the other hand, is manageable and offers great potential for this area to be won over in the future. To implement sustainable green infrastructures in the city, facade greening must be made affordable; both in production and in maintenance. However, the awareness of city residents about the advantages of facade greening is the greatest challenge. The private market is not prepared yet to invest in VG if they do not know the added value. One of the possible added values of VG is urban farming, a concept that aims at primary food production in urban areas for the citizens' own use. This idea can be implemented easily and practically on VG, as the lack of space in the city means that new areas can be created for agricultural production.

Ground-based systems and the trough system are particularly suitable for this trend. The sales market for this form of subsistence farming is not yet covered and leaves new opportunities to enter the business and to stand out from other providers.

5.3 Business models for VG 2.0

VGs require close cooperation between governments, city authorities, companies, investors, citizens and other important interest groups (Bocken et al., 2014). At the same time, the social, economic, and ecological advantages of implementing VG in urban areas are increasingly being considered in the scientific community and slowly in planning and decision-making processes. However, there remains a gap between the potential for the implementation of VG, its benefits and its current acceptance. For the general recognition of business success, business models can be seen as a key element. They can provide arguments that can bridge the gap between the importance of vertical greening and its acceptance. For the general recognition of business success, business models can be seen as a key element. They can provide arguments that can bridge the gap between the importance of vertical greening and its acceptance. With the help of interviews with various VG providers, we can compare business models and thus map the value that VG generate.

The need for new innovative business models – impact driven market instruments (instead of only profit-driven market instruments), based on the co-benefits of VG.

Regardless of the general description of a market for NBS, the largest part for VG is characterized by a special feature. This is because many owners of vertical surfaces are private owners, sometimes they are individual owners, sometimes they are property associations. Market-based instruments are often not feasible, precisely for this reason, as individual owners of individual properties often find it difficult to achieve profit margins. The costs of VG often seem higher than potential cash flow. This also applies to the potential impact that a single property can achieve. Improved thermal performance, significant contributions to rainwater management or greywater utilization seem only possible via the city or area level.

This, however, presents a very frequent potential for conflict due to diversified and different ownership. Which is, why it calls for new forms of co-development, co-financing and co-management between private owners, the local community, stakeholders and the city municipality.

When NBS are connected to a building (i.e. green roofs, building-integrated agriculture), the investment decision takes place primarily at a decentralized level with the building/home owner or with the entrepreneur carrying out building-integrated agriculture. One strategy to stimulate upfront investment at a consumer level is using a tripartite model in which costs and benefits are shared equally between citizens, government and businesses/developers. Clear communication of the benefits to both society and the individual customer may drive adoption of NBS such as VG. Some studies have calculated the expected cash flows (NPV) from investing in a green facade and found that incentives such as municipal subsidies can potentially be highly effective in increasing the returns of green facade investment to trigger larger scale green roof adoption. The private benefits do not in themselves make a green roof an attractive enough investment (NPV-positive), therefore public subsidies (such as those in flanders or Rotterdam) or storm water tax cuts (found in some regions in Germany) can stimulate private investment into green facades.

Another option would be to shift from purely profit-based instruments to impactdriven instruments, as e.g. impact bonds, and to create a collaborative model of impact driven payback that allows public-private co-financing at a wider scale. In the US or the UK, such instruments already do exist. However, in continental Europe, impact-based instruments are still not really in place yet, due to legal inconsistencies.

Environmental Impact Bonds

Impact bonds are a new, impact-related form of financing for projects and are therefore fundamentally different from conventional financial instruments traded on the capital market. It is a relatively complex form of contract between private parties and the public sector that has been used frequently, especially in UK and USA.

Generally speaking, impact bonds (IBs) are financial solutions that are in line with the implementation of the UN Sustainable Development Goals (SDGs) and are intended to have a positive impact on the environment or society. IBs are divided into the social and environmental areas. Social Impact Bonds (SIBs) deal with social sustainability, health and education, among other things, while Environmental Impact Bonds (EIBs) focus on green energy, clean water, the environment and climate change. Collectively referred to as IBs.

Despite the somewhat misleading name, IBs are not traditional bonds traded on capital markets, but contracts between several parties that finance green or social programmes through results-based instruments. Here, upfront capital (upfront investment) is provided by (private) investors for projects, either to test a new approach whose success is considered uncertain, or to scale up a solution that has been tested in a pilot programme. In contrast to most traditional investment instruments, the achievable return is not profit-dependent but impact-dependent (so-called pay for-success model). Pay-for-success is an innovative and result-oriented financing and/or funding instrument that directly and measurably improves social or sustainable problems. Three basic principles apply:

- Clearly defined results
- Data-driven decision-making
- Results-based payment

The basis for an IB is an agreement on the desired effect or success of the project ("pay-for-success agreement"). Usually, it is the public sector that wants to achieve results for communities and brings together private organisations and (private) investors. The public sector contractually defines the target group, the goal, the key performance indicators and the financial framework for an IB project in advance. Charitable foundations, (private) investors and/or investor groups then take over the financing of the project. If all target criteria are met in the course of the IB project and thus the agreed impact is achieved, the public sector pays for the project costs and, if applicable, an additional target achievement premium (e.g. interest or fixed premium). An external, independent evaluation (e.g. auditor) decides on the achievement of the target. If the target is not achieved, there is usually no repayment by the public sector.

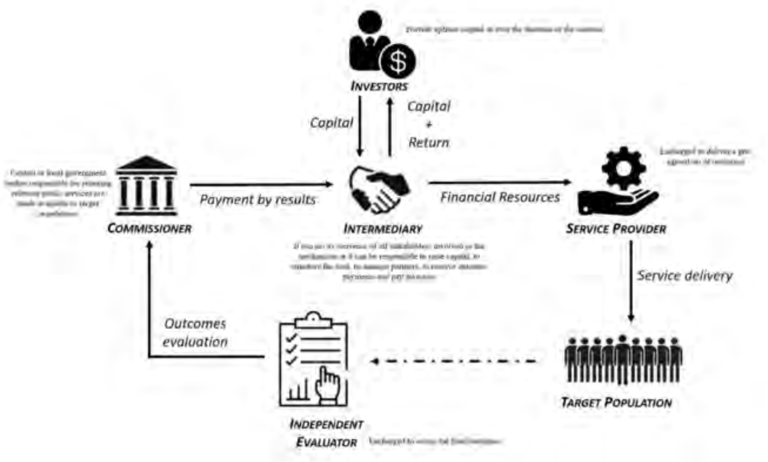


Figure V.18: Critical Success Factors, Motivations and Risks in Social Impact Bonds (Carè et al. 2020, licensed under the Creative Commons License CC BY 4.0) link

Advantages

- Developing a new source of funding for the scalable vertical greening funding.
- Encourage close cross-sectoral collaboration between the public sector, business and private investors.
- Creating transparency on which approaches and programmes have a demonstrable positive impact
- Creating transparency about the use of taxpayers' money
- Transferring risk from taxpayers to investors: testing preventive measures and new project approaches to existing problems without using public funds as long as there is no evidence of their effectiveness.
- Potentially implement more green/social projects, as the public sector does not bear the entire risk of project failure.
- Possible implementation of "riskier" projects through risk sharing.

- Green / social service providers get guaranteed long-term funding which gives them great flexibility in project implementation.
- “Savings”: The social and economic costs of green / social problems are higher than the costs of an IB project.
- Investors can use funds to make a positive contribution and receive a risk-adjusted return in return; if successful, capital can potentially be used repeatedly through participation in further IBs
- The target group/underlying problem benefits from a tailor-made solution regardless of the achievement of the goal over the entire term

Disadvantages

- Depending on the design, loss of investment possible for private investors
- Cost- and time-intensive preparation
- A lot of know-how necessary
- Risk of operational deficiencies on the part of the private organisation or the evaluator
- Political risks, e.g. change in political majority or spending freeze in the public sector concerned
- Use of inconclusive indicators or too short evaluation period for evidence of impact
- Investors may demand extensive reporting and/or covenants, which means more work for the service provider and can negatively influence the achievement of objectives.
- Reputational risk

Additional innovations needed – the Impact Bonds use case

Impact bonds are being traded as a promising option for the efficient implementation of climate measures with relatively high leverage for the integration of private and public capital in an international context (www.clever-cities.eu). Especially when it comes to financing vertical green and other NBS measures. However, only with the prerequisite that the comprehensive implementation of NBS brings with it a correspondingly comprehensive cost reduction. This is especially the case in the area of rainwater management at scale. Smaller individual projects, such as individual greening facades are not yet considered an option, as no concrete cost reduction (opportunity cost reduction) for the public sector can be calculated at this time. The implementation of green infrastructure thus generates costs and small amounts of revenue stream. The complexity of the instrument and the additional administrative and organisational costs therefore do not stand in favour of the use of climate adaptation measures when it comes to implementing vertical green facades in existing individual buildings. The project size of such individual projects is also considered to be too small to make the complexity of the instrument appear meaningful.

Expansion of the market size and depth could be reached through the integration of more fields of action within the framework of impacting climate resilience measures through target agreement (namely mobility and energy). There is also the optional possibility of further funding for the greening of private facades adjacent to public space. The local project-relatedness of the Impact Bonds instrument presumably also promotes ownership to local stakeholders. Within the framework of the NBS-Business model Canvas, statements can be made about the meaningfulness and practicability of linking the fields of action.

The definition of cash-back models. If different fields of action are linked together at the spatial level within the framework of the instrument (also in the processual sense), fields of action that generate cash flow (e.g. energy industry) and those that do not (e.g. VG greening) can be linked together. For example, the renovation of houses or the installation of PV and the resulting reduction of CO2 consumption could trigger compensation payments from the voluntary market; the transformation of public open space can create new jobs and thus tax revenues.

The cost reduction (e.g. less energy payments) or revenues (compensation payments) can be used to finance the production costs of vertical green.

Impact bonds area meaningful, as they link all instruments and financial flows with a common impact target (defined KPIs) within the framework of a single instrument. This can create efficiency and identity. An organisational and process-innovation is necessary for this at local level.

A proposal on a new co-creative business model – Environmental Impact Bonds to finance VG at scale

An overview of the needs and motivations of the stakeholders was used to develop an innovative business model – the collaboration business model. As a participation-oriented model, all stakeholders are involved in the planning, implementation, manufacture, installation and maintenance of VG.

A property developer decides to take part in the project and to green up a facade. In the first step, he turns to the consulting and competence organization that mediates providers and customers. The municipality, in which the construction of a VG takes place, has an interest and is involved in the financing. For example, it can be agreed that the district will be cooled by 8 degrees through greening measures and provides a budget for reaching the goal. financing through crowd funding and private investments, for example through foundations, are also possible. However, since not only the initial costs for VG are high, but also the maintenance costs, the population should participate in the maintenance of green facades in this participation project. Above all, vulnerable groups (retirees, long-term unemployed, etc.) are addressed. They maintain VG and in return receive benefits for living and public transport, for example.

Type of market

The VG market in the urban context is a relatively new one. Considering the current societal, political and individual needs in urban realities and considering the clear political guidelines for future urban developments towards NBS in all European cities on all levels, the market is expected to potentially grow exponentially. This is supported by various studies and policies. Beside the Green Deal, the biodiversity strategy requests "To bring nature back to cities and reward community action, the Commission calls on European cities of at least 20,000 inhabitants to develop ambitious Urban Greening Plans by the end of 2021. These should include measures to create biodiversity, urban farms and green walls. They should also help improve connections between green spaces. Such plans could mobilize policy, regulatory and financial tools."

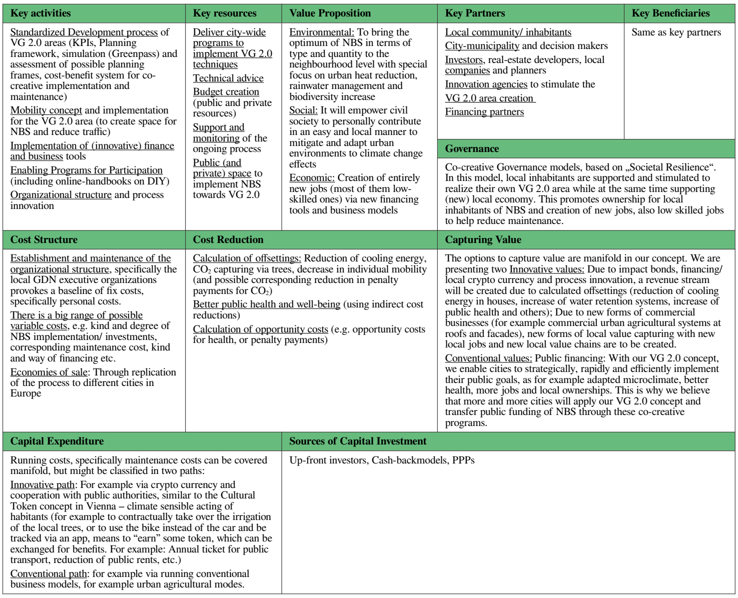
Also, first numbers of the so called European Green Market Report from the European Association of Green Roofs and Walls suggest not only measurable effects towards climate change, but also a huge potential to booster the economy. In Austria for example (according to the "Green Market Report Austria", Green Market Report, 2020) a growth of 8,000 direct and 25,000 indirect jobs might be possible in the next years. From a policy point of view, the implementation of NBS will be ever more obligatory in the urban context, requiring ambitious mitigation and adaptation interventions in the very near future (for example the preparation of urban green plans for each city with more than 20,000 inhabitants) while using policy and financial tools.

At the same time, no effective and rapid approaches for a strategic, holistic, efficient and co-creative implementation at the city level of NBS are in place yet. This also includes financing schemes. For which we propose a comprehensive, collaborative, entrepreneurial and effective solution, proposing ownership and participation, new financing models, and the creation of new jobs while promoting co-creative governance models. Precisely the implementation of NBS measures holds the potential to effectively integrate citizens, to convert just affected citizens to integrated ones, being able to personally contribute to mitigate and adapt climate change effects in their very local living space, and being remunerated for the engagement.

In order to draw a picture of the type of market and its economic business potential, we will use the so called NBS business model canvas. This model has been developed in order to picture the special characteristics of the NBS market and its business potentials, including specifically the high involvement of governance structures and the potential of cost reduction for governments through using NBS (Connecting Nature, 2021). There are some slight differences to common business model canvas, namely governance and cost reduction are added:

- Governance is a new addition to the NBS Business Model Canvas. This reflects the importance of identifying early on how the NBS will be managed on an operational basis. NBS are often very complex with many different partners and beneficiaries involved. It is important to consider early on in the planning process how different stakeholders will be engaged in ongoing management and operations, and what governance structures are needed to facilitate this.

- Cost Reduction is also a new addition to the NBS Business Model Canvas. This reflects the specific characteristics of NBS which sometimes allow for different ways to reduce direct costs e.g. use of social business models, use of permaculture principles to reduce costs, reducing waste etc.



Key activities	Key resources	Value Proposition	Key Partners	Key Beneficiaries
Standardized Development process of VG 2.0 areas (KPIs, Planning framework, simulation (Greenpass) and assessment of possible planning frames, cost-benefit system for co-creative implementation and maintenance) Mobility concept and implementation for the VG 2.0 area (to create space for NBS and reduce traffic) Implementation of (innovative) finance and business tools Enabling Programs for Participation (including online-handbooks on DIY) Organizational structure and process innovation	Deliver city-wide programs to implement VG 2.0 techniques Technical advice Budget creation (public and private resources) Support and monitoring of the ongoing process Public (and private) space to implement NBS towards VG 2.0	Environmental: To bring the optimum of NBS in terms of type and quantity to the neighbourhood level with special focus on urban heat reduction, rainwater management and biodiversity increase Social: It will empower civil society to personally contribute in an easy and local manner to mitigate and adapt urban environments to climate change effects Economic: Creation of entirely new jobs (most of them low-skilled ones) via new financing tools and business models	Local community/ inhabitants City-municipality and decision makers Investors, real-estate developers, local companies and planners Innovation agencies to stimulate the VG 2.0 area creation Financing partners	Same as key partners
			Governance	
			Co-creative Governance models, based on „Societal Resilience“. In this model, local inhabitants are supported and stimulated to realize their own VG 2.0 area while at the same time supporting (new) local economy. This promotes ownership for local inhabitants of NBS and creation of new jobs, also low skilled jobs to help reduce maintenance.	

Cost Structure	Cost Reduction	Capturing Value
Establishment and maintenance of the organizational structure, specifically the local GDN executive organizations provokes a baseline of fix costs, specifically personal costs. There is a big range of possible variable costs, e.g. kind and degree of NBS implementation/ investments, corresponding maintenance cost, kind and way of financing etc. Economies of sale: Through replication of the process to different cities in Europe	Calculation of offsettings: Reduction of cooling energy, CO_2 capturing via trees, decrease in individual mobility (and possible corresponding reduction in penalty payments for CO_2) Better public health and well-being (using indirect cost reductions) Calculation of opportunity costs (e.g. opportunity costs for health, or penalty payments)	The options to capture value are manifold in our concept. We are presenting two Innovative values: Due to impact bonds, financing/ local crypto currency and process innovation, a revenue stream will be created due to calculated offsettings (reduction of cooling energy in houses, increase of water retention systems, increase of public health and others); Due to new forms of commercial businesses (for example commercial urban agricultural systems at roofs and facades), new forms of local value capturing with new local jobs and new local value chains are to be created. Conventional values: Public financing: With our VG 2.0 concept, we enable cities to strategically, rapidly and efficiently implement their public goals, as for example adapted microclimate, better health, more jobs and local ownerships. This is why we believe that more and more cities will apply our VG 2.0 concept and transfer public funding of NBS through these co-creative programs.

Capital Expenditure	Sources of Capital Investment
Running costs, specifically maintenance costs can be covered manifold, but might be classified in two paths: Innovative path: For example via crypto currency and cooperation with public authorities, similar to the Cultural Token concept in Vienna – climate sensible acting of habitants (for example to contractually take over the irrigation of the local trees, or to use the bike instead of the car and be tracked via an app, means to "earn" some token, which can be exchanged for benefits. For example: Annual ticket for public transport, reduction of public rents, etc.) Conventional path: for example via running conventional business models, for example urban agricultural modes.	Up-front investors, Cash-backmodels, PPPs

Figure V.19: Business model canvas for VG 2.0 as NBS

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