GREENERGY

Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas

(H.F.R.I. Project Number 015376)

Structural Typologies of VF buildings

Deliverable D1.3 Work package 1

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LIST OF ACRONYMS

CO_2	Carbon Dioxide
BSO	EU Building Stock Observatory
CoM	European Covenant of Mayors
EEA-38	European Environment Agency network, Eionet
EED	Energy Efficiency Directive
ELSTAT	Hellenic Statistical Authority
EPBD	European Energy Performance of Buildings Directive
ES	Ecosystem Service
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
LCA	Life Cycle Assessment
LWS	Living Wall System
NBS	Nature Based Solutions
NOK	National Construction Regulation
RED	Renewable Energy Directive
TIR	Thermal Insulation Regulation
UHI	Urban Heat Island
UN	United Nations
VF	Vertical Forests
VG	Vertical Green

ΠΕΡΙΛΗΨΗ

Το ερευνητικό έργο GREENERGY ακολουθεί τις πλέον πρόσφατες αντιλήψεις και εξελίξεις στον κατασκευαστικό τομέα, που αποσκοπούν σε ένα δομημένο περιβάλλον μηδενικής κατανάλωσης ενέργειας και ενός ουδέτερου αποτυπώματος άνθρακα, προκειμένου να προωθηθεί η «πράσινη συμφωνία» της ΕΕ. Το έργο GREENERGY έχει σκοπό να αναδείξει την χρηστικότητα και τη σημασία των κάθετων δασών για την άμβλυνση των επιπτώσεων των ακραίων καιρικών συνθηκών και την παροχή οικοσυστημικών υπηρεσίων από «πράσινα» ανακαινισμένα κτίρια, ακόμα και σε περιβάλλον υψηλής σεισμικότητας.

Το παρόν έγγραφο (Παραδοτέο D1.3) υλοποιείται στο πλαίσιο του πρώτου πακέτου εργασίας (WP1) του έργου, δηλαδή «Τυπολογίες κτιρίων με κάθετα δάση, οφέλη, διακινδύνευση από κινδύνους και βασικές παράμετροι για την ανακαίνιση προς ένα αστικό περιβάλλον υψηλής πράσινης πυκνότητας».

Ως εκ τούτου, το παρόν παραδοτέο προσδιορίζει τον κατάλληλο τρόπο ενσωμάτωσης της βλάστησης και προτείνει μια ενιαία ταξινόμηση βάσει τεχνικών και δομικών χαρακτηριστικών τους. Τελικός σκοπός είναι να δημιουργηθεί ένας κατάλογος συστημάτων ενσωμάτωσης κάθετων δασών, τα οποία θα προσομοιωθούν και ως προς τις πραγματικές δυνατότητες ενσωμάτωσής τους σε αστικά περιβάλλοντα και σε σχέση με τη σεισμική συμπεριφορά τους.

Ειδικότερα, όπως περιγράφεται και σε προηγούμενα παραδοτέα, οι πράσινοι τοίχοι προσφέρουν μια σειρά από οφέλη τόσο για τα κτίρια στα οποία ενσωματώνονται όσο και για το αστικό μικροκλίμα γύρω τους. Συνεπώς, όταν χρησιμοποιούνται ως μέτρο ολιστικής προσέγγισης μεγάλης κλίμακας κτιριακών αναβαθμίσεων, οι πράσινοι τοίχοι μπορούν να λειτουργήσουν ως κάθετα δάση, οδηγώντας στην ουσιαστική ανάπλαση του αστικού δομημένου περιβάλλοντος με γνώμονα τη βιωσιμότητα.

Στο πλαίσιο αυτό, το παραδοτέο D1.3, στοχεύει να αναδείξει τις τεχνικές πτυχές των κάθετων δασών (VF), όσον αφορά κατασκευαστικές, νομοθετικές και άλλες τεχνοοικονομικές παραμέτρους, με βάση τα τυπολογικά τους χαρακτηριστικά. Έτσι, βάσει των αποτελεσμάτων του D1.1 “Κατάλογος φυτικών ειδών για κτίρια VF” και του D1.2 “Αξιολόγηση των ωφελειών που προκύπτουν από τα κτίρια VF”, το D1.3 παρουσιάζει τα δομικά και τεχνικά χαρακτηριστικά των τύπων κάθετων δασών προκειμένου να δημιουργηθεί μια εκτενής κατηγοριοποίησή τους. Αυτή η κατηγοριοποίηση είναι κρίσιμη για την περαιτέρω αξιολόγηση των κάθετων δασών όσον αφορά τη στατική τους αποδοτικότητα και το δυναμικό μεγάλης κλίμακας εφαρμογής. Τα αποτελέσματα αυτών των περαιτέρω αξιολογήσεων θα παρουσιαστούν στο WP2 “Πειραματική δυναμική αξιολόγηση της φυσικής δομής του μοντέλου με στόχο την ολιστική ανακαίνιση”, καθώς και στο WP3 “Μοντέλο ψηφιακού διδύμου ”.

SUMMARY

GREENERGY goes beyond the leading state of the art concepts in the area that aim mainly to produce nearly zero energy consumption and neutral carbon footprint within built environment in urban areas in order to promote the "green deal" while the real green nature itself is suppressed. Such an approach may satisfy merely mathematical indices and goals. However, it fails to revive natural growth in areas forests were once dominating, i.e. before urbanization. It holds down the decisive, that is natural mechanisms for sustainable environment of high air quality, controlled humidity, satisfaction and comfort for habitants.

GREENERGY envisions forest diffusion to alleviate extreme weather conditions impacts in coastal seismic urban regions and to optimize inclusive people-centric social engagement towards habitant comfort and satisfaction, through high-density urban forestation starting from green- renovated buildings. Based on the poor state of the art in the field of renovation towards vertical forests and the great necessity for their urgent development to really cope with detrimental climate change consequences and advance environmental resilience.

Against this background, this document (D1.3) is developed within the framework of the first work package (WP1) of the project namely "Vertical Forest buildings typologies, benefits, hazard-dependent risks and key parameters for renovation towards high-density urban greening". The goal of the deliverable is to formulate a coded database of VF system solutions, categorized according to specific technical and constructional characteristics.

As described in previous deliverables, green walls offer a series of benefits both for the integration buildings as well as for their surrounding microclimate. Hence, seen as a measure of holistic large-scale renovation approach, green walls can function as vertical forests, enabling the transformation of the urban built environment towards holistic sustainability.

More specifically, this deliverable aims at highlighting the technical aspects of VFs, in terms of constructional, legislative and other technoeconomic aspects, based on their typological features. Thus, building on the results of D1.1 "Catalog of plant species for VF buildings" and D1.2 "Assessment of benefits resulting from VF buildings", D1.3 presents the structural and technical features of VF types in order to create an extensive categorization. This categorization is crucial for further assessing VFs in terms of their static efficiency and large-scale implementation potential. The results of these further assessments will be presented in WP2 "Experimental dynamic assessment of physical model structure towards holistic renovation", as well as WP3 "Digital twin model".

1 INTRODUCTION

1.1 CITIES AND CLIMATE CHANGE

1.1.1 The role of the built environment in urban resilience

According to the UN humanity is at a critical stage in terms of global urbanization. Thus, more than 50% of the world's population lives in cities, whilst it is expected that this share will reach 70% by 2050. Hence, cities need to prepare for the accommodation of additional 3 billion billion (Clos, 2015), whilst ensuring high living standards and climate change resilience. Against this background, rapid urbanization offers a unique opportunity for positive developments through strategic urban planning. On the other hand, it is important to underline the significant risks that come along with the rapid urbanization at global scale, requiring institutional frameworks to be reexamined to address challenges like climate change mitigation, adaptation and resilience.

Besides resilience, cities offer a high climate change mitigation potential, as they are among the largest contributors to greenhouse gas emissions. Since cities vary in their characteristics, needs and goals towards decarbonization, the proposal of tailor-cut, local policies is of great importance. Hence, Local Authorities are focusing on the design and implementation of targeted climate actions, focusing on low-carbon and resilient urban development. Effective urban planning is essential to manage the complexities of urbanization, so as to help cities become sustainable and resilient. Based on the projection that approximately 6 billion people will live in urban areas by 2050, cities will also face intensified climate-related impacts, including heightened GHG emissions and exacerbated Urban Heat Island effects (McCarthy, et al., 2010). More specifically, cities contribute approximately 70% of the global carbon dioxide (CO_2) emissions (International Energy Agency, 2021).

As societies recover from the impact of the COVID-19 pandemic, CO_2 levels are rebounding rapidly, with global CO_2 emissions growing by 410 million tones in 2023. This number represents a historic high of 37.4 billion tones, according to IEA (International Energy Agency, 2024). Cities are accelerating their climate initiatives and are setting ambitious climate goals, increasing investments in renewable energy and innovative policies, so as to cover up most of their energy demand by 2050. This city-based approach is critical for driving the necessary changes to mitigate climate impacts effectively. Against this background, urban buildings significantly contribute to global energy consumption. More specifically, recent studies show that urban buildings account for approximately 39% of total energy use in the United States, and 28% of greenhouse gas emissions, whilst in dense urban environments this share can be even higher (Wang et al., 2023). European buildings are responsible for about 40% of energy consumption and 36% of greenhouse gas emissions, emphasizing the need for city-based actions against climate change (European Parliament, 2023).

Within this framework, the European Green Deal represents Europe's pathway towards a green transition, through a series of policies, aiming at climate neutrality by 2050. Fit for 55 represents the updated and concrete framework, in order to reduce net greenhouse gas emissions by at least 55% by 2030. More specifically, Fit for 55 represents a set of proposals to revise and update EU legislation aiming at providing a consistent framework for reaching the EU's climate objectives, such as (i) just and socially fair transition to carbon-free economies, (ii) increased innovation and competitiveness of the EU industrial sector, (iii) ensuring EU's position as leading partner in the global battle against climate change (Council of the European Union, 2023).

In addition, the recast of the European Energy Performance of Buildings Directive (EPBD) aims to align the guidelines of the European Green Deal with the energy performance of buildings that will lead to the decarbonization of the European buildings by 2050 (Article 14). District and large-scale policy measures are strongly encouraged as well (Article 8), whilst tackling energy poverty and protecting vulnerable consumers represent key aspects of the recast (Articles 21 and 22). The revised EPBD represents the ambition of the Commission's Renovation Wave Strategy to create a dedicated regulatory framework and structure a series of funding instruments, in order to support energy efficiency, building renovation and renewables integration in buildings, neighbourhood and district level. Moreover, the new Energy Efficiency Directive (EED) introduces local heating and cooling plans for municipalities with a share of renewable energy reaching 100% by 2040, urging them to design related plans. Finally, the recast Renewable Energy Directive (RED) sets binding and indicative targets for renewables for buildings and district H&C systems. Besides energy related aspects of urban mitigation and adaptation of Climate Change techniques, energy renovation also leads to tackling energy poverty and holistic refurbishment of worst-performing buildings, two factors that represent important targets of the EU as part of the Renovation Wave strategy (nearly 34 million Europeans are energy poor (European Commission, 2023).

More specifically, urban buildings' retrofitting policies offer benefits with multiple positive impacts, addressing the living conditions of vulnerable people while reducing their energy consumption and operating costs. The European Renovation Wave recognizes the need for promoting integrated, participatory and neighbourhood-based approaches at the heart of its goals along with the acceleration of investments focusing on digital technologies. In addition, globally, 12,000 cities have submitted mitigation and adaptation Strategic Plans including building renovation strategies and energy poverty action plans, within the framework of the European Covenant of Mayors (CoM) initiative. Hence, CoM Action Plans could feed into the future updates of Long-Term Renovation Strategies and result in aggregated green procurement to which mayors commit under the Covenant. Finally, to further support long-term growth after the pandemic, the Commission's recovery plan further supports building renovations, since, given the labour-intensive nature of the construction sector, renovations will play a critical role in the recovery of the European economy. Moreover, the European Commission introduced a series of actions to ensure just transition into carbon-free societies by 2050, providing financial and technical support for the most climate change vulnerable regions. Focus is also on mobilizing funds, to support work opportunities and reskilling as well as to retrofit the residential building sector. This measure is not only important for the minimization of energy consumption but also an important tool for the fight against energy poverty (i.e. Greece).

1.2 URBAN HEAT ISLAND EFFECT IN CITIES

Based on recent studies, it is evident that measures must be taken in cities in order to tackle UHI phenomena, that affect urban health and adaptation parameters in cities. Hence, distinct air temperature variations emerge between urban zones and the surrounding rural landscapes, leading to the Urban Heat Island (UHI) phenomenon (Oke, 1987). The UHI is intensified, among other factors, by the continuing replacement of permeable natural surfaces with coarse mineral materials (i.e. asphalt and concrete). This shift results in increased retention and re-radiation of solar radiation within urban built environments, hence cities. Additionally, the reduced sky view factor intensifies the trapping of both short and long-wave radiation in urban canyons, impeding natural cooling processes (Memon, et al., 2008). It is important to note that the intensity of the UHI phenomenon (UHII) is rising during cloudless and windless nights and may vary throughout seasons and daily cycles (Klsyik, et al., 1999; Kim, et al., 2002; Kim, et al., 2005).

According to the 2023 World Population Data, the changes in daily temperatures due to climate change has led to mean projected changes in annual death rates per 100,000 people in many countries, that are constantly rising; in Greece the annual average change for the period 2040-2059, will rise to an annual death rate of 10 per 100,000 people, according to a Moderate Emissions scenario, studied by the Climate Impact Lab and UNDP (Population Reference Bureau, 2023).

Cities face the critical need for efficient and holistic measures to mitigate UHI so as to improve thermal comfort conditions and reduce their building stock's carbon footprint due to increased cooling loads. More specifically, numerous studies have assessed the positive influence of UHI related measures in urban Mediterranean areas (Oliveira, et al., 2011; Zinzi, 2016; Fintikakis, et al., 2011; Salata, et al., 2017; Santamouris, et al., 2012; Salvati, et al., 2017).

In Greece, various researchers presented positive results on the influence of public spaces' retrofitting (Chatzidimitriou, et al., 2006; Chatzidimitriou, et al., 2015) and increased vegetation practices, such as a large-scale implementation of green (Karteris, et al., 2016). These studies mainly focus on the two largest cities, namely Athens (capital city) and Thessaloniki, which are considered typical in terms of their building stock typologies and built density. Another study regarding the five largest Greek cities, evaluated the UHII, showing clear surface UHI intensities between rural and urban areas, reaching 3.3 °C in Athens and 2.7 °C in Thessaloniki (Stathopoulou, et al., 2007). More recently, another study assessed the intensity of the UHI in Thessaloniki, demonstrating a variation between 2-3 °C during hot summer days (Giannaros et al., 2012).

UHI in Greek cities is linked not only to outdoor thermal comfort conditions, but also to increased cooling loads of the built environment (Hassid et al., 2000; Santamouris et al., 2001) as well as to smog release (Taha, 1994). Numerous studies analysed the UHI phenomena in the city of Thessaloniki and other Greek cities (Balafoutis et al., 1998; Stathopoulou et al., 2007; Stathopoulou et al., 2011; Stathopoulou et al., 2008; Stathopoulou et al., 2010; Papanastasiou et al., 2011; Dimoudi et al., 2013; Kolokotsa et al., 2009; Vardoulakis et al., 2013). Further studies analysed the improvement of the urban climatic conditions at district scale (Tsoka 2017; Tsoka et al., 2017) in the city of Thessaloniki, considering the unique typological features of the Greek built environments. In Thessaloniki IHU's maximum intensity ranges from 2°C to 4°C and 1°C to 3°C during the summer and winter periods (Giannaros et al., 2013). Another study showed how urbanisation, lead to the intensity of UHI by approximately +0.2 ºC per decade, since 1975 (Founda et al., 2004) in the city of Athens, along with a seasonal change in the rate of UHI, accounting for approx. 40% of the observed warming rates of summer air temperature.

1.3 TACKLING CLIMATE CHANGE WITH NBS

Tackling climate change in cities is being approached with numerous policies, including the refurbishment of urban building stocks, planning urban renovation with sustainability interventions, such as sustainable urban mobility, rainwater management, renovation of urban spaces with low solar absorptance and more. An important approach that continues to attract interest among researchers is Nature-Based Solutions (NBSs). Thus, numerous urban greening practices, such as green roofs and green walls are assessed in terms of their ability to address and reduce climate change phenomena (Molari, et al., 2024). These strategies, called nature-based solutions, are used to promote sustainability and enhance natural processes within cities. Molari et al. (2024) highlight the fact that especially green walls, play an essential role by reintroducing greenery into densely built environments. Although green walls offer energy, environmental and social benefits, there is still a need for reliable methods to measure their social impact accurately (Molari et al., 2024). Research on green wall systems has advanced, but this technology is still not widely adopted, despite its substantial potential (Ascione et al., 2020) Hence, according to Ascione et al., many studies highlight system functionality and benefits but often lack specific design methods and technical data, leaving designers without complete guidelines for all components.

Thus, in order to successfully integrate green walls into urban environments, their assessment must extend beyond their positive effects on energy reduction, indoor thermal comfort and environmental impact. It is equally crucial to evaluate technical aspects, their actual potential for integration into urban building stocks (surface availability), static and structural efficiency, associated construction risks and legislative barriers. Such a holistic approach is essential for the effective and scalable implementation of green walls across cities. In this line of thought, this deliverable aims at the creation of a solid methodological approach, that can be implemented in various cities in order to thoroughly assess the actual benefits of green wall implementation, maximizing their benefits and -at the same time- reduce related risks.

Green infrastructures related to buildings can help mitigate various challenges associated with urban built environments and living standards. Hence, although green roofs have been extensively researched over the past years, the environmental sustainability of vertical greening systems remains under-assessed (Rowe et al., 2022). The analysis of Rowe et al. (2022) reveals significant variations in the boundary conditions and assumptions utilized across existing studies, regarding the holistic LCA approach of green walls. Ultimately, it is suggested that a more accurate representation of the environmental impact of vertical greening systems requires a different evaluation of VFs' combined benefits. Thus, by means of certain benefits of VFs, such as energy, CO_2 sequestration and air pollution reduction, an LCA assessment is rather straightforward and feasible, considering the easy access to basic models and input data. However, for other benefits, including increased biodiversity, noise reduction as well as improved psychological and health standards, quantitative data remains insufficient, necessitating further research to facilitate their inclusion.

A recent review by Fang et al. highlights key research gaps and benefits in using nature-based solutions (NBS) for urban sustainability (Fang et al., 2024). Thus, while NBS studies commonly address urban flooding and UHI issues with green roofs, significant gaps remain in assessing ecosystem service (ES) flows and demand, two aspects that are essential for NBS and their positive influence on urban challenges. Another gap lies in implementing interdisciplinary approaches, as institutional and societal impacts on NBS are under-researched.

Against this background, GREENERGY aims at creating a thorough methodological framework, that will enable the overall analysis of VFs, not only by means of energy and environmental aspects, but also by means of actual integration potential into built environments, offering scalability of their benefits in urban environments.

2 METHODOLOGY

Based on the results of D1.2 "Assessment of benefits resulting from VF buildings", D1.3 aims to set the outlines of the technical characteristics of VF systems and their structural typologies by means of their integration potential in existing urban building stocks, in order to accelerate urban sustainability through large-scale VFs integration in urban developments. These developments should be based on tailor-cut Action Plans for each city/neighbourhood in order to avoid barriers related to buildings' typologies and maximize the benefits from a large-scale VF application. Thus, D1.3 will present a technical categorization of VF systems and, at the same time, of a case study building stock analysis in order to demonstrate the most suitable VF solutions for specific urban built environments. Hence, a specific methodological procedure is followed in D1.3 as shown in the graph below (Figure 1).

In addition, moving beyond the potential of VG integration into single building uses, towards large scale applications that would have significant positive impact on the urban microclimate, calculations related to actual available surfaces need to be assessed. Hence, besides technical and constructional characteristics of both the VG types and the buildings themselves, each new large-scale VG implementation approach for urban buildings needs to be designed on the basis of a surface availability analysis of urban building stocks.

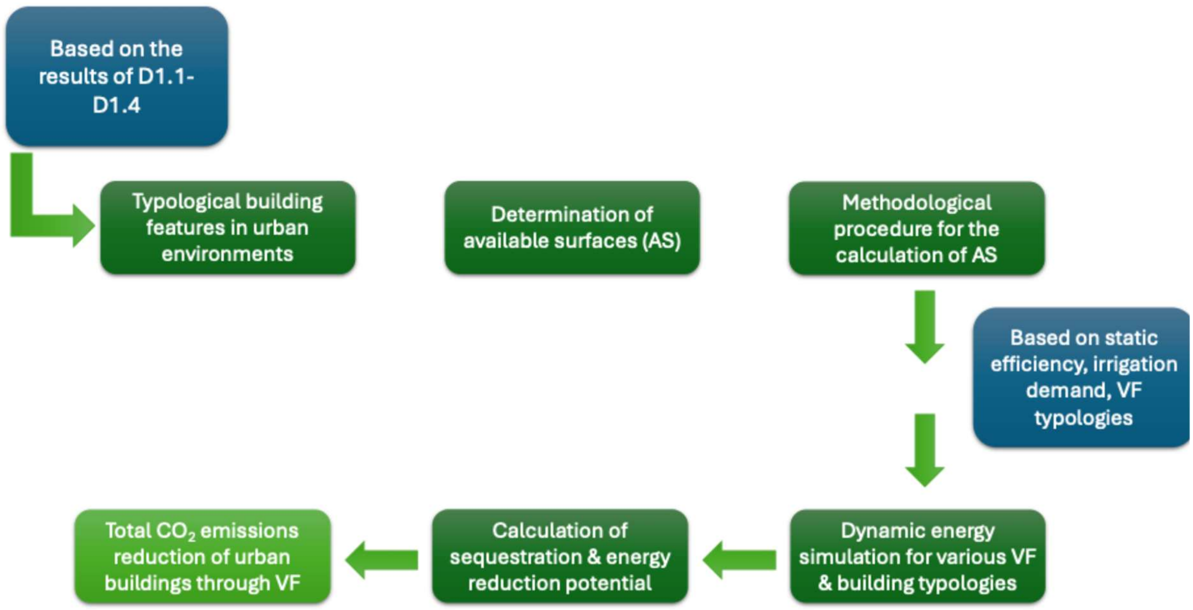


Figure 1 Main methodological steps from VG categorization to digital twin application modeling

In the following chapters, all related parameters of the potential in VG implementation will be assessed thoroughly, through a multi-variable analysis that will conclude into specific VG typologies for further analysis.

In order to provide official and similar data on a European level, to promote energy efficiency across Europe, the EPISCOPE EU project, provides national building typologies. They are developed to represent the residential building stock in each participating country. The project builds on the common TABULA concept, a standardized approach that helps assess the energy performance of residential buildings and supports energy-saving initiatives (Episcope, 2024).

Each national typology includes, (i) a structured classification for residential buildings by factors such as age and size, with additional relevant parameters, (ii) a selection of representative buildings illustrating different national building types, (iii) typical energy consumption metrics for these representative buildings, (iv) example calculations demonstrating possible energy savings, (i) statistical data on buildings and supply systems for a comprehensive analysis. The typology information is made available in two Country Pages, that provide an overview of the typology and essential statistics, accompanied by detailed brochures in each country's language and the TABULA WebTool, which enables access to building data, offering online calculations of standard energy consumption values.

A similar EU project for non-residential buildings' typologies is the EU Building Stock Observatory (BSO). This initiative aims to provide thorough data on the constructional characteristics and energy performance of buildings across Europe. Thus, the BSO collects, monitors and analyzes key data about national building stocks, including energy consumption, renovation rates and performance improvements. By gathering standardized and reliable information, the project supports policymakers, industry stakeholders and researchers in assessing the effectiveness of energy policies (European Union, 2024).

These data were used to organize the statistical and typological analysis of the case-study building stocks of this project. The detailed methodological procedure will be presented in WP5. The proposed methodology is applied in Greece's second largest municipality, namely Thessaloniki, as a typical sample of urban building stock.

2.1 ANALYSIS OF THE GREEK BUILDING STOCK

2.1.1 The typological features of Greek urban environments

Greek cities have witnessed substantial growth since World War II, though governed by a centralized urban-planning system, that led to extensive and continuous built systems, characterized by social practices diverging from established scientific and technical planning norms (Papamanolis, 2015). Thus, the organization of Greek urban spaces, mainly Athens and Thessaloniki, has been and still is non-functional, featuring very high built density, lack of coordination in central operations, restricted access to natural surroundings as well as urban sprawl towards the city outskirts (Maloutas, 2000).

Greek cities represent some of the densest urban built environments in Europe; it is characteristic that 61.2% of Greece's total population lives in cities. More specifically, the metropolitan areas of Athens and Thessaloniki account for almost 36% of the entire population according to the Hellenic Statistical Authority. In addition, about 80% of the urban population lives in the 18 largest cities, exceeding 50,000 inhabitants each, whilst 20% resides in 66 cities with populations ranging from 10,000 to 50,000 inhabitants (Hellenic Statistical Authority, 2012). Hence, according to Theodoridou et al., (2012) 73% of the total population living in urban areas, mainly in the two largest Prefectures of Athens and Thessaloniki (Theodoridou, et al., 2012). More specifically the population density in the Municipality of Athens rises up to19,133.41 people/km^2 with an even higher concentration in Thessaloniki, reaching 20,429.20 people/km^2, compared to Berlin (3,796.30 people/km^2), inner London (8,902.00 people/km^2), Stockholm (280.90 people/km^2), and Zurich (733.50 people/km^2). Hence, Greek cities diverge in their typological features, concerning built-up density compared to Western-European and North-American cities, as post-war Greek urban architecture lacks a distinct 'own identity', leading to its manifestation in disorderly forms (Gospodini et al., 2006). It becomes obvious, that the compactness and density of Greek cities is high, a fact that explains the link between Greek urban built environments and the energy behaviour of their building stocks (Tsirigoti et al., 2017).

Thus, Greek cities have less green space per person compared to other European cities. More specifically, the percentage of total green infrastructure, urban green space and urban tree coverage in EEA-38 capital cities, Athens is in the second last position, before Valletta. Hence, Athens features 11% urban tree cover and 17% total green infrastructure, while the related numbers for EEA-38 cities average are 30% and 42% respectively (European Environment Agency, 2022).

The above data underline the lack of accessible green spaces in Greek cities, as a significant portion of the city surfaces is covered by asphalt roads and concrete pavements (Papamanolis, 2015). More specifically, the defining feature of Greek cities is residential buildings, particularly the prevalent MF-building typology known as Polykatoikia (Greek: polys—many and katoikia—dwelling). Despite diverse influences from Italic, German, Ottoman, and French rule, as well as remnants of ancient Greece and Byzantium, Polykatoikies persist as a dominant architectural form across all Greek urban areas, regardless of climatic conditions or historical contexts. In both Thessaloniki and Athens, roughly 80% are residential buildings, with 90% of mixed-use located in Polykatoikies, predominantly featuring apartments (Theodoridou, et al., 2011). It is evident that this MF-building typology serves as the central and pervasive element of Greek urban built environments. Thus, measures to minimize IHU and improve the built environment of Greek urban centers will have a direct positive impact on their domestic building stock, with various benefits in terms of social aspects besides reduced residential energy consumption. This was shown in a research concerning the influence of large-scale green roof implementation in Thessaloniki; the results showed that the implementation of GR in the residential building stock can lead a reduction in heating and cooling consumptions up to 5% and 16% respectively (Theodoridou, et al., 2017). Hence, methods to increase grass coverage and greenspace overall is considered to be an important tool, towards IHU minimization and urban cooling in Greek cities (Tseliou, et al., 2022; Georgi, et al., 2010; Dandou, et al., 2021).

2.1.1 The typological features of Greek urban buildings

Considering that nearly 71% of Greek buildings were constructed before the first Thermal Insulation Regulation (TIR), Greek cities suffer from aged building stocks with high needs in energy consumption (Theodoridou, et al., 2011). Additionally, residential buildings make up 83% of this stock, highlighting significant opportunities for energy conservation along with tackling energy poverty and poor indoor conditions for citizens (Theodoridou, et al., 2011). To effectively design and implement energy renovation strategies, a comprehensive analysis of the Greek building typologies must be conducted, particularly in terms of their relation to the urban built environment. To facilitate this, a classification of the dominant MF- building typologies is crucial, along with an examination of representative examples (archetypes).

Large-scale approaches, concerning holistic interventions in urban building stocks, are considered to be powerful tools for efficient and safe extrapolations of both risks and benefits from retrofitting measures in built environments. Against this background, the European Commissions is promoting digital twin technologies, to enable acceleration of climate change mitigation and adaptation in cities, through policies that offer scalability of energy efficiency, environmental improvement and improved living standards. Thus, working with building typologies and archetype buildings, is essential to enable large-scale assessments, whilst elaborating specific intervention scenarios for urban buildings. The building's age parameter is significant, since it discloses important information about the building's typology, such as:

- the building envelope materials
- elements of the façades (projections, balconies, etc.)
- HVAC systems
- construction practices applied,

All of the above parameters are strongly linked to the building's energy behaviour and the potential of a successful green wall integration or other retrofitting techniques.

Thus, building typologies exist in most of the EU countries. For instance, in Germany the Federal Statistic Authority classifies residential buildings according to their year of construction and divides the building stock in eight classes since the beginning of the 20th century (German Federal Statistic Authority). In Switzerland buildings the respective building categories start with those constructed before 1920, during 1921-1980 and after 1981 (Hassler, 2009). Similar categorizations can be found in the UK (English Housing Survey - Department for Communities and Local Government, 2010), Italy (Ballarini, et al., 2009) and Denmark (National Building Research Institute, 2007; Danish Energy Agency, 2008; Tommerup et al., 2006). Moreover, Gustavsson et al. assessed energy refurbishment strategies according to the life cycle of residential buildings, using a classification based on the year of construction as well (Gustavsson, et al., 2010). In the same line, Jaber studied the Jordan building stock according to the year of construction among other parameters (Jaber, 2010). Balaras et al. categorized buildings between single and multi-family ones, whilst using a generalised typological organization according to their year of construction (Balaras, et al., 2005). Besides building typologies and archetypes, the built system also plays a significant role in large-scale analysis of buildings' retrofit, as it influences the following parameters:

-heat losses (number of surfaces in direct contact with the outdoor conditions)

-total available surface areas for green wall integration and RES systems

-constructional and technical barriers related to the building's shape and volumetrics

-shading from the surrounding buildings

Up to now, several authors tried to investigate the residential energy consumption and demand in Greece (Rapanos et al., 2006), mainly focusing on heating and electricity demand (Tsani, 2010; (Rapanos et al., 2005; Papathanasopoulou, 2010; Agoris et al., 2004). Balaras et al. (2000) studied the the effect of various energy refurbishment scenarios in Greek residential buildings using the EPIQR methodology (Balaras et al., 2000). Papadopoulos et al. assessed the most efficient retrofitting measures under the aspect of their economic viability for 90 buildings in Northern Greece during a 6-year period (Papadopoulos et al., 2002). Finally, Santamouris et al. (2007) collected data from 1,110 households in Athens during 2004, studying the links between socioeconomic characteristics and the energy behavior of the Greek residential buildings (Santamouris et al., 2007).

For the GREENENERGY project it was important to determine the relations between the most important variables of urban building stocks, such as typological and energy behaviour characteristics, with green wall and VF system technologies. This step is crucial for the development of an integrated VF retrofitting approach on the basis for a bottom-up methodology. The details of the proposed bottom-up methodology, based on statistical and building physics data will be presented in WP5. The scope of this methodology is on the one hand to create an interactive relation between the parameters of energy efficiency and economic feasibility with VF and on the other hand to evaluate energy efficiency strategies taking into consideration their environmental impact as well as technical and legislative aspects, to ensure their actual applicability in real environments.

More specifically, based on the national statistical data, the majority of urban built environments in Greek cities consist of residential multifamily buildings, in a continuous building system, constructed before 1980 and the first Thermal Insulation Regulation.

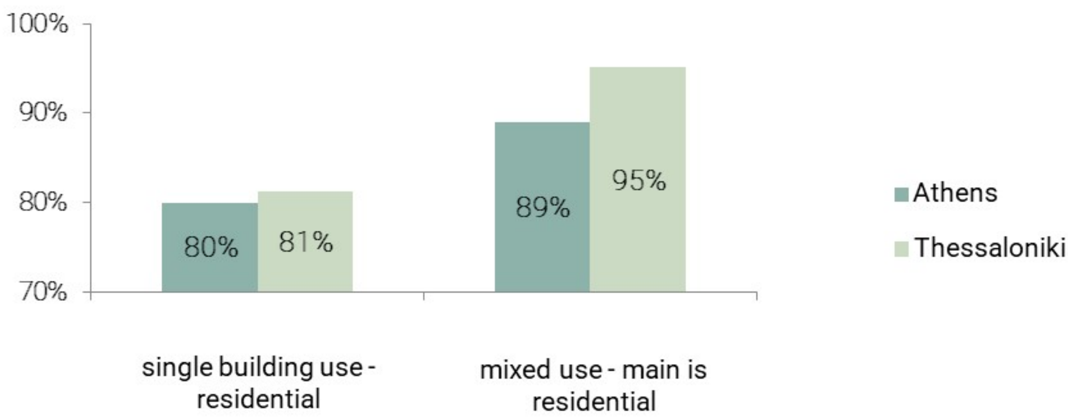


Figure 2 Statistical data regarding the majority of building usages in the two largest Greek cities (Hellenic Statistical Authority)

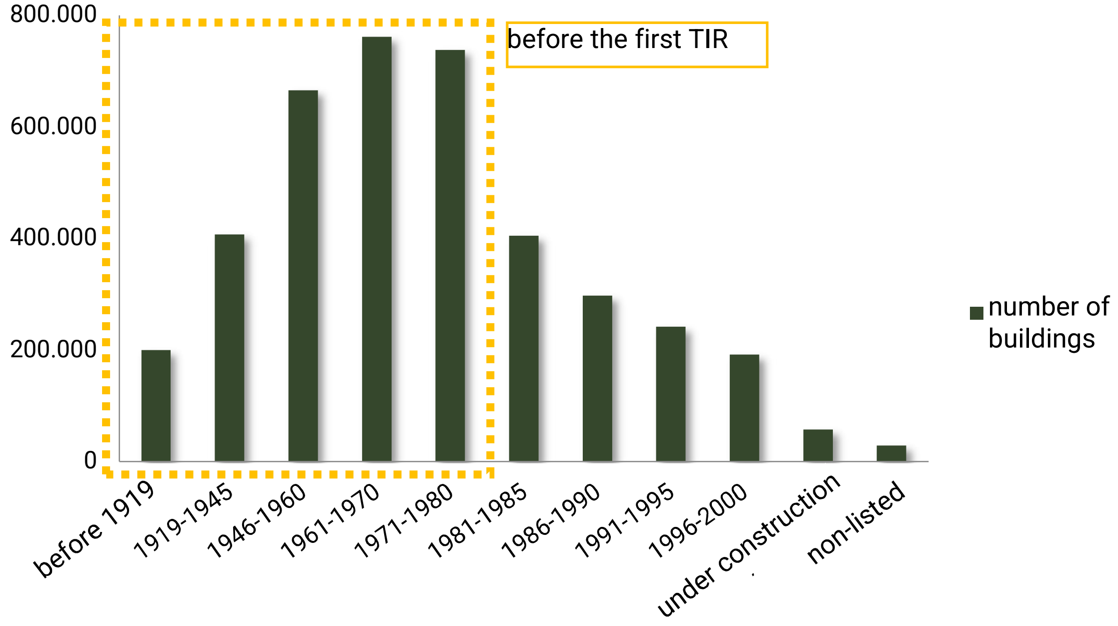


Figure 3 Number of buildings constructed before the first Thermal Insulation Regulation (TIR) (Hellenic Statistical Authority)

These findings are crucial for the overall approach of GREENENERGY as it influences the following research parameters:

- the expected available surfaces for VF systems
- the static efficiency of the buildings that will be simulated in the Lab

Hence, the static tests will focus on non-thermally insulated building envelopes, with pre-1980 static efficiency. In addition, the integration of VF systems must be flexible so as to adjust to the maximum available facade surfaces of the buildings. More information is available in chapter 4 of this deliverable.

2.2 LEGISLATIVE BACKGROUND

Green walls are foreseen by the National Construction Regulation (NOK). More specifically, according to the Article 11 (paragraph 6) "double energy façades", all building envelope constructions for the integration of green walls are allowed as long as they do not exceed 70 cm width. In addition, the green wall surface of each building cannot exceed 50% of the total exterior envelope surfaces of the building. Additionally, the regulation offers various incentives for energy-efficient features, such as the use of photovoltaic systems and thermal façades, which align with the broader goal of reducing a building's carbon footprint. These initiatives form part of Greece's overall effort to encourage sustainable urban development, providing a framework that supports green building practices across new construction and renovations.

It should also be underlined that specifications are foreseen in terms of pedestrian access and the building's relation to it. Namely, no interventions are allowed if the building has a zero-lot line, which applies to over 95% of the urban buildings in Greek city centers. This highly affects the choice of the VF systems that can be integrated into a large-scale analysis and reflect actual conditions of Greek cities environments as analyzed in chapter 4.

3 TYPOLOGIES OF VF SYSTEMS

A vertical forest (VF) system refers to all systems that can green vertical surfaces. Vertical green technologies are classified as green façades and living walls based on vegetation and substrates. Figure 4 presents the classification of vertical green technologies (Wang et al., 2022). The main factors affecting vertical green design are climatic conditions, structural performance of buildings, orientation, height, plant species, construction and maintenance costs, safety, durability and other factors.

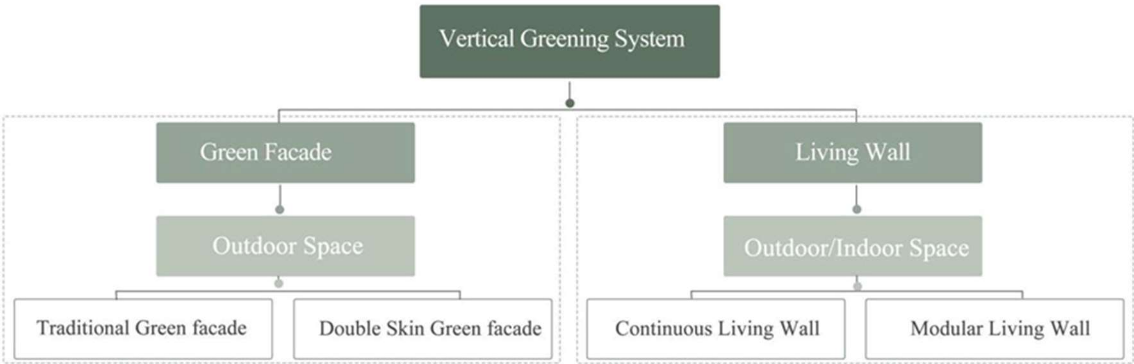


Figure 4 Classification of vertical greening system (Wang et al., 2022).

3.1 GREEN FAÇADES

Green façades consist of climbing plants rooted in the ground that grow over support structures or hanging plants along the wall. These systems are distinguished by their simplicity and ability to transform existing buildings.

Plants can grow up the vertical surface, like the traditional examples, or grow down the vertical surface, in case they are hung at a certain height (Dunnett & Kingsbury, 2008). Green façades can be classified as direct (traditional green façade) or indirect (double skin green façade) (Figure 5).

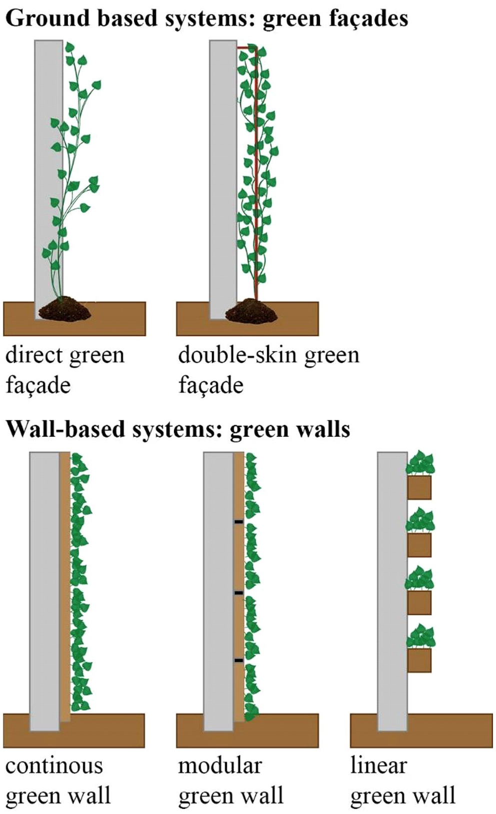


Figure 5 Green façades- ground-based greening methods. Direct (left) and indirect (right) green façade (Medl et al., 2017)

3.1.1 Direct green façades

Direct green façades (Traditional green façade) (Figure 6 and Figure 7) are those in which the plants are attached directly to the wall (Manso & Castro, 2015). Direct green façades are defined by the presence of plants with adhesive root system, that enables their direct attachment to the façade; due to this mechanism, supplementary structural components are not needed.

Figure 6 Direct green façade, Colega, Portugal (Manso & Castro, 2015)

Figure 7 Direct green façade, Leida, Spain (Perez et al., 2014)

Perimeter flowerpots (Figure 8) are also a kind of direct green façade. They are hung and planted around the building as part of the façade composition to form a green curtain.

Figure 8 Perimeter flowerpots, Leida, Spain (Perez et al., 2014)

3.1.2 Indirect green façade

Indirect green façades (Figure 9) (double -skin green façade) include a support structure for the vegetation (Manso & Castro, 2015) creating a double -skin or green curtain separated from the wall. Indirect green façades divided into two systems: tensile wire meshes or simple wire ropes and metal cages.

Modular trellises are very light trellis metal modules mounted on the building wall or on independent structures. These structures become the support for climbing plants. In wired structures a system of steel cables, anchorages, separators, and other features are used to constitute a light structure that serves as support for climbing plants. Metal cages consists of a very light structure that provides support for the climbers. It is made with a steel mesh an chored to the building wall or to the building structure (Perez et al., 2011). Plants to be applied in are climbing species. Green façades provide thermal insulation, improve air quality, and reduce energy consumption.

Figure 9 Indirect green façades (Manso & Castro, 2015)

3.1.3 Typology, advantages and disadvantages of green façade systems.

In Table 1 a synoptic overview of green façade systems is presented, alongside advantages and disadvantages. Direct green façades host climbing plants that grow directly on the building surface. This approach has a reduced environmental footprint as it requires no extra materials like substrates or support structures. This simplicity minimizes manufacturing costs and environmental impact, making it an affordable and sustainable option. However, this approach has limited plant selection due to its lack of structural support, limiting its adaptability to different climates. Coverage is slow, often taking up to five years, and can be uneven, affecting aesthetic consistency. Maintenance can be challenging as climbing plants may detach over time, potentially damaging the façade.

Indirect façades incorporate external structures to support plant growth, allowing for controlled growth patterns, greater maintenance flexibility, and sometimes irrigation systems. However, these structures often come with higher costs and environmental impacts. Two main types of indirect façade cultivation are identified:

i. **Tensile Wire Meshes** or **Simple Wire Ropes**: This system guides plant growth, ensuring more uniform coverage than direct systems and reducing water consumption by controlling plant size and growth areas. Despite its guiding structure, this system still has limited plant selection and climate adaptability, restricting its use to specific plants and environments. Like direct façades, coverage is slow and can take up to five years, with uneven coverage being a potential drawback. Additionally, certain materials used in wire meshes and ropes may have a large environmental footprint, counteracting some sustainability benefits.

ii. **Metal Cages**: Metal cages provide robust support, enabling lightweight construction and easier plant management through controlled irrigation and drainage systems. They allow easy assembly and disassembly for maintenance, providing the flexibility to replace plants as needed. Similar to other indirect systems, plant selection is limited due to structural and climatic constraints. Metal cages often involve high installation costs and can have a significant environmental footprint depending on the materials used.

Table 1 Classification of green façades according to their construction characteristics

Category	Subcategory		Advantages	Disadvantages
A - Green façades	**A1 Direct**	**A1A** climbing plants **A1B** flowerpots	• no extra materials are needed (support, substrate, irrigation) • reduced environmental footprint • reduced manufacturing costs	• reduced plant selection and limited climate adaptation •slow coverage of the aspect (can reach up to 5 years). • uneven coverage of the face • maintenance problems. • plant detachment • damage to the façade
	A2 Indirect	**A2A** tensile wire meshes or simple wire ropes	• guided plant growth. • reduced water consumption	• reduced plant selection and limited climate adaptation. • slow coverage of the aspect (can reach up to 5 years). • uneven coverage of the face. • large environmental footprint of some materials
		A2B metal cages	• lightweight construction • guided plant growth • controlled irrigation and drainage • easy assembly and disassembly for maintenance work • possibility of replacing plants	• reduced plant selection and limited climate adaptation • large environmental footprint of some materials • high installation costs

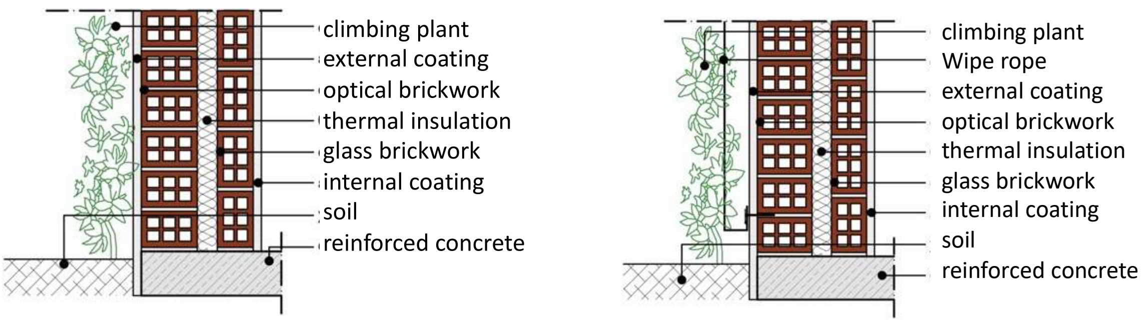


Figure 10 Schematic representation of green façade systems (source Theodoridou, 2018). Direct (left) (A1) and indirect (right) (A2) green façade

3.2 LIVING WALLS

Living walls or biowalls are more complex systems where plants grow in vertically installed units, which can be incorporated into the walls of new or existing structures. It is a fairly recent area of innovation in the field of wall cladding. They emerged to allow the integration of greenwalls in high buildings as allow a rapid coverage of large surfaces and a more uniform growth along the vertical surface. They also allow the integration of a wider variety of plant species (Manso &Castro-Gones, 2015). These systems require irrigation and fertilization systems, but offer excellent benefits such as improved building insulation and reduction of urban noise pollution (Golasz-Szołomicka & Szołomicki, 2019). Living wall systems (LWS) can be classified as continuous or modular depending on their method of application (Figure 11).

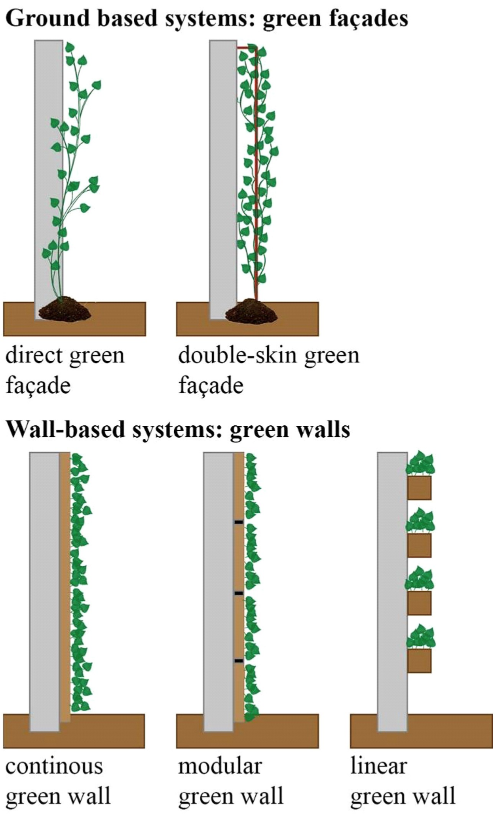


Figure 11 Green walls, wall-based greening methods include continuous (left) and modular (right) green walls (Medl et al.,2017).

3.2.1 Continuous Living wall system

Continuous green walls usually include a structural framework that supports the base panel and protects the wall from humidity. The application of a fabric layer (permeable, flexible and root proof screens, also serving as drainage) serves as growing media. Consequently, continuous green walls frequently exhibit no additional necessity for a soil substrate. This hydroponic technology provides water and nutrients to the plants. The fabric layer is attached to waterproof membranes that serve to shield the construction materials from moisture exposure. (Manso & Casto-Gomes, 2015; Charoenkit & Yiemwattana, 2016; Medl et al., 2017)

Continuous LWS are also known as Vertical Gardens (VG). This name was given by the French botanist Patrick Blanc, who popularized the application of this type of LWS worldwide. His work is included in many buildings of the most famous architects (Figure 12).

Figure 12 Continuous living wall system, Caixa Forum, Madrid.

3.2.2 Modular living wall system

Modular LWS are special dimensional elements that include the growing media where the plants can grow. Each element is supported by a complementary structure or fixed directly to the vertical surface. Modular green walls consist of several modules in form of pocket typed planters and panels. Each module is designed to hold soil or substrate and is fixed to a structural frame behind (Charoenkit & Yiemwattana, 2016). Growing media are either organic (e.g. soil) or inorganic (e.g. granular material like perlite, foam, mineral wool, felt (Mir, 2011; Perini et al.,2012).

Modular living wall system can be classified as modular tray system, prefabricated planter boxes, flexible cases and geotextile felt cases. Modular trays are usually rigid containers, attachable to each other, that can hold the plants and substrate weight. Flexible bags include a growing media and lightweight components that facilitate the cultivation of vegetation on surfaces with varying geometries, such as those that are curved or inclined.

3.2.3 Typology, advantages and disadvantages of living wall systems.

In Table 2, a synoptic overview of the living wall systems and their characteristics is presented. Living walls are classified based on their structural and functional designs, providing flexibility in architectural application and plant diversity, but each type has specific limitations in cost, complexity, and environmental impact. Two types of living walls are identified: (a) Continuous living walls and (b) Modular living walls.

The continuous living walls include a soil planting substrate, and their main advantage is that they can support a uniform plant growth and allow a broad range of plant selection, due to its soil-based substrate. They also have a flexible, lightweight construction, which makes them adaptable for various structures, and ensures even distribution of water and nutrients. However, their continuous design requires complex installation, high water and nutrient consumption, and frequent maintenance. These factors can increase ongoing operational costs, making this option more intensive for maintenance teams and water management.

The modular living walls offer distinct advantages in maintenance flexibility, with specific types designed to balance aesthetic and practical benefits. However, many modular systems have challenges related to space limitations for root growth and environmental impacts from construction materials. The modular living walls can be classified into four different categories / types, based on the systems and material used, as follows:

i. **Modular Tray System**: This system enables easy disassembly for maintenance and controlled irrigation and drainage, which helps prevent overwatering and improves plant health. It also allows for flexible plant selection. However, modular trays offer limited root growth space, which may restrict plant size and type. The construction is often heavier and more costly, and the final look is constrained by tray shapes, which may limit design flexibility. Additionally, materials used in modular systems can have a large environmental footprint, raising sustainability concerns.

ii. **Prefabricated Planter Boxes**: Prefabricated boxes offer a high aesthetic appeal and enable broad plant selection, ideal for decorative applications in visible locations. Like the modular tray system, these boxes limit root space, which can impact plant health and longevity. They also have high construction and installation costs and complexity due to their weight and structural requirements.

iii. **Flexible Cases**: These cases can be applied on inclined surfaces, expanding their utility in varied architectural settings, while also allowing diverse plant selections. Installation is more complex and costly due to the heavier weight of the substrate, which requires reinforced structural support. These characteristics make flexible cases less suitable for lightweight or low-budget projects.

iv. **Geotextile Felt Cases**: These cases have similar attributes with flexible cases, however they differentiate in the materials used.

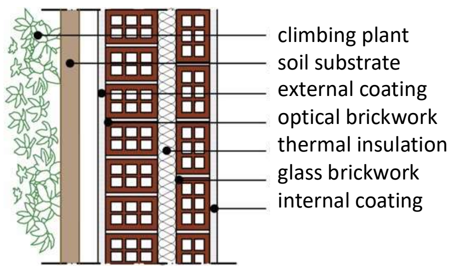
Table 2 Classification of living walls according to their construction characteristics

Category	**Subcategory**		**Advantages**	**Disadvantages**
B - Living walls	**B1 Continuous**	**B1A** Living wall type with soil planting substrate - continuous system	• uniform plant growth • flexible and light construction • increased possibility of plant selection. • uniform distribution of water, fertilizers and trace elements	• complex installation. • high consumption of water and nutrients. • need for frequent maintenance
	B2 Modular	**B2A** modular tray system	• easy disassembly for maintenance work • increased possibility of plant selection • controlled irrigation and drainage	• limited space for root growth • high construction costs • complex installation • heavier construction • the final configuration of the face is limited by the shape of the discs • large environmental footprint of some materials

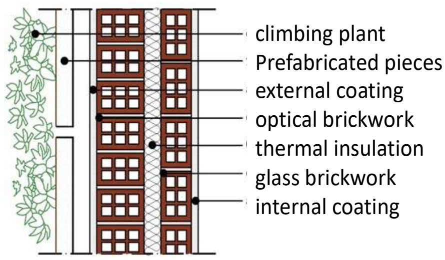
		B2B prefabricated planter boxes	• offering more options for plants' selection • high aesthetics	• high construction costs • complex installation• limited space for root growth • the overall configuration of the view is limited by the form of the boxes
		B2G flexible cases	• possibility of application on inclined surfaces • increased possibility of plant selection	• high construction costs • complex installation • heavier construction due to substrate • high installation costs
		B2D geotextile felt cases		

Direct façades are a simpler, cost-effective, and eco-friendly option but offer limited plant adaptability, slow coverage, and potential maintenance issues. Indirect façades, while more complex and costly, offer controlled growth, flexibility in maintenance, and faster establishment. However, they often come with environmental impacts from supporting materials, which could be mitigated by using sustainable materials. Direct green façades may be ideal for projects prioritizing minimal environmental impact and cost, whereas indirect façades suit projects where flexibility, plant control, and aesthetic uniformity are essential, provided that budget and environmental concerns are addressed.

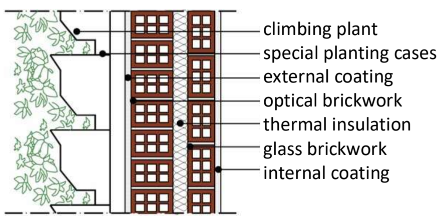
On the other hand, continuous living walls offer more flexibility in construction and uniform growth but have high water and nutrient requirements, making them resource- intensive. Modular systems like trays, planter boxes, and flexible cases offer easier maintenance and controlled irrigation, but they often come with high construction costs, root space limitations, and higher environmental impacts from materials. In terms of application, continuous walls may be more suitable for projects with lower maintenance constraints and highwater availability, while modular systems might work better in urban or smaller spaces where maintenance access and aesthetic control are priorities.



B1 (Continuous Living wall system)



B2B (Modular Living wall system -prefabricated planter boxes)



B2G (Modular Living wall system - flexible cases)

Figure 13 Schematic representation of green façade systems (Theodoridou, 2018).

4 TECHNICAL DETAILS-EXAMPLES

In this chapter the technical features of the main systems presented in Table 1 and Table 2 are described. A selection among the category "A – Green façades – A2 Indirect systems" and the category "B – Living walls – B1 continuous and B2 modular systems" was performed, based on applicability criteria and the systems' flexibility by means of a large-scale application in urban building stocks. Hence, the most indicative typologies and their technical features of chapter 3 are described through applied examples of various VF types.

4.1 GREEN FAÇADES

As regards the first category presented in chapter 3 "A – Green façades – A1 Direct", this chapter offers a deeper focus on A1B indirect VF systems, since they represent a very suitable solution for a large-scale implementation in Greek building stocks. Their high adjustability and integration potential in existing building elements such as balconies and other projections are an important factor of their overall evaluation. Examples of their implementation are presented in the following chapters.

4.1.1 Direct façade systems A1B – Flowerpots and treepots

Flowerpots represent a direct green façade solution were specific plants with various heights grow on a horizontal direction across specific parts of the building's façade. They are integrated in large horizontal projection elements of building façades, usually in the form of flower- or even tree pots, offering a great range of plant species for incorporation into the building.

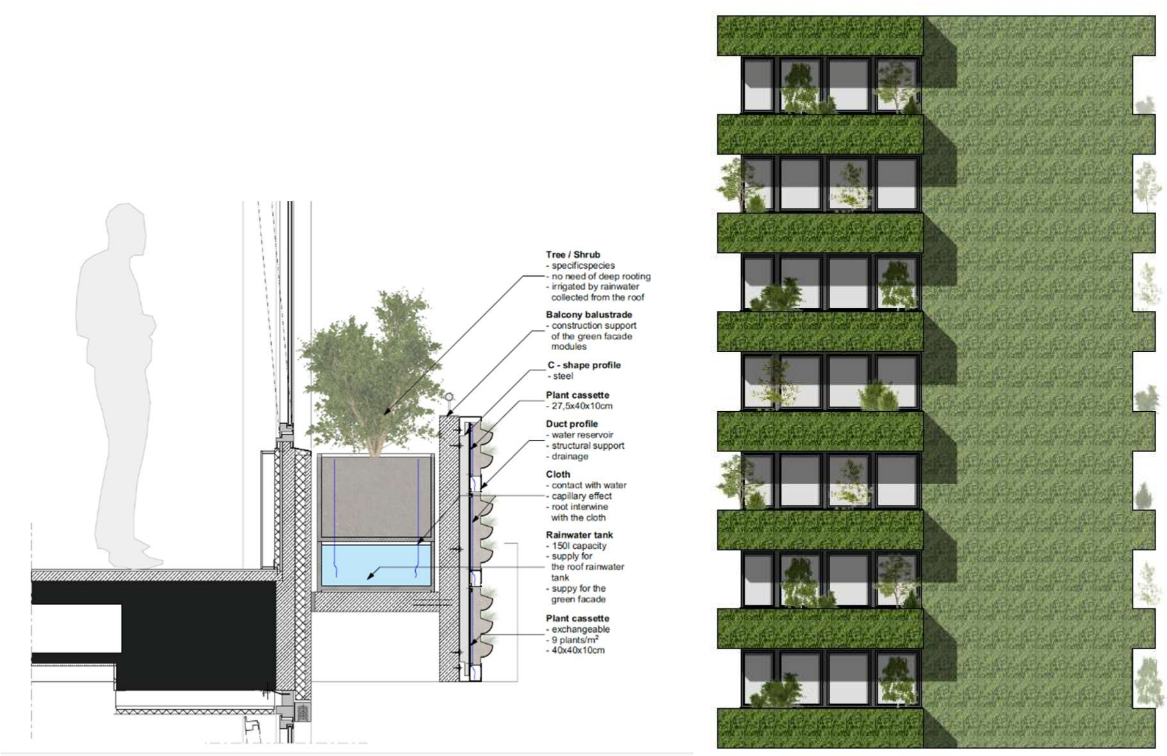


Figure 14 Section detail of a flowerpot system. (Stanislav Rezucha)

In another example, a treepot system is featured in the case of a trapezoidal, six-storey office and commercial building that forms a green urban ensemble together with the "food court" opposite. The building is planted with over 30,000 hornbeams – a novel application for European standards. The hedges are set in a kind of trough-in-trough system. The rows of troughs are positioned in relation to each other in a way, sunlight and rainwater to the plants is being guaranteed. To ensure adequate height access for pruning and maintenance of the plants in the façade, maintenance walkways and safety systems for the gardeners have been installed. In places where there was no space for maintenance walkways, a drive-on system has been installed along the trough rows (www.wernersobek.com).

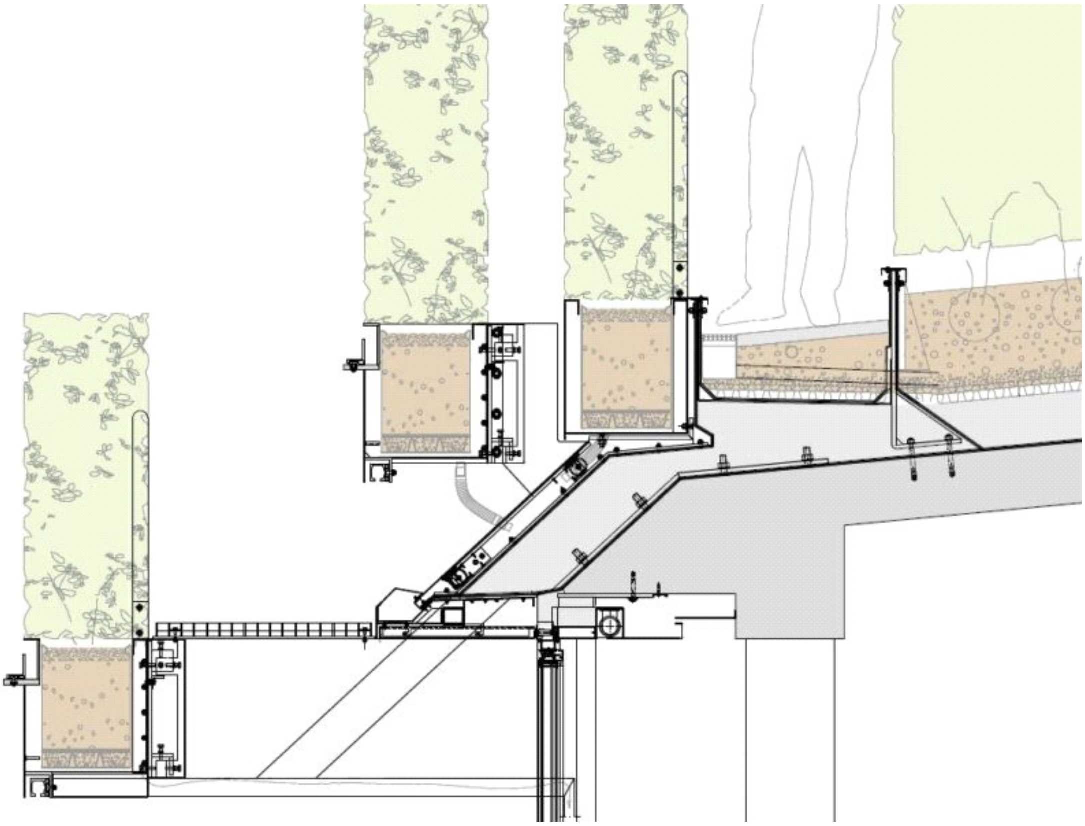


Figure 15 Design sketch for the supporting structure of the treepot system (KII, Düsseldorf, Wernersobek).

In order to keep the number of penetrations of the insulated building envelope as low as possible, a special substructure with intermediate beams in the insulation level was developed for the green façade. A sheet metal cladding above the insulation and waterproofing layer acts as weather protection and allows fallen leaves and branches to slide down as if on a large slide. On the ground floor, the green waste is collected in large-volume gutters and removed by the landscape gardeners.

The hedges were pre-cultivated over a long period of time in a tree nursery and delivered to Düsseldorf for installation in the interior troughs. The façade structures include supply systems for irrigation, fertiliser admixture and drainage. The installed technology partly regulates itself automatically on the basis of information on humidity, temperature, etc. provided by sensors distributed throughout the façade. In addition, the façade is being inspected and maintained at regular intervals by experienced gardeners (www.wernersobek.com).

Figure 16 Green façade (KII, Düsseldorf, Wernersobek)

4.2 LIVING WALLS

4.2.1 Modular systems-B2

The main difference of modular systems B2 (Figure 17) is that they have no soil layer; instead, panels are foreseen for the integration of special geotextiles, ideal for vertical plant growth, placed in two layers (hydroponic vertical garden). Thus, the plants grow directly on the special geotextile and are automatically nourished with water and the necessary fertilizers through a special irrigation and nutrition system. The system is monitored through a control room. Typical panel measurements are 2000x12x3000 (mm) and weigh 45kg/m^2. In the next chapters, a detailed analysis of modular living wall systems examples follows.

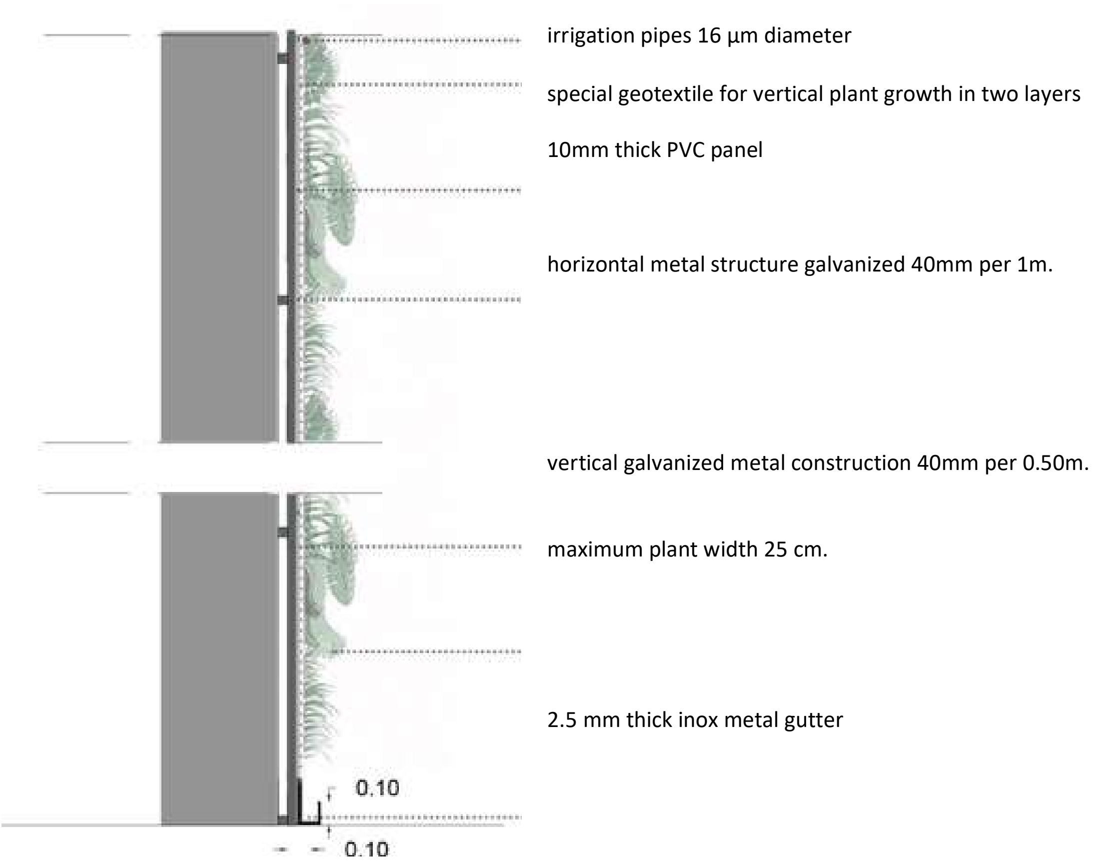


Figure 17 Section of green wall (Vita Verde Vertical Garden)

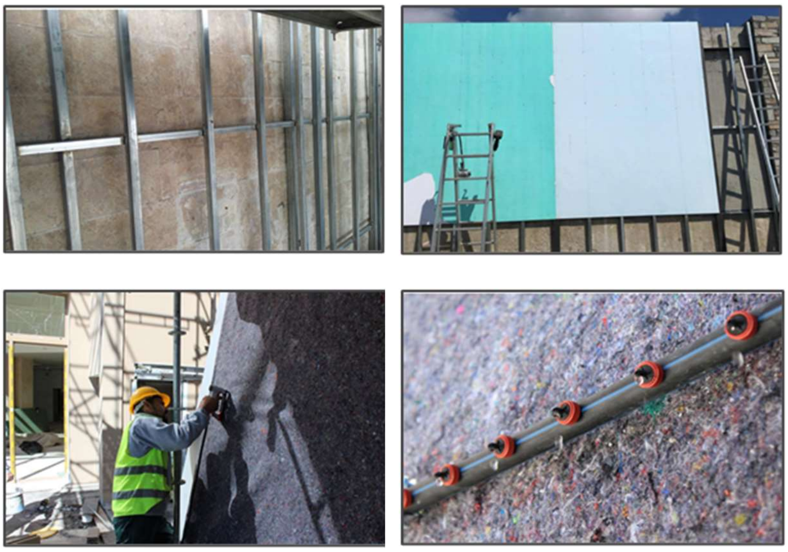


Figure 18 Application to building façade (Metal construction, PVC panels, planting geotextile, irrigation system)

4.2.1 Living wall continuous system – B1A

An example of a typical continuous living wall system is presented in this case. Thus, the aluminium baton system is the most frequently used Living Wall build-up system, suitable for any application where there is a solid brick or concrete surface to fix back to as shown in the next figures.

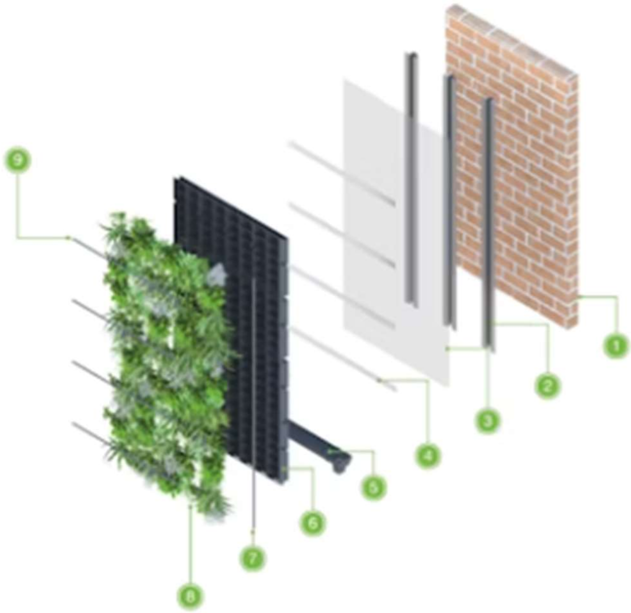


Figure 19. Indicative brick or concrete surface, 2. Vertical Omega carrier rail, 3. Breathable membrane, 4. Horizontal Fixing Rail, 5. Squareline Gutter or client specified, 6.ANS Living Wall Module 250x500x100mm, 7. 16mm vertical irrigation pipe, 8. Planting, 9. 16mm inline emitter pressure regulated irrigation pipe (source:Viritopia)

Figure 20 Deansgate Metrolink, Manchester, United Kingdom (Viritopia)

4.2.2 Modular tray systems - B2A

The standard panels in the Biotecture system are 600mm wide x 450mm high. When fully saturated the system weighs 75kgs per sqm. The panels complete with plants sit on pre-fixed T section recycled aluminium rails which in turn are fixed to a cement particle backing board through the drainage void former material. This ensures that the irrigated zone remains in front of the backing board and there is no chance of any moisture tracking back to the rest of the fabric of the building.

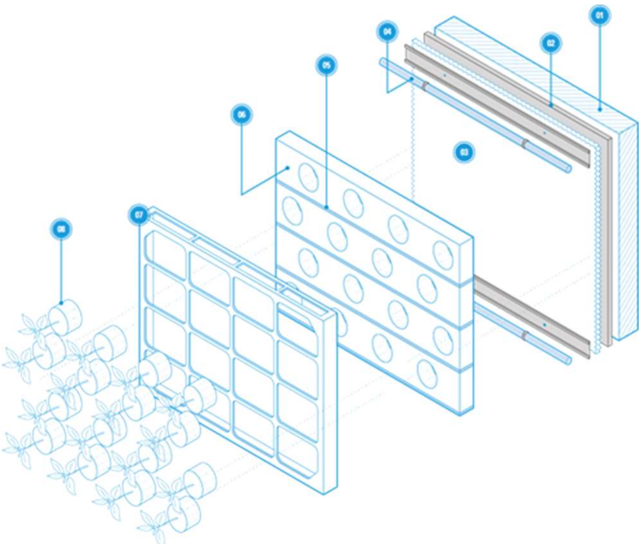


Figure 21 Support system,2 Waterproof backing board, 3.Rear drainage layer,4.Aluminium rails and dripline, 5.Capillary breaks, 6.Growing medium, 7.Panel box, 8.Plants (Biotecture)

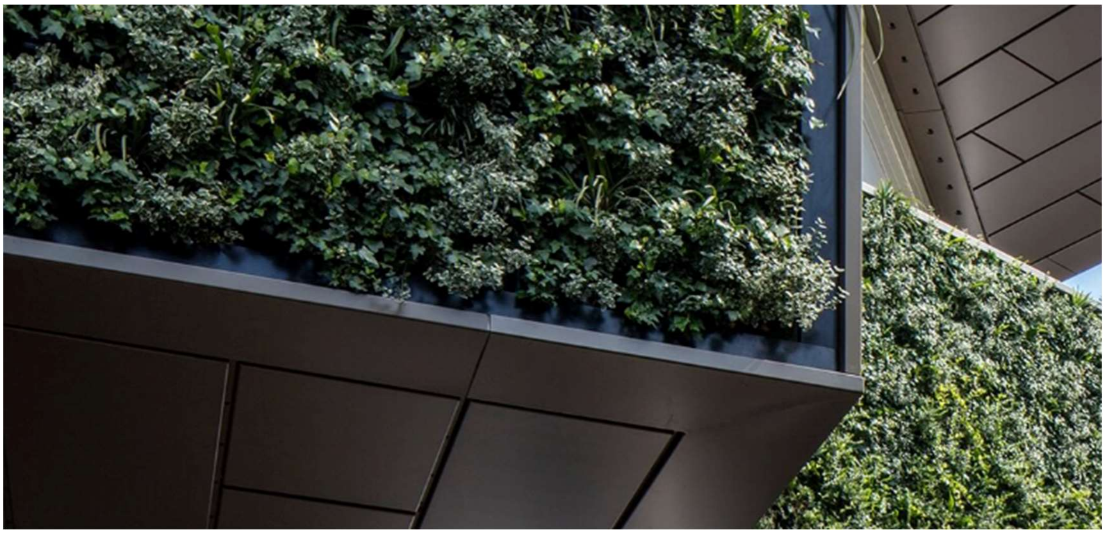


Figure 22 Detail of the planting support system

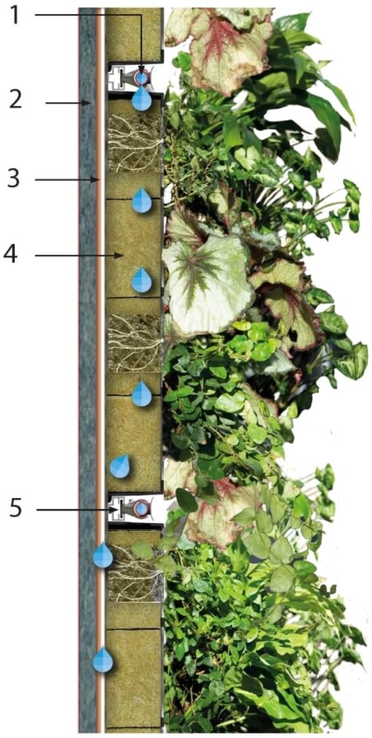


Figure 23 Diagramatic section. 1. Pressure compensated Dripline,2 Waterproof backing board, 3.Rear drainage layer,4. Growing medium, 5. Rail carrier system, dripline and coverstrips (Biotecture)

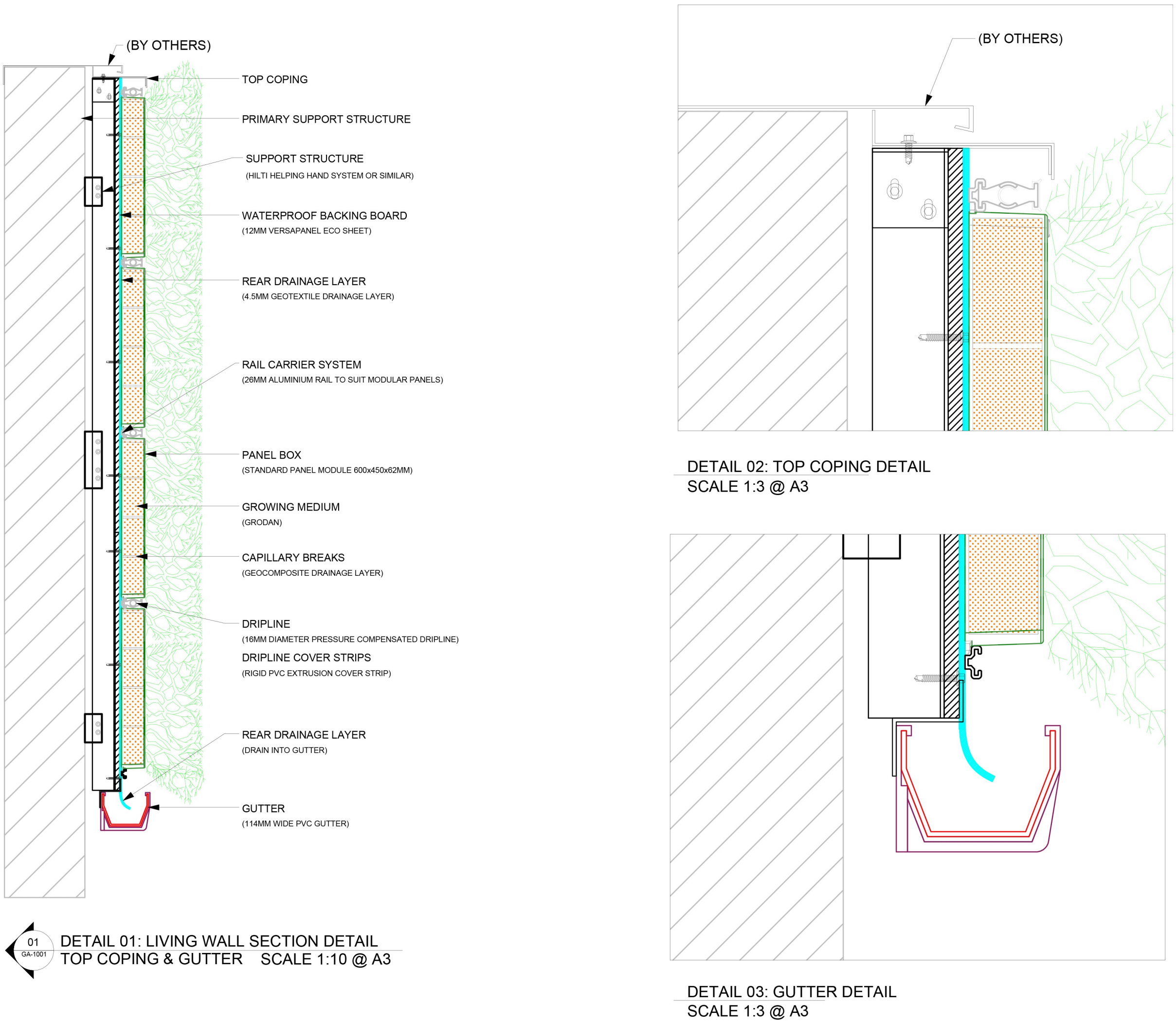
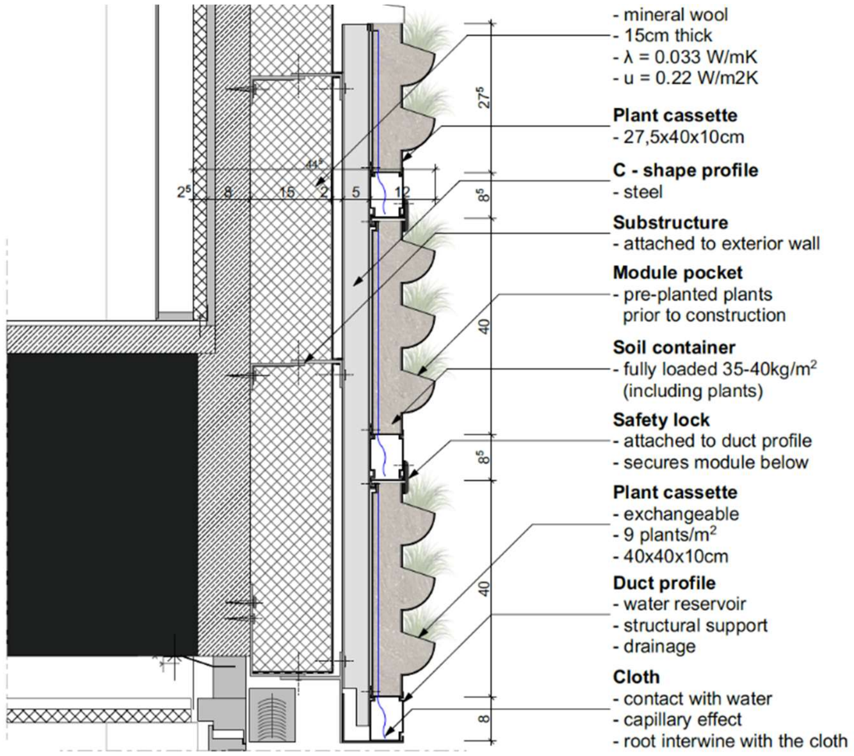


Figure 24 Living wall- section details (Biotecture)

4.2.3 Modular flexible cases - B2G

This category features prefabricated planter boxes in the form of modular pocket systems, which enable more options for plant selection and high adjustability in terms of their vertical application in existing building façades.



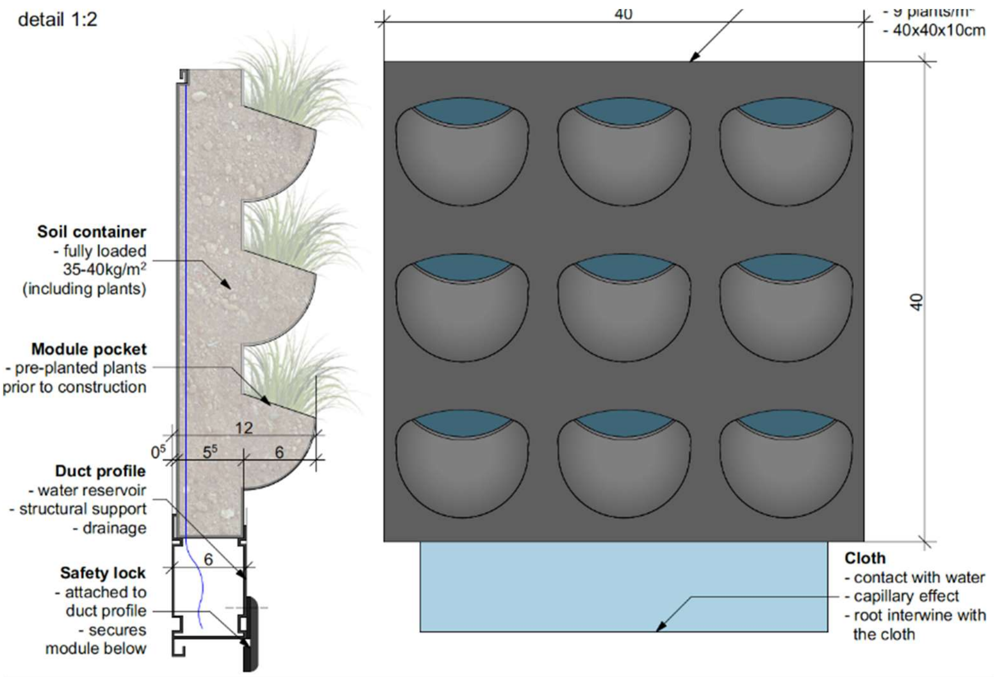


Figure 25 Application to building façade. Section details

5 FINAL SELECTION OF VF TECHNOLOGIES

Based on the results of the analysis proposed in this deliverable, two VF systems were chosen for further analysis in the next deliverables of WP2 and WP3. Thus, due to the complexity of urban built environments, an analysis was based upon the VF categories presented in tables Classification of green façades according to their construction characteristics and Classification of living walls according to their construction characteristics.

More specifically, according to the categorization proposed by the Greenergy project, the Green façade systems were evaluated according to their advantages and disadvantages, mainly in terms of their applicability. Thus, it is important to highlight the fact that not all systems presented in both the category A1 (direct green façades) and category A2 (indirect green façades) represent equally efficient solutions for a VF urban large-scale implementation or equally vulnerable to seismic excitations in some cases. Hence, A1A (climbing plants), A2A (tensile wire meshes) and A2B (metal cages) represent solutions that are not equally suitable for further analysis due to the following reasons:

- Legislative restrictions as described above – requirement for public area usage (usually pedestrian, which is not possible)
- Rare full façade available surfaces, since buildings are constructed in row-systems, leaving only 2 façades exposed to the exterior conditions
- Surfaces exposed to outdoor conditions, are not full-opaque surfaces; On the contrary, these surfaces are often the building's main surface, with a high window to wall ration, leaving very few room for the plants to grow
- The development of the plants is interrupted by horizontal projections (i.e. balconies), the domestic feature of urban Greek buildings. Hence, a whole height implementation is not possible
- High risk of damages, as described in Deliverable 1.4
- Usually they are solutions of low weight/square meter of façades. Therefore, the relatively low attached VF mass excited by a severe earthquake is not expected to produce seismic related vulnerabilities on site or in lab structural testing, when compared with other offered solutions attached to an existing building (beyond the Greek or EU legislative restrictions, if applied to other world regions).

On the other hand, A1B (flowerpots) can represent a solution of direct green façades, featuring flower (or tree) pots on balconies' edges in various dimensions, offering numerous vegetation solutions. This flexibility and adjustability, establish flowerpots as a suitable large-scale VF system, that will be further explored within the Greenenergy project.

By means of category B "living walls", B2G system was selected for further research due to its modular and flexible system. More specifically, systems of category B1 (continuous) were excluded for the next stage of analysis, due to their complex installation procedures, high needs in irrigation and frequent maintenance as well as the high risk of constructional failures. B2 systems (modular) offer more flexibility, but B2G-flexible cases were selected for further analysis, due to their increased flexibility and adjustability on reduced available surfaces.

In conclusion, two subcategories were chosen for further analysis within the Greenergy project, since they offer easier and safer applicability in the built environment, aligned with National Construction Codes and actual applicability and available surface potential. Further, they are expected to reveal seismic-related vulnerabilities during earthquake excitations, related to proper anchoring etc. These two systems are:

i. *A1B – Green Façades – Direct – Perimeter flowerpots,* which are a very suitable solution for the reduced whole-building-height façade areas due to (a) typological features of buildings (as analysed the majority of the existing building stocks refers to residential buildings that have balconies, organizing the façades per building floors) and (b) the density of the built environments, leaving very few free whole-building-height façades, due to the continuous built systems. Thus, a solution referring to balconies' applications, was very crucial for the analysis expected in the following Deliverables.

ii. <u>*B2G – Living walls – Modular – Flexible cases,*</u> since they offer lightweight applications, controlled irrigation and maintenance, easy assembly and high adjustability to complex building surfaces. These VF systems are meant to be applied in available free vertical façades surfaces.

These two systems are proposed to be simulated according to their static efficiency, as well as their influence on the built environment, as applied through a digital twin system in the city of Thessaloniki. These results will be described within the framework of WP2 and WP3 Deliverables.

Figure 26 Example of A1B perimeter flowerpots (parkroyal collection pickering)

Figure 27 Typical B2G modular flexible cases (Mobilane – Building Green systems)

6 CONCLUSIONS

This deliverable offers an in-depth assessment of vertical forest (VF) systems, focusing on their role in promoting urban sustainability in built environments. Thus, the analysis was structured so as to address both the technical characteristics and practical applicability of various VF systems. A categorization system is proposed, including coding per VF typology and two detailed tables were presented, that summarize specific VF types, including benefits and restrictions. This allows for a clear comparison of each system's specific attributes and suitability for urban implementations according to cities' typologies and their building stock characteristics. Hence, the goal of this deliverable was to present a structured approach, that analyzes each VF system's potential for integration into urban environments, whilst assessing their core features, material requirements, technical restrictions, maintenance needs and environmental benefits.

An important parameter for this categorization was the analysis and presentation of the specific restrictions arising from the application of the National Building Codes in Greece, which enforce specific guidelines for retrofitting practices. Recognizing these regulatory boundaries, the analysis examined how VF systems could adapt to meet compliance standards while still delivering environmental and aesthetic benefits. Hence, it was important to determine the specific parameters of VF large-scale applications that are affected by national regulations and standards, as well as the nature of Greek cities, considering structural support requirements and regulations on greenery applications on building façades, that lead to detailed approaches by means of suitable VF system selection and design. By considering these restrictions, the deliverable ensures that the proposed VF systems align with national regulations, making them feasible for practical application in Greek cities.

In addition, a thorough analysis of Greek urban built systems was also conducted to further assess the potential impact of VFs. This analysis examined current urban structures, green spaces and architectural building typologies within Greek cities, emphasizing the challenges of limited greenery in densely populated areas, along with the urgent need to tackle the growing problem of urban heat island effect. Against this background, the role of VF systems in the sustainable renovation of built systems was highlighted, since they offer increase in vegetation coverage, reduced solar absorptance and enhanced biodiversity without requiring additional urban land space, which is very difficult to find in dense cities.

Based on this comprehensive analysis, two VF systems were identified as suitable interventions in existing urban building stocks, that can exploit both vertical façades surfaces as well as horizontal façade elements (i.e. balconies). In addition, it was important to propose systems that can be tested and applied in a complementary way. These systems, described in the previous chapter, were chosen for their high flexibility in terms of their application in very densely built systems, offering maximum possible VF coverage. Matters regarding their structural - seismic efficiency will be assessed in following Deliverables, so as to offer a continuous and holistic assessment of their benefits, when applied in large-scale urban built environments. This is enabled with the introduction of digital-twin based analysis, which will enable the modeling of the proposed VF systems in order to quantify the actual available surfaces, their environmental benefits, such as energy savings through and reductions in CO2 emissions. This will provide a holistic approach to understand how VF systems might contribute to the improvement of urban sustainability in the context of Greek cities.

In conclusion, this deliverable not only identifies two VF systems with significant application potential but also establishes a framework for evaluating vertical forests within the specific regulatory and environmental context of Greece. By addressing legislative, technological and constructional restrictions, this analysis provides a robust approach for the large-scale integration of VF systems in Greek urban areas, aiming to support sustainable development of built environments and improve urban living conditions. The methodology presented in this deliverable may serve as a basis for further studies and pilot projects, helping to shape the efficient introduction of VF solutions in European cities and beyond.

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