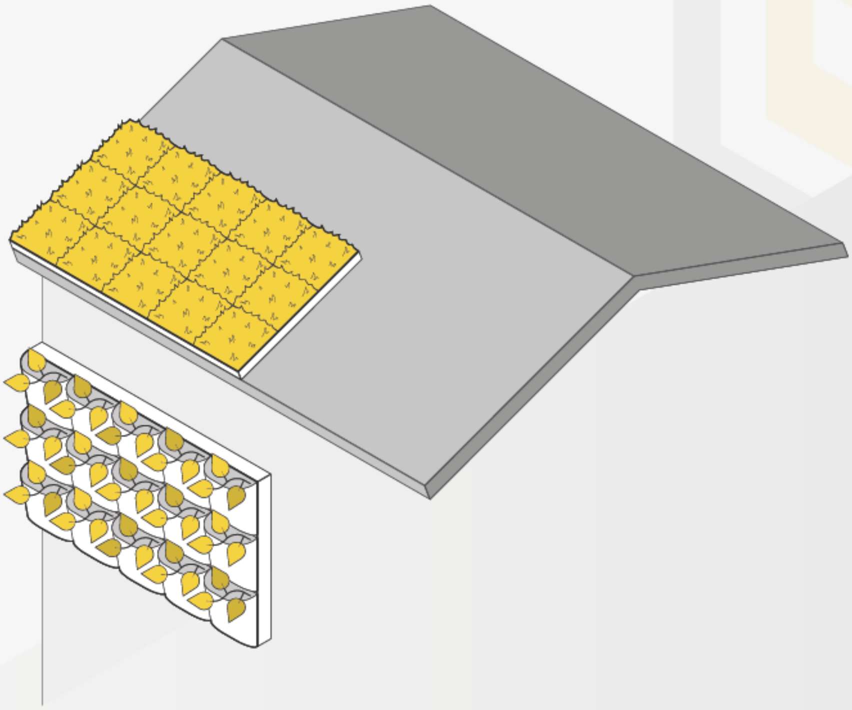
INFINITE
BUILDINGRENOVATION
Industrialised envelope solutions



Greening solutions for industrialised deep retrofit

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Project information

Title: Industrialised durable building envelope retrofitting by all-in-one interconnected technology solutions (INFINITE)

EC Grant Agreement Number: No 958397

Duration: November 2020 until April 2026 (66 months)

Coordinator

Project Partners

About the project

Off-site prefabrication of multifunctional envelopes has been shown to be a technically viable approach to increase rate and quality of deep renovation of residential buildings. However, several barriers are still preventing a massive adoption of prefabricated solutions.

INFINITE aims at boosting the building renovation sector through the so-called "**Renovation4.0**" approach, which leverages on both digitalisation and industrialisation to offer **tailor-made solutions** with a high level of **design freedom**, **decrease retrofit costs and time** thanks to the optimisation of the value-chain and **foster the adoption of eco-compatible long-lasting products** and systems.

To do so, the INFINITE Project relies on three main pillars:

1. cross-fertilisation from digitalisation trends in other markets (i.e. Industry4.0),
2. exploitation of industrial capabilities and coupling with LC-thinking approach
3. experience gained from the 1st generation of multifunctional prefabricated envelopes.

INFINITE promotes a life cycle approach that allows for comprehensive design, optimisation of the operation and maintenance (O&M) and depletion of end-of-life residual value.

INFINITE partners cover the whole renovation value-chain. Together, the INFINITE partners developed a new generation of residential building renovation products and actions centred on the all-in-one industrialised Life-Cycle-based approach. Outputs were:

- a set of multi-user and **multidisciplinary design tools**,
- **process-optimised all-in-one industrialised eco envelope kits**,
- **adaptive control systems**,
- set of **demand- and industry-side matched business models** to show the Renovation4.0 market potential,
- a **structured framework of entities and knowledge** able to clearly and widely demonstrate the Renovation4.0 benefits.

INFINITE unleashed the potential of the renovation industry by increasing the market penetration of sustainable, high-quality and long-lasting building retrofitting products and methods. This ultimately contributes to the decarbonisation of the European building stock.

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1 Executive Summary

This document shows that green solutions (green roofs and green façades) can be successfully integrated into **serial, modular renovation.** For a successful integration, the green solutions with their technical implementation and vegetation requirements need to be included in the planning process from the beginning. The INFINITE project develops **prefabricated all-in-one envelope kits** to reduce energy demand, extend building service life, and shorten renovation time and cost through industrialisation and digitalisation (Renovation 4.0 concept). LCA/LCC integration supports transparent decisions on environmental and economic performance, while the IDR Observatory enables knowledge transfer for scaling.

Urban climate pressures (heat waves, heavy rainfall, sealed surfaces) increase the relevance of building greening as a viable mitigation strategy. Greened façades and roofs contribute to **shading, evapotranspiration cooling, rainwater retention, biodiversity, and air/pollutant filtration**. Where combined with energy systems, greenery can also support overall performance (e.g., microclimatic benefits around PV). (Enzi-Zechner et al., 2025)

INFINITE mock-ups confirmed feasibility and highlighted boundary conditions. At FlexiLab (Aug 2022 – Aug 2024), the wall-bound green façade (GREEN) produced clearly lower surface temperatures than a dark reference cladding (Building integrated solar thermal system (BIST)), consistent with evaporative cooling and shading. The green roof greywater mock-up (Mar 2024 – Mar 2025) demonstrated the technical potential of combining modular roof vegetation with decentralised water management, provided that the treatment/disinfection of the greywater and maintenance of the greening are reliable.

Key implementation barriers were identified: strict weight/thickness limits, irrigation sensitivity in small substrate compartments, dripper clogging, winterisation needs, supply-chain distance and the requirement for year-round maintenance. **These findings underline that success depends on quality of planning, plant selection, resilient detailing and clear operational responsibilities**.

Key Recommendations

1. Apply step-by-step feasibility checks (statics, waterproofing/root resistance, drainage/overflow, roof type/ventilation, access and safety).
2. Prefer prefabrication-compatible systems: wall-bound modular façades and modular green roofs; use climbing plants with trellis as a low-cost option where slower coverage is acceptable; avoid self-climbers on modular joints.
3. Design for resilience: adequate substrate buffering where possible, orientation-specific strategies, freeze protection and drain-down, safe overflow routing.
4. Base plant selection on microclimate (sun, wind, humidity, frost); prioritise native/pollinator-friendly species.
5. Embed maintenance: accessible inspection points, defined routines, more frequent checks in summer. Recommended Austrian Standards are described in ÖNORM L1131, B1131 (yellow pages) and ÖNORM L 1136 (Austrian Standards Institute / Österreichisches Normeninstitut [ON], 2010; Austrian Standards International - Standardisierung und Innovation, Yellow pages, 2021).
6. For greywater irrigation, increase inspections, prevent clogging/biofilms, add outlet sampling, and allow supplementary water in dry periods.

2 Green solutions in serial modular renovation

The INFINITE project focuses on the innovation and development of prefabricated all-in-one technologies for the deep building retrofit. These solutions aim to reduce energy demand during the renovation of building envelopes, while at the same time extending the building's service life and reducing the time and costs required for retrofitting.

The concept is based on the Renovation 4.0 approach, which combines industrialisation and digitalisation to provide customised, environmentally friendly, affordable and cost-effective retrofit solutions for existing buildings. The INFINITE All-In-One kits include Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) analyses at all stages of the refurbishment process. This allows the project to demonstrate both the extended lifespan of buildings and the improved performance of the building envelope.

INFINITE is funded by the European Union's Horizon 2020 research and innovation programme. In addition to developing all-in-one technologies, the project supports the establishment of an Industrialised Deep Retrofit (IDR) Observatory. This platform aims to bring together international experience and knowledge in the field of low-carbon building renovation.

In recent years, nature-based solutions like greening buildings have gained increasing importance across European cities. 91 % of local action plans already include such measures. Rising temperatures and more frequent heavy rainfall events highlight the need for innovative solutions in the built environment. Cities consist of sealed surfaces, limited vegetation and dense population. These conditions contribute to the formation of so-called urban heat islands, especially in densely built-up areas. As another result, rainwater is less easily absorbed, which makes urban areas vulnerable to flooding. (European Environment Agency, 2023)

Nature-based solutions provide a multitude of co-benefits like the protection and enhancement of biodiversity, rainwater retention, air and pollutant filtration, and increased efficiency of photovoltaic (PV) systems when greenery is installed underneath or around them. (Enzi-Zechner et al., 2025; European Environment Agency, 2023) To tackle the climate and biodiversity crisis, 88 research and innovation projects including the implementation of nature-based solutions in different environments were funded by the EU. Examples of projects for nature-based solutions in urban areas are Urban GreenUP, UNaLab, Grow Green or GreenInCities as seen in European Research Executive Agency (2024).

Within the INFINITE project, the goal was to identify green systems for building retrofits that can be combined with prefabricated timber-frame constructions. The project also explored green systems that can be partially assembled in the factory, thereby increasing the potential for industrialised production within the INFINITE GREEN KIT solutions.

In general, several options are available for greening buildings, including ground-based, plant-trough-based, and wall-mounted systems for façade greening, as shown in Figure 1. For green roof solutions, different system depths are available, ranging from extensive (10 cm) to intensive systems (150 cm), as illustrated in Figure 2.

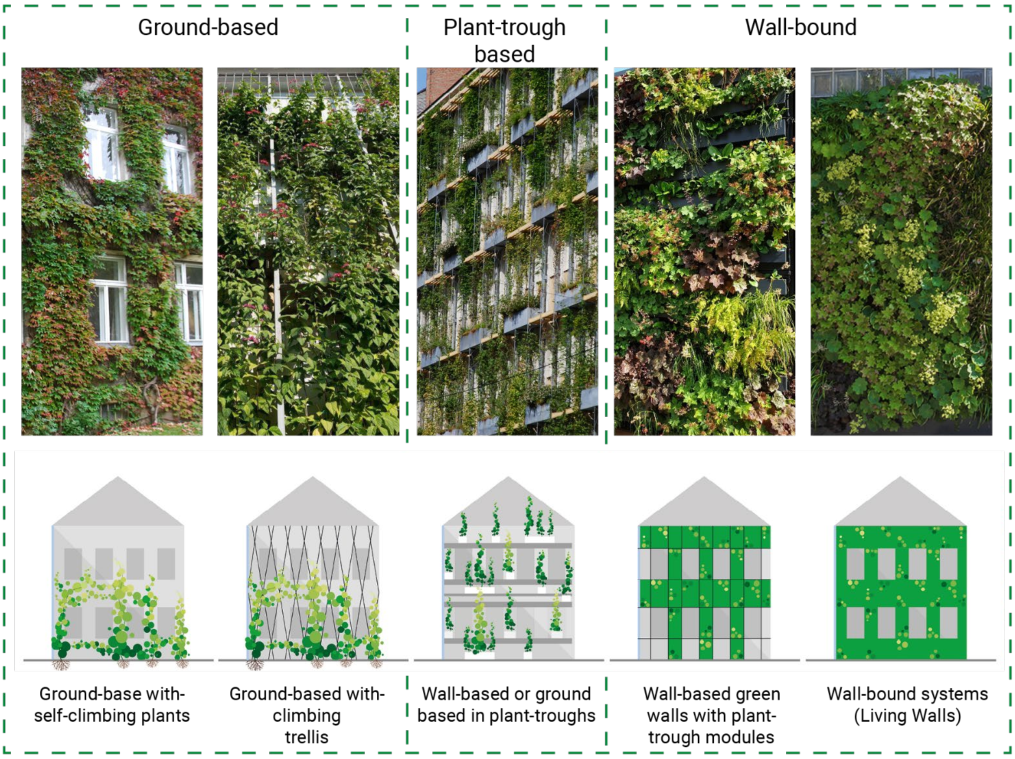


Figure 1: Greening solutions for façade greening of buildings (© GRÜNSTATTGRAU)

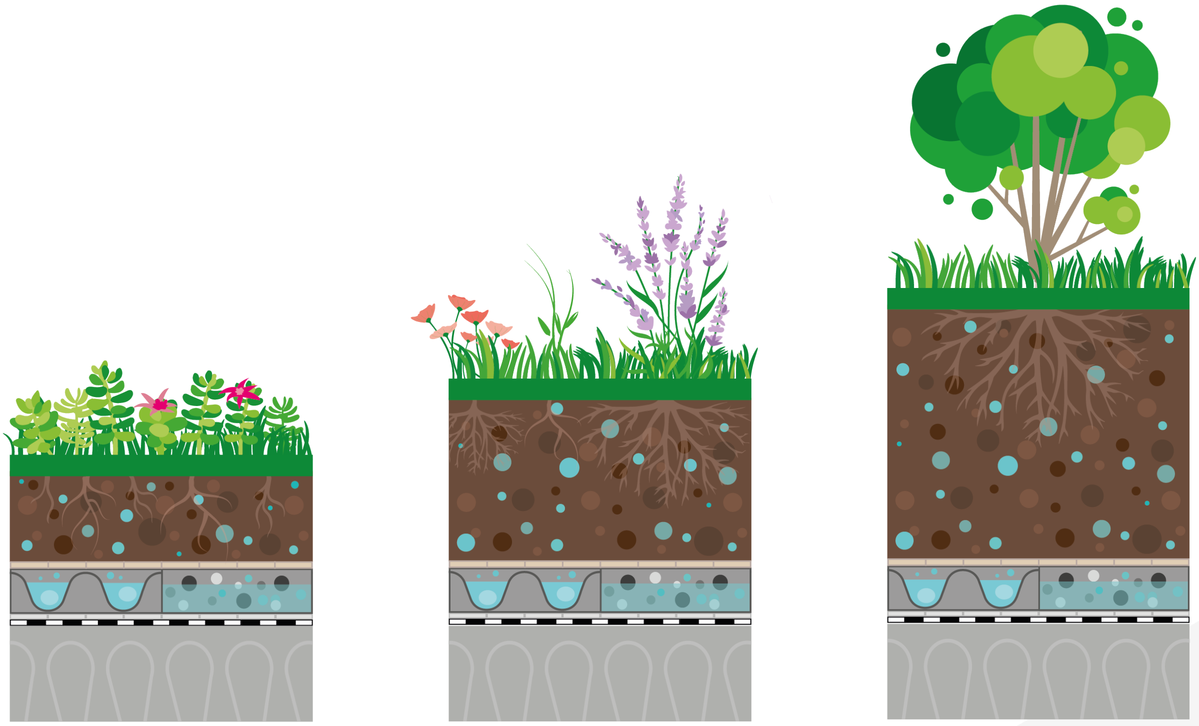


Figure 2: Green roof solutions depending on their substrate height, extensive green roof on the left, reduced intensive green roof in the middle and intensive green roof on the right (© GRÜNSTATTGRAU)

3 Criteria for implementing green solutions during renovation

Green solutions such as green roofs and green façades can provide multiple benefits: they reduce surface temperatures, improve the local microclimate, retain rainwater, support biodiversity, and can increase comfort and quality of life (see Figure 3). Despite these advantages, there is still reluctance to use them in traditional renovations and in serial renovations (renovations using prefabricated building elements) due to lack of knowledge, costs, building owners' scepticism, lack of performance data, etc. Within INFINITE project, has been developed a GREEN KIT based on a series of evaluation and criteria that are described in this chapter.

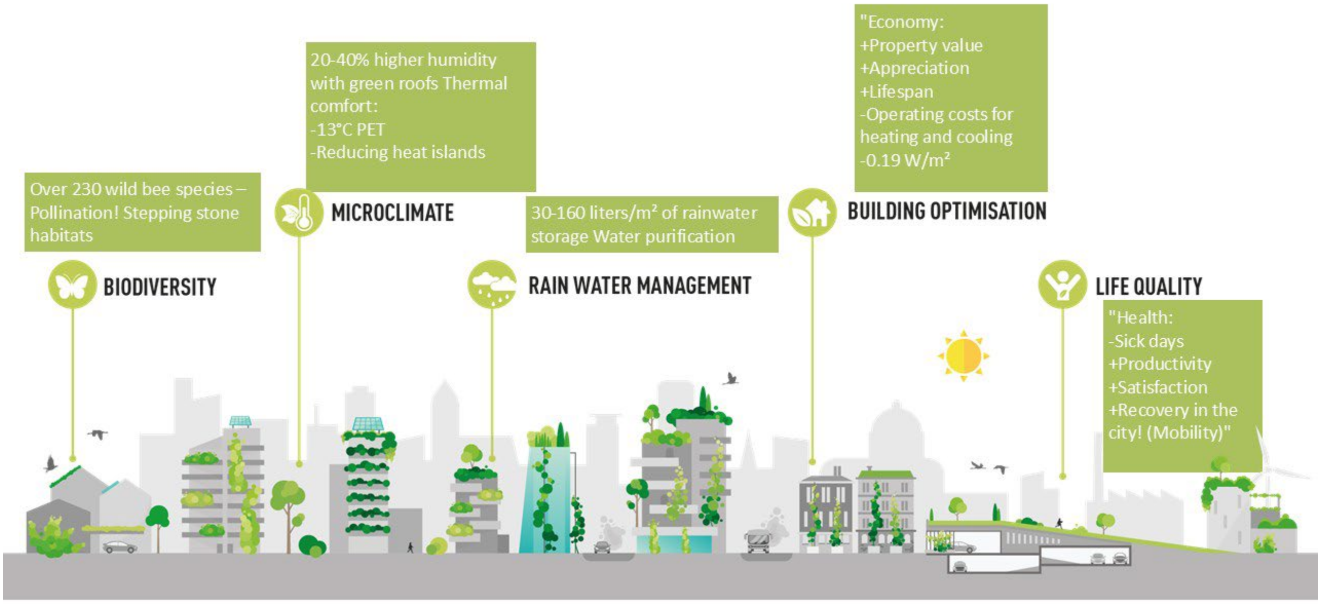


Figure 3: Benefits of green infrastructure (© GRÜNSTATTGRAU)

3.1 Assessment criteria for green roofs and façades

Experience from the INFINITE project shows that green solutions can be combined with prefabricated timber-frame modules. However, they cannot be applied everywhere. For each building, a step-by-step check is needed to decide whether a green roof or green façade is technically feasible and reasonable.

In serial renovation, some parts of the greening system (for example, substructures, planters, or irrigation components) can sometimes be pre-installed off-site in prefabricated elements. This can speed up installation on-site, but it also requires careful planning and quality control.

3.1.1 Criteria for green roofs

Before planning a green roof, the following criteria should be checked.

Structural capacity (statics)

- Load-bearing capacity of the roof
  - A typical extensive green roof (low-growing plants, thin substrate) with 10–19 cm build-up depth (according to ÖNORM B 1131:2026 yellow pages) has an approximate weight of 100–200 kg/m² (depending on water content and system design). (Austrian Standards International - Standardisierung und Innovation, Yellow pages).
  - In general, greater substrate depth allows more plant species to establish and can improve resilience (e.g., drought tolerance), but it also increases weight.

Building physics (roof build-up)

- Thermal insulation and roof type
  - Determine whether the roof is cold, warm, or inverted, and whether insulation is present.
- Moisture management
  - Check if elements such as vapour barriers and rear ventilation are included and compatible with the planned roof design.

Waterproofing and root resistance

- Waterproof and root-resistant layer
  - The area to be greened must be watertight and protected against root penetration.
- Execution
  - Root-resistant waterproofing must be installed by qualified specialists (roofers/waterproofing contractors).

Edges, upstands, and connections

- Upstands and raised waterproofing
  - Waterproofing should be raised at all edges, upstands, and penetrations to protect against water ingress.
  - A common requirement is a minimum upstand height of 15 cm above the vegetation surface (this must be considered early when defining the target build-up height).
- Vegetation-free strips
  - At roof edges, connections, and terminations, 25–50 cm wide vegetation-free strips (e.g., gravel or paving) are typically required for fire safety, drainage control, and maintenance access.

Roof slope (pitch) and shear protection

- Determine roof pitch
  - For roof pitches of approximately 26% to 40%, shear protection is required to stabilise the vegetation layers (according to Austrian regulations).

    - For pitches > 40%, structural shear protection is generally required and must be integrated into the roof system design, including the waterproofing and substrate arrangement.

Drainage

- Drainage concept
    - Existing drainage elements must be assessed (e.g., drains, scuppers).
    - Precipitation, roof pitch, drainage length, and the green roof build-up must be considered to avoid waterlogging and ensure safe runoff.

Irrigation

- Water availability
    - For extensive green roofs, irrigation is usually required mainly during the establishment phase, but a water connection on the roof is recommended to ensure plant survival during heat and drought periods. Intensive green roofs require irrigation through their whole life-cycle.

Roof safety and access

- Safe access and fall protection
    - Maintenance requires safe roof access and fall protection systems (e.g., guardrails or rope safety systems).
    - The green roof build-up can sometimes support the anchoring of safety equipment, but this must be structurally verified.

Site conditions and plant selection

- Microclimate on the roof
    - Plant choice should be based on light conditions (full sun/partial shade/shade), wind exposure, and climatic constraints (e.g., frost at higher altitudes).
- Specific planting requirements
    - If specific goals exist (regional seed mixes, defined colour schemes, biodiversity targets), these requirements should be communicated early to the executing company.

3.1.2 Criteria for green façades

Façade greening also requires a technical pre-check. Key criteria include:

Structural capacity (statics)

- Façade type and load-bearing capacity
    - Identify the façade construction and verify whether it can carry the greening system (including wet substrate, mature plant biomass, and wind loads).
    - Define the type of load bearing to be sure to distribute the weight and to avoid critical point (e.g. punctual or linear anchoring of the façade).

Technical elements and conflicts

- Nearby building services
    - Elements such as ventilation grilles, gutters/downpipes, external shading devices, pipes, outdoor lighting, and signage must be mapped.
    - For climbing plants and support structures, these elements must be protected from entanglement, shading, or mechanical damage.
    - These interfaces must also be included in the maintenance plan.
- Thickness and dimensions
    - Evaluate the overall thickness of the façade in order to be compliant with the maximum thickness allowed by the municipality regulations.
    - Check the distances from other buildings to be compliant with the local regulations.

Façade surface and condition

- Surface properties
    - Dark wall colours or glass surfaces can increase heat loads; this should be considered when selecting climbing plants (heat stress tolerance) and planning distances.
- Condition in renovation projects
    - Existing damage (cracks, holes, unstable layers) must be repaired before greening, especially when the system is attached directly to the façade.

Irrigation and drainage

- Water supply
    - A nearby water connection is required.
    - Automatic irrigation advisable for all kinds of green façade systems.
- Drainage and overflow management
    - For plant-trough-based systems, overflows must be planned so that water does not create hazards on walkways (e.g., slipping risk), and does not damage the building fabric.

3.1.3 Conclusion for renovation planning

In both traditional and serial renovation, green roofs and green façades should be implemented only after verifying structural feasibility, roof/façade build-up compatibility, waterproofing integrity, drainage/irrigation needs, and safe maintenance access. Addressing these criteria early reduces technical risk, improves cost predictability, and increases acceptance among project stakeholders.

4 Methodology for integrating green solutions into an industrial retrofit using modular serial timber-frame constructions

The INFINITE GREEN Kit combines a prefabricated timber-frame retrofit module with either green façade or green roof elements. Because no partner in the INFINITE consortium manufactures green façades or green roofs, the project integrated commercially available systems. Consequently, suitable market solutions were researched, identified, analysed, and compared with respect to their technical compatibility with the timber-frame modules and their suitability for industrialised renovation. Furthermore, the topics on potential for circularity and data for life cycle assessments have been researched and used for the decision-making process.

4.1 Screening and comparison framework

In an initial screening, a broad set of green façade and green roof systems was assessed using four main categories:

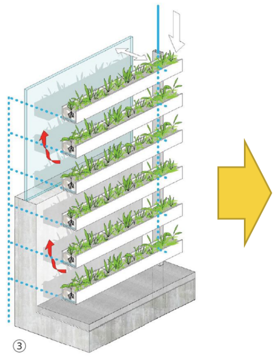
1. **Operation and maintenance (O&M)**
    a. Effort and complexity of routine care, inspection intervals, accessibility, expected maintenance costs, and long-term service requirements.
2. **Integration aspects**
    a. Adaptability to the timber-frame retrofit module, geometric compatibility, required substructures, interfaces (fixings, waterproofing, drainage, irrigation), and impact on façade/roof build-up.
3. **Installation process**
    a. Simplicity of mounting and dismounting, installation time, need for specialised labour, and suitability for prefabrication (division of off-site and on-site activities).
4. **Performance characteristics**
    a. Durability, certifications and compliance, water demand, thermal behaviour, potential for water reuse, and “smart” features (e.g., sensors or control systems).

In addition, the assessment incorporated the INFINITE project drivers (Figure 4), namely:

1. Applicability to **retrofit of existing buildings**
2. Compatibility with **industrialisation and prefabrication**
3. **Cost-effectiveness**, including time and process efficiency
4. **Market readiness** and robustness of the solution
5. **Lifecycle thinking**
6. Eco-design, and **suitability for assembly/disassembly** (including repair and replacement)

INFINITE DRIVERS

Modular – Metallic systems



Living Walls (modular)
(irrigation system necessary, installation according to the principle of a ventilated curtain wall)

Operational and Maintenance ⚠

Advantages:
- Possibility to mount/dismount single elements
- Possibility to have feedback from sensors
- Possibility to fertilize the plants with the irrigation system
- Fully recyclable materials

Disadvantages:
- Movable lift for maintenance in the façade
- Check periodically the irrigation system (pipes - pumps)
- Needs to maintain periodically the plants (cutting/replace) and the overall system (many parts)

Integration aspects ⚠

Advantages:
- Modular elements
- Metallic substructure with many point of anchoring
- Possibility to decide the greening density level?
- Interesting thickness (10-22 cm)

Disadvantages:
- High weight (70-230 kg/sqm)
- Not large availability of smaller or corner elements
- Water pipes in the façade with many “sensitive” points

Installation process

Advantages:
- High level of offsite installation activities
- Easy mounting system -> fast module installation
- Possibility to storage water (include water treatment/BES (?)
- Possibility to have the modules already with plants

Disadvantages:
- Many elements in the façade (modules, pipes, connectors, fixing systems, etc.)
- Needs of an irrigation system with a technical room/space (pipes, pumps, etc.)

Performances

Advantages:
- Some certification from the manufacturer (fire resistance, etc.)
- An almost uniform thermal resistance value (R value)
- Possibility to decide the greening density (flexibility)
- Irrigation and monitoring systems available?

Disadvantages:
- Special care to the humidity control
- If the existing wall load resistance is poor -> less greening density (less module -> less coverage)

Figure 4: Example of a reviewed green wall type and the INFINITE drivers further looked into the advantages and disadvantages of the systems (© Nicole Pfoser: graphic of the Living Wall (modular); adapted with INFINITE Drivers)

4.2 Shortlisting and provider engagement

As a final decision layer, the local conditions of the demonstration building(s) (e.g., structural capacity, geometry, climatic exposure, logistics) were included. Shortlisted providers were contacted to obtain additional technical documentation and implementation details, with the aim to:

- identify barriers and limitations,
- clarify interfaces with the INFINITE kit,
- verify performance claims and certification status,
- assess supply capacity and interest in cooperation.

Providers who responded with detailed information were considered for the final selection.

4.3 Technical boundary conditions for the INFINITE GREEN FAÇADE KIT

Based on the constraints of the prefabricated timber-frame base module and typical limits of existing buildings, key technical requirements for façade systems were defined:

- **Maximum saturated weight**: 75–85 kg/m² (depending on the existing building); systems below 40 kg/m² were considered particularly favourable.
- **Maximum total system thickness**: 130–150 mm.
- **Supply chain feasibility**: production facilities or partners preferably close to the demo site(s), and the ability to supply multiple EU countries.
- **Material sustainability**: preference for systems with components that can be reused, recycled, or replaced.

Façade candidates then underwent additional comparison rounds focusing on weight, materials, costs, irrigation demand, maintenance activities, dimensional constraints, and fire behaviour.

4.4 Technical boundary conditions for the INFINITE GREEN ROOF KIT

For roof systems, the detailed analysis identified the following key constraints:

- **Prefabrication potential** and fast, simple installation.
- **Maximum saturated weight**: approximately 100 kg/m², preferably lower.
- **Material sustainability**: reuse and recycling potential of components.
- **Minimum substrate height**: 8 cm.
- **Supply chain feasibility**: production close to demo sites where possible, and capacity for multi-country EU supply.

Selected green roof candidates were analysed in further comparison rounds to ensure that critical aspects and possible conflicts at interfaces (e.g., drainage, waterproofing, transport, and mounting) were fully evaluated in combination with the INFINITE prefabricated façade approach.

4.5 Final selection and validation through mock-ups

Systems were selected based on (1) compatibility with the INFINITE prefabricated timber-frame module and (2) alignment with the INFINITE drivers. The selected solutions were then implemented in mock-ups to validate the combined system under realistic conditions. These mock-ups served as a practical verification step before installing the INFINITE GREEN Kit on the demonstration buildings.

5 General description of the INFINITE GREEN Kit and its main features

Within the INFINITE project, five prefabricated “all-in-one” construction kits for building envelopes are being developed for industrialised renovation. These kits are tested first in full-scale mock-ups and then on existing buildings requiring refurbishment at several locations across Europe. The systems are additionally monitored during operation to assess performance over time and to evaluate how different climatic conditions influence their behaviour. The overall objective is to upgrade existing buildings towards a zero-energy performance level by using these integrated, prefabricated envelope solutions.

Core concept: modular prefabricated timber-frame envelope

The INFINITE approach is based on a modular timber-frame construction that is installed on the external envelope of existing buildings. By adding a high-performance layer outside the building, the system aims to:

- improve energy efficiency and indoor comfort, and
- reduce renovation time and costs through prefabrication and streamlined installation.

Integrated components (technology options)

Depending on project requirements, each prefabricated module can integrate one or more technical components, including:

- **GREEN**: environmentally friendly envelope solutions such as **green façades and green roofs**
- **Energy and fresh-air distribution system**
- **Intelligent windows/glazing**
- **BIPV**: building-integrated photovoltaic system
- **BIST**: building-integrated solar thermal system
- **BIM**: Building Information Modelling as the digital backbone for design and coordination
- **Customisable BMS:** building management system for monitoring and control

Digital planning and decision support

The design and planning of the construction kits are supported by a **multi-user BIM platform** with dedicated plug-ins for:

- **LCA** (life cycle assessment) and **LCC** (life cycle costing),
- **energy and comfort** evaluation,
- **Installation,** and
- **operation and maintenance** (O&M) planning.

This digital framework is intended to improve coordination among stakeholders, reduce planning errors at interfaces, and support decisions that enhance both environmental and economic performance over the building life cycle.

5.1 Green façade kit

Within the INFINITE project, several vertical greening approaches were analysed with regard to their suitability for prefabrication and integration into the modular timber-frame retrofit system. The assessed options included ground-based greening, plant-trough-based systems, and wall-bound systems. For industrialised renovation, the highest prefabrication potential was identified for wall-bound systems, followed by climbing plants combined with a trellis.

Two options were excluded at an early stage due to technical risks in retrofit applications:

- Ground-based systems with self-climbing plants were overruled because adhesive organs (e.g., rootlets or holdfasts) may penetrate joints and small gaps between retrofit modules and potentially damage façade surfaces over time.
- Plant-trough systems with large integrated troughs at different heights on the façade were excluded because they can create high point loads, which may be critical when attaching prefabricated kits to existing buildings with limited structural reserves.

5.1.1 Wall-bound façade greening

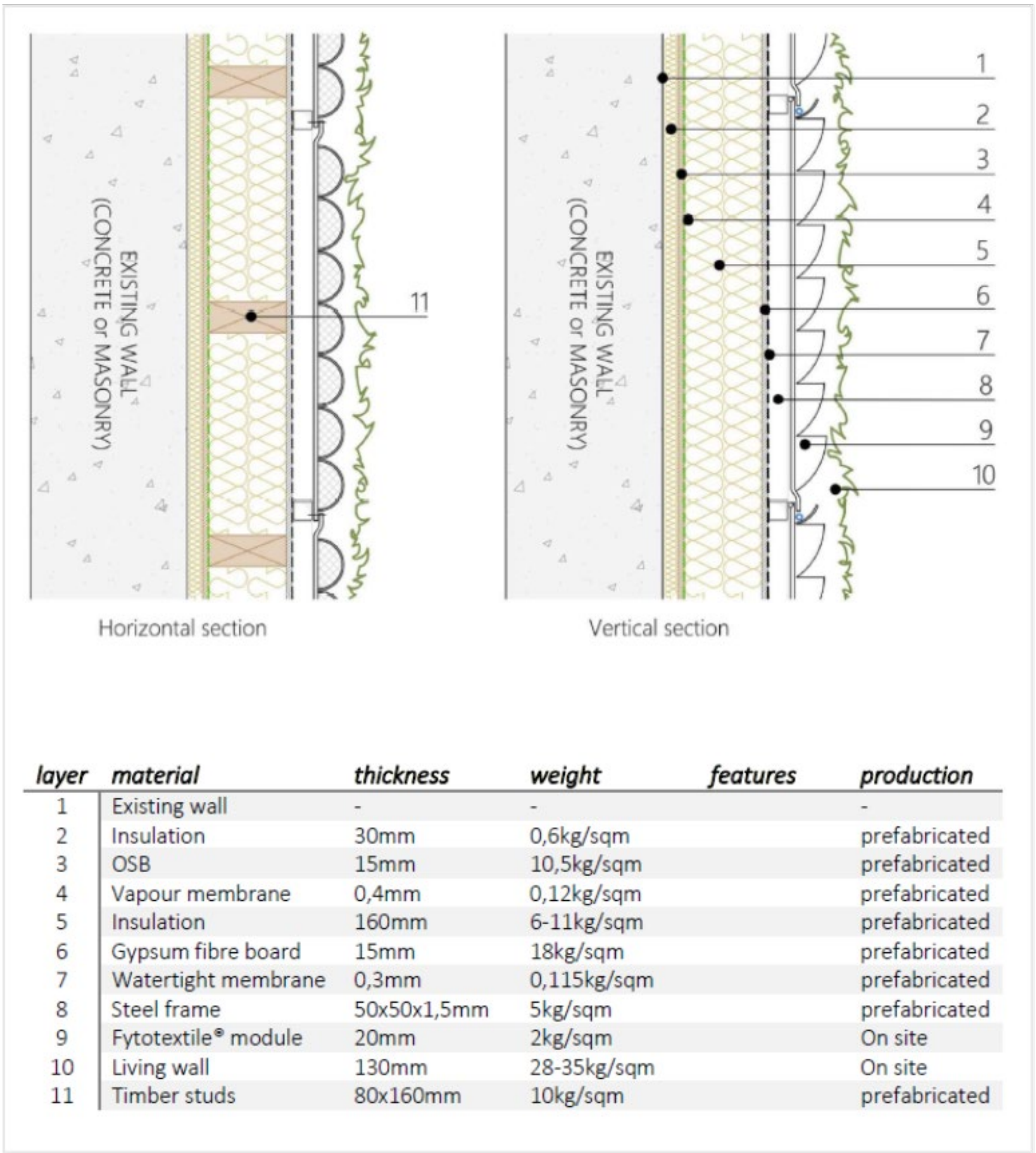
Wall-bound greening can be implemented in two main ways:

1. Wall-based green walls using modular trough or planter elements fixed to the wall, and
2. Living wall systems, i.e., wall-bound systems where plants grow in a continuous support layer (often textile- or panel-based).

Following the selection criteria of the INFINITE GREEN Kit—particularly the strict constraints on weight for retrofit applications—textile-based living wall systems were prioritised. For the INFINITE mock-up, a fleece (fabric) system was selected (see Figure 5). At this stage of the project, it is important to note that several alternative façade greening solutions that may be more robust, less expensive, or potentially more durable could not be considered further because they exceeded the allowable weight limits.

The selected living wall concept consists of textile modules shaped into pockets. These pockets are filled with substrate and planted with vegetation. Water supply is ensured through an automated irrigation system. The textile modules are mounted on steel profiles, which form the interface for attachment to the prefabricated timber-frame modules.

For the GREEN kit mock-up, the system provider Terapita Urbana was selected. The system is modular, which supports prefabrication and simplifies integration with the timber-frame construction. Due to the textile-based structure, the system has low weight and limited thickness, which is advantageous for retrofit conditions.



layer	material	thickness	weight	features	production
1	Existing wall	-	-		-
2	Insulation	30mm	0,6kg/sqm		prefabricated
3	OSB	15mm	10,5kg/sqm		prefabricated
4	Vapour membrane	0,4mm	0,12kg/sqm		prefabricated
5	Insulation	160mm	6-11kg/sqm		prefabricated
6	Gypsum fibre board	15mm	18kg/sqm		prefabricated
7	Watertight membrane	0,3mm	0,115kg/sqm		prefabricated
8	Steel frame	50x50x1,5mm	5kg/sqm		prefabricated
9	Fytotextile® module	20mm	2kg/sqm		On site
10	Living wall	130mm	28-35kg/sqm		On site
11	Timber studs	80x160mm	10kg/sqm		prefabricated

Figure 5: Green wall data sheet, based on the GREEN kit with Terapia Urbana solution. (© Rubner)

5.1.2 Climbing plants with trellis structures

Climbing plants supported by a trellis represent a potentially lower-cost alternative to wall-bound living walls. In many cases, this approach can reduce costs by minimising technical equipment requirements (e.g., fewer irrigation components and less complex support layers).

Climbing plant systems are attractive within INFINITE because they can offer low operational effort and comparatively low maintenance, depending on plant selection and site conditions. Suitable species depend on local climate, façade orientation, exposure (sun and wind), and the intended visual effect.

Climbing plants can be implemented (as seen in Figure 7) as:

- **Ground-based systems**, where plants root in open soil at the base of the building. This option provides the root system with more volume, can enable greater vertical growth, and may reduce or eliminate irrigation needs once plants are established.
- **Plant-trough-based systems**, where plants grow in planters. This is relevant where soil is not available (e.g., sealed surfaces around buildings) or where greening is required at different façade heights.

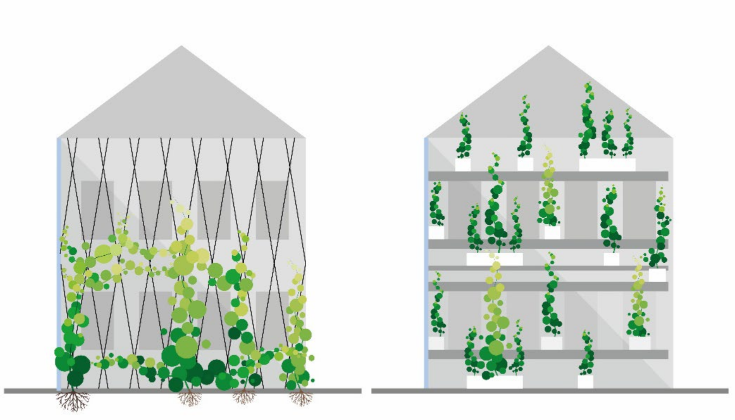


Figure 6: Schematic representation of ground-based or plant-trough-based greening systems © GRÜNSTATTGRAU

Plant-troughs can accelerate visible greening because plants can be positioned higher on the façade (as seen in Figure 7), reducing the time needed to reach a target coverage height. However, plant-trough-based solutions increase point loads and therefore may not be suitable for all buildings targeted for renovation—particularly within a prefabricated retrofit concept.

Figure 7: Example of plant-trough-based façade greening system with climbing trellis © Weiss-Tessbach

Despite their advantages, climbing plant systems also have limitations for industrialised renovation. Prefabrication potential is lower because plant establishment and growth depend on time and site conditions, and the system cannot provide immediate full façade coverage. As a result, an additional background cladding is typically required behind the trellis, at least during the establishment period. Furthermore, climbing plant systems can be constrained by limited attainable height, depending on species, support design, and maintenance strategy. Within the INFINITE project, the implementation of climbing plant systems has been discussed, however, this potential solution hasn't been designed, build or tested, since the green façade kit was focussed on wall-bound-greening-solutions.

5.2 Green roof kit

Based on the selection criteria described in Chapter 3, three green roof typologies were identified as suitable candidates for integration into the INFINITE kit:

- **Modular green roofs**
- **Sedum mats**
- **Solar green roofs** (combined PV + green roof)

In general, a green roof consists of several functional layers, typically including vegetation, substrate (growing medium), filter fleece, a water storage and/or drainage layer, a protection layer, a root-resistant waterproofing layer, and a structurally suitable roof build-up (see Figure 8). The exact configuration depends on roof type, structural capacity, and climatic conditions.

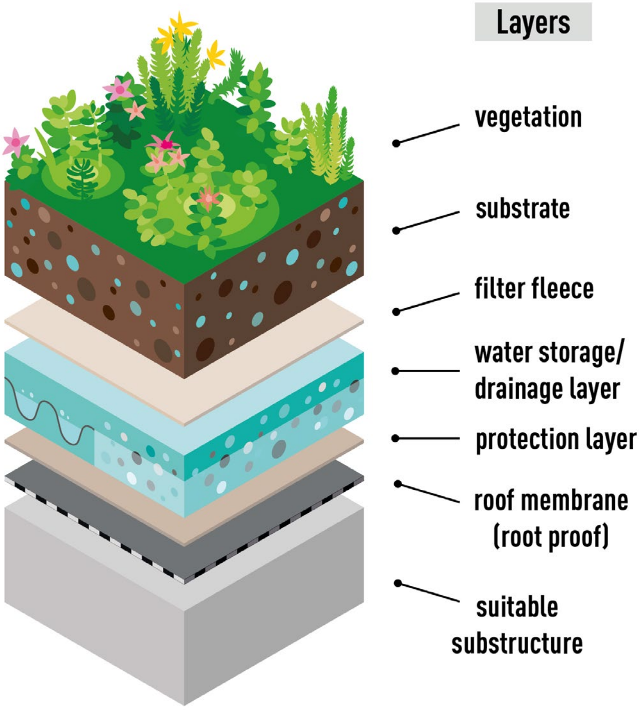


Figure 8: Green roof layers (© GRÜNSTATTGRAU)

5.2.1 Modular green roofs

Modular green roofs consist of preformed cassettes or trays that are filled with substrate and planted vegetation. The modules are typically laid directly onto a root-resistant waterproofing membrane (with the required protection and drainage layers depending on the system design). A major advantage is the immediate green appearance after installation, because the vegetation is usually pre-grown.

Among the assessed technologies, modular systems offer the highest potential for off-site prefabrication, as multiple green roof functions are combined within a single element. Vegetation is cultivated by horticultural or landscaping companies before delivery. To support successful establishment, it is beneficial if plants are pre-grown under climatic conditions similar to those at the installation site (ideally in facilities close to the region of the project).

Modular green roofs often show comparatively low saturated weight relative to more intensive systems and are therefore suitable for retrofit applications where structural reserves are limited. Module dimensions are typically standardised; however, modules can be cut or adapted around roof penetrations and details, allowing adjustment to roof geometry.

Regarding material sustainability, trays are frequently manufactured from recycled plastics (e.g., HDPE and related polymers) to achieve sufficient mechanical strength and durability. Some modular systems can also incorporate additional rainwater retention elements, which increase temporary storage and can delay runoff peaks during heavy rainfall events.

5.2.2 Sedum mats

Sedum mats (also referred to as sedum carpets) represent a lightweight, shallow, and low-maintenance green roof solution. They consist of pre-vegetated mats—often made of woven fibres—cultivated with established sedum species. On site, the mats are placed on top of a green roof build-up that typically includes substrate, with filter fleece and drainage below.

The pre-grown vegetation provides an immediate green surface after installation. However, while sedum mats represent a high degree of prefabrication for the vegetation layer, other roof layers (e.g., waterproofing, protection, drainage, substrate) still need to be installed step-by-step on site.

From a circularity perspective, sedum mats are often produced using woven structures that combine synthetic and organic fibres, which can complicate disassembly and recycling. For this reason, systems using biodegradable meshes (e.g., coconut fibre) are generally preferable when end-of-life recovery is a key objective.

5.2.3 Solar green roofs

Solar green roofs combine the functions of photovoltaic (PV) electricity generation with benefits of green roofs such as biodiversity support and rainwater retention. In a typical configuration, PV mounting frames are positioned above the green roof build-up (as seen in Figure 9), and the system uses ballast (often substrate and vegetation layers) to resist wind loads. This ballast principle can reduce or avoid the need to penetrate the roof membrane for anchoring, thereby lowering waterproofing risks.

Prefabrication potential is more limited for solar green roofs compared to modular green roofs, because both the green roof build-up and the PV installation are largely executed on site and require careful coordination. Maintenance planning is essential to ensure that vegetation does not shade the PV modules and reduce electricity yield; therefore, regular inspection and vegetation control is required.

Instant full-area greening is not always achievable if seeding is used, because vegetation requires time to establish. Faster visual coverage can be achieved by using pre-grown vegetation elements (e.g., mats or plant modules) in the areas under and around the PV structures.

PV and green roofs can be combined either by:

- arranging PV and vegetation zones side-by-side, or
- elevating PV modules (commonly ~30 cm above the vegetation layer) to allow plant growth and maintenance access.

An additional combined concept is the use of walkable pergola structures equipped with (semi-) transparent PV modules, integrated with greening (e.g., green roof surfaces or planting troughs). While pergolas have a long history as shading elements, PV pergolas adapt this typology to current energy and climate needs. In dense urban contexts, such systems can provide shaded outdoor spaces that support social use while contributing to energy generation and urban greening objectives.

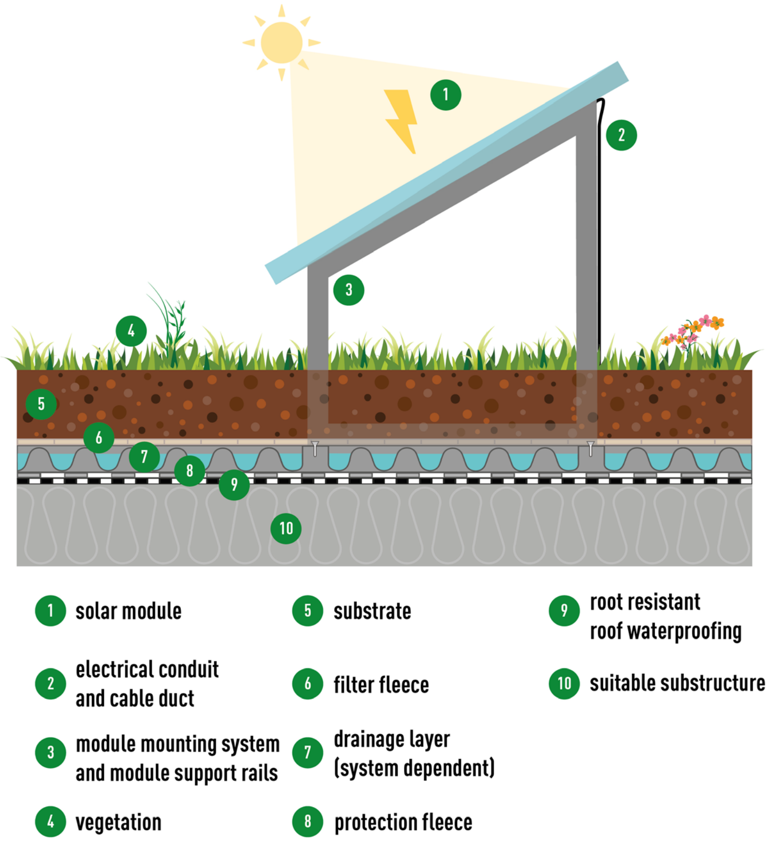


Figure 9: Solar green roof (© GRÜNSTATTGRAU)

6 Mock-ups and results of the GREEN INFINITE KIT

A large share of the European building stock has insufficient thermal insulation and therefore requires substantial energy input to maintain comfortable indoor temperatures throughout the year. (INFINITE Building Renovation) In this context, Amann (2022) used scenario-based modelling to show that increasing the renovation rate from approximately 1.5% (as of 2022) to 2.8% starting in 2030 could enable refurbishment of the thermally inadequate building stock by 2040. Combined with a transition to renewable energy sources, such a renovation pathway could also support the decarbonisation of the building sector by 2040.

The EU Horizon 2020 project INFINITE addresses this challenge by developing prefabricated, all-in-one construction kits intended for the rapid, industrialised renovation of existing buildings.

Mock-up approach within INFINITE

Within the INFINITE project, two GREEN-related mock-ups were implemented and tested:

- a façade mock-up to validate the integration and operation of the green façade solution, and
- a green roof mock-up focusing primarily on the integration of a greywater system.

In INFINITE, mock-ups (full-scale test models) were developed for all construction kits and installed at dedicated test facilities to enable controlled evaluation before deployment at demonstration buildings.

Façade mock-up: living wall integration and monitoring

Within the INFINITE project, the options for the combination of green solutions and modular timber-frame-constructions have been analysed according to the currently available solutions on the European market and the applicable Austrian standards. Since the locations of the mock-ups and the demo buildings are not within Austria, the used green solutions aren’t conformed according to the Austrian Standards for green façade systems (ÖNORM L1136).

For the mock-up the environmentally friendly building envelope solution implemented as the Living Wall System was the Fytotextile® solution developed by Terapia Urbana. This green façade system was tested as part of a larger façade prototype installed at FlexiLab, Eurac Research’s open-air laboratory facility (see Figure 10). The façade prototype combined the prefabricated timber-frame retrofit construction with selected INFINITE kits (GREEN (greening solution), BIPV (building integrated photovoltaic), and BIST (building integrated solar thermal solution).

To assess operational performance, the installation was equipped with multiple sensors and monitored from August 2022 until August 2024. The monitoring programme includes measurements of:

- temperature,
- humidity,
- air velocity,
- water consumption (irrigation demand), and
- PV electricity production (for the BIPV elements).

The GREEN façade tests addressed four main objectives:

1. Demonstrate feasibility of integration into the prefabricated façade system, considering both off-site preparation and on-site installation.
2. Evaluate operational performance for two façade orientations (south and east), using a shared irrigation concept.
3. Collect environmental data in the ventilated rear layer of the façade (temperature, humidity, air speed) and compare these conditions with other façade typologies.
4. Assess potential benefits of green cladding relative to conventional passive façade claddings (e.g., with respect to microclimatic effects and surface temperature behaviour).

Figure 10: Mock-up "FlexiLab" (© Eurac Research)

Green roof mock-up: greywater integration

Although the initial plan was to install the green roof mock-up at the INFINITE demonstration sites and at Eurac Research, the system was ultimately implemented at LEITAT facilities. This decision was primarily driven by practical considerations: greywater could be accessed and managed more easily at this location without imposing additional costs or operational burdens on building owners.

The Leitat site also enabled more controlled test conditions and ensured a reliable greywater supply, which supported stable system operation and facilitated consistent monitoring of the water regeneration and reuse performance of the integrated greywater concept. This is presented in Figure 11.

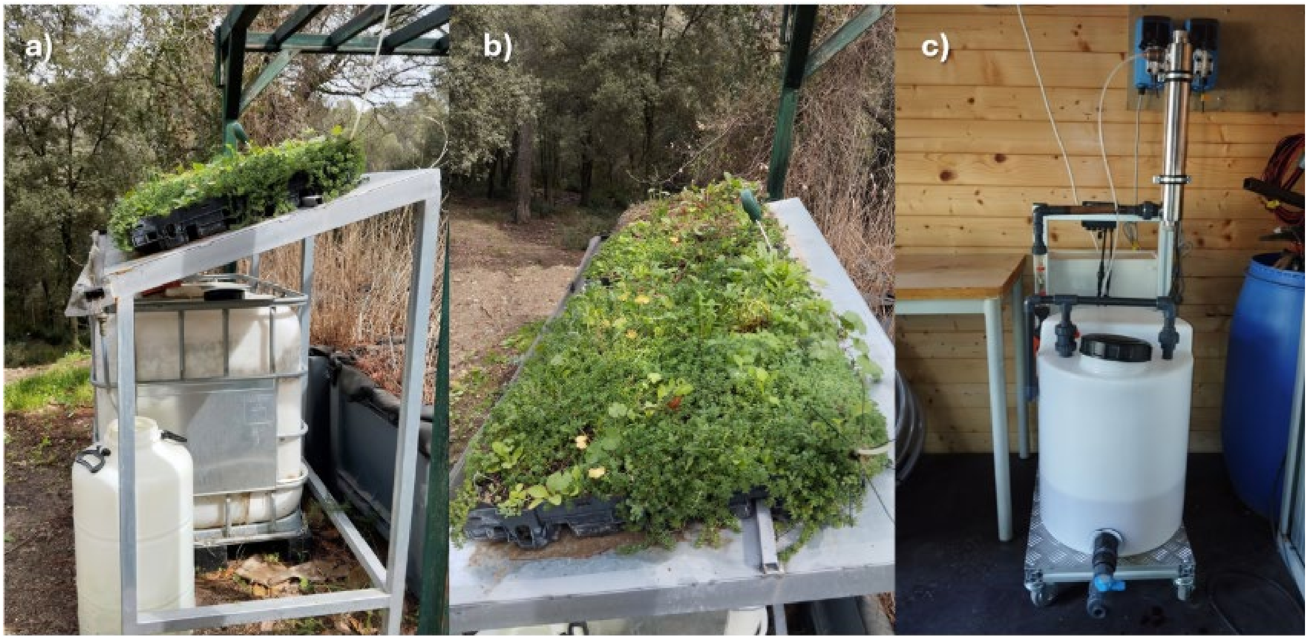


Figure 11: INFINITE Green roof set up. a) artificial roof with the modules above and the collection tank below. b) modules with sedum plants. c) disinfection UVC lamp and collection tank below. (© LEITAT)

6.1 Green façade: Experimental Investigation of Ventilated Façade Performance

The outdoor laboratory facility 'FlexiLab' at Eurac Research was developed to conduct comprehensive functional and performance evaluations of prefabricated façade systems under real environmental conditions. The monitoring campaign spanned two years, from August 2022 to August 2024, enabling long-term assessment of installation processes, operational behaviour, and maintenance requirements.

Research Objectives

The experimental program aimed to:

- Evaluate installation processes, connection details, and overall aesthetic quality.
- Monitor real environmental performance of three different prefabricated façades with varying cladding systems.
- Assess the thermal and humidity behaviour of rear ventilation cavities across different cladding types.
- Evaluate the efficiency of Building-Integrated Photovoltaic (BIPV) panels in five different colours.
- Analyse the performance of green living façades in two orientations (south and east)
- Conduct comparative analysis of different façade solutions.

Measurement Parameters

The monitoring system recorded the following parameters:

- Temperature profiles: rear ventilation cavity (CAV), timber frame surface (WS), and cladding backside (BC)
- Relative humidity and air velocity within the ventilation cavity (CAV)
- Water consumption and precipitation data for the green façade system
- Solar radiation incident on façade surfaces (pyranometer)
- Ambient environmental conditions: temperature (T) and relative humidity (RH) via weather station

A comprehensive scientific paper detailing the complete methodology and results for all rear-ventilated cladding systems is currently in preparation. This chapter presents a focused summary of the main findings, emphasizing the performance of green living façade elements.

Data Analysis Approach

The evaluation synthesized both daily profiles and annual cumulative data, with particular emphasis on comparing the GREEN façade against the BIST (solar thermal) façade. The BIST panels served as a reference representing typical "black" cladding behaviour.

Experimental Configuration

The study compared two distinct ventilated façade configurations:

1. **BIST façade**: Solar thermal panel cladding
2. **GREEN façade**: Living green module cladding

Instrumentation and Sensor Layout

A comprehensive sensor network was deployed within the ventilated cavity, distributed both vertically and horizontally to capture spatial variations. The measurement points recorded:

- Air temperature and relative humidity within the ventilation gap
- Air velocity through the cavity
- Surface temperatures on the cladding backside (BC) and timber wall exterior layer (WS)

Sensors were positioned identically on both BIST and GREEN façades to ensure comparable measurements. An outdoor weather station provided continuous monitoring of ambient air temperature, relative humidity, wind conditions, and solar irradiance. The complete sensor arrangement is illustrated in Figure 12.

This experimental setup enabled direct comparison of thermal and moisture control performance between the two façade types under identical environmental conditions.

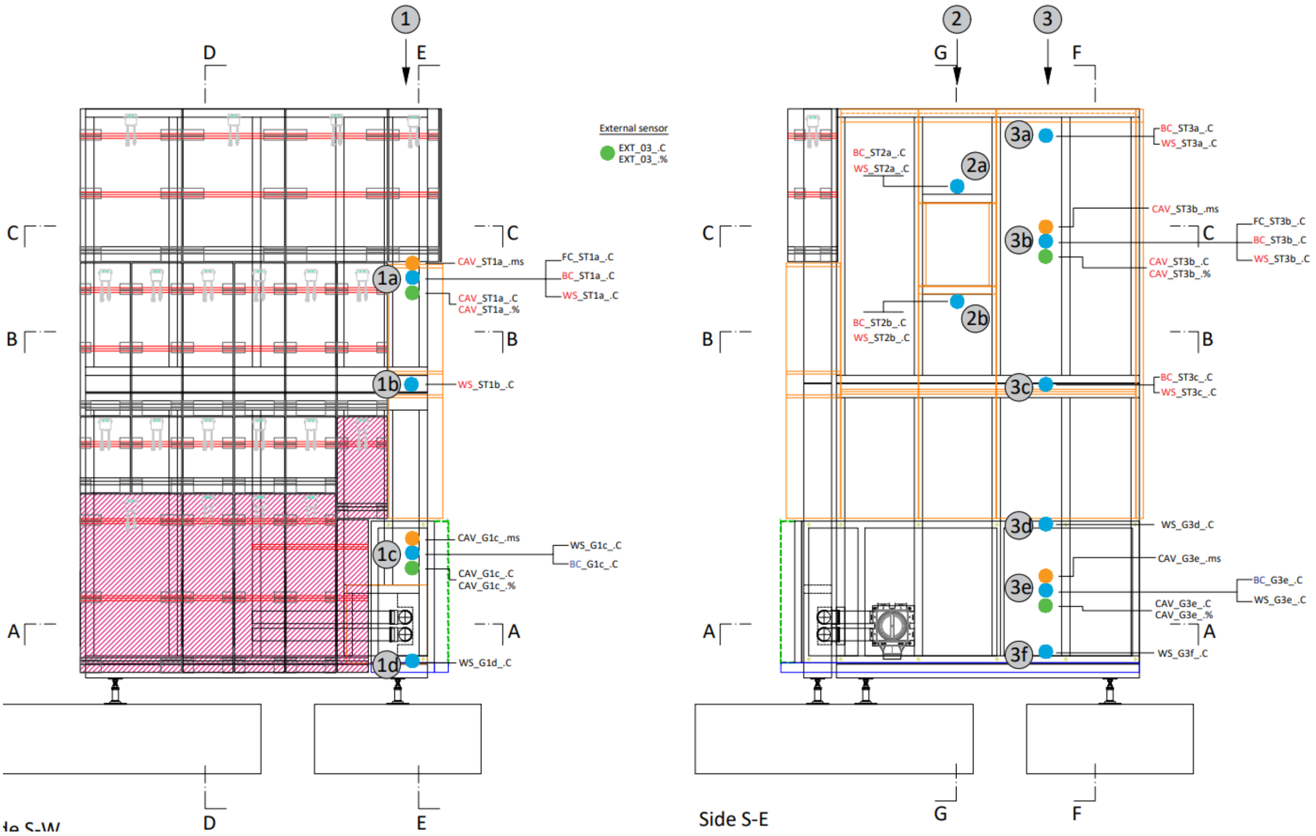


Figure 12: Sensor's layout and positioning in the vertical elevation - 1 and 3 are related to the data reported (© Eurac Research)

Measurement Locations

For each façade configuration, temperature profiles were analysed at three representative positions within the wall assembly:

- **WS (Wood Structure)**: External surface of the timber frame wall
- **CAV (Cavity Air)**: Mid-depth of the ventilated air cavity
- **BC (Back Cladding)**: Interior surface of the external cladding

The following sections present the principal results, acknowledging that certain limitations and boundary conditions with minimal impact on overall trends are not detailed here.

6.1.1 Results and Discussion

The following section introduces the principal results and discussion arising from the monitoring campaign of the façade configurations. Temperature profiles were systematically evaluated at three key positions within the wall assembly—namely, the external surface of the timber frame (WS), the mid-depth of the ventilated cavity (CAV), and the interior surface of the external cladding (BC). These measurement locations were selected to capture the thermal behaviour of the wall assemblies under varying environmental conditions. The analysis focuses on comparing the performance of the GREEN and BIST façades, particularly in terms of their ability to moderate surface and internal temperatures during peak summer periods.

Initial findings reveal marked differences in thermal response between the two façade types. Notably, the GREEN façade consistently achieved significantly lower surface temperatures compared to the BIST system, with reductions of up to 11°C on the south timber frame surface and up to 18°C on the backside of the cladding. Furthermore, a distinctive phenomenon was observed where the GREEN façade's surface temperature frequently remained below the ambient air temperature during daytime, underscoring the efficacy of evaporative cooling inherent to living façades.

While these results provide valuable insights into the comparative performance of the façade systems, it is important to acknowledge certain limitations and boundary conditions inherent to the experimental setup. These include potential variations in local microclimate, the absence of a conditioned room on the back of the mock-up and the specific characteristics of the test facility. Nonetheless, the main trends identified offer a robust basis for further discussion regarding the implications and potential applications of advanced living façade technologies.

Peak Summer Temperature Performance

Figure 13 presents surface temperature variations recorded on the hottest day of the monitoring period. Significant temperature differences were observed between the GREEN and BIST façades:

Timber frame surface (WS) temperature differentials:

- South façade: up to 11°C lower for GREEN versus BIST
- East façade: up to 10°C lower for GREEN versus BIST

Cladding backside (BC) temperature differentials:

- South façade: up to 18°C lower for GREEN versus BIST
- East façade: up to 14°C lower for GREEN versus BIST

External air temperature (Temp_Ext) and incident solar irradiance (IRR_EXT) are included as reference parameters for comparative evaluation.

A notable phenomenon was observed for the GREEN façade: surface temperatures frequently remained below ambient air temperature during daytime hours, as indicated by the 'Temp_EXT' reference line in Figure 13. This behaviour demonstrates a significant departure from conventional "black cladding" performance typified by the BIST system, highlighting the evaporative cooling effect of the living façade.

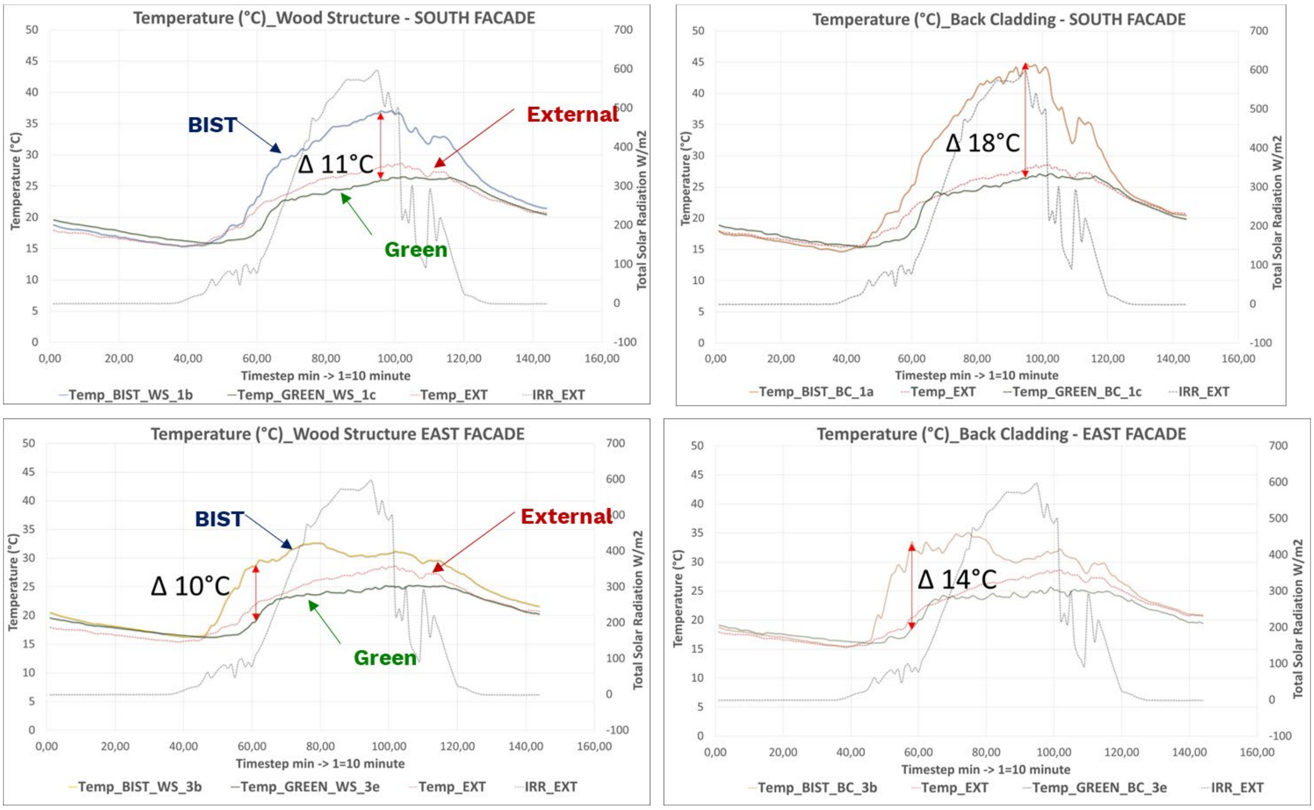


Figure 13: South- and east-facing daily temperature changes of the surface temperature on the timber frame structure (WS - Wood structure) and the back of the curtain wall (BC - backside cladding), as well as the outside air temperature (© Eurac Research)

Annual Hygrothermal Performance Analysis

Figure 14 and Figure 18 examine the frequency and magnitude of conditions where cavity parameters exceeded external environmental values (i.e., cavity temperature > external temperature and cavity relative humidity > external relative humidity). Comparison of the BIST and GREEN systems revealed substantial performance differences across orientations and measurement positions.

Cavity thermal and humidity comparison (first graph, Figure 14):

The cavity (CAV) temperature and relative humidity data for both systems showed marked differences:

- GREEN cavity conditions compared to the BIST: 45% and 57% of hours exceeded external temperature and humidity, respectively.
- BIST cavity conditions: Substantially warmer and drier than GREEN throughout the year.
- BIST backside temperature exceeded external conditions 83% of the time.
- GREEN backside temperature exceeded external conditions only 38% of the time.

These data indicate that the GREEN façade maintains a significantly cooler and more humid microclimate in the ventilation cavity compared to the BIST system.

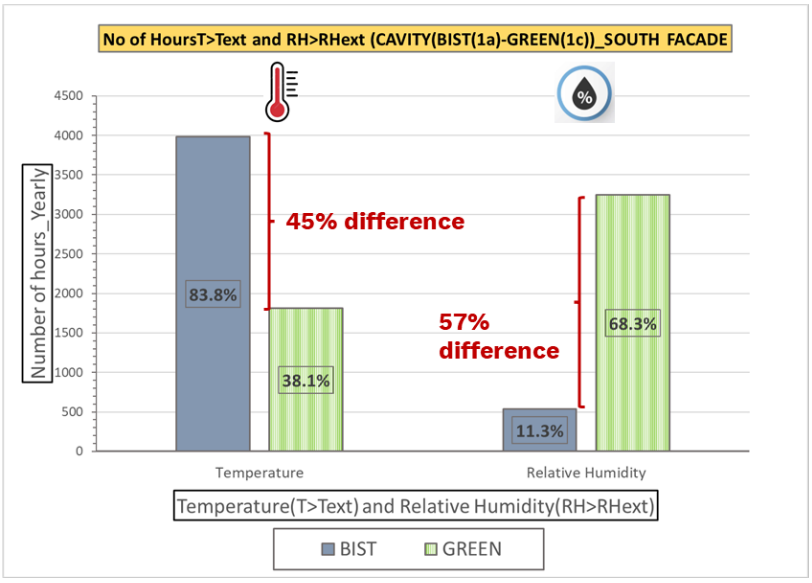


Figure 14: Number of hours that the registered cavity air Temperatures and relative humidity are higher than reference air temperature and the related differences between these data behind the GREEN and the BIST (© Eurac Research)

To understand the air properties in the air cavity between the cladding and the timber frame construction better, the Figure 15 has been created. The Figure 15 shows a representative hot summer day and the trend of the absolute humidity within the air cavity behind the GREEN and the BIST-cladding. For this graph, the data of the south façade has been used. Throughout the night, the air cavity behind the GREEN and the EXTERNAL weather data show similar absolute humidity that is slightly higher than the BIST. The graphs of GREEN and BIST absolute humidity align during the sunrise in the morning between 8 am and 11 am, as well as after the sunset after 6 pm. Throughout the day, while the BIST air cavity rises to an air temperature up to 41 °C, the GREEN stays below 27 °C. This is a difference of up to 14 °C. During this time, the GREEN absolute humidity shows a higher humidity than the BIST. This connected with the evapotranspiration process of the green wall, which also leads to a cooler air temperature and shows that the GREEN solution doesn't heat up as much as the BIST-cladding. The drop in humidity during the day is connected to a local weather event, which lasts for the shown date. An overall increase in humidity can be again seen in the following graphs (Figure 16, Figure 17).

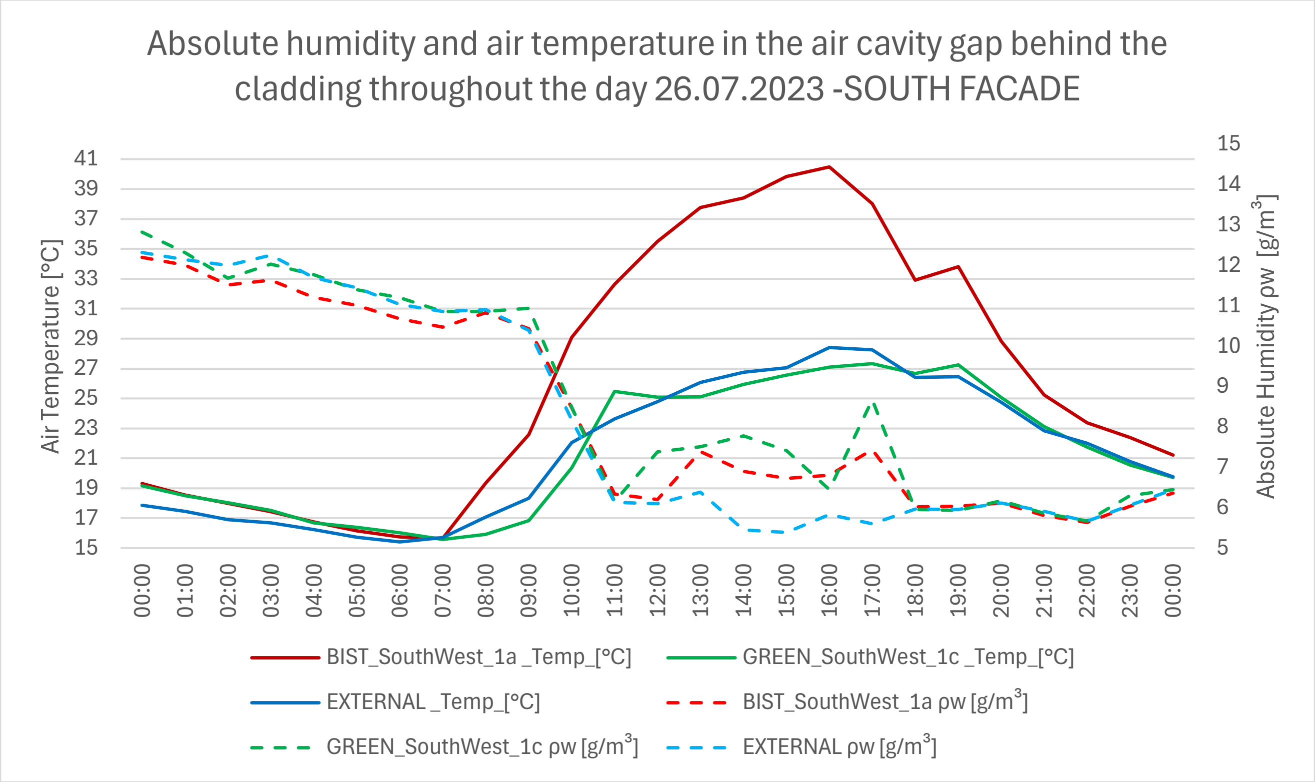


Figure 15: Daily course of air temperature and absolute humidity for a representative hot summer day on 26.07.2023 for the SOUTH Façade on the FlexiLab showing BIST- and GREEN-Cladding and local weather data © GRÜNSTATTGRAU

Throughout the course of three days (Figure 16, Figure 17) during the selected summer period, a trend of high air temperatures in the air cavity of the BIST-façade was measured. The air cavity temperature of the GREEN stays throughout the period close to or below the air temperature on site. Regarding the absolute humidity, slightly higher absolute humidity values can only be observed during the day, when directly exposed to the sun. These is an indication of transpiration from the leaf surfaces, which are responsible for the lower air temperatures measured.

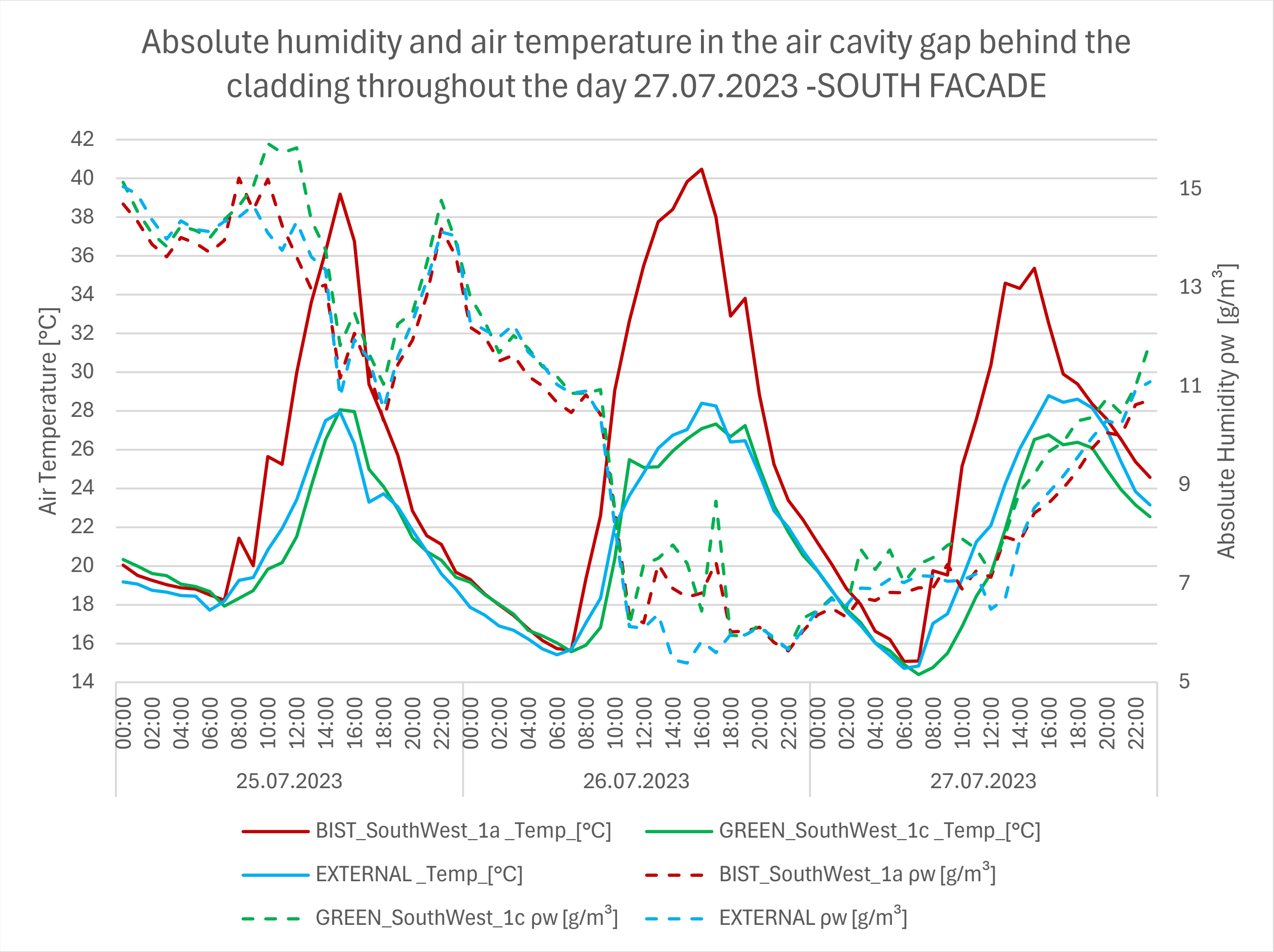


Figure 16: Three-day course of air temperature and absolute humidity for a representative hot summer period 25.-27.07.2023 for the SOUTH Façade on the FlexiLab showing BIST- and GREEN-Cladding and local weather data © GRÜNSTATTGRAU

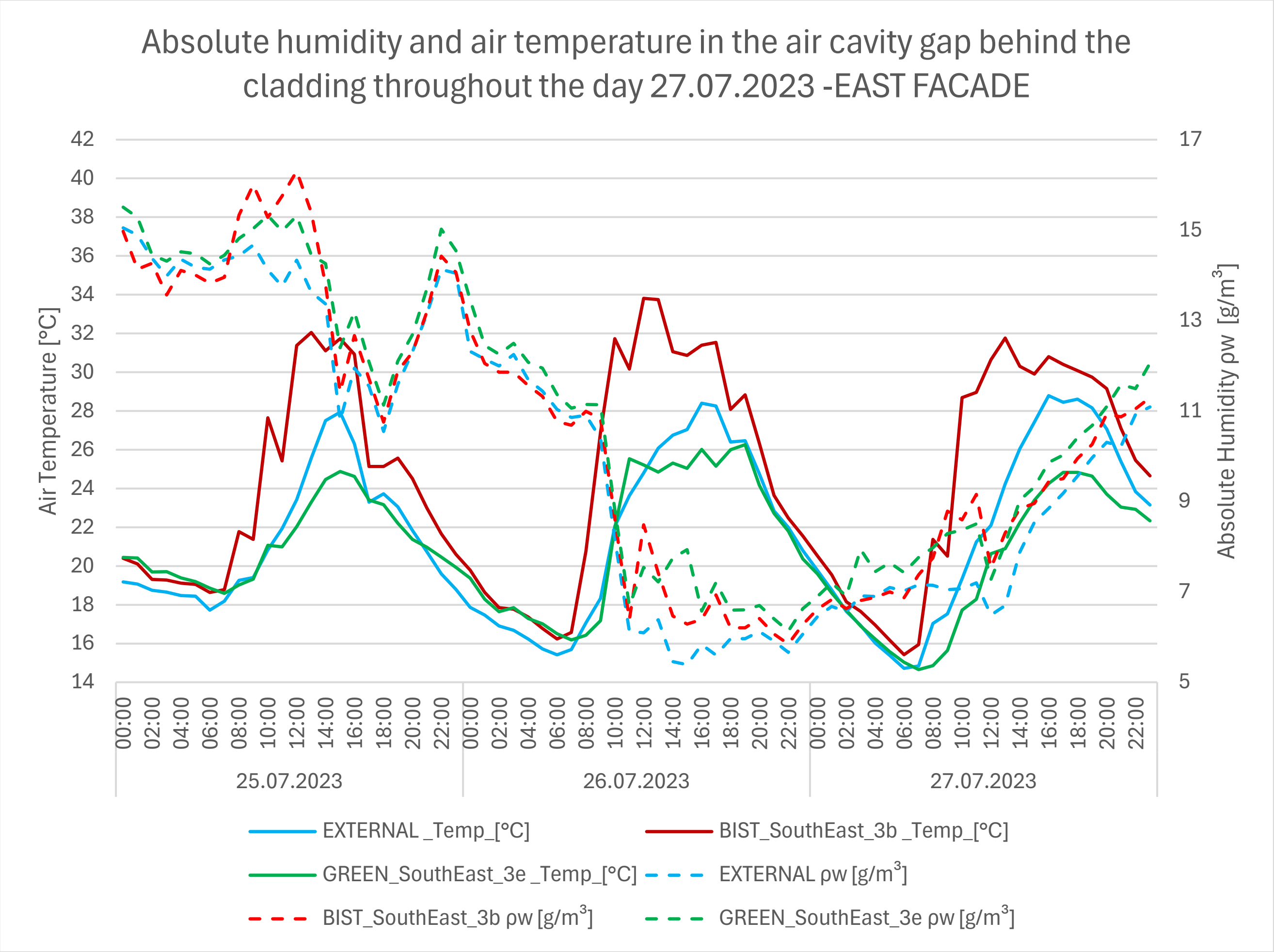


Figure 17: Three-day course of air temperature and absolute humidity for a representative hot summer period 25.-27.07.2023 for the EAST Façade on the FlexiLab showing BIST- and GREEN-Cladding and local weather data © GRÜNSTATTGRAU

To sum up, while the Figure 14 indicated by looking at the relative humidity, that the air cavity behind the GREEN might be more humid than the BIST. The previous figures (Figure 15, Figure 16 and Figure 17) only show a higher absolute humidity in the air cavity of the GREEN during the day which is because of the evapotranspiration that leads to cooler air temperature as well. Due to the significant differences in air temperature, it makes sense to compare air humidity based solely on absolute humidity. On average, there is no significant difference in the moisture content of the air between the GREEN and BIST façades. Therefore, the GREEN façade doesn't indicate a lasting higher absolute humidity in the air cavity gap and any risk that is connected to that.

Temperature differential analysis during daytime hours (second graph, Figure 18):

The south-facing façade was analysed specifically during daytime hours (07:00–19:00), with temperature differences between GREEN and BIST categorized into three ranges:

1. **ΔT < 5°C**: Small differential
2. **ΔT = 5–10°C**: Moderate differential
3. **ΔT > 10°C**: Large differential

At the cladding backside (BC), temperature differences exceeded 10°C for 30% of daytime hours. However, after air passage through the ventilation cavity, this proportion decreased to 12% at the timber frame surface (WS). This reduction demonstrates the moderating effect of the ventilation gap on extreme temperature differences between the two cladding systems.

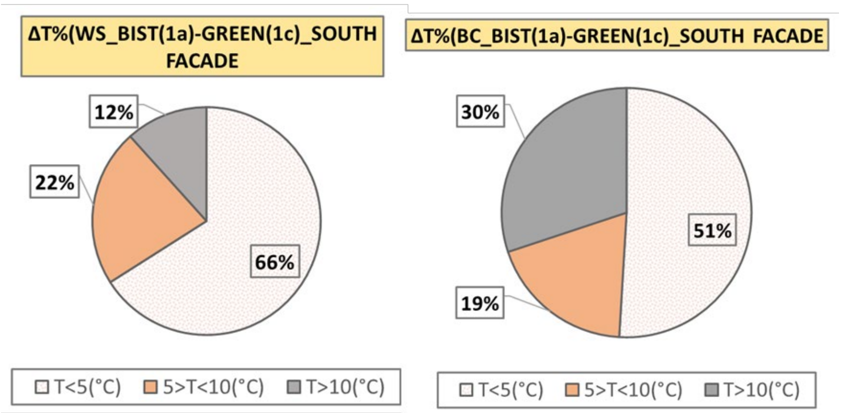


Figure 18: Share of the yearly hours based on 3 different delta T: deltaT<5 degree Celsius; deltaT between 5 and 10 degrees Celsius and delta t < 10 degree Celsius. (© Eurac Research)

Comparative Performance Summary

When evaluating the GREEN and BIST façades relative to external environmental conditions, the following conclusions emerge:

Temperature behaviour:

- The GREEN façade consistently exhibited lower temperatures at both BC and WS positions compared to the BIST façade, though the magnitude of reduction was moderate in some conditions.
- GREEN façade surface temperatures typically fell below ambient during daytime hours and rose above ambient during nighttime.
- BIST façade temperatures consistently exceeded both GREEN façade and ambient conditions throughout the diurnal cycle.

Relative humidity behaviour:

- GREEN façade relative humidity levels were lower during daytime and higher during nighttime compared to external conditions for most of the monitoring period.
- BIST façade consistently maintained lower relative humidity than both the GREEN façade and external environment.

Daytime performance (07:00–19:00):

Analysis of daytime hours revealed particularly instructive patterns:

- Annual data showed temperature differences between GREEN and BIST façades typically remained below 5°C.
- During daytime hours, however, temperature differentials in the 5–10°C range and exceeding 10°C occurred with notable frequency.
- These elevated differentials highlight the peak cooling benefit provided by the living façade during periods of highest solar gain.

6.2 Green Roof

The green roof consisted of four plastic modules filled with inorganic and draining substrates (perlite and volcanic stone) and cultivated with *Sedum* plant species and other mediterranean plants, placed in an artificial roof pilot specifically design for the placement of the modules (Figure 19). Sedum was selected due to several factors such as its tolerance to contaminated water, its temperature adaptability, its fast growth, its small roots, and its low water needs because of their high capacity to accumulate water in the leaves Figure 20.

Figure 19: Image of the two Sedum modules of the roof-pilot structure with the IBC tank with ray water and the effluent tank, ready for disinfection underneath (©LEITAT)

Figure 20 Composition of different species of Sedum in the green module (©LEITAT)

On the other hand, the greywater influent was prepared in a 600L IBC tank and pumped to the green roof with a dosing pump and hoses. The influent was distributed equally among the four modules thanks to the irrigation drippers, and the effluent was collected through the gutter of the roof and stored in a 50L barrel. Also, a fine plastic mesh was installed over the gutter to retain the bigger solids. Finally, the collected effluent is conducted to an ultraviolet (UVC) lamp (21 W) which disinfects the final effluent in one single pass, removing bacteria such as e-coli and other possible coliforms.

Monitorization

The system was operated over one year (March 2024 – March 2025) and divided into three stages at different seasons to evaluate its efficiency (Figure 21).

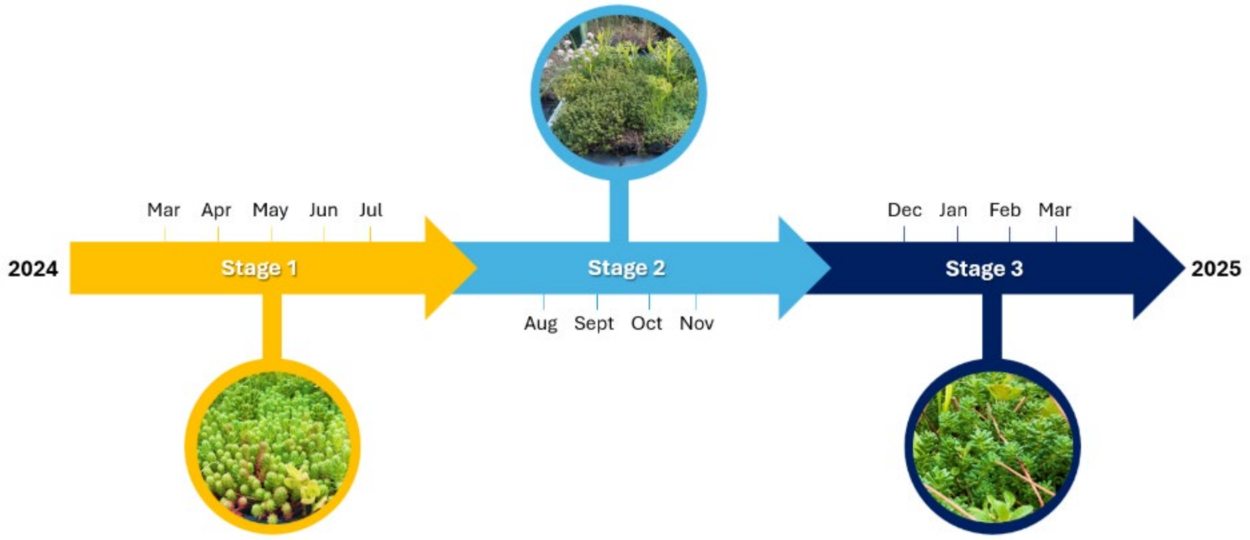


Figure 21 Schematic diagram of the different monitoring stages across the year (© LEITAT)

Stage 1 corresponds to the warm season (spring and summer), where for five continuous months the green roof was irrigated with greywater in order to acclimatize the plants and allow the growth of microorganisms. The greywater was obtained from LEITAT facilities, and the chemical oxygen demand (COD), a parameter used to measure the organic matter in water, was initially around 30 ppm, but this value gradually and artificially increased until 500 ppm to evaluate the capacity of the system. This influent was pumped to the system at a discontinuous flow of 0,7 L/h (175 ml/h/module), for 1 hour every 4 hours, which means 4,2 L/d. Every 5 days, when the collection tank had enough water (around 20 L), the system was stopped for 2 days in order to take samples and make the water analysis, and the effluent of the green roof was introduced in the disinfection system. The UVC lamp removed the e-coli and other coliforms with only one pass. The results showed that sedum successfully resisted the highest contamination loads, and the highest reduction efficiencies were also shown at the highest contamination loads (average of 80 % reduction of COD). On the other hand, the e-coli and coliforms concentrations were quite low but the green roof and, especially, the UVC lamp removed 100% of these microorganisms.

In August, stage 2 started, which consisted of an intermediate period of four months where the system was irrigated first with tap water and later with rainwater, to see the performance of the green roof in the rainy season. From August to November, the accumulated precipitation in Terrasa reached 390 mm, being October the rainiest month of the whole year (148,7 mm). The results showed that rainwater had very low values of contamination and after crossing the green roof, the values were even lower. For instance, COD average values in the influent and effluent were 75 and 50 ppm, and for turbidity remained stable around 7 NTU.

In the cold season, from December to March, stage 3 started, and a new synthetic wastewater was prepared with higher COD concentration (around 600 ppm) and inoculating e-coli in high concentration (2419 CFU). The low temperatures (9,2 ºC on average) didn't affect plant growth, and the COD loads were assimilated successfully by the sedum. Regarding the e-coli, it was removed around 10% by the green roof, but the lamp fully eliminated this contaminant in one single pass. I

Overall, the pilot green roof system demonstrated strong and resilient performance as a nature-based solution for decentralized wastewater treatment under variable climatic and loading conditions. The modular green roof, planted mainly with *Sedum* species and filled with inorganic, well-draining substrates, proved capable of withstanding high organic loads, temperature fluctuations, and changes in influent quality over a full year of operation. Across all monitoring stages, the system consistently reduced organic matter, achieving its highest efficiencies under elevated COD concentrations, with average reductions of around 80%, confirming a high treatment robustness. Seasonal changes did not compromise plant vitality or system functionality, even during the cold period with average temperatures below 10 °C.

While the green roof alone provided limited removal of microbial contaminants, it effectively complemented the disinfection step. The integration of a UVC lamp ensured complete elimination of *E. coli* and other coliforms in a single pass, resulting in a safe final effluent. During the rainy season, the system also showed a polishing effect, further improving the already low contamination levels of rainwater.

Taken together, these results highlight the suitability of green roof–based treatment systems as compact, low-energy, and adaptable solutions for water reuse and urban water management, particularly when combined with a simple and reliable disinfection technology.

7 Plants - Maintenance

To ensure that green roofs and green façades deliver their intended benefits—especially shading and evapotranspiration—two aspects are essential: plant selection adapted to local conditions, and a structured maintenance plan. Both are prerequisites for stable long-term performance and for maintaining the desired green appearance.

In this chapter, the key decision factors for plant selection and the recommended maintenance measures are summarised.

7.1 Selection of the plants

A detailed microclimatic assessment is essential before implementing any vegetated system, as local climatic conditions directly influence plant survival, water demand, and overall system efficiency. For example, the analysis should cover temperature, sunlight exposure, wind patterns, and humidity levels throughout the year in the study area, serving as the basis for plant species selection and irrigation strategy design (Figure 22).

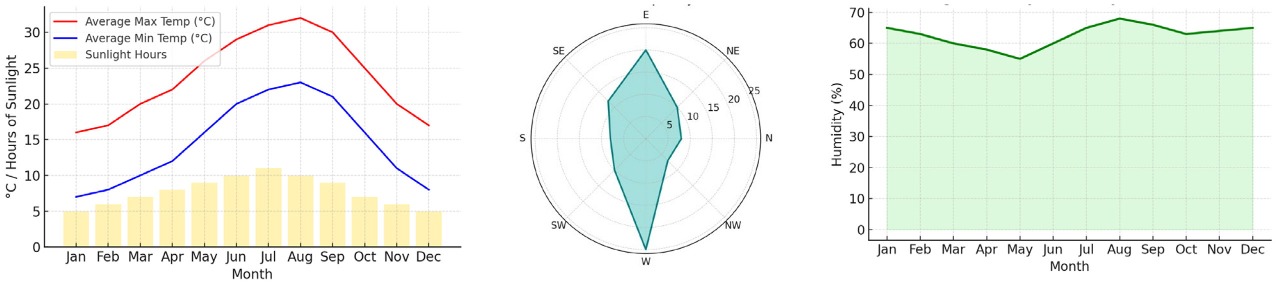


Figure 22: Examples of typical graphs about climatic conditions: accumulated monthly precipitation, temperature, wind direction and humidity (data randomly generated).

Based on the identified microclimatic conditions, the plant palette should include drought-tolerant, sun-exposed species for south-facing façades and shade-tolerant species for north orientations. Evergreen species provide year-round coverage, while deciduous plants contribute to seasonal variation and biodiversity. Native and pollinator-friendly species are prioritized to reduce irrigation needs and enhance ecological performance.

It is highly recommended to design a maintenance plan, especially if the green module is irrigated with greywater or other non-tap water source. E.g. once month all the connections and pipes for irrigation should be checked to see if there is any precipitation or accumulation due to water hardness but if greywater is used, frequency should be increased to see if biofilms or foams are affecting the system and all the treatment and disinfection units are working correctly. In that case, also an extra water sampling should be performed to assess water quality at the end of the process.

7.2 Austrian maintenance guidance to ensure vital green roofs and façades

For example, in Austria, there are regulations in place in order to guarantee a successful greening of the green roof or façade.

Regarding the **green roof, the Regulation ÖNORM L 1131,** soon to be followed by **ÖNORM B 1131** (yellow pages), gives information about growth management and regular maintenance. The growth management is especially important to guarantee a green result after installing the solution and can be done by a contractor. Essential measurements that need to be done within such a contract for extensive green roof solutions are (ON, 2010; Austrian Standards International - Standardisierung und Innovation, Yellow pages):

- Replanting bare patches
- Removing unwanted foreign growth
- Fertilize as needed and
- Keep gravel strips and areas clear

Additionally, the irrigation, technical equipment and drainage facilities should also be checked.

In Figure 23 the measurements according to the extensive or intensive green roof solutions are presented:

Measures	Extensive green roof	Intensive green roof
Watering as required until handover	If necessary	Standard case or always required
Regular irrigation	If necessary	Standard case or always required
Follow-up fertilisation	If necessary	Standard case or always required
Removal of foreign growth	Standard case or always required	Standard case or always required
Reworking joints in vegetation mats	If necessary	If necessary
Vegetation cutback	Exceptional case	Standard case or always required
Woody vegetation cutback		If necessary
Reseeding	If necessary	Exceptional case

Replanting	If necessary	Exceptional case
Plant protection		If necessary
Inspection of drainage facilities	Standards case or always required	Standard case or always required

Figure 23: Measures for growth maintenance for extensive and intensive green roofs

If the commissioned plant development maintenance is done with a contractor, it is recommended to ensure the following points are met when installing an extensive green roof:

- Uniform vegetation cover in an uncut state, at least 75% ground cover
- The seeded or planted vegetation should have survived at least one growing season and, if possible, one dry and frost period before handover. This condition is usually achieved within 18 months

After that, it is recommended to have a maintenance contract in place. This would include to check:

- The functionality of roof drains and technical equipment for drainage and/or irrigation
- Checking for contamination, deposits and root ingrowth
- Stability of edging, surface fixings and other components that are functionally related to the green roof

Maintenance checks might also include the following, if necessary:

- Fertilization
- Removal of foreign wood
- Pruning to thin out
- Reseeding in case of larger gaps
- Replanting in case of larger gaps
- Refilling substrates in case of erosion
- Keep technical equipment free of vegetation
- Keep gravel strips free of leaves and vegetation

For extensive green roofs, which are more likely used with serial renovation it is usually done within one or two inspection rounds per year.

When looking closer at the maintenance care for the vertical vegetation with **greening façades**, there is also the Austrian regulation **ÖNORM L 1136** to consider for the recommended maintenance.

The measurements, depending on the application area as well as the greening goal, are recommended:

- Shaping and pruning
- Keeping technical equipment free of vegetation
- Removal of unwanted growth
- Supplying nutrients as needed
- Irrigation
- Guiding climbing plants
- Plant protection measures
- Replanting and reseeding
- Replenishment of substrate in case of erosion
- Checking the Functionality of the irrigation system
- Checking for contamination and deposits in drainage facilities
- Visual inspection of the stability of fastenings and other components insofar as they are functionally related to the wall greening

After the first growth maintenance comes the regular maintenance that would include:

- Checking and, if necessary, adjusting the irrigation system
- Carrying out manual irrigation as required
- Guiding plant shoots
- Visual inspection of plant health
- Clearing technical equipment and components
- Carrying out pruning measures (e.g. training, clearance cutting and topiary pruning)
- Removal of damaged or dead plant parts and shoots from rootstocks
- Fertilisation as required
- Removal of unwanted foreign growth
- Removal of unwanted foliage accumulations in the wall area
- Regular visual inspection

When plants are mature and advanced in age, particular attention must be paid to ensuring that safety measures are in place, as well as replanting dead plants as a result of pest infestation, vandalism, extreme weather events, irrigation failure, etc., and plant protection measures.

8 Overcoming barriers during the implementation of green solutions in INFINITE

During the INFINITE project, the implementation of green solutions in combination with a prefabricated timber-frame retrofit system revealed several practical barriers, particularly during the mock-up phase of the INFINITE GREEN façade kit. The main challenges and the corresponding mitigation measures (applied or recommended) are summarised below (see Figure 24).

Barriers and challenges during the mock-up phase	Mitigation (recommended/applied/reported)
The supplier/manufacturer of the green façade system was located ~300 km from the mock-up site, complicating regular inspection and maintenance visits	Contract a local maintenance partner (e.g., regional gardener/landscape company) for routine inspection and servicing.
The selected façade modules had small substrate compartments, requiring highly precise irrigation and fertilisation. Plants showed drought stress and had to be replaced twice during operation at FlexiLab.	Consider alternative systems with larger substrate volume to improve water and nutrient buffering, reduce maintenance sensitivity, and enhance plant vitality.
The green elements required year-round attention to maintain a continuous green appearance.	Implement continuous checks and improve monitoring, irrigation, and fertilisation routines—particularly during summer—to reduce drought risk.
Plant performance was weak throughout the year.	Improve species selection and planting design according to the local microclimate (orientation, wind exposure, solar radiation, frost risk). Better matching of species to site conditions would likely reduce replacement frequency.
Plastic pipes and the technical “room” for the greening system were not designed for mock-up winter conditions, leading to freezing and damage during the first winter.	Insulate pipes and the technical unit, and implement a procedure to drain pipes at the end of the operating season or during frost periods.
Irrigation drippers frequently clogged.	Improve irrigation system design and calibration, including orientation-specific hydraulic balancing. In the mock-up, drippers on the south façade were replaced and regularly checked for blockage.

Greywater-only irrigation: Risk of plant desiccation during periods with low rainfall or insufficient greywater availability	Upgrade the irrigation concept by allowing supplementary water input in dry periods to avoid drought stress.

Figure 24: Barriers and challenges during the mock-up phase and mitigation measures.

Since no green roof solution was actively implemented as part of the INFINITE kits during the monitored mock-up phase, important practical insights on serial renovation with green roofs could not be generated to the same extent as for façade greening. Including a roof-based GREEN implementation would likely have strengthened the evidence base for industrialised renovation applications combining both green façades and green roofs.

9 Conclusion and Recommendations

This document shows that green roofs and green façades can be successfully integrated into industrialised renovation when technical feasibility, system interfaces, and long-term operation are addressed early and systematically. Compliance with standards such as the upcoming B1131 or L1136 is recommended in Austria. The INFINITE approach—based on prefabricated modular timber-frame elements—demonstrates high potential to reduce renovation time and improve building performance while enabling additional “GREEN” functions such as shading, evapotranspiration cooling, rainwater retention, and biodiversity support.

The monitoring at FlexiLab (August 2022–August 2024) confirms that a living green façade can significantly modify the hygrothermal conditions of a ventilated façade compared to a dark reference cladding (BIST). On peak summer days, the GREEN **façade** achieved markedly lower surface temperatures (up to ~11°C at the timber frame surface and up to ~18°C at the backside of the cladding, depending on orientation). The results indicate that evaporative cooling and shading can reduce thermal loads on the façade, especially under high solar radiation.

The green roof mock-up focusing on greywater irrigation and treatment (March 2024–March 2025) indicates that modular planted systems can contribute to organic load reduction (COD reduction in the reported range, with best performance under higher loads) and that UVC disinfection can reliably eliminate E. coli and coliforms in a single pass. This highlights the technical feasibility of combining green roof modules with decentralised water management—provided that operation, monitoring, and hygiene safeguards are robust.

At the same time, the INFINITE mock-up phase revealed practical barriers: weight and thickness constraints, irrigation sensitivity in small substrate volumes, supply-chain distance, winterisation issues, and clogging of drippers. These findings underline that the long-term success of GREEN solutions depends not only on design, but equally on maintenance planning, appropriate plant selection, and resilient technical detailing.

9.1 Recommendations

Decision-making and feasibility checks

1. **Apply a step-by-step suitability assessment** before selecting any green roof or façade system. Minimum checks should include:
    a. structural capacity (including saturated weights),
    b. waterproofing and root resistance (for roofs),
    c. façade condition and interfaces (for façades),
    d. drainage concept and safe overflow routes,
    e. access and safety requirements for maintenance.
2. **Define limits early** (and treat them as design constraints, not afterthoughts):
    a. for façades: maximum saturated weight and allowable build-up thickness,
    b. for roofs: maximum saturated weight, slope-related requirements, drainage capacity, and safe access.

System selection for serial renovation

1. **Green façades**
    a. For high prefabrication potential, prioritise **wall-bound modular systems** that can be mounted directly onto prefabricated timber frames.
    b. Avoid self-climbing plants for module-based façades where adhesive organs may damage joints and interfaces over time.
    c. Treat plant-trough-based façade greening with caution where it causes **high point loads**, unless the existing structure is clearly verified to carry these loads.
2. **Green roofs**
    a. For serial renovation, **modular green roof trays** are typically the most compatible due to fast installation and high off-site prefabrication potential.
    b. **Sedum mats** provide rapid green appearance and low maintenance, but disassembly and recycling can be challenging when mixed fibre meshes are used; prefer **biodegradable or clearly separable materials**.
    c. **Solar green roofs** are valuable for combining energy generation and greening but require careful maintenance planning to avoid vegetation shading and to ensure safe access.

Design recommendations for robust performance

1. **Prioritise substrate volume where possible**
    a. Systems with very small substrate compartments require precise irrigation and fertilisation and are more vulnerable to heat stress and desiccation. Where weight limits allow, prefer solutions with **greater water and nutrient buffering capacity**.
2. **Plan orientation-specific strategies**
    a. South-facing façades and roofs should use drought- and heat-tolerant species and robust irrigation redundancy.
    b. East/west façades should consider alternating sun exposure and wind-driven drying.

3. **Design for winter and extreme events**
    a. Insulate pipes and technical units; include a drain-down strategy to prevent freeze damage.
    b. Ensure safe overflow routes to avoid slip hazards and building damage.

Operation and maintenance as part of the design

1. **Make maintenance "designable"**
    a. Ensure that irrigation filters, drippers, and inspection points are accessible.
    b. Include clear maintenance paths, vegetation-free strips (where required), and safe anchoring/fall protection for roof work.
2. **Use structured maintenance regimes**
    a. For Austrian contexts, align routines with **ÖNORM L 1131 (green roofs) / ÖNORM B1131 (green roofs / yellow pages)** and **ÖNORM L 1136 (façade greening),** covering establishment and long-term care. Updates will be (ON, 2010; Austrian Standards International - Standardisierung und Innovation, Yellow pages, 2021)
    b. Extensive green roofs typically remain manageable with **one to two inspections per year**, but only if the system is well designed and site exposure is moderate.

Greywater irrigation and hygiene safeguards

1. **Do not rely on greywater alone during dry periods**
    a. Include the option for supplementary water to avoid plant desiccation when greywater supply or rainfall is insufficient.
2. **Increase inspection frequency for non-potable water systems**
    a. Check for clogging, scaling, and biofilm formation more frequently than with tap water.
    b. Add routine water sampling at the system outlet to confirm treatment/disinfection performance.
3. **Keep disinfection and treatment components fail-safe**
    a. Ensure that UVC units, filters, and control systems are monitored, and that failures trigger maintenance action.

Implementation strategy and supply chain

1. **Prefer regional maintenance capacity**
    a. If the system provider is far from the site, contract a local partner for routine checks and rapid response.
2. **Use mock-ups as a mandatory validation step**
    a. Mock-ups are strongly recommended before demo-site installation to test interfaces, irrigation stability, freeze protection, and maintenance routines under real conditions.

For industrialised renovation, GREEN solutions should be treated as **technical building systems**, not only as architectural add-ons. The most reliable pathway is to combine:

- **prefabrication-friendly system typologies** (modular façade and roof elements),
- **clear technical limits** (weight, thickness, interfaces),
- **site-appropriate plant selection**, and
- **maintenance and monitoring plans embedded from the start.**

This approach maximises the probability that green façades and roofs deliver measurable benefits in thermal behaviour, comfort-related microclimate effects, water management, and biodiversity—while remaining feasible for large-scale serial renovation.

10 Literature list

Amann, W. (Hrsg.) (2022). *Sanierte Gebäude in guter Gesellschaft: Wie schaffen wir die Dekarbonisierung unserer Gebäude bis 2040?* IBO Verlag.

Austrian Standards Institute / Österreichisches Normeninstitut (ON) (1. Juni 2010). *ÖNORM L 1131: 2010 06 01: Gartengestaltung und Landschaftsbau - Begrünung von Dächern und Decken auf Bauwerken: Anforderungen an Planung, Ausführung und Erhaltung* (ÖNORM L 1131). Austrian Standards plus GmbH.

Austrian Standards International - Standardisierung und Innovation (Yellow pages). *ÖNORM B 1131 (Gelbdruck): 2026 01 01: Begrünung von Dächern und Decken auf Bauwerken: Planung, Ausführung und Erhaltung* (ÖNORM B 1131 (Gelbdruck/draft/yellow pages). Austrian Standards plus GmbH.

Austrian Standards International - Standardisierung und Innovation (1. April 2021). *ÖNORM L 1136: 2021 04 01: Vertikalbegrünung im Außenraum: Anforderungen an Planung, Ausführung, Pflege und Kontrolle* (ÖNORM L 1136). Austrian Standards plus GmbH.

Enzi-Zechner, V., Mann, G., Mollenhauer, F., Landwehr, R., Mauss, K., Weiss-Tessbach, E. & Konchenko T. (2025). *Benefits of Green Buildings (Green Roofs, Green Walls and Vertical Indoor Geenery): A compliation of numbers, data and facts from different investigations 2025.*

European Environment Agency. (2023). *Urban adaption in Europe: what works? Implementing climate action in European cities*. https://www.eea.europa.eu/en/analysis/publications/urban-adaptation-in-europe-what-works

European Research Executive Agency. (2024). *Nature-based solutions: EU-funded NBS research projects tackle the climate and biodiversity crisis*. Publications Office. https://doi.org/10.2848/8542246

INFINITE Building Renovation. *INFINITE: Industrialised durable building envelope retrofritting by all-in-one interconnected technology solutions* [The INFNITE project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958397]. https://infinitebuildingrenovation.eu/about-infinite