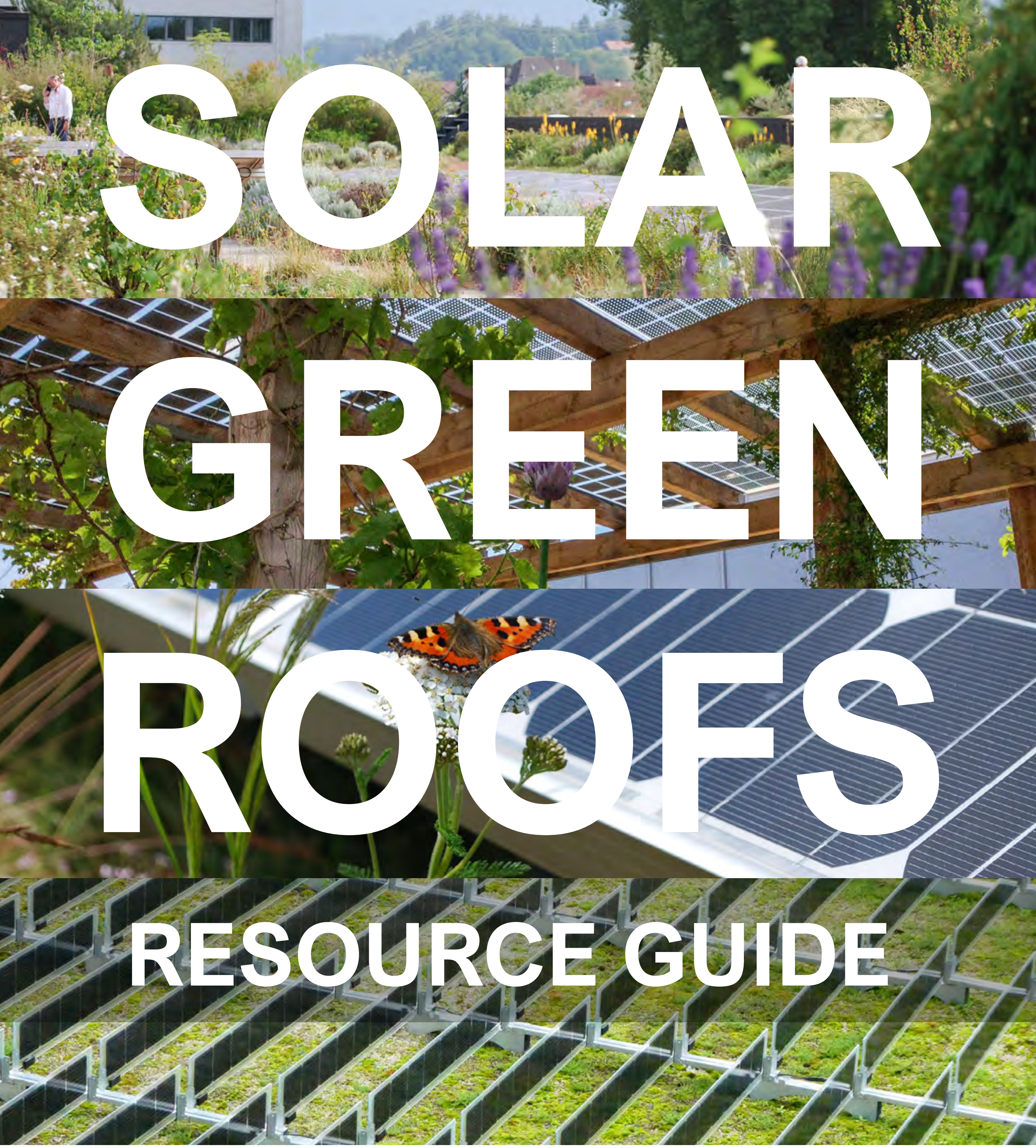

SOLAR GREEN ROOFS

RESOURCE GUIDE

JUNE 2025

WGIN
WORLD GREEN INFRASTRUCTURE NETWORK

EFB
EUROPEAN FEDERATION GREEN ROOFS & WALLS
GREENER CITIES IN EUROPE

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This document was completed on June 5, 2025.

Cover images: Elisabeth Weiss-Tessbach, Dusty Gedge, BuGG, Over Easy Solar

Layout design by Isabel Mühlbauer

About the World Green Infrastructure Network (WGIN)

The World Green Infrastructure Network (WGIN) is a non-profit organization whose mission is to advocate and promote the integration of green infrastructure in urban planning, globally with a passion and strong united belief that our world must develop in respect and synergy with nature. The transition from 'grey to green and blue infrastructure' for building and urban design is the goal of our efforts as a collaborative global network because "vegetation makes it possible".

About the European Federation of Green Roofs & Walls (EFB)

The European Federation of Green Roof and Living Wall Associations (EFB) was founded in 1997 through the collaborations of green roof associations of Austria, Germany and Switzerland, and expanding to 18 national member associations as of 2025. The Federation and its national members actively promote the use of green roofs and green facades throughout Europe to provide a better quality of life for towns and cities by returning sealed surfaces back to nature.

About Solar Power Europe

SolarPower Europe, the premier association for the European solar PV sector, unites 320+ organisations. Collaborating with members, we shape regulations and business landscapes for solar's growth. SolarPower Europe's top analysts provide market intelligence through reports like the Global Market Outlook for Solar Power and EU Solar Jobs Report. Our events, including the SolarPower Summit and RE-Source, bring policymakers and stakeholders together for networking and business opportunities.

Acknowledgements

This Resource Guide is the result of a collaboration between various public and private organisations as well as individuals who served on the Working Committee which developed it. Special thanks to the City of Vienna, Energy Department for allowing the use of important content they developed in this area, and for the input from solar representatives of SPE and Austrian Solar, as well as our private sector partners.

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FOREWORD

Our world is facing multiple crises that require new, more holistic, and innovative ways of thinking in order to respond effectively. The roofspaces within our cities present significant opportunities for us to utilize technologies that provide multiple solutions to the challenges of the climate crisis, the biodiversity crisis, the human health crisis, and the need to densify our cities. We need to make the best possible use of roofspaces to generate renewable electricity, manage stormwater, support biodiversity, reduce greenhouse gases, cool our overheating cities and contribute to human health and well being. All of these things are achievable on our roofs. Green roof and solar technologies have been in use for decades, combining the two is a relatively new endeavour not fully exploited or supported by government or the private sector.

The World Green Infrastructure Network (WGIN), the European Federation of Green Roofs & Walls (EFB) and Solar Power Europe have identified a need to inspire public authorities to develop policies and programs that support the more rapid increase in the design, implementation and maintenance of solar green roof solutions. Our organizations represent the multidisciplinary professionals involved in the practice of greening buildings. We worked together to write this document, so that the construction industry, designers, manufacturers and public authorities can understand the opportunities involved and take action to combine these technologies.

To scale these technologies, supportive policies combined with industry capacity building are needed to fully exploit their many benefits. More investment and policy support, particularly from senior levels of government, is needed. We need not choose one technology over the other. Integration allows us to use limited roofspace in our cities for even greater benefits for citizens, building owners and urban biodiversity. Policy makers, designers, contractors and building owners need to build on the progress made to date, and increase their support of integrated solar and green roof technologies. We hope that you benefit from this Resource Guide. It provides practical information on integrated solar green roof best practices, design considerations, policies, project case studies and resources. The rapid scaling up of these technologies around the world is essential to achieving a more positive future for us all.

Sincerely yours,

Manfred Köhler
President, World Green Infrastructure Network

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President, European Federation of Green Roofs & Walls (EFB)

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EXECUTIVE SUMMARY

How we develop our cities is either going to be part of the solution to the many crises we face, or part of the problem. The United Nations estimates that 55% of the world's population lives in cities, with that figure expected to rise to 68% by 2050.

As our cities grow denser and more populated, space comes at an increasing premium. Moreover, the climate crisis is creating problems that are particularly acute in urban areas - compromised air quality, infrastructure stress, and extreme weather events which amplify the impacts of the urban heat island effect and large areas of impervious surfaces.

In addition, the loss of biodiversity and natural (green) spaces continues. This constitutes a major challenge for our ecosystems, in turn threatening food systems and other critical resources. The climate crisis jeopardizes the comfort, safety, health, and wellbeing of people and communities across the globe.

Students on a solar green roof, Klagenfurt, Austria
Source: Irene Zluwa, GrünStattGrau

The greening of buildings - both roofs and facades - provides an effective, proven and much needed response to these challenges. At the same time, the need to develop decarbonized, renewable energy supplies to reduce greenhouse gas emissions and improve energy security has led to the more rapid deployment of solutions such as solar photovoltaics and solar thermal systems - technologies that are even more essential because energy supplies have become strained in many parts of the world.

Solar green roof integration may involve the use of solar photovoltaic panels or solar thermal panels. Biosolar projects are focused on supporting biodiversity, while agrivoltaic projects are focused on food production.

The Resource Guide provides a review of different systems and scientific research on their many benefits. Green roofs and rooftop solar energy: two solutions with a shared installation site - but why should we choose?

It is not only possible, but also advantageous, to combine the two and benefit from an enhancement of their benefits. The combination of multiple technological systems requires special design considerations and more cooperation across multiple trades but provides a wider range of additional social, environmental and building level benefits than green roof or solar panels alone. These enhanced benefits include:

- Biodiversity support through microclimates that help plants and invertebrates;
- Improved PV panel energy generation performance;
- Ballasting without roof penetrations and by using growing media;
- Integrated fire protection from aggregate growing media which is highly fire resistant;
- Energy efficiency through thermal applications and reducing heat loss and gain in the building;
- Lifecycle benefits by extending waterproofing system duration;
- Ecosystem services such as air quality improvements, cooling, water management and improved human well being;
- Green jobs creation including manufacturing, design, installation and maintenance; and
- Rooftop food production located under solar panels which has numerous benefits.

Students plant peppers in test beds under an agrivoltaic array. Credit: Kevin Samuelson, Colorado State University Spur

As with most design processes, there are tradeoffs when combining systems. For example, while covering a roof entirely in solar PV panels can maximize renewable energy generation, one sacrifices many other benefits that are particularly important in urban areas - such as the cooling of the urban heat island, reducing flooding, membrane durability, air quality improvements and the provision of green space for growing populations etc.. Policies and programs that promote the integration of the technologies maximize the overall public and private benefits that are attainable.

Sedum under semi-transparent panels Credit: GrünStattGrau

The successful integration of solar and green roof technologies involves a number of different trades, and careful design considerations that vary from project to project. We've used averages and ranges from various resources to illustrate benefits and best practices. The following are **10 steps** to completing a successful solar green roof design, installation and maintenance project.

1. Complete a **feasibility study** taking into account various project parameters including the type of project, objectives, budget, etc.
2. Hold an initial **on-site consultation** with key team members to develop a basic assessment of potential site parameters and constraints, indicative costs, access logistics, shading, structural considerations, and others.
3. Obtain necessary **permits and approvals** as well as clarify **funding** parameters and identify any possible **grants and incentives**.
4. Engage a qualified **multidisciplinary design/engineering team**, preferably with past experience in integration of green roof and solar systems, to develop a project plan with cost estimates, project schedule, and maintenance plan.
5. Identify **potential interfaces and opportunities** for the incorporation of solar technologies as well as projected performance output.
6. Bid **offers from specialist contractors** for the design, installation and maintenance of the system and components.
7. Secure necessary **planning permissions** including any expert appraisals such as **structural load** calculations, **mitigating wind uplift and tunnels**, and a **structural review** of the building.
8. **Commission and schedule contractors** to install components of selected green roof and solar systems.
9. Finalize acceptance, sign-off, and transition to the **post-installation management team**; as well as contractor invoices and any applied-for grants.
10. Complete **final quality control check and receive final sign-off**. Ongoing care and maintenance to be completed per the maintenance plan.

There are many design and maintenance details in the Resource Guide that build on these 10 steps. Fortunately, there are manufacturers, projects, design best practices and policies that are a foundation we can build upon to grow the solar green roof market around the world. To scale these technologies, supportive policies combined with increased industry capacity building afre needed to fully exploit their many benefits.

More investment and policy support, particularly from senior levels of government, is a necessity. We need not choose one technology over the other. Integration allows us to use limited roofspace in our cities for even greater benefits for citizens, building owners and urban biodiversity. support and develop an integrated approach to solar and green roof technologies to obtain the highest and best possible uses of roofspace in our cities.

Solar green roof integrated project in France
Credit: Vegetek

1. INTRODUCTION

Humanity is faced with a range of pressing issues which require swift and decisive action. These include the climate crisis - with heat waves, droughts, and storms all becoming increasingly intense, frequent, and long lasting; the loss of biodiversity and natural spaces in cities; the need to rapidly phase out the use of fossil fuels to reduce greenhouse gas emissions; widening gaps in community access to wealth and resources; and, in Europe particularly, the current management of the energy crisis. To address these issues we need to implement proven solutions that can simultaneously address multiple concerns. We need to think and act more holistically.

Emerging in the 1980s and increasing dramatically since 2000, solar (photovoltaic and thermal) systems have been developed and installed on buildings to provide both low-carbon energy production and energy autonomy as well as a significant return on investment for owners. Simultaneously, for more than 30 years, modern green roof solutions - extensive, semi-intensive, and more traditional intensive systems - have been developed and widely deployed, making it possible to provide cooling from urban heat islands, improve rainwater management, provide thermal and acoustic comfort, contribute to the protection of the building envelope, and enhance building energy performance.

Today's challenge is to find a way to cohesively maximize the returns available from exploiting underutilized roofspace through the synthesis of methods, techniques, and technologies that accumulate greater benefits. To this end, the combination of green roofs and solar systems provides an ideal solution for many buildings. In most cases, the benefits provided by either system can be amplified by their combination. The wide scale deployment of these technologies, supported by additional senior government investment and public policy, is needed to have greater positive impacts.

> As roof space and other building surfaces are limited resources, it is important that we exploit them to their full potential by integrating solar and green roof technologies wherever possible.

Solar Green Roof integrated project
Credit: Permavoid

This Resource Guide has been designed for public and local policy makers, as well as building owners, project managers, manufactures, designers, builders and contractors.

It is designed to provide a detailed overview of what integrated solar green roofs are - defining them; highlighting their individual and combined benefits; specifying points of attention for their successful design, implementation, and maintenance - and presenting policies that encourage these integrated solar green roof solutions. The Resource Guide explains what integrated green roof and solar technologies can do under certain conditions by providing details of their unique and combined performance benefits.

Key project management, design, installation, and maintenance best practices are presented along with many of the factors related to the costs and benefits of integrated systems. Finally, to illustrate these points and inspire stakeholders, the Resource Guide presents a number of policies and projects to demonstrate how this synthesis and the associated benefits can be realized on different buildings and in different contexts.

Solar green roof, Thun, Switzerland
Credit: Elisabeth Weiss-Tessbach

A HOLISTIC APPROACH

The United Nations estimates that 55% of the world's population lives in cities, with that figure expected to rise to 68% by 2050. As our cities grow denser and more populated, space comes at an increasing premium. The need to achieve multiple sustainability and livability targets, as well as contend with the climate crisis, puts increasing pressure on municipal services and infrastructure systems. A more holistic approach to the use of space is desperately needed.

The combination of green roofs and solar energy systems into a single integrated solution offers substantial performance enhancements while maximizing the per square area benefit output. This approach offers harmonised technology performance and investor safety as well as lower maintenance and care costs. The combination of multiple technological systems requires special design considerations and cooperation across multiple trades but provides additional social, environmental and economic benefits. Some example benefits of the synthesis of these technologies include:

- Biodiversity support;
- Energy Generation Performance;
- Ballasting;
- Integrated Fire Protection;
- Energy Efficiency;
- Lifecycle Benefits;
- Ecosystem Services;
- Green Jobs Creation;
- Rooftop Food Production.

The exact nature of these benefits is specific to the types of technologies involved and will be discussed in more detail further in this Resource Guide, but their combination can be leveraged to enhance the output and impact of both technologies. In general, green roofs provide a wider range of benefits than solar technologies alone.

Photography of an agrivoltaic green roof research project (Environmental Protection Agency office, Denver Colorado)
Credit: Thomas Slabe

Moreover, there are many opportunities to optimize benefits by, for example, cooling the ambient air temperatures to facilitate greater energy production from solar photovoltaic systems. Multidisciplinary knowledge is required to identify the many benefits of these technologies, and how they can work together for a more positive set of performance outcomes.

Vertical Bifacial Panels on an Oslo school building
Credit: Over Easy Solar

2. TECHNOLOGY OVERVIEW

As cities grow and densify, the premium on developable area increases, while the amount of permeable surfaces and natural spaces decreases. Land utilization is prioritized for the development of buildings often at the expense of the pre-development natural spaces. The roofscape is an ideal place for solar energy generation and green roofing, because it takes advantage of under-utilized space with minimal obstructions.

This section identifies the fundamental technological aspects of both green roof technologies and rooftop solar energy technologies. Many of these aspects will factor into the decision making process when specifying a specific rooftop solar system or a green roof system, or as we will explore later, a combination of the two.

Davout School, Paris, Francec
Credit: Le Prieure

2.1. GREEN ROOF TECHNOLOGIES

Given the numerous regional variations in policy, standards, and practices around the world, there is no universally accepted technical definition of green roof technology. The main practical difference in green roof types is between extensive, intensive, and semi-intensive systems - a difference determined largely by the depth of growing media (substrate) used.

These differences are described in detail first in the German FLL Green Roof Guideline (latest version 2018) which has since been used as a role model for many green roof guidelines and standards worldwide. Since then, other organizations and municipalities have elaborated on these distinctions in their own standards, including the City of Vienna's green roof guidance - Leitfaden für Dachbegrünung (2020) and the relevant Austrian standard ÖNORM L 1131 (2010 - update 2025) on green roofs; the Green Roof Organisation (GRO) Green Roof Code of Best Practice (2021 incorporating 2023 amendments); the City of Toronto's Green Roof Construction Standard (2009); Professional rules to design and implement a green roof (Adivet and CSFE - France - 2018) and many others.

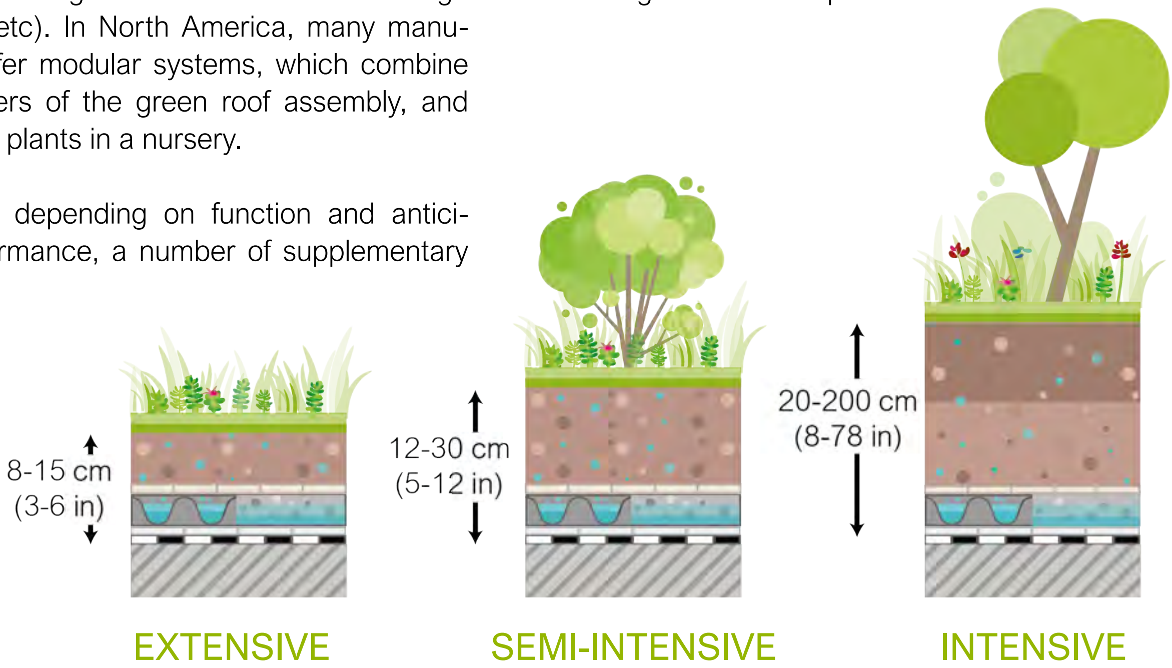
These measures specify regulatory requirements with respect to green roofs including definitions of composition, basic structure, basic performance and management.

TYPES OF GREEN ROOFS

Green roof systems differ in growing media thickness and composition, weight, functionality, plant communities, and material composition. They can be installed on flat or pitched roofs and may have a single or multi-layer structure.

Depending on the roof's intended function, a green roof system may be installed on all or part of the roof surface (less any necessary mechanical systems and penetrations) and may also be designed as a hybrid system (i.e. a combination of variable growing media thickness and drainage structures, etc). In North America, many manufacturers offer modular systems, which combine multiple layers of the green roof assembly, and pregrow the plants in a nursery.

Additionally, depending on function and anticipated performance, a number of supplementary support systems are recommended to ensure long-term success - these include a connection to a building's water supply system or a rainwater harvesting system for irrigation; and ample vegetation free zones and edge restraints for access to, and control of, the vegetation. Finally, a critical step in the long term success and viability of a green roof is an ongoing and comprehensive maintenance plan beyond initial plant establishment at installation. Green roofs are living systems that require varying degrees of care and intervention throughout their lifespan.



Credit: Isabel Mühlbauer

Old Chicago Post Office (Green Roofs for Healthy Cities Awards of Excellence Winner 2021) Extensive green roof installed on an adaptive reuse project. Credit: Scott Shigley

EXTENSIVE GREEN ROOFS

The average minimum thickness of an extensive green roof growing medium is 8-10 cm (3-4 in) in Europe and 15 cm (6 in) in North America and generally weighs between 80-190 kg/m^2 (16-30 lb/ft^2), although this may vary by region. Low-growing plant species including succulents, mosses, herbs, and grasses dominate this classification.

Residential building, Vienna
Credit: Verband für Bauwerksbegrünung VfB

Extensive green roofs generally require minimal maintenance, except in the event of major disruptions of the vegetation or substrate. As this type of green roof is not usually accessible to building occupants or visitors, it can provide suitable habitat for a variety of plants and animals and is typically employed in integrated solar green roof systems.

INTENSIVE GREEN ROOFS

The average minimum thickness of an intensive green roof growing medium is generally accepted at 20-200 cm (8-78 in) and typically weighs between 260-3,000 kg/m^2 (573-6,614 lb/ft^2). Depending on the thickness of the substrate, a wide variety of larger, woody plants, including small trees, can be grown.

Because of the greater substrate depths and water support requirements for larger plants, these systems are almost always irrigated. An intensive green roof can be utilized for a wide variety purposes including amenity spaces, and public parkscapes, to community gardening and even agriculture. The integration of solar technologies with intensive green roof systems is possible but not, at present, common.

Phipps Center for Sustainable Landscapes - Green Roofs for Healthy Cities Awards of Excellence Winner 2020
Intensive green roof installed installed as part of a larger ecological system at the Phipps Conservatory in Pittsburgh PA.
Credit: Paul G. Wiegman

Private Intensive Rooftop garden on a townhouse from 1870 in Vienna
Credit: Elisabeth Weiss-Tessbach, GrünStattGrau

SEMI-INTENSIVE GREEN ROOFS

The average minimum thickness of a semi-intensive green roof growing medium is generally 12-30 cm (5-12 in), and can vary across the installation depending on project specifications and in particular, loading capacity. They are traditionally characterized by small herbaceous plants, ground covers, grasses, and small shrubs which require moderate maintenance and occasionally irrigation. Though it has more demanding maintenance requirements than an extensive roof, a semi-intensive green roof is a generally more resilient system which provides the capacity for a wider range of uses, higher capacity for stormwater management, and offers greater ecological benefits than extensive systems.

Semi-intensive green roof, Germany
Credit: BuGG

GENERAL GREEN ROOF CHARACTERISTICS

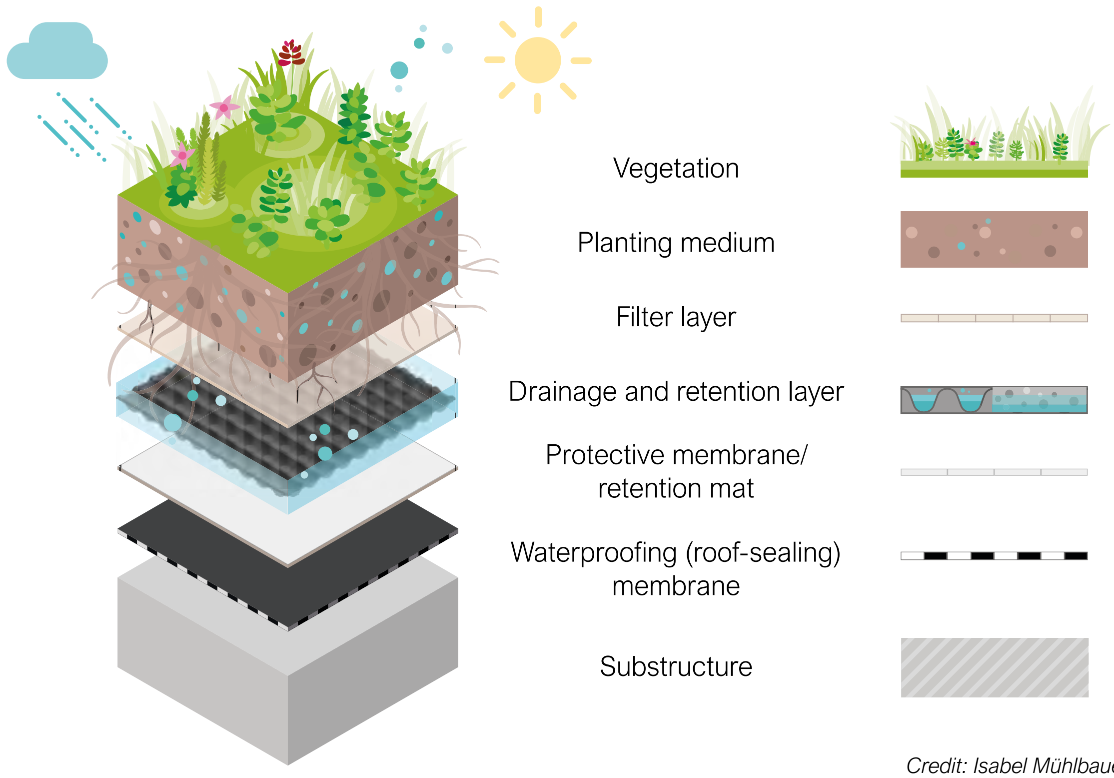
Type	Extensive	Semi-Intensive	Intensive
Use	Ecological Landscape	Garden/ Ecological Landscape	Roof Garden/Park
Type of Vegetation	Sedum-Herbs-Grasses	Grass-Herbs-Shrubs	Perennials, Shrubs, Small Trees
General Benefits	W-T-B	W-T-B-A	W-T-B-A
Depth of Growing Medium (Substrate)	8-15 cm (3-6 in)	12-30 cm (5-12 in)	20-200 cm (8-78 in)
Weight (fully saturated)	48-170 kg/m^2 (10-35 lb/ft^2)	130 - 450 kg/m^2 (287-992 lb/ft^2)	260 - 3,000 kg/m^2 (573-6,614 lb/ft^2)
Cost	Low	Medium	High
Potential for Solar Integration	High	Medium	Medium to Low

W - Water Management, T - Thermal Performance, B - Biodiversity Support, A - Amenity Creation

Tab. 1: Green Roof Characteristics
Source: Green Roof Professional Training, Green Roofs for Healthy Cities

STANDARD COMPONENTS OF GREEN ROOF SYSTEMS

Green roofs consist of essential engineered and natural components as well as a number of optional components and support infrastructure to enhance their functionality, create or amplify specific performance elements, or achieve particular design/policy driven goals, such as minimum stormwater retention, aesthetic objectives, or biodiversity. Essential components are found on virtually every green roof system. Optional components related to a specific project design, such as safety railings required for accessibility. Some elements, such as irrigation systems, leakage detection, insulation, may be essential for some projects to support the vegetation, but not required in others. Below is a diagram which provides generally accepted essential green roof components.



Credit: Isabel Mühlbauer

VEGETATION

A wide range of plant communities can be supported on a green roof, which is determined by a number of factors - growing medium (substrate) depth and composition, available roof space, and maintenance plan of the green roof. This can range from ground covering succulents to shrubs, and in some cases small trees. Initial planting may be done with seeds, cuttings, potted or baled plants, vegetative blankets, pre-cultivated mats, modules, trays, or turf.

Hydroseeding the growing medium
Credit: Christian Oberbichler, Dachgrün GmbH

Sedum Cuts for plant installation
Credit: Christian Oberbichler, Dachgrün GmbH

GROWING MEDIUM/SUBSTRATE

Green roof growing medium (substrate) is an engineered material which provides space for plants to root, stores water and nutrients, circulates air, resists compaction, drains efficiently, and in the case of extensive and semi-intensive systems, maintains a relatively light weight. Growing media that meets relevant standards consists of mineral open pore aggregates (such as hard-fired clay, expanded shale, or recycled brick chippings) which are mixed with organic materials (such as quality certified compost) in varying proportions. The share of organic material is low in extensive green roofs and higher in intensive systems to accommodate for the different needs of the plants.

Local regulatory requirements may prescribe a detailed description of the growing medium requirements associated with performance characteristics such as water retention ability, porous air capacity, drainage rate, proportion of fines, etc). For example, the Austrian standard ÖNORM L 1131 and the United Kingdom testing standard BS 8616:2019, the FLL-Guidelines in Germany, or the Règles professionnelles in France (2018).

Substrate installation blower truck for a nursery roof (France) Credit: Dynergis

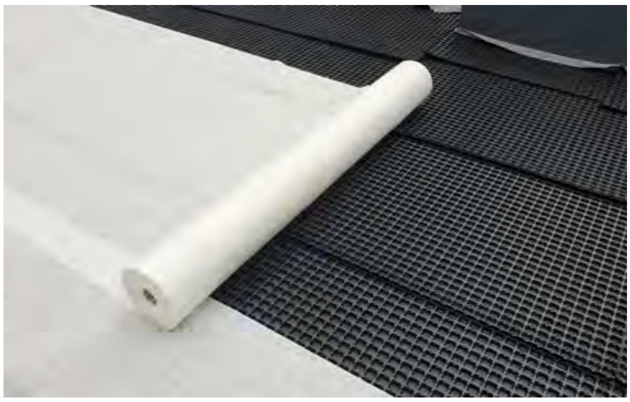
DRAINAGE AND RETENTION LAYER

The drainage and retention layer is designed to control the movement of water from the roof - detaining and retaining water when it falls on the system, and slowing its release from the roof if the storage capacity is exceeded. This layer consists of either mineral materials, prefabricated synthetic filling materials, or material mixes with or without water storage characteristics.

Drainage and retetion layer
Credit: Christian Oberbichler, Dachgrün GmbH

FILTER LAYER

The filter layer is a lightweight, rot-proof material separating the growing medium from the drainage and retention layers, preventing the drainage layer from becoming clogged with fine particulates from the growing medium and minimizing the erosion of the growing medium. The filter layer is made of a water permeable geotextile which can be penetrated by plant roots.



Filter fabric being unrolled over the drainage laye
Credit: Christian Oberbichler, Dachgrün GmbH

PROTECTIVE MEMBRANE/LAYER/FLEECE

The protective membrane is a dedicated layer of geotextile blanket, thermoplastic mat, or protection board which protects the waterproofing membrane from damage during construction and after completion of the project.

Protection and retention layer
Credit: Christian Oberbichler, Dachgrün GmbH

ROOT BARRIER

A root barrier is a layer of material that is either physically or chemically resistant to root penetration, and serves to protect the waterproofing membrane. Some waterproofing systems can even serve as root barriers. These barriers are generally sheets of synthetic materials like high density polyethylene (HDPE) or polypropylene (PP) or copper based foils or impregnated fabrics.

Waterproofing membrane being installed
Credit: Christian Oberbichler, Dachgrün GmbH

WATERPROOFING MEMBRANE

The waterproofing (roof-sealing) membrane is a layer of material that is able to resist hydrostatic pressure for periods of time (RCI) which, in conjunction with other elements of the waterproofing system, prevents water from entering the building and facilitates, and has to comply with the standard requirements.

Prefabricated tray grown plants
Credit: Christian Oberbichler, Dachgrün GmbH

2.2. SOLAR ENERGY TECHNOLOGIES

Green roof beneath solar PV array
Credit: Kevin Samuelson, Colorado State University Spur

Solar energy generation broadly describes the act of converting the photons from sunlight into usable energy through a photovoltaic panel, a solar thermal collector or both technologies combined in one panel/collector (PVT). Fundamentally, solar energy is the capture and conversion of sunlight into heat, electricity , or both. Different solar technologies provide different types of energy. The two major types of solar technologies are photovoltaic (PV) systems and solar thermal energy (ST) with the main difference being that PV generates electric power whereas solar thermal supplies heat.

The amount of solar energy, either electrical or thermal, which can be generated at a given installation is dependent on a number of factors such as location; time of day; season; local landscape; and local weather patterns. Similarly, the amount of ecosystem services and site specific benefits delivered by a green roof will be dependent on local climatic conditions, as well as the type of system used, regulations and design objectives.

PHOTOVOLTAICS (PV)

Photovoltaic systems are devices that convert sunlight directly into electricity. These are generally arranged into panels which are then mounted on a racking system in part of a larger array, and can be used anywhere from consumer to commercial grade energy projects.

Photovoltaic panels are made of arranged photoresponsive cells which are joined together in a series to form larger arrays, creating direct current (DC) voltage. Arrays are routed through inverters to convert direct current (DC) to alternating current (AC) which then directs power into batteries or directly into a larger electrical grid. These systems can be installed at grade, on rooftops, or in some instances incorporated into building facades. Arrays can also be mounted in fixed positions and angles, or on motors that allow the tilt and alignment to be adjusted to capture more sunlight.

There are generally two different types of panel compositions - crystalline silicon and thin-film. Considerations around system selection and use ultimately come down to national or local building safety requirements, such as fire performance of roofs and/or walls, and project considerations such as budget, engineering, availability, and aesthetics to inform the best choice of solar energy generation.

Monocrystalline solar panel array
Credit: CEC - Lee County Electric Cooperative

CRYSTALLINE SILICON PANELS

The most common form of solar panels currently on the market are composed of crystalline silicon formed and cut into wafers. Silicon is an effective, abundant, and durable semiconductor which has high conversion efficiency, allowing for more electricity to be generated. Crystalline silicon panels are subdivided into two categories, monocrystalline panels and poly- or multicrystalline panels, with monocrystalline panels being more common.

Monocrystalline panels are made from single crystals of pure silicon which are formed and cut into wafers. Because they use whole, contiguous pieces of pure silicon, they are more durable and consistent than alternatives. However, these panels are more expensive to produce, relying on whole, pure silicon crystals and generate more waste silicon because they are cut to size and need, discarding the excess.

Polycrystalline panels are also made from silicon, but instead of using whole silicon crystals, are fabricated from multiple silicon crystal fragments which are melted and shaped into cells. These panels are much less expensive to produce as they do not require whole silicon, produce much less waste, and still have a high conversion efficiency, although there are several drawbacks when compared to monocrystalline panels. Polycrystalline panels generally have slightly lower conversion efficiency and less heat tolerance because of microfractures in the silicon stemming from the heat welding of disparate sources. Because of the lower conversion efficiency, more panels are needed to match the generative capacity of monocrystalline systems.

All types of Crystalline Silicon panels require a facing and backing that encase the solar cells. The perimeter of the panel is then typically framed to encase the unit together and facilitate handling and installation. The facing is typically glass, but the backing can be either glass or plastic. In terms of fire performance, a glass/glass panel offers higher fire resistance.

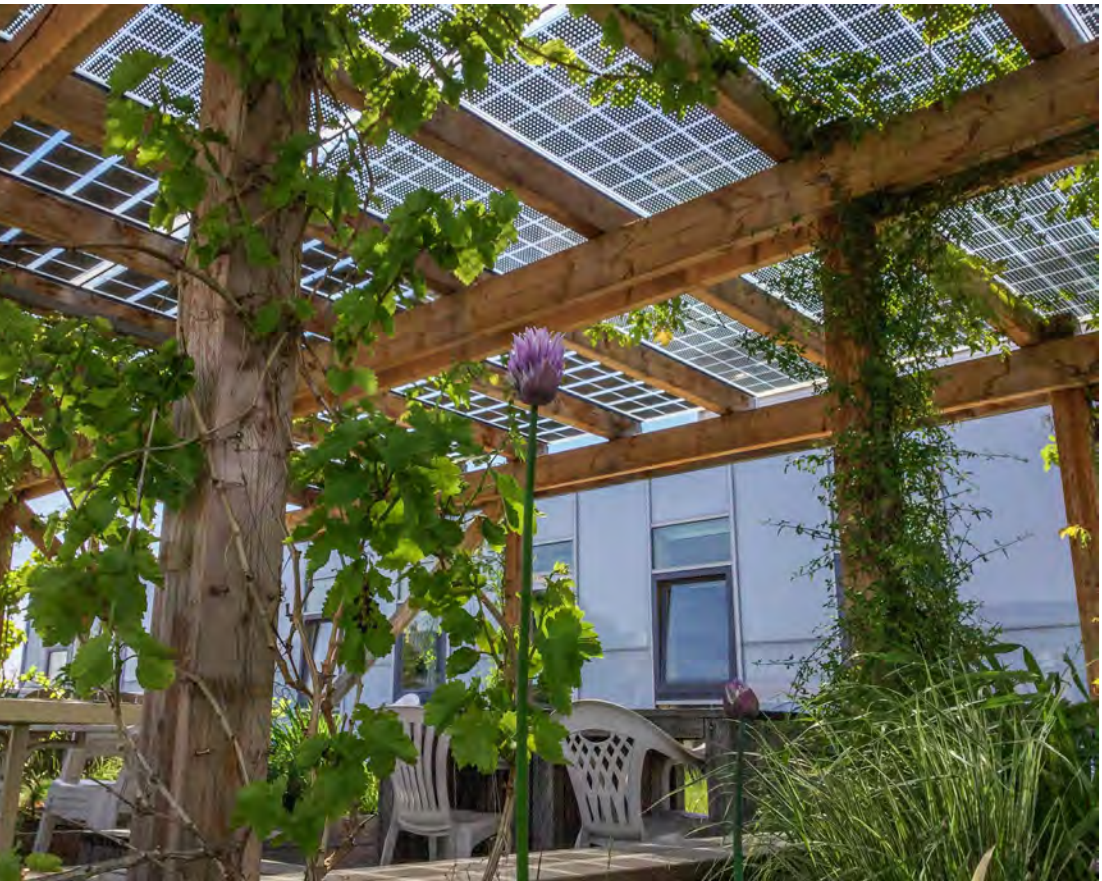
THIN-FILM PANELS

Thin-film photovoltaic panels are thin, lightweight, and flexible. They can be crafted from several different, primarily non-silicon, materials. Unlike their crystalline silicon counterparts, some of these systems do not require racking or mounting systems, and can be installed directly onto a surface. Given their weight, size, and flexibility, these panels have a much wider potential application, and require minimal, structural loading capacity assessments or retrofits to accommodate them. These systems are also generally the lowest cost system available. However, thin-film solar panels generally have the lowest conversion efficiency of the panel options owing to the conversion efficiency of the materials used, particularly when utilizing non-silicon materials, although developments and improvements to non-silicon conversion efficiency are developing as the industry matures.

TRANSPARENT/SEMI-TRANSPARENT MODULES

An emerging trend in solar panel technology development is the use of semi and fully transparent modules. These are similar to thin-film solar panels, constructed of ultra-thin primarily non-silicon photosensitive semiconductive materials, but offer the benefit of a range of transparencies. While these generally have much lower conversion efficiency, they can often be applied over much larger areas in aggregate. The transparency of the panels provides light underneath, enabling the underlying plants to photosynthesize.

Semi-transparent glass modules into which solar cells have been integrated provide improved static capacities and are therefore suitable for use on pergolas or other mounting systems, allowing them to be combined with green roofs or amenity decks. The penetrating residual light can be varied by the spacing between the cells and is available to plants for photosynthesis.



PV roof garden Vienna, Austria
Credit: Dusty Gedge

SOLAR THERMAL (ST)

Solar thermal systems are devices that convert sunlight directly into heat by converting the energy stored in solar radiation. These systems direct sunlight to the heating of a heat transfer fluid - most commonly water mixed with propylene glycol. The captured thermal energy can then be used for hot water generation, residential heating, or industrial processes. The central components of solar thermal systems are the collector, a storage tank, and the hydraulic system that connects them. The contained transfer fluid is generally located behind the solar collector. Once heated, the fluid is pumped through the heat exchanger, which heats water in the storage tank. The cooled transfer fluid is then pumped back up to the collector to be reheated.

The collected heat can be utilized for various purposes - most commonly hot water generation and space heating in single or multi-family homes. Other types of solar thermal applications include Solar District Heating (SDH) and Solar Heat for Industrial Processes (SHIP), both of which require much larger collector areas and/or storage volumes than small-scale residential systems.

Solar thermal systems differ primarily through the type of collector used. The two most common collectors are *flat plate collectors* and evacuated tube collectors. Less common collectors include *hybrid photovoltaic thermal (PVT)* and other more specialized collectors.

FLAT PLATE COLLECTORS (GLAZED OR UNGLAZED)

Thin-film photovoltaic panels are incredibly thin, lightweight, and flexible. They can be crafted from several different, primarily non-silicon, materials. Unlike their crystalline silicon counterparts, these systems do not require racking or mounting systems, and can be installed directly onto a surface. Given their weight, size, and flexibility, these panels have a much wider potential application, and require minimal, structural loading capacity assessments or retrofits to accommodate them.

These systems are also generally the lowest cost system available. However, thin-film solar panels generally have the lowest conversion efficiency of the panel options owing to the conversion efficiency of the materials used, particularly when utilizing non-silicon materials, although developments and improvements to non-silicon conversion efficiency are developing as the industry matures.

EGlazed flat plate collectors mounted on a flat roof
Credit: Gasokol GmbH

Glazed flat plate collectors mounted on a flat roof
Credit: Gasokol GmbH

EVACUATED TUBE COLLECTORS

Evacuated tube collectors consist of a series of evacuated glass tubes, the interior of which is covered with a dark-colored absorber layer, which surrounds the pipes containing the heat transfer fluid. The evacuation ensures a higher energy yield than with flat plate collectors, and lets the collector operate at higher temperatures. Evacuated tube collectors also operate more efficiently in winter, when solar exposure is lower. However, this type of collector is generally more expensive than flat plate alternatives. Evacuated tube collectors comprise 61% of the global installed capacity of ST systems, and are the predominant system in Asia, in particular in China.

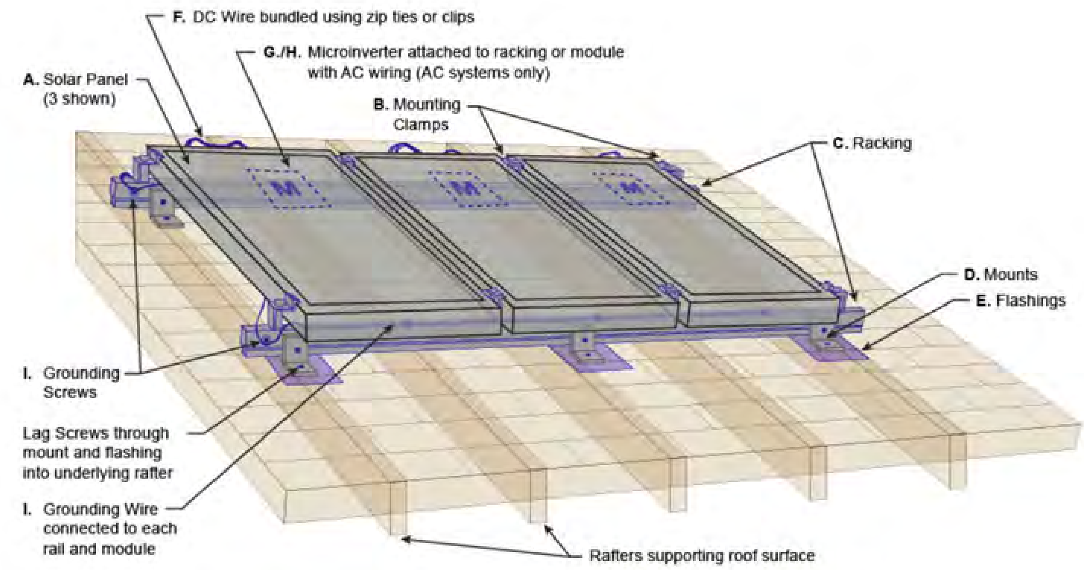
HYBRID PHOTOVOLTAIC THERMAL (PVT)

Photovoltaic Thermal collectors combine PV modules and ST collectors to produce both heat and electricity at the same time. Functionally they resemble flat plate collectors, but instead of using a metal sheet absorber, a PV module is used. During operation, the solar thermal components of the collector cool the PV module by transferring the heat away from the cells, improving PV efficiency.

As of 2025, PVT systems are a relatively novel approach to solar energy production, although it is growing in market share. Per the International Energy Agency's Solar Heating and Cooling Programme, 1.6 million square meters (17.2 million square feet) of PVT are in operation globally.

Hybrid PVT collectors on a green roof
Credit: Alexander Friedrich

STANDARD COMPONENTS OF A SOLAR SYSTEM



Anatomy of solar mounting system
Credit: American Solar Energy Society

Pavers used to ballast solar panels are placed on the green roof along with electrical conduit.
Credit: Steven Peck

MOUNTING STRUCTURE

The mounting structure holds and joins panels, for example a rigid metal frame affixed to the roofing structure or a pergola. Mounting systems require some degree of reinforcement or ballasting to ensure that panels can withstand high windshear, particularly on rooftops.

INVERTERS

A critical component of photovoltaic systems are the inverters, which allow for the conversion of Direct Current (DC) power generated by the panels or from batteries into Alternative Current (AC) which can be transmitted or utilized at an outlet.

STORAGE SYSTEM

Storage systems such as batteries, thermal tanks, or metered connections to a larger utility grid reduce waste from unutilized power, and can be employed for emergencies or redundancy in the event of lower power output or heating disruptions.

PANEL ORIENTATION

Panel layout and orientation will directly impact generative capacity and peak generating periods in relation to the average exposure to the sun.

OBLIQUE PANELS

The standard orientation and layout for solar panels in an array. Solar panels operate most efficiently when their face is directly exposed to the sun. In this orientation, panels are both tilted and oriented at an angle and position to maximize solar collection and energy generation annually based on the elliptical path of the sun. Panel orientation is thereby maximized against two points:

- the Elevation Angle, or vertical tilt relative to the ground;
- the Azimuth Angle, the horizontal position relative to the equator.

In general, the Elevation Angle will be equal to the installation's latitude, although this angle can change slightly with the seasons. After orienting panels towards the equator, the Azimuth Angle will be based on the magnetic declination, or the difference between true north/south and magnetic north/south of the installation.

Oblique panels on a solar green roof
Credit: Permavoid

Vertical Bifacial Panels on an Oslo office building
Credit: Over Easy Solar

VERTICAL AND BIFACIAL PANELS

An innovative approach to combining solar photovoltaic (PV) systems with green roofs has emerged in recent years: the use of bifacial vertical solar panels. Unlike traditional tilted solar panels, which can obstruct rain distribution and create uneven microclimates, vertical bifacial panels allow uninterrupted rainfall across the entire green roof surface. This helps maintain consistent soil moisture levels and prevents concentrated water runoff that could influence plant growth. While the panels do create some shading, this is spread evenly across the roof, reducing the risk of excessive drying and benefiting plant health. This enables the use of the full roof area for both green roof and PV.

For low-growing sedum roofs, vertical panels can be installed with a clearance of just 10–20 cm above the soil. For biodiverse or taller vegetation roofs, higher-clearance mounting solutions are available to accommodate the plant life beneath.

Another method of enhancing conversion efficiency that is becoming increasingly affordable and prevalent is the utilization of bifacial photovoltaic panels. Bifacial panels utilize light from both sides of the panel, creating opportunities for additional generation through diffuse or reflected sunlight on the shadowed side of the array. Although generally more expensive than monofacial panels, these panels have a higher generative capacity from the additional light utilization.

Vertical Bifacial System
Credit: ZHAW, Dreisiebner

Panel orientation is still a consideration, however maximizing generation is easier since there is more surface area. Bifacial panels may be oriented vertically above the roof, rather than at an angle. This way they capture sunlight all day except when the sun is directly overhead allowing for greater solar exposure for green roof plants.

Vertical bifacial solar green roof on a multi-unit apartment building in Amstelveen, Netherlands
Credit: Over Easy Solar

In addition to their ecological benefits, vertical bifacial panels offer a unique and complementary energy generation profile. When oriented east-west, they produce peak electricity in the morning and late afternoon, aligning with typical building energy demand patterns. This can enhance self-consumption rates and reduce reliance on external energy sources, making them a strategic choice for improving energy efficiency.

Vertical Bifacial Panels on an Oslo office building
Credit: Over Easy Solar

3. BENEFITS OF SUSTAINABLE ROOFTOP SOLUTIONS

When considering an integrated approach, it is important to take into account the various performance values of all the technologies used. To maximize the benefits of integrating solar and green roof technologies, benefits must first be identified and understood, and a comprehensive understanding of where they intersect must be achieved.

3.1. BENEFITS OF GREEN ROOF SYSTEMS

Green roofs are high performance engineered systems that provide analogs to the performance aspects of the natural world. They are designed to confer a wide range of ecosystem service benefits, from positive impacts to the local ecology, water management systems, temperature, air quality, and more.

Green roofs benefit not just the building owners and occupants, but the broader neighborhoods and cities that they are in. The precise performance benefits of green roofs are a function of many different factors, only some of which may be controlled by the design team. These include the following:

- Type of green roof system (substrate depth and composition, plant diversity, etc);
- Requirements of public policies;
- Building attributes(i.e.,new/retrofit, structural loading capacity, installation access, sun/shading, roof slope etc);
- Local climatic and contextual conditions (temperature, precipitation, sunlight, etc);
- Client objectives (i.e.,budget, viewable or accessible, aesthetics, water management);
- Project design and installation (i.e.,landscaping, placements, continuity);
- Integrated systems (i.e., solar PV/thermal, rainwater capture, greywater use); and
- Frequency and quality of the maintenance provided.

PV roof garden on a residential building
Biotope City Wienerberg, Vienna
Credit: Irene Zluwa

Credit: Isabel Mühlbauer

The following list of performance areas, indicators, and values are drawn from scientific research on green roof projects from across Europe and North America, as well as digital modelling summarized in a recent publication (Benefits of Green Buildings, EFB 2025). Because of the variability in system, location, context, and conditions, performance results cannot be considered universal. However, they provide an indication of what is generally possible. This underscores the need to scale up green roof implementation to take advantage of as wide an array of benefits as possible. Broadly speaking, green roof benefits can be subdivided into two categories - public benefits, or those which impact the public realm and community, and private benefits, or those which impact private interests such as building owners or businesses.

PUBLIC BENEFITS

Public benefits of green roofs are those realized by a public entity, generally a regional government, municipality, or community. These benefits tend to be more abstracted, involving considerations of ecosystem services, infrastructure functionality, and climate metrics. Public benefits are no less important than private benefits and justify the many supportive public policies in place around the world. The public benefits at scale can be quite profound and have significant financial implications.

Performance hall named Colisee - Chartres,France
Credit: Le Prieure

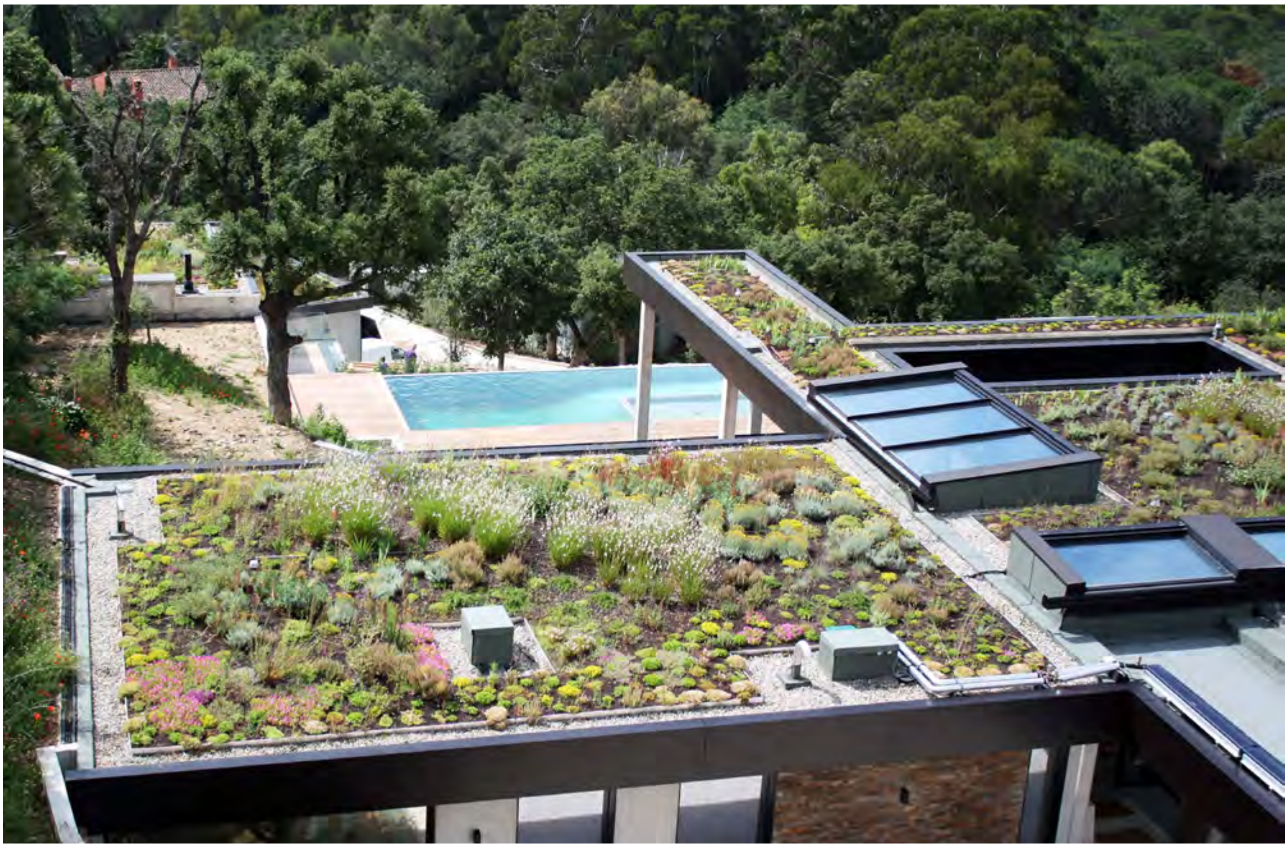
THERMAL COMFORT

The Urban Heat Island (UHI) effect describes the circumstances by which urban environments experience hotter and dryer conditions than their less developed surrounding areas. The intensity of the UHI effect is influenced by a number of factors, but the primary driver is the amount of densely packed, impervious built surfaces in a given area, primarily roads, parking lots and roofs. These surfaces absorb heat throughout the day and radiate that heat out in cooler periods, maintaining high ambient temperatures. At the same time, because of the impermeability of these surfaces, any water introduced is either quickly evaporated or rapidly conveyed out of the area through municipal sewers. This creates and reinforces a cycle of very hot, dry conditions in urban interiors, which has cascading effects on energy loads for cooling, water requirements, and human comfort. It also exacerbates the impacts of climate change in cities, magnifying heat waves. Green roofs can help ameliorate these effects by reducing the amount of impervious surfaces, lowering surface temperatures, retaining moisture in a given area, and introducing a cooling effect through the release of water vapor into the surrounding area.

SELECTED RESEARCH FINDINGS
THERMAL COMFORT

- Day to night temperature amplitude of 50 K for bitumen roof compared to 10 K for green roofs in a pannonic climate. (Senatsverwaltung für Stadtentwicklung Berlin, 2010)
- In a specific continental climate project, the annual temperature amplitude from -5°C in winter and +70°C in summer was changed by implementing a retention wetland roof to 10°C in winter and +30°C in summer. (Pfoser, 2014)
- Other international studies report larger temperature differences comparing green roofs to reference roofs, with a maximum of 33°C, continental to subtropical climate. (DeNardo, 2005) (Jim, 2011) (Takebayashi, 2008)
- Heat flow through the building roofs in summer can be reduced by approximately 70-90% via green roofs in continental to sub-tropical climates. (Liu, 2005)
- The temperature difference between conventional and green roofs in summer is about 12 °C, whereas it is 4 °C in winter under mediterranean conditions. (Bevilacqua, 2016)
- Teemusk and Mander (2009) analysed the temperatures under a green roof (10 cm thick) and under a grass roof (15 cm thick) in comparison to conventional roofs with bitumen and metal coverings. The temperature profile was similar: unwanted higher temperatures on the surfaces of the green roofs did not lead to a significant increase in temperatures under the substrate layers. The difference between the temperature amplitude under the substrate layers of the green roofs and the surfaces of the conventional roofs was 20 °C on average. In autumn and spring, the soil layer of the grass roof had higher temperatures and a lower amplitude than the substrate layer of the green roof, which cooled down more. In winter, the temperatures under the substrate layers of the planted roofs were higher than the surfaces of the conventional roofs; the average amplitude was 1 °C and 7-8 °C.
- In one study, a temperature reduction of up to 3°C was generated for Chicago due to green roofs. (Smith & Roebber, 2011)
- In one city quarter study related to pannonic/continental climate, a moderate greening scenario of roofs and walls and other green infrastructure elements resulted in a reduction of 2.2°C in air temperature but up to 22.3°C PET reduction, significantly improving thermal comfort. (Note: the physical equivalent temperature (PET) is a more realistic performance indicator than air temperature because it measures individual thermal comfort of humans derived from a set of parameters in a given situation). (Biotope City, 2019)
- Beradi (2016) found out that an increase in the amount of leaf area on a green roof leads to a reduction in temperature of 0.4°C at the pavement level during the day, with a greater reduction in temperature occurring at the roof level. In addition, the green roof has a cooling effect on the floor underneath the green roof.

Garage roof in Leipzig with a small pond.
Habitat and cooling
Credit: BuGG



Green roof on a private house in the South of France, aiming to provide cooling in summer
Credit: Biotopes Creation

- Dong et al. (2020) analyzed Landsat 8 data for the city of Xiamen in China. Between 2015 and 2019, approximately 540,000 m² of green roofs were installed in this city. With the relatively coarse pixel grid, it was determined with an accuracy of about 1,000 m² that a temperature reduction between 0.4 °C and 0.9 °C resulted from green roofs based on the satellite images.
- If green roofs are deployed widely, the average air temperature of the related area can be reduced by 0.3–3.0 °C. (Santamouris, 2014)
- The results demonstrated the ability of a vegetated roof to notably contribute to the mitigation of UHI in summer without penalizing the thermal performances of the roof in winter, mediterranean climate study. (Bevilacqua, 2017)
- Evaporation of partially covered intensive green roofs (utilising large scale planters) of 200 l/m² during one vegetation period. (Schmidt, 2003)
- Test by Christen & Vogt (2004) for central European cities:
  - Utilising a 90-100% green space coverage, 80% of the available energy originating from the sun (global radiation) is transformed into evaporation on the earth's surface.
  - With green space coverage from 0-30%, only 20% of the energy transforms into evaporation (therefore cooling).
- Depending on water availability, green roofs evaporate more than 400 l/m² annually (Gijsbert Cirkel, 2018).
- The cooling performance leads to an average reduction in the ambient air temperature of 1.34 °C for green roofs. (Manso, 2011)
- Evapotranspiration is composed of evaporation and transpiration, removing heat through convection and evaporation, accounting for 51.5% of heat dissipation in green roofs in China. (Xiao, 2014)

BIODIVERSITY IMPROVEMENTS

Although engineered systems, green roofs can closely emulate natural environments. In addition to their introduction of permeable surfaces into largely impermeable urban environments, they can introduce important natural analogs, replacing biotopes lost to development. As a green roof establishes and matures it will increasingly accumulate soil organisms and other species which use these ecosystems. Intensive green roofs in particular can serve as a valuable urban stepping stone habitat for pollinators and their food chain, such as birds and bats. These animals can utilize green roofs as corridors and connections to other green spaces, accessing additional food and nesting sites that would otherwise be inaccessible. Biodiverse green roofs, those designed specifically to provide critical biodiversity enhancing elements, can support a wide range of plant and animal species through their structure, layout, and supplementary elements such as shelter spaces, logs, stones of different sizes and water features. Research on green roofs that are over 100 years old have shown that they are capable of supporting and/or reintroducing rare species to an environment, and are increasingly being considered by municipalities for species protection programs.

Residential building, Berlin, Germany
Credit: Optigrün International AG

SELECTED RESEARCH FINDINGS
BIODIVERSITY IMPROVEMENTS

- Green roofs can harbor over 100 different species. (MacIvor, 2010)
  - 18 different wild bee species found on four solar green roofs in Vienna area (Weiss-Tessbach, 2019)
  - Discoveries from Switzerland:
    - Dry grass habitat green roof: approximately 80 beetle species.
    - Sedum roof: approximately 5-10 beetle species.
    - A total of over 300 beetle species have been found, 30 of them on the Red List.
    - Discovery of over 175 plant species (including 9 species of orchids) on a 100-year-old roof.
- 90 different wild bee species on 9 green roofs (extensive to intensive) in Vienna. Wild bee diversity and abundance was strongly positively affected by increasing forage availability and fine substrates. Furthermore, the installations of areas with finer and deeper substrates showed the benefit for ground nesting and eusocial wild bees. (Kratschmer, 2018)
- The crested lark (Galerida cristata), whose populations are shrinking worldwide, is observed regularly on a long-term study as the main bird species that benefits from biodiverse green roofs in Vienna. (Krampl, 2016)
- From a group of 37 native plant species (planted, sowed or spontaneous, during a 6-year period), ca. 40% were able to thrive

in extensive green roofs under Mediterranean conditions. (Rodrigues, 2024)

- The abundance of pollinators on intensive and semi-intensive roofs is comparable to that observed in other urban green spaces. Soils on green roofs have a comparably high level of microbial biomass (129.4 µg DNA/g soil), about twice the average level measured with the RMQS benchmark (59.2 µg DNA/g soil). (Barra, 2021)

Thermal solar green roof near Paris (Village Delage, France)
Credit: Topager

Young seagulls on a roof near Hamburg
Credit: BuGG

AIR QUALITY AND POLLUTANTS, BIOMASS

Air quality management is of increasing concern, particularly in the face of worsening climate impacts such as wildfires, heat domes, and severe storms. As these climate forces settle over municipalities and regions, airborne pollutants - volatile organic compounds (VOCs), particulate pollution, and other airborne contaminants emitted by vehicles, buildings, and industry - become trapped by restricted air flows. Urban vegetation and soils like those found on a green roof, bind and absorb fine dust and other particulates, filtering them out of circulation. Similarly, green roofs bind and store carbon over time, in growing media and plants, storing and utilizing it for photosynthesis. Finally, the harvesting of green roof derived biomass can be used to contribute to regenerative energy concepts on a district scale.

SELECTED RESEARCH FINDINGS
AIR QUALITY AND POLLUTANTS, BIOMASS

- 7.3 g/m²/year nitrogen and sulphur oxides binding in Chicago. (Yang, 2008)
- 10-20% higher particulate filtering effect in comparison to non-vegetated roofs in Berlin. Extensive green roofs fine particulate binding maximum 10 g/m²/year. (Heusinger & Weber, 2017)
- Brunnetti et al (2021) investigated the ability of green roofs to convert nitrogen-rich water. As a result, 94% of the nitrogen introduced was washed out on a non-greened green roof (substrate only) and 67% of the nitrogen introduced on a green roof with vegetation. This means that up to 32% of the nitrogen introduced could be converted. The amount of nitrogen conversion could be increased by selecting suitable plants and avoiding periods of water stress.

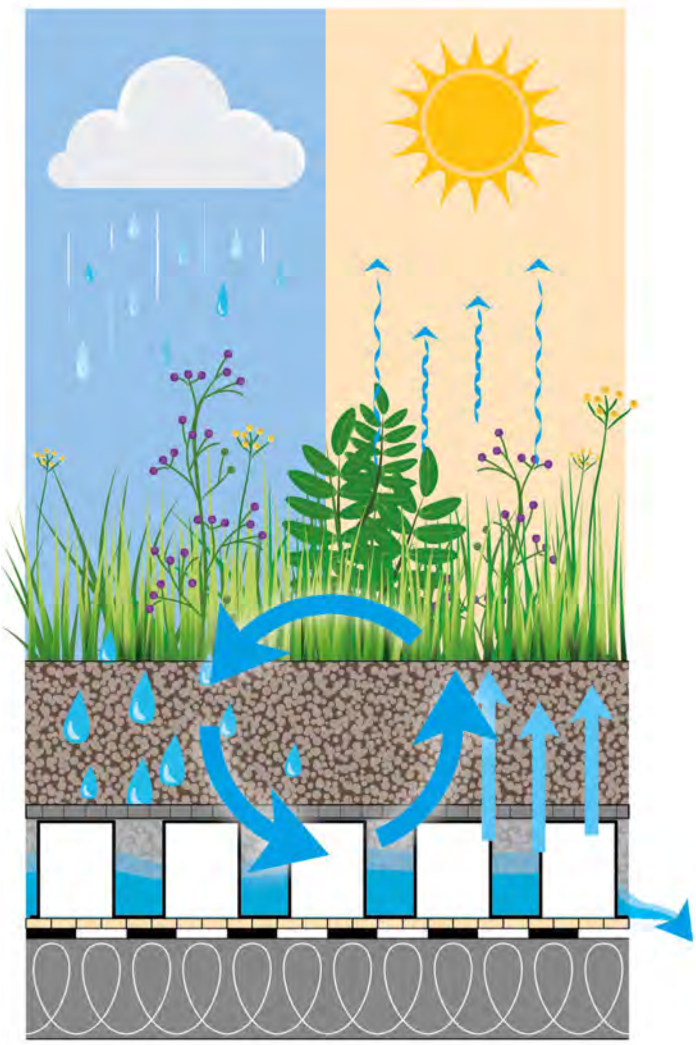
- Kuronuma et al. (2018) calculated the payback period of green roofs based on their CO_2 storage capacity. The CO_2 emissions generated during their production were also considered. The results showed that the payback period for extensive greenroofs ranged from 5.8 to 15.9 years. Therefore, they contribute to CO_2 reduction over their lifespan.
- Unirrigated extensive green roofs carbon absorption of 0.313 kg/m²/year (313 kg for 1000 m² green roof). (Heusinger & Weber, 2017)
- Extensive green roofs absorb approximately 0.5 kg of CO_2 per m² per year. (Getter, 2009)

Extensive green roof in the city center of Stuttgart
Credit: BuGG

WATER MANAGEMENT

One of the primary strengths of any green roof system is its ability to detain, retain, and slow the flow of stormwater, mitigating stress placed on sewers and water treatment facilities and local water cycles. As the effects of climate change intensify, both extreme storms and extreme droughts will become more frequent. Municipalities are forced to contend with water stress which is often exacerbated by many other impacts of climate change. A green roof's ability to capture water where it falls keeps that water out of stormwater and/or wastewater treatment infrastructure and unlocks it for use by plants and animals. As excess water enters existing treatment infrastructure, it is cleaner than runoff from traditional flat roofs, because particulates and contaminants are trapped by the green roof, much in the same way that airborne particulates are.

Furthermore, green roofs unlock the potential of the capture and reuse of untreated rainwater for irrigation and maintenance purposes, relieving pressure on fresh water systems. The principles of a sponge city, one that is highly porous, absorptive, and water efficient are built on the basic functionality of a green roof. With the scaling up of green infrastructure on roofs, walls and at grade, combined with temporary storage, communities can protect themselves more effectively from extreme rainfall events, avoiding the disruptive and costly impact of flooding.



Water cycle on a green roof
Credit: BuGG

SELECTED RESEARCH FINDINGS
WATER MANAGEMENT

- In extensive green roof substrates, water storage depends on substrate thickness, composition, the type of drainage system, and the intensity of precipitation on a yearly average. Therefore, it varies between 0 (for rainfall > 40 mm h-1) and 100% (for rainfall < 10 mm h-1), with average delay of 3 to 5 hours. (Fournier & Boivin, 2016)

- 65-70% of the yearly precipitation is retained by extensive green roofs with a substrate depth of 10 cm, while a gravel roof retains 18%. (Köhler et al., 2018)
- Intensive green roofs retain between 60-99% of the total precipitation, depending on their build-up, with a storage capacity of 30-160 l/m². (Appl & Mann, 2012)

The green roof of this laboratory has been designed to manage rainwater in order to promote evapotranspiration by plants. Credit: Sopranature

- Around 80% of the plant species studied were found to be tolerant to the use of greywater. (Jauch, 2014)
- Extensive green roofs result in an average reduction of stormwater runoff by 58%, while intensive green roofs reduce it by 79%. The peak runoff is also reduced by an average of 71% with extensive green roofs. (Manso et al., 2021)
- A study investigated the climate change adaptation benefits of green roofs through „a systematic review process and an in-depth investigation and statistical analysis of a total of 123 scientific studies.“ The results showed that all studies found that green roofs provide a certain level of stormwater retention and delay the onset of runoff and peak runoff. On average, different types of green roofs retained about 40% of stormwater during the winter months and up to 73% during the summer months. For individual events, values of 60% stormwater retention, peak runoff coefficients of 0.37, and delays in the onset of runoff and the runoff maximum of 235 and 250 minutes, respectively, were achieved. Parameters such as substrate thickness, pre-moisture, the age of the roof, slope, amount of rainfall and rain intensity, season, latitude, plant species, and substrate composition can influence effectiveness. The comparison of regulations for the hydrological design of green roofs showed wide ranges in the calculation of effectiveness. In nearly all comparative calculations, the currently relevant methods in German planning practice showed increased flood protection due to underestimating the retention capacity of green roofs, while also highlighting the potential for systematic over dimensioning of downstream drainage systems. (Richter, 2022)
- The average rainfall retention for 76 observations in green roofs under Mediterranean climate was 62% and the rainfall peak attenuation was 75%. (Silva et al., 2021)
- There are wide variations between roofs in terms of their water retention capacity: 6 L/sq.m. for the least absorbent roof compared with 532 L/sq.m. for the most absorbent. (Barra et al., 2021)

PRIVATE BENEFITS

Private benefits of green roofs are those realized by a private entity, generally a developer, building or unit owner, or facility manager. These benefits tend to be more easily quantified than public benefits, as they are often realized financially at a smaller per unit or building scale.

Needs	TEMPERATURE		LIGHT	VENTILATION
Action taken	Adiabatic cooling	Heat storage, buffer effect	Outside shading	Air preconditioning natural/ controlled ventilation
Effects of exterior building greening	• Shading and evaporation by plants prevents building surfaces/interior spaces/absorbers from heating up	• Reduction of building shell heat losses • Reduced wind pressure	• Shading protects against glare • Functions of technical systems taken over by plants • Translucent, depending on selected plants	• Air purification • Air humidification • Cooling of air inflow in summer
Savings Benefits	Cooling cost savings	Reduction of heat transfer	Reduced primary energy needs, savings on maintenance of technical systems	Auxiliary system for/replacement of air-conditioning systems

Needs	ELECTRICAL ENERGY	WATER	MATERIALS LIFECYCLE ASSESSMENT
Action taken	Green energy	Greywater purification and use	UV ΔT Carbon footprint
Effects of exterior building greening	• Increase in efficiency of technical systems • Support for active and passive energy harvesting	• Tap water savings • Cooling • Pollutant filter • Design feature	• Carbon sequestration • O_2 production • Reduction of energy needs • Particle filter • Protection of building components, prolongation of their service life
Savings Benefits	Efficiency increase of PV systems, savings on energy for cooling, harvesting of biomass	Savings depend on the system deployed	Savings on roofing/facade materials, longer service life

Credit: Nicole Pfoser, adapted by Isabel Mühlbauer

THERMAL PERFORMANCE

Green roofs enhance the annual thermal performance of a building by providing an insulative layer in colder periods, and creating a cooling effect through evapotranspiration during warmer periods when air conditioning is used. The multiple additional layers of a green roof system serve as a barrier to heat loss through the building envelope, serving as additional insulation alongside the standard insulation installed in the building envelope during construction. Additionally, as water moves through the green roof system - a combined process called evapotranspiration where water is evaporated through the substrate and transpirated from the plants during respiration - it is released into the air as water vapor and the process absorbs heat when it changes from a liquid to a gaseous state thereby cooling the surrounding environment. This allows the green roof to maintain a temperature barely above the ambient air temperature, while a non-greened roof would have a significantly higher temperature due to absorption of solar radiation by the roof material and its transfer to the surrounding air.

Comparative studies on temperature, water balance, evaporation near Vienna
Credit: BuGG

SELECTED RESEARCH FINDINGS
THERMAL PERFORMANCE

- Improved winter insulation effect of the roof structure of 2-10%.(Senatsverwaltung für Stadtentwicklung Berlin, 2010)
- With 10 cm substrate depth, an extensive green roof achieves an additional R-value (heat transfer resistance) of 0.14 to 0.40 m^2K/W under maximum water saturation, depending on the type of substrate. This corresponds to approx. 6 mm to 16 mm of conventional insulation of the thermal conductivity group (WLG) 040. (Köhler & Malorny, 2009)
- 3-10% less heat loss in winter with a green roof (installation height 10-15 cm) compared to a gravel roof. (Scharf et al., 2012)
- Zhao et al. (2015) studied the impact on heat flow through a green roof and a conventional roof in winter. The heat transfer on the green roof was reduced by 23% compared to the conventional roof, and by 5% with a snow cover on top.
- Penalvo-Lopez et al (2020) measured the cooling energy consumed by a green roof compared to a conventional roof on the Mediterranean coast of Spain. On a standard summer day, 30% of the cooling energy could be saved, and on a winter day 15% of the heating energy could be saved.
- In winter, extensive green roofs lead to energy savings of up to 8% on already insulated roofs, while intensive green roofs save up max. to 10%. In summer, however, green roofs can save up to 84% of energy. The thicker the substrate layer, the greater the insulation performance. (Zirkelbach & Schafaczek, 2013)
- The reductions of heat loss from roofs in winter are about 10–30%, and in summer, heat flow is reduced by 70–90%. (Liu & Minor, 2005)

Comparison with and without protection by a green roof in the Karlsruhe metropolitan area
Credit: BuGG

STRUCTURAL PROTECTION

In general, green roofs act as a protective buffer against many of the physically and chemically destructive interactions of the surrounding environment which may otherwise shorten the lifespan of a building's envelope, waterproofing, and other components. Environmental ballistics such as hail and wind debris, solar degradation from continuous exposure, or water damage from severe storms can all wear down or compromise the structural integrity of a building's seal leading to costly repairs, higher insurance premiums, or further damage to the building's structure. Mechanical damage to waterproofing is another cause of leakage, which can be prevented by green roofs. Green roofs serve as an effective measure to protect building stock and increase longevity of waterproofing.

SELECTED RESEARCH FINDINGS
STRUCTURAL PROTECTION

- The hail resistance of green roof structures and the underlying roof waterproofing have shown that green roofs with a substrate layer thickness ≥ 80mm have a high resistance. In compliance with the minimum requirements of ÖNORM B3691 and L1131, the roof waterproofing does not suffer any damage. Thus, the green roof structure is an effective and sustainable protective layer to prevent hail damage to the roof waterproofing and thus prevent water ingress into the interior of the building. (Manso et al., 2021)
- BuGG - Bundesverband GebäudeGrün (2021) found in a survey conducted together with the ZVDH - Zentralverband des Deutschen Dachdeckerhandwerks among roofers that the majority of respondents stated that the lifespan of a roof sealing until the first major repair was over 20 years, both under a green roof and under a solar green roof. The life span of a conventional roof sealing until the first major repair was mostly stated as 16-20 years, the life span of a non-green roof seal with a PV system was only stated as 11-15 years.
- The green roofs also reduced the maximum roof membrane temperature in the summer by more than 20°C and daily temperature fluctuations experienced by the roof membranes by about 30°C. These reductions will lower the ageing and thermal stresses associated with temperature fluctuations, thus contributing positively to membrane durability. Preliminary observations and membrane temperatures recorded also suggest that green roofs could likely improve membrane durability by reducing heat aging, thermal stresses, ultra-violet radiation and physical damages. (Liu & Minor, 2005)

RETURN ON INVESTMENT

A building's return on investment is a critical consideration for developers, building owners, and facility managers. Balancing upfront costs and ongoing expenses against an anticipated payback structure and timeframe can be a challenging and variable process. Green roofs can assist in the optimization of multiple return considerations - improving a building's energy efficiency profile, enhancing building marketability through the creation of amenity spaces, and enhancing property values through sales and lease-out premiums.

Decades-old rooftop garden in Stuttgart still used as a break area
Credit: BuGG

SELECTED RESEARCH FINDINGS
RETURN ON INVESTMENT

- The construction costs of a (green) roof amount to about 1,3 % of the total construction costs of buildings. In multi-storey residential buildings, the cost share of the green roof can even be as low as 0.4% of the construction costs. (Freie und Hansestadt Hamburg, 2017)
- 5000 m² roof with multifunctional green roof can save up to €6,000 in electricity costs per year with rainwater harvesting and the cooling effect. (Kaiser, 2008)

- Teotonio et al. (2016) investigated citizens' willingness to pay for green roofs. The results show a higher willingness to pay for accessible green roofs. About this, knowledge of the benefits and accessibility have a major influence on willingness to pay. The recreational benefit is the top priority for the individual, even before aesthetics.
- The green roofs are reported to consume less energy in the range of 2.2–16.7% than traditional roofs during summertime. (Coma et al., 2016)

Solar green roof on a kindergarten in Dresden
Credit: BuGG

NOISE REDUCTION

Similar to the mechanics by which they enhance insulation, green roofs can provide mitigating relief in noise management, particularly in dense urban environments. As our cities densify, the ambient level of noise generated by daily operations from all directions increases. Because of the many layers involved in the construction of even a lightweight extensive green roof as well as the structural variability of the installed vegetation, green roofs have the ability to mitigate and absorb sonic vibrations which are translated through the building envelope into the interior.

SELECTED RESEARCH FINDINGS
NOISE REDUCTION

Noise from above:

- If substrate is dry, then 8 dB; if substrate is moist, then 18 dB. (Pfoser, 2013)
- Extensive green roof (7 cm); at 1400 Hz = 5 dB; at 750 Hz = 20 dB. (Lagström, 2004)
- 15 cm substrate depth at 50-2000 Hz 5-13 dB; at more than 2000 Hz = 2-8 dB. (Connelly & Hodgson, 2008)

Noise from side:

- Extensive greened flat roof, sound source neighbouring street maximum noise reduction at 1000 Hz = 6 dB. (Van Renterghem & Botteldooren, 2008)

Other:

- Comparative measurement of green roofs with different properties to the absorption coefficient Range from 0.2 – 0.63. (Pfoser, 2013)
- Even extensive green roofs with a thin substrate layer can reduce noise in the indoor spaces below. The reduction in sound ranges from 5 to 20 dB. (Manso et al., 2021)
- Measurements from an indoor-to-outdoor sound transmission lab and field evaluations of vegetated roofs of varied substrate depths, water content, and plant species showed that the sound transmission loss of vegetated roofs is greater than that of non-vegetated reference roofs by up to 10 and 20 dB in the low and mid frequency ranges, respectively. (Connelly & Hodgson, 2013)

3.2. BENEFITS OF ROOFTOP SOLAR ENERGY SYSTEMS

Rooftop solar energy systems (PV and ST) confer a number of benefits which can be subdivided into three categories - economic, life cycle, and sustainability benefits.

Project GREENsChOOLENERGY - Testing innovative combinations of solar/greening combinations for cooling buildings and outdoor spaces - Klagenfurt, Austria Credit: Irene Zluwa, GrünStattGrau

ECONOMIC BENEFITS

Solar energy systems reduce the overall dependence on traditional grids and fossil fuel based energy generation, and in most cases, will provide a net financial gain over time. This reduced reliance on large scale infrastructure can reduce electricity and heating costs, hedge against supply and demand based price increases and fluctuations, and enhance property values. Localizing energy and heat generation also protects against larger scale grid failures and service delivery logistics, ensuring more consistent system uptimes and resilience. In many regions government support or energy-as-service delivery models have emerged in a variety of forms, reducing much of the necessary upfront capital costs and investments for system installation.

Depending on the location and system design, a rooftop PV system can produce up to between 120 kWh per year in northern Norway and 350 kWh per year in southern Spain per 1 m^2 (11 ft^2) of roof space covered by panels. Similarly, in the northern hemisphere, solar thermal systems generate an average of between 400 and 600 kWh per square meter (11 ft2) of collector surface per year, with generation rates increasing closer to the equator. This is due to the fact that solar thermal systems are highly efficient (generating on average three times more energy than PV systems), converting approximately 70% of incoming solar energy into usable heat.

Once installed, a solar system generally requires minimal maintenance and has negligible operating costs. Energy generation can be monitored remotely and components are relatively easy to repair or replace. This allows the energy costs and payback periods to be plannable and independent of the often heavily fluctuating prices of energy sources, in particular fossil fuels. Generally, initial cost payback periods are amortized in 5-10 years of system operation, beyond which they provide free energy for the rest of their system life expectancy, generally 25 or more years.

SELECTED RESEARCH FINDINGS
ECONOMIC BENEFITS

- Energy production from PV: between 120 kWh/year (northern Norway) - 350 kWh/year (southern Spain) per m^2 (11 ft^2) of roof space
- Energy production from solar thermal: between 400 and 600 kWh/year per m^2 (11 ft^2) of collector surface
- Payback period: dependent on location and system specifics, but commonly initial cost payback periods can be amortized in 5-10 years of system operation

Vertical Bifacial Panels on an Oslo school building
Credit: Over Easy Solar

LIFE CYCLE BENEFITS

Solar energy systems offer access to clean, renewable, and low cost energy generation. Solar systems do not emit greenhouse gasses or VOCs, do not require specialized materials for maintenance, and can integrate with other heat generators or electrical systems to enhance functionality. The impacts of industrial manufacturing and processing notwithstanding, the fabrication process of solar modules is a relatively efficient one, leading to a product with lower carbon footprints than alternative traditional energy generation technologies. This results in electricity with a very low emission per kWh production profile, particularly when taking into account the entire life cycle of solar modules.

The expected lifespan of PV and ST systems is generally accepted to be 25-30 years (often longer in practice), although this timeframe is expected to grow as technologies develop. Maintenance of solar systems is relatively straightforward, ensuring panels are clean, systems are functioning within anticipated ranges, and connections are secure and free of damage or wear. Within a PV system's lifespan, it is expected that a system owner will have to replace an inverter (the component which converts DC to AC) once. Energy generation occurs locally avoiding costly and resource intensive transmission, and, in the case of ST systems, panels are often locally manufactured, reducing scope 3 emissions. Finally, as systems approach end of life, components can be recycled with increasing efficiency. ST system components are entirely recyclable, while PV panel recycling integrates into municipal electronics recycling programs, with recycling technologies developing to enable full material recyclability.

SELECTED RESEARCH FINDINGS

- Expected lifetime of PV system: 25-30 years
- No greenhouse gas emissions during operation
- Very low lifecycle carbon footprint
- Simple maintenance

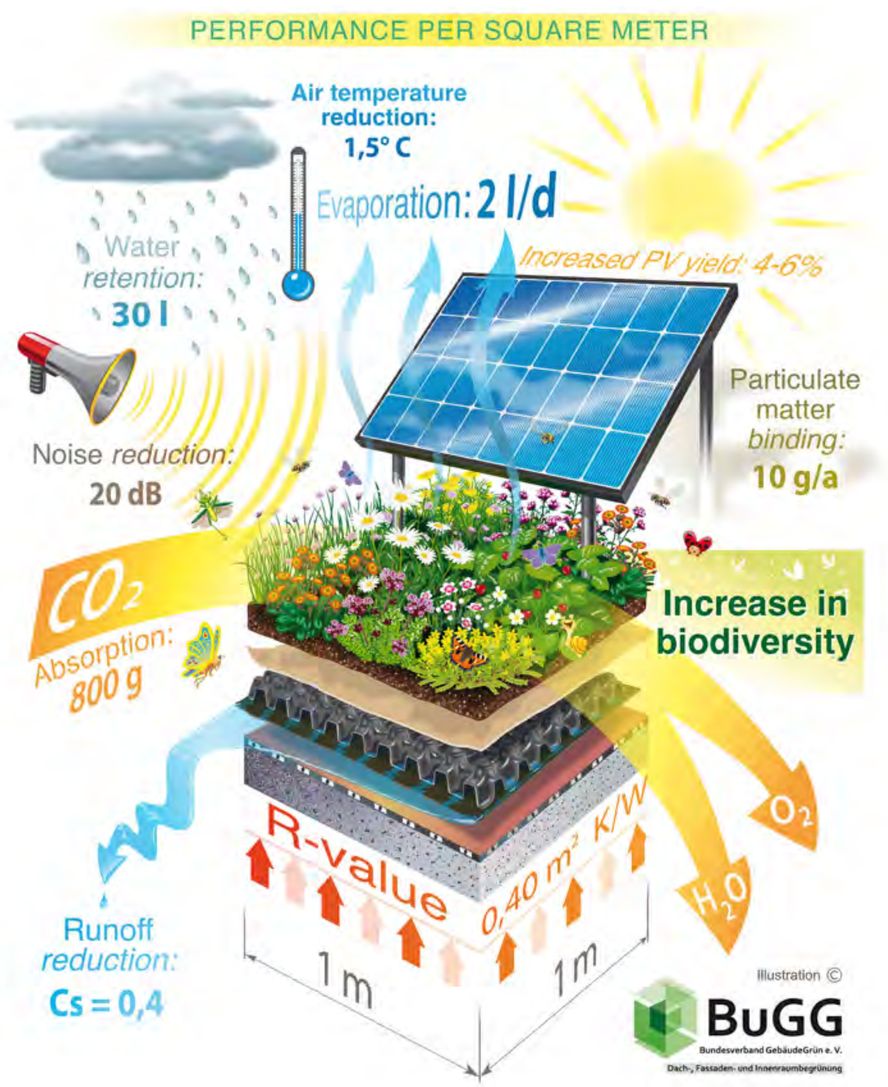
SUSTAINABILITY BENEFITS

Solar energy generation systems address localized demand with localized solutions, reducing transmission lengths and demand allocation. Heating accounts for approximately 50% of total energy consumption globally, and in areas of the world where space heating is necessary in the winter, the share of heat increases to 80%. Fossil fuel based energy generation comprises around 80% of global production, and per the U.S. Energy Information Administration, utility scale net energy generation produces an average of 2.6 kg (5.7 lbs) of CO_2 per kWh, independent of any transmission loss through distribution. Producing heat and electricity close to its end use reduces transmission loss and relieves strain from existing grids and translating to lower emissions. Adding local energy storage with a battery system further reduces grid demand and enhances system delivery efficiency and value. Similarly, ST systems can serve as a foundation for a renewable heating system owing to the ease with which it integrates with other renewable heat sources such as heat pumps or biomass boilers. The flexibility can scale and service a variety of applications, from single or multi-family residential buildings to industrial and district heating considerations.

Leveraging traditionally underutilized building space such as roofscapes for power and heat generation further enhances the value proposition of solar energy systems, taking advantage of low value space for high value infrastructure systems.

Sempergreen's head office in the Netherlands is a laboratory. The roof is planted with a combination of sedums and pollinator-friendly aromatic plants. Since 2024, vertical bi-facial photovoltaic panels have been installed to demonstrate feasibility and study interactions with vegetation. The facade has been planted for over 17 years with a varied palette of plants. Inside, the walls are also planted, for the well-being of employees.
Credit: Sempergreen and Over Easy Solar

3.3. BENEFITS OF SOLAR GREEN ROOF INTEGRATION



Benefits of solar green roof

The development pressures on municipalities to achieve local and regional action targets is extremely high, requiring surfaces and spaces to be increasingly multifunctional. The integration of solar and green roof technologies can be adapted to local needs; can enhance compliance with local regulatory requirements; and focus on different performance benefits. For example, some municipalities may have a higher demand for local energy production due to increasing urban heat islands and a weak local grid, while other cities may focus on reducing stormwater runoff and creating amenity spaces for the enhancement of biodiversity and the public realm powered by local clean energy generation.

The nature of the benefits attainable from solar green roof integration depends on factors such as:
- system design and implementation;
- local regulatory requirements;
- building structure and characteristics.

In many cases, an integrated solution offers substantial performance enhancements while maximizing the per square area benefit output. This approach offers harmonised technology performance and investor safety as well as lower maintenance and care costs. The combination of multiple technological systems requires special design considerations and cooperation across multiple trades but may confer a wide range of additional social, environmental and building level benefits.

These benefits include:

- Biodiversity support;
- Energy Generation Performance;
- Ballasting;
- Integrated Fire Protection;
- Energy Efficiency;
- Lifecycle Benefits;
- Ecosystem Services;
- Green Jobs Creation; and
- Rooftop Food Production.

Aglais urticae on a PV panel
Credit: BuGG

BIODIVERSITY SUPPORT

Solar green roof projects provide opportunities to create micro climates for insects and plants associated with water and shading. The conventional rooftop environment is generally a harsh one for green roof vegetation - high temperatures, higher winds, constant sun exposure, low moisture, and no direct connection to ground water. The installation of a solar system over or amidst a green roof can help mitigate some of those conditions.

Panels or collectors create shade against wind and sun relieving some of the stressors on the vegetation and creating more favorable conditions for plant density and diversity. The reduction in sun exposure and wind shear can also translate into improved water retention as the rate of evapotranspiration ratio is reduced. The addition of solar panels and associated change in exposure and wind stress creates a more dynamic landscape of sun, shade, moisture, and structure, becoming a more direct analog to natural environments. This has been observed to lead to an increase in both floral and faunal biodiversity, creating new spaces for ecological niches and habitats.

Biosolar green roof, Switzerland
Credit: Elisabeth Weiss-Tessbach

Some countries, such as Switzerland, specify biodiversity features for solar integrated green roofs in areas of the roof that cannot support solar panels for one reason or another. This is achieved through a variety of design choices, for example intermittently increasing substrate depths to create hillocks for a varied landscape; or the inclusion of deadwood, sand, or temporary water features to satisfy habitat conditions.

ENERGY GENERATION PERFORMANCE

The cooling effect of green roofs through evapotranspirative processes can benefit an integrated solar system by reducing not just the surrounding air temperature, but panel temperatures as well. Above 25 degrees Celsius solar cells lose efficiency of electricity production. The lower ambient temperatures generated by green roofs can help reduce the operating temperature, keeping them closer to their optimal temperature. The degree to which this effect increases electricity generation ranges from 2 to 8% annually, with the potential for peak energy benefits of up to 20%. These benefits will depend on a number of factors including:

- Climate;
- Panel height;
- Plant species;
- Irrigation; and
- Plant density.

For example, panels that sit too close to the vegetation will limit the circulation of air underneath pitched panels, limiting the cooling effect, although this can be mitigated with specifications for minimum panel heights or using vertically aligned panels. Similarly, different plant species transpire at different rates, so some plant communities may provide more or less impact on cooling, which can be mitigated through the use of a diverse planting palette. A broad plant palette will provide a broader array of performance and benefit, along with enhancing biodiversity capacity. Improved panel energy production helps to reduce the loss of electricity associated with providing space for the underlying green roof.

Furthermore, green roofs aid in temperature management for solar panels - improving generative capacity, while solar panels help provide shade and maintain moisture within a green roof assembly - improving plant survivability and performance. Further syntheses can be leveraged however. By employing bifacial photovoltaic modules which have generative capacity on both sides of the panel, the photovoltaic system can generate electricity not just from the side facing the sun, but also from sunlight reflected off of plants, a measure of reflectivity of a surface known as the albedo. Bifacial modules can experience a 17% higher yield from the higher albedo of silver-leaved plants such as woolly thyme and white rock rose and light-coloured substrates compared to the standard green roof while still maintaining the evapotranspirative benefits.

BALLASTING

A key component in rooftop solar systems is the need for ballast to prevent wind uplift. Solar systems need to be securely affixed to the roof to ensure panels do not move or fall, leading to damage to the building, or damage to the waterproofing. Solar systems need to be weighted down or mechanically attached to some component of the roof or building structure to prevent wind uplift. The integration of a green roof with a solar system can provide ballast without roof penetrations, which are often the source of future leaks, from the combined weight of the substrate, drainage and vegetation layers. In this circumstance panels would avoid penetrating the waterproofing membrane and keep the building envelope secure, as well as provide resistance to wind uplift.

Non-Integrated Ballast
Credit: Steven Peck

Integrated Ballast
Credit: Steven Peck

Vertical panels generally require less ballasting when compared to angled horizontal panels, as they experience less wind uplift because of their orientation and their ballast is incorporated into their racking design. These systems can sometimes create higher wind loads from wind tunnels created by longer rows of panels, depending on panel height and the spacing between rows.

In many cases, systems with especially low panel heights do not require ballast owing to the low uplift forces generated, although this should always be confirmed with local regulatory officials and system manufacturers.

Integrated Ballast
Credit: Bauder

INTEGRATED FIRE PROTECTION

Fire safety is a priority for any construction project, and although in a well designed and maintained solar system the fire risk is limited, it should still be a consideration as it is with any electrical system. Design flaws, component defects, and faulty installation can all increase the risk of fire through arcs between conductors or to the ground, as well as hot spots which could potentially ignite nearby flammable materials. Green roofs are highly fire resistant because of the moisture in the vegetation and growing media, as well as the synthetic layers below. Even a dry green roof can provide a degree of fire protection to the roof because the aggregates in the growing media are an excellent fire break. As such, they can be considered as a part of an integrated fire protection system for solar systems, and the building more broadly. It is important to keep a green roof well maintained and guarantee an adequate water supply to avoid any fire risk associated with the presence of dry vegetation.

Fire protection considerations can vary by country or governing region, with different classifications and considerations for performance. In Europe generally, roofing materials must comply with fire rating standard EN 13501-5, which classifies their resistance as BROOF (T1-4). In this classification, green roofs are categorized as T1, or basic fire resistance protecting against the spread of fire from external sources. In Austria and Germany, green roofs built with standard-compliant vegetation base layers per ÖNORM L1131 and FLL are considered equivalent to gravel fill of at least 5 cm (2 in) in terms of fire protection. In the United Kingdom, a green roof with a substrate depth of 8 cm and less than 50% organic matter is considered to achieve BROOF (T4), the highest fire safety rating. In North America, the ANSI/SPRI VF-1 External Fire Design Standard for Vegetative Roofs provides guidance for reducing the potential of fire risk associated with green roofs.

green.LAB Graz, Austria - modular timber building
Credit: GrünStattGrau

ENERGY EFFICIENCY

Both green roofs and solar energy systems contribute to the energy efficiency of a building, and when combined, those benefits are magnified. A green roof's impact on a building's thermal performance, through both insulative and cooling effects, contribute to improvements in the energy usage profile of a building. Photovoltaic systems relieve grid dependence and provide on-site energy generation as either a primary or backup energy source for building systems. Solar thermal systems provide independent, low carbon heating solutions for building occupants, reducing the reliance on systems with either a higher electrical demand or a higher carbon footprint. However, when combined, these systems can improve each other's performance as well, enhancing their performance and further improving efficiency.

Setting up rooftop agrivoltaics under a solar PV array
Credit: Kevin Samuelson, Colorado State University Spur

LIFECYCLE BENEFITS

Rooftop solar energy technologies typically have a life expectancy of 20 to 25 years while many rooftop waterproofing systems typically have a life expectancy of 10 to 20 years. Green roofs typically increase the lifecycle of the underlying waterproofing by double or more (see section 3.2), so that it will not be necessary to replace the waterproofing beneath a solar technology to fix or replace waterproofing, thereby eliminating the costly need to do so.

ECOSYSTEM SERVICES

Ecosystem services are the direct and indirect benefits to human life and wellbeing which are provided by natural ecosystems. Biodiversity support, oxygen production, carbon sequestration, cooling, and water management are all ecosystem services provided by a solar green roof. With specific design intent however, some additional ecosystem services can be delivered by these integrated technologies.

Green roofs can be used to maximize the usable square footage of a building, opening up traditionally underutilized roof space as amenity spaces for building occupants. Furthermore, introducing raised (>200 cm / >79 in) solar collectors affixed to a pergola or other mounting solution provides shade to the amenity space while not sacrificing generative capacity. In another arrangement, lower lying photovoltaics can be used to power rooftop amenity space improvements such as pathway lighting or other features to enhance the space, making it more desirable to residents and users. Access to roofspace provides a wide range of human health and well-being benefits and can contribute to the value of the building.

Ducklings in a biotope on an intensive green roof, Vienna, Austria
Credit: Elisabeth Weiss-Tessbach

GREEN JOBS CREATION

From the perspective of creating meaningful employment opportunities there are more jobs opportunities associated with the design, implementation and maintenance of solar green roofs than with solar only or green roof only projects.

Rooftop farming on semi-intensive green roofs allows for food production as well as education and community building on this Toronto Metropolitan University farm in Canada. Credit: Steven Peck

ROOFTOP FOOD PRODUCTION

Another option is to incorporate solar panels and agricultural production, an approach known as rooftop agrivoltaics. In this setup, food producing plants are grown beneath the solar panel system, taking advantage of the more moderate conditions created by the solar panel system. Solar panel systems that incorporate semi-transparent panels provide plants with additional access to sunlight for growth while still maintaining many of the preferable growing conditions created by opaque solar panels. Studies show that shade provided by solar panels slows plant growth and plants 'stretch' to access more available light. Substrate moisture remains higher under solar panels and plants use less water. Air and substrate temperatures are moderated, which reduces plant stress. Solar panels reduce severe weather (hail, frost, wind) impacts on crops and pest pressures shift. Whether it is for personal rooftop gardening or market based farming, the conditions created by the solar system can enhance crop outputs, protect plants, and maximize returns on the upfront investment in the solar green roof.

One of the oldest rooftop farms in North America is used to teach highschool students about farming (Chicago, Illinois). Students are required to plan, implement and maintain vegetables during the year Credit: Steven Peck

SELECTED RESEARCH FINDINGS
SOLAR GREEN ROOF INTEGRATION

- New habitat niches for animals are created under photovoltaic modules. (Nash et al., 2016)
- 18 different wild bee species found on four solar green roofs in Vienna area. (Gruchmann-Bernau, 2019)
- Heller 2020: Study on locust surveys on green roofs in Basel, Zurich and Aarau (103): 20 different roofs were examined, among other things to shed light on the influence of solar green roofs on species abundance
  - 21 locust species and the European praying mantis were found.
- The efficiency of the PV in a specific project was improved by 6,5% on an extensive green roof compared to a bitumen roof. (Köhler et al., 2007)
- Evaporative cooling of plants can reduce the heating of PV modules and thus increase energy yield by about 2.6%. (89)
- The efficiency of the PV was improved by 8,3% on an extensive green roof compared to a bitumen roof. (Manso et al., 2021)
- Green roof can increase energy generation of a PV panel up to 1.3 ± 0.4% compared to a concrete roof. (Hui & Chan, 2011)
- With a temperature coefficient of 0.5%/°K (e.g., crystalline), a solar module installed over a green roof can achieve 4-5% higher performance (0.5%/K * 8K = 4%) compared to a bitumen roof. (Osma-Pinto & Ordóñez-Plata, 2019)
- According to HENKE (2017), the level of additional efficiency of the PV modules in combination with a green roof can be narrowed down to a range of 0.8-8%. (161)
- Gupta et al. (2017) investigated the performance improvement of PV modules on green roofs compared to a concrete roof in Singapore. The experimental results showed that the power output of a PV green roof system can be about 8.60% higher than that of a reference PV system on a bare concrete roof, while the maximum improvement in efficiency can be up to 3%. Evaporation was found to play an important role in reducing cell temperature and improving performance on days with clear skies and relatively high and constant solar irradiance. However, the evaporation rate may fluctuate on days with low irradiance, which may make the improvement in efficiency and performance of PV green roof systems minimal compared to PV systems on bare concrete roofs.
- The presence of an 8 cm vegetated substrate under a photovoltaic system reduced the average monthly temperature of the roof surface by 4.5°C in summer (in August 2021) compared to a photovoltaic system without substrate. (Steffen et al., 2024)

Solar green roof in Bad Vöslau, Austria
Credit: Elisabeth Weiss-Tessbach

4. DESIGN AND IMPLEMENTATION CONSIDERATIONS

The performance of an integrated solar green roof system will depend on the types of technologies involved, the roof structure and orientation, and the design and maintenance of the systems. The combined experience of the working group in planning and implementing hundreds of projects allows for the articulation of general principles that pertain to most systems. Multidisciplinary knowledge and expertise is required to identify the many benefits of these technologies, and how they can be designed and maintained for a more positive set of performance outcomes. It is important to work with individual manufacturers of these systems to gain the direct benefit of their experience.

This section describes some of the key design, installation, and maintenance considerations that must be addressed when combining these technologies. The specific details will vary based on a number of project specific factors including, the type of system selected as integrated solar green roofs are not a one size fits all technological application.

Office building, Oslo (Norway) Credit: Over Easy Solar

10-STEP PROCESS TO IMPLEMENT A SOLAR GREEN ROOF PROJECT

1. Complete a **feasibility study** taking into account various project parameters including the type of project, objectives, budget, etc.
2. Hold an initial **on-site consultation** with key team members to develop a basic assessment of potential site parameters and constraints, indicative costs, access logistics, shading, structural considerations, and others.
3. Obtain necessary **permits and approvals** as well as clarify **funding** parameters and identify any possible **grants and incentives**.
4. Engage a qualified **multidisciplinary design/engineering team**, preferably with past experience in integration of green roof and solar systems, to develop a project plan with cost estimates, project schedule, and maintenance plan.
5. Identify **potential interfaces and opportunities** for the incorporation of solar technologies as well as projected performance output.
6. Bid **offers from specialist contractors** for the design, installation and maintenance of the system and components.
7. Secure necessary **planning permissions** including any expert appraisals such as **structural load** calculations, **mitigating wind uplift and tunnels**, and a **structural review** of the building.
8. **Commission and schedule contractors** to install components of selected green roof and Zsolar systems.
9. Finalize acceptance, sign-off, and transition to the **post-installation management team**; as well as contractor invoices and any applied-for grants.
10. Complete **final quality control check and receive final sign-off**. Ongoing care and maintenance to be completed per the maintenance plan.

4.1. PLANNING AND DESIGN

Rather than competing for rooftop space, forcing designers and building owners to choose one sustainable technology over another, these two systems can not only co-exist but enhance one another (see Section 3.0). Solar green roof projects come in all shapes and sizes, each with their own opportunities and constraints. Identifying the specific context and conditions of each project and working to accommodate them is key to maximizing the realized benefits of an integrated solar green roof. Implementing solar green roof projects is a more straightforward process on new construction as compared to retrofits, as they can be factored into loading, spacing, and scheduling from the start. However, retrofit projects may also allow for modifications (e.g. changing of rooftop insulation or removal of pavers) that enable a solar green roof to be installed at a later date. Identifying the right structural parameters are an essential prerequisite for retrofit projects.

ASSEMBLING A TEAM

Addressing these considerations requires the coordination of trades and other professionals with clear communication along each step of the project to ensure that project goals and objectives are met, timelines are respected, and client expectations are achieved. Engaging a diverse and multidisciplinary team of professionals including landscape architects, architects, structural engineers, solar technicians, green roof professionals, system manufacturer, and others to collaborate to ensure that each goal of a given project is met appropriately. Key members of the project team have a responsibility to engage with the building owners to articulate the possible benefits of the project and possible tradeoffs.

SITE EVALUATION

Before initiating any project, a thorough site evaluation needs to be conducted in order to ensure that the overall project goals can be met without major cost overruns or unexpected complications. In terms of a solar green roof, this can mean identifying how best to distribute and arrange both solar panels and vegetation, what kind of plants to use, and what the anticipated energy yields will be. This will also involve assessing local climatic conditions and changes over the course of a year, and overall site conditions.

Extensive sloped roof greening in Liggersdorf (Germany)
Different vegetation depending on north or south orientation. Credit: BuGG

STRUCTURAL LOADING AND WIND UPLIFT

Structural loading capacity and roof level wind forces are both key considerations during the project conception and design phase, as they will impact decisions on feasibility and layout. The loading capacity of a building will inform decisions around system selection, system area, nature of access, and any other aspect that will add mass to a roof, either permanently or temporarily. Green roof manufacturers should be able to supply the loading requirements of their green roof systems. Other possibilities include installing prefabricated green roof systems with lower loads. Similarly, the pressure exerted by the movement of air across the roof and on the various components installed there can impact considerations of loading, resistance, ballast, and layout to prevent any damage to either system, the building itself, or its occupants. Several jurisdictions require wind uplift studies on projects to ensure they are engineered correctly. Providers of integrated systems typically have conducted research on their systems and can provide technical data. The Canadian Standards Association (CSA) has established wind uplift thresholds for various types of green roof systems, CSA A123. The National Building Code of Canada (NBC's) incorporates a procedure to calculate wind loads on rooftop solar arrays.

Integration of fall protection into the solar green roof system on a roof in Nürtingen
Credit: BuGG

ACCESSIBILITY

An important design consideration that should be made early in the process is whether a roof and the associated systems installed there will be generally accessible to building occupants or the public, versus only accessible for maintenance purposes. This decision will impact structural loading, safety features, and the layout of the systems and their components. Whether accessibility is public or limited only to approved personnel, permanent access to the roof and the associated equipment is essential for planned maintenance or incidental repairs, along with electrical safety considerations. The positioning of the panels also needs to facilitate access for green roof maintenance.

Clarification on whether and how maintenance access is possible (Ulm, Germany)
Credit: BuGG

WATER MANAGEMENT

One of the key features of green roofs is their ability to manage stormwater. An extensive green roof system, depending on design conditions and rainfall patterns, can reduce total runoff of a rainfall event by 50% to 70% and detain up to 99% for several hours before it is released into a storage device or directly into a storm or waste sewer system. Water is absorbed and held by the growing media and utilized by the vegetation, while excess water moves slowly through the green roof towards drains. Some green roofs incorporate water retention features, such as cisterns, moisture retention mats, or detention layers, which also prevent the release of additional water into the stormwater system. These features are complimented by naturally occurring processes such as evapotranspiration. A solar green roof and its substructure must be designed to ensure that all rainwater that falls on the roof is utilized to the fullest extent possible. The addition of solar panels will alter the movement of water into and through the green roof system, so adjustments and accommodations will need to be considered to preserve and protect the underlying vegetation from erosion. Areas where water is directed will likely grow more vigorously than those, for example, beneath the solar panels.

Irrigation systems may be required depending on the type of green roof assembly and the local rainfall patterns in order to avoid the negative impacts of drought conditions. Solar green roofs can also be combined with water retention and drainage layers. The presence of water within the growing media is what facilitates evapotranspiration, which cools the ambient air temperature thereby increasing the energy generation efficiency of the panels.

Lawn roof, intensive greening on a hotel in Düsseldorf, Germany
Credit: BuGG

MATERIAL HANDLING

Knowing when and where materials will be - when and how they will arrive, where they will be stored, and how they will be conveyed to their final destination - ensures that installation can proceed smoothly and timelines can be maintained. Components should arrive as close to when they need to be installed as possible, and stored in designated areas so they can be accessed easily and protected from any accidental damage. Materials that arrive too early can either take up valuable space or, in the case of plants and other live material, result in spoilage. Materials that arrive too late can lead to cascading delays, cost overruns, and other installation difficulties. In an ideal situation, installation of the green roof and solar components should occur in an interlocking fashion, trading priorities as elements are completed. Generally speaking, green roof base layers should be laid down first, followed by the solar racking, followed by the media, and then the installation of panels. Plant installation will depend on what type of green roof has been specified and the planting method. Plants should accommodate the installation of the panels and other components. Many green roof plants cannot tolerate the impacts of being walked upon, so care needs to be taken to protect vegetated areas during the installation of solar panels.

4.2. LAYOUT AND INSTALLATION

A comprehensive site plan is essential for an integrated solar green roof system as it will ensure that both systems have sufficient roof area to function and perform as anticipated. Balancing generative capacity with green roof performance will come down to the plants selected and the arrangement of solar panels. The wrong species of plants may shade solar panels. The wrong arrangement of solar panels may prevent plant growth, or inhibit maintenance activity. It is not possible to cover roofs entirely with solar panels in an integrated system so there are tradeoffs between energy production and the benefits provided by green roofs. Many jurisdictions have minimal coverage requirements that designers will have to incorporate.

PLANT SELECTION

Plant selection impacts both the design goals of the project as well as the functionality of both the solar system and the green roof.

Considerations include:

- plant height at full growth, and whether they will shade the solar panels;
- foliage deciduousness, which will determine how much loose biomass is produced which can interfere with generative capacity;
- water requirements - do they require supplemental irrigation or not;
- shade tolerance and if plants under the panels will be able thrive; and
- plant diversity, affecting aspects like insulation, cooling, thermal dynamics, and water balance.

Growing media depths under and around solar panels needs to be considered, particularly for intensive and semi-intensive systems. Deeper levels of growing media can support taller and woodier plants, along with unexpected volunteer species that are blown onto the roof by the wind. If given ample space and nutrients, these plants can begin to interfere with the solar system, shading panels, interfering with maintenance, or damaging the mounting structure.

For lower lying solar panels, extensive green roof depths and shorter growing succulents such as sedums are recommended. It is also generally recommended that plants installed close to low lying solar panels produce minimal biomass and do not require much fertilizer or pruning. Solar panels that sit higher or are mounted to a structure like a pergola will allow for a broader variety of underlying plants. It may be advisable to reduce growing media depths immediately in front of solar panels to help reduce the potential of shading by plants. Another technique is to use pavers, or aggregates in front of panels, again to reduce plant growth in this area.

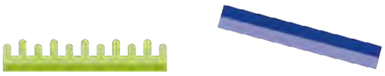
Solar green roof in Stuttgart
Credit: BuGG

PANEL SPACING AND HEIGHT

Panel height needs to be considered when installing a solar green roof. To ensure that it doesn't interfere with the panel surface, the vegetation canopy at full growth should be lower than the panels themselves. To ensure that the plants receive adequate sunlight beneath the panels, it is recommended that modules leave a minimum clearance of 20 cm (8 in) between the module and the upper surface of the substrate.

Reduced clearance may be possible if the underlying vegetation is particularly low-lying, such as with mosses and succulents. The actual distance will depend on the system and vegetation targeted, along with the tilt angle of the panels, and wind load. Special attention must be paid to the wind load if modules are required to be positioned further apart and/or at a steeper tilt.

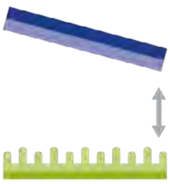
side by side



Credit: Weiss-Tessbach

Credit: Weiss-Tessbach

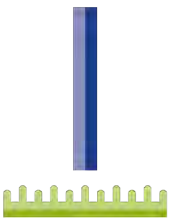
> 20 cm (8 in) apart



Credit: BuGG

Credit: BuGG

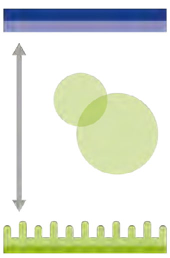
bi-facial configuration



Credit: BuGG

Credit: OverEasySolar

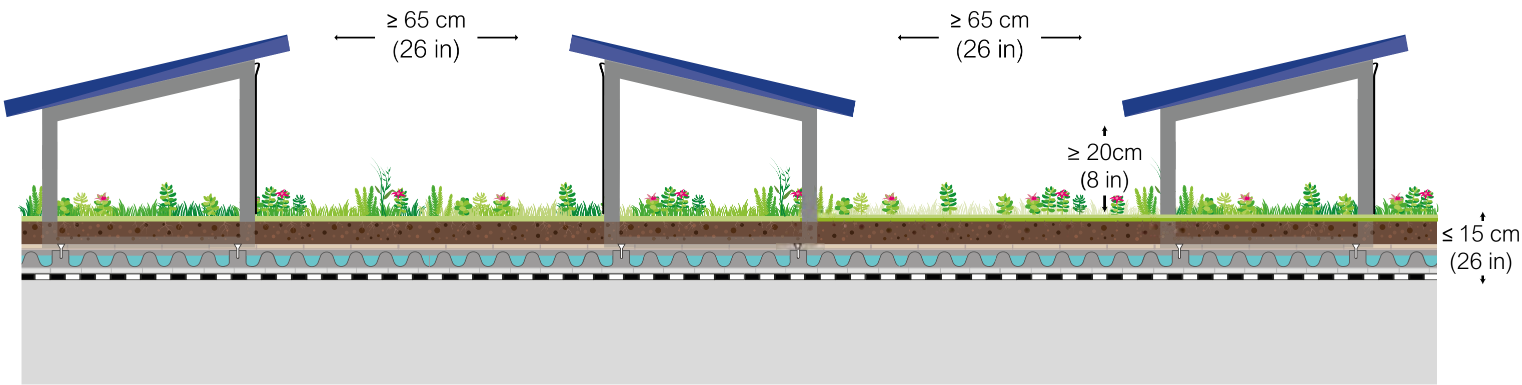
> 200 cm (80 in) apart

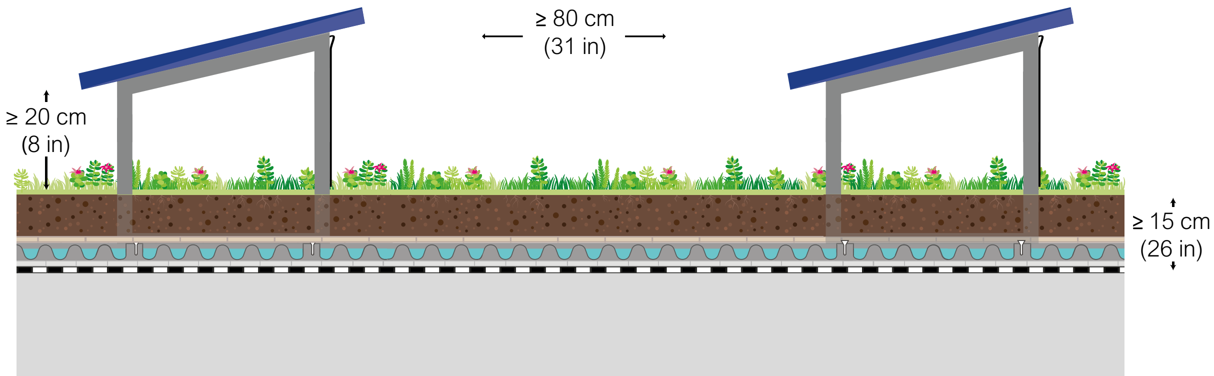


Credit: Weiss-Tessbach

Credit: Zluwa

Inter-row spacing of solar modules must balance generative capacity with vegetation needs. Maximizing the roof space only for solar panels will have a detrimental effect on the green roof and sometimes panel performance. Spacing between rows is generally recommended to keep a horizontal distance of at least 65 cm (26 in) clear minimum width between the rows of modules, including substructure. In some standards, regardless of the type of installation and orientation, this spacing is considered essential for maintenance. The introduction of low vertical, bifacial systems enable a different approach, where one can access between every row of panels. In this case horizontal distance can be reduced to 30-40 cm (12-16 in). In systems with deeper (>15 cm / >6 in) profiles the distance between module rows should be adjusted to accommodate the vegetation, around 80 cm (31 in) in the case of tilted modules.





Credit: Isabel Mühlbauer

No yield reduction due to enough spacing
Credit: BuGG

Overgrown PV modules due to insufficient spacing
Credit: Elisabeth Weiss-Tessbach

AVOIDING MISTAKES

- Maintain a minimum clearance of **20 cm (8 in) between greenery and sensitive structures** (e.g. cable runs and feeder/ distribution manifolds) to comply with guidelines on vegetation free zones in relevant standards/guidelines.
- **Avoid panel shading by plants** at all costs to ensure optimal performance (less critical with solar thermal systems).
- Keep solar modules free of dirt and debris for prolonged periods (e.g. leaves, growing media, snow, etc).
- Ensure **professional care and maintenance access** of the vegetation.
- Choose the **appropriate green roof system** for the setting.

Insufficient spacing
Credit: Weiss-Tessbach

Ecologically valuable vegetation causes yield reduction
Credit: Weiss-Tessbach

Regular maintenance can compensate for planning errors, but is often more expensive
Credit: Weiss-Tessbach

No vegetation growing under the panel
Credit: Weiss-Tessbach

4.3. MAINTENANCE

Regular and comprehensive maintenance is essential for solar and green roof systems. While either system, depending on design and objectives, can be low maintenance, neither should be considered to require no maintenance.

Maintenance of a Solar green roof
Credit: ZinCo AG

A visual inspection is the first step in any maintenance visit. For solar systems, in the event of reduced performance or other issues, inspection of the modules using infrared thermography or electroluminescence should be used to identify the cause. Regular cleaning, debris removal, and in some circumstances, pruning of the vegetation, will keep power outputs at a maximum. For green roofs, observing the vegetation for damage, poor health, or vegetation loss may suggest larger underlying issues with the system, such as nutrient deficiencies. Similarly inspecting the growing media for erosion or wind scarring is important as it may expose the underlying layers of the green roof which could lead to damage to the system or waterproofing membrane. Comprehensive record keeping including photographs and detailed notes on interventions is critical to maintenance to ensure the continuity of care and long term health of the solar green roof.

Supplementary systems and connections such as irrigation systems and drains on a green roof, and inverters and electrical connections should be checked for blockage, damage, or failures. Problems in these areas could lead to flooding, electrical fires, or reduced system output and performance.

Identifying goals and timetables for vegetation coverage at installation and over time will help guide maintenance and care of the solar green roof. Moreover, it is important to consider the altered site conditions due to shade and wind patterns arising from the installation of solar panels when considering vegetation coverage and care.

Before maintenance. Credit: BuGG

After maintenance. Credit: BuGG

For example, in Austria, maintenance must achieve a coverage rate of over 70% of the target vegetation two years after installation and development care must achieve a coverage rate of 80%. For pre-vegetated systems such as tray or mat based systems, coverage will generally start quite high and may change somewhat over the course of establishment. Similarly, managing the growth of plant communities and volunteer species on the roof is important to ensure that solar panels are not obscured. Due to condensation and rain falling from the panels onto the underlying plants, growth can be more vigorous around the solar panels. If unmaintained, tall vegetation can grow and shade the panels, having a negative impact on energy production. Object related targets can be used for technical or design reasons which may, in some instances, allow for lower coverage rations.

Maintenance considerations will generally be more demanding in circumstances where the solar system and green roof are not deployed as an integrated system. For example, when a solar array is either mounted to a metal frame on top of the green roof and ballasted with non-green roof materials as opposed to being fixed to the roof deck or ballasted by the green roof there will be additional considerations and care requirements for plants, growing medium, and system design. Solar panels installed after the green roof may damage or displace vegetation or other green roof components temporarily.

MAINTENANCE **INNOVATION**

Recent innovations from Switzerland have explored **mowing robots** for solar green roofs above a certain project size. The robot is integrated as part of the whole project and feeds itself from **locally produced renewable energy.**

The robots are designed such that they can distinguish between areas to mow (ex. flat areas with low lying vegetation below panels) and areas not to mow (ex. areas with higher substrate levels and biodiversity elements).

Mowing robot
Credit: growsolutions, Andreas Dreisiebner

MAINTENANCE **STANDARDS**

The Green Infrastructure Foundation has established a voluntary performance standard for green roofs and walls called the Living Architecture Performance Tool. This standard requires proof of five years of maintenance planning and budgeting as a prerequisite to obtaining certification.

4.4. CHALLENGES AND TRADE-OFFS

The integration of solar and green roof systems requires additional considerations around planning, coordination, logistics, scheduling, and physical allowances such as space and loading capacity. In jurisdictions where there are no minimum green roof requirements, an integrated solar green roof will likely reduce the overall number of solar pv panels installed and renewable energy generated, but in exchange will result in many additional public and private benefits from the green roof. In the majority of cases, particularly if appropriately designed and implemented, the benefits outweigh the energy trade-off and additional complications. Fortunately, a number of manufacturers have developed and tested integrated systems that help building owners, design professionals and contractors implement these projects with greater ease. The green roof and solar industries provide comprehensive solutions for new and retrofit construction projects. Professionals can assist in the planning and execution to ensure an optimal spatial configuration of solar technology and green elements.

Retrofitting green roofs onto buildings with an existing solar installation can often be more complex and expensive. Decisions must be made according to project capacities and additional changes should be considered to enhance cost efficacy. In some cases, overlapping integration will not be feasible to implement based on the building conditions, in which case a more practical side-by-side approach should be explored. In projects involving subsidies, incentives, or other financial assistance programs; and/or projects installed as part of a municipality's green enhancement program or mandatory green requirements (as outlined in the building plan), the relevant public authorities must be informed of any retrofit changes as they will be key partners in the redesign.

In some cases, the roof design as well supports a division of technologies (Switzerland)
Credit: Elisabeth Weiss-Tessbach

In other parts of the roof, an integration is favourable (Switzerland)
Credit: Elisabeth Weiss-Tessbach

From a legal perspective, many countries regard roofs with limited accessibility (e.g. limited only to skilled maintenance professionals) as a lower safety and fall protection class compared to roofs that are publicly accessible or intended for non-skilled individuals. In reality, safety always takes priority particularly as green roofs change over time, altering the physical parameters or use cases for the roof. In any new or retrofit project, it is essential to plan for safety and make the necessary investments to ensure the roof is usable and can be developed to its full potential over time. In North America, safety requirements for roof access are clearly spelled out in National and Regional building codes.

YIELD **INNOVATION**

This roof in Switzerland is designed to work for a mixed energy use with peak demand in the morning and late afternoon (peak demand periods for resident energy use). The vertical, bi-facial arrangement allows easy maintenance and the use of specified plants.

The project by Andreas Dreisiebner and ZHAW monitors additional potentials to yield increases by enhanced reflection of sunrays, due to the use of plants with silver and light colour leaves and light colour substrates. The positive effect could already get traced and is monitored for optimization.

Bifacial panels in Winterthur (Switzerland)
Credit: Elisabeth Weiss-Tessbach

4.5. SUMMARY

The performance and outcomes of integrated solar green roof systems are variable and depend on the context in which the system is installed (climate, exposure, height, etc), the design and layout of the system (inaccessible extensive, accessible intensive, transparent solar, bifacial solar, etc), and the particular performance goals specified by the designer or client (amenity use, food production, biodiversity support, etc). It is often difficult to identify performance outcomes beyond generalizations because of the many variables that can influence the system over the course of its lifespan. However, it is important to understand that irrespective of multitude of approaches and conditions, an integrated solar green roof project will deliver a wide range of significant benefits to each individual system, the building, and the surrounding environments. Integrated solar green roofs can accommodate a wide range of building types, can be designed for new or retrofit projects, and deliver tangible performance results which, if adequately maintained, will realize those benefits over the long term.

Thermal solar green roof installation about to be finalized (Village Delage, Courbevoie, France)
Credit: Topager

5. COST FACTORS AND MARKET TRENDS

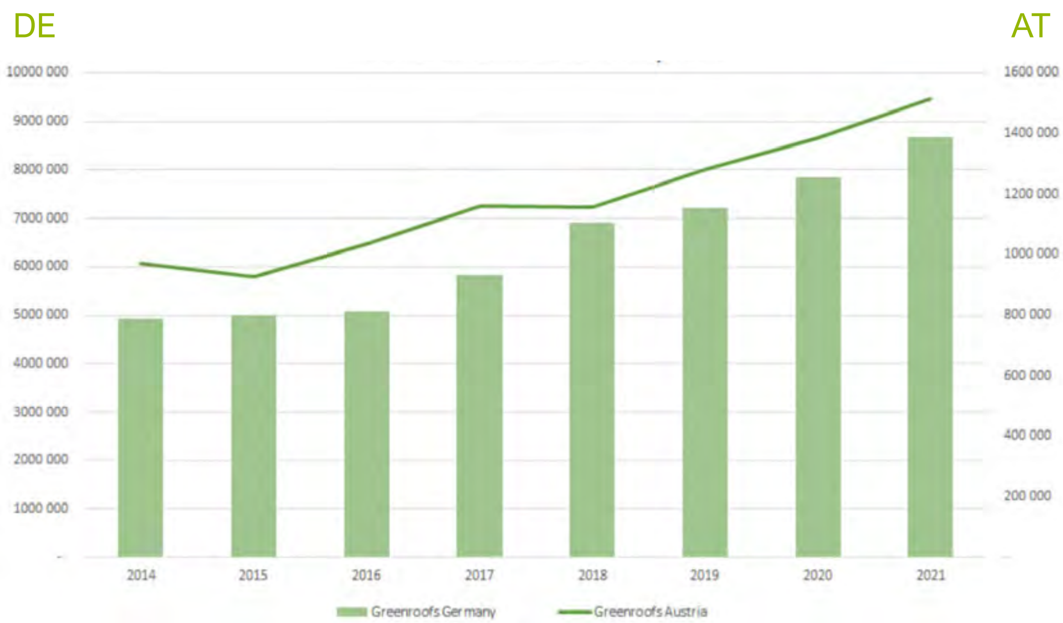
Specificity around the costs of integrated systems is difficult as cost factors will vary based on local resources, professional experience, and the context and conditions of the building or project site. There are, however, a number of factors that impact the costs and benefits of solar green roof projects. Some of these factors include:

Roof garden with PV panels affixed to pergola - Austria, University of Life Sciences Vienna
Credit: Irene Zluwa

- **Design Objectives**
  The overall goals and anticipated performance of a given project will impact the costs and benefits as it will determine the type and size of system used.
- **Regulations and Incentives**
  The policy landscape in which a project is implemented can impact project costs by establishing incentives or preferential markets for materials and outcomes.
- **Structural Loading Capacity**
  Loading capacity is an extremely important design consideration which can impact cost and even overall installation feasibility.
- **Project Size**
  The larger the project, the lower the per square area cost for installation and maintenance stemming from wholesale purchasing of materials and the lower relative material staging costs.

5.1. MARKET TRENDS FOR GREEN ROOF PROJECTS

Tracking of the size and capacity of the green roof market has occurred around the world in various forms. One such approach is the Green Roof Market Report Initiative, a transnational group of experts that work to surface facts, figures, and trends across different national markets across Europe. This initiative has identified market growth across Europe. Similar measures in North America by organizations such as Green Roofs for Healthy Cities have found similar trends.

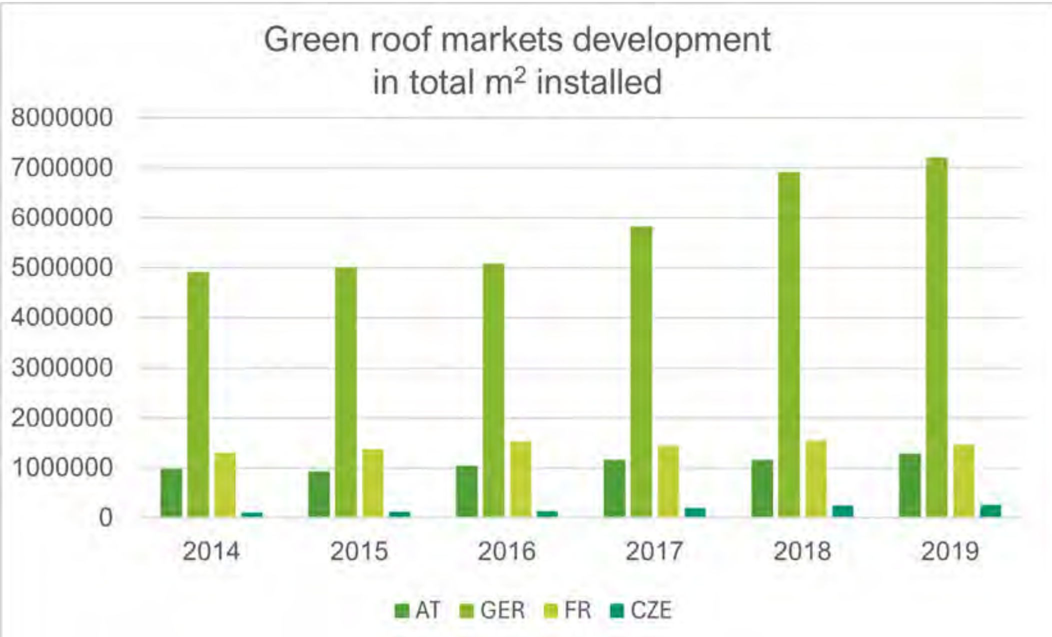


Credit: Green Market Report, GrünStattGrau

Compound annual growth rates (CAGR), a measure of an investment's annual growth rate over a period of time, in Germany and Austria were 7.83% and 9.31% from 2018-2021. The Austrian Turnover monitor, reporting the value executed transactions in a given time period, indicated a 17% increase for the green roof market from 2019-2022, an increase from 9% from 2014-2018. Still, across Europe generally, only approximately one in ten newly built flat roofs have a green roof installed. The market potential, even in developed green roof markets of central Europe, is significant.

A comparison between 4 EU-countries, Austria, Germany, France and Czech Republic has shown similar market trends during the years of 2014-2019 (continuously growing) but different market total sizes (from 200.000m2 to 7,2 Mio m2 deployed annually in newly installed flat roofs). The annual growth rates vary from 7,5% in average during the last 10 years (Germany) to increase in 2021 and 2022, over 17% (Austria).

Solar green roof, Germany
Credit: BuGG



Credit: EFB, Vera Enzi-Zechner

The annual turnover of exemplar markets is 19,7Mio. € (CZE 2020), 220 Mio.€ (FR 2021), 147,5 Mio.€ (AT 2021). Still, the % of green roofs in comparison to the total new flat roofs markets is low- 9-10% (Austria 2017-2022), 12,5-24% (CZE 2017-2020) and 8,5% (FR 2019).

In the UK, the total installed green roofs are mapped to measure the exact development. A comparison from 2010, 715.000 m^2 to 2017, 1.510.000 m^2 showed a clear policy driven growth.

Another possibility for green roof market development is the Green Roof index. With this method, specific cities join a ranking in their green roof availability per inhabitant, a recent Market Report by the German Green Roof Association BuGG provides an overview across different cities:

Ranking	City	Year of Data Collection	Inhabi-tants	Green Roofs without Under-ground Car Parks [m²]	"Green Roof Index" [m² green roof/inhabitant]
1	Stuttgart	2017	632,742	2,593,670	4.1
2	München	2016	1,464,301	3,148,043	2.1
3	Frankfurt am Main	2015	732,688	1,436,371	2.0
4	Düsseldorf	2020	620,523	972,800	1.6
5	Hamburg	2018	1,121,000	1,684,355	1.5
6	Nürtingen	2015/2008	40,395	59,450	1.5
7	Hannover	2016	532,864	633,076	1.2
8	Osnabrück	2017	164,374	157,000	1.0
9	Nürnberg	2016	511,628	450,000	0.9
10	Berlin	2016	3,574,830	2,969,396	0.8
11	Dresden	2018	560,641	463,670	0.8
12	Essen	2018	583,393	449,000	0.8
13	Braun-schweig	2008/2010	246,012	186,536	0.8
14	Straubing	2019/2020	48,110	33,617	0.7
15	Karlsruhe	2015	300,051	177,546	0.6
16	Ottobrunn	2016	21,000	9,500	0.5
17	Rostock	2016	206,011	34,000	0.2
18	Aachen	2022	259,839	30,400	0.1
19	Mannheim	2014	296,690	22,000	0.1
20	Mainz	2019	217,118	9,228	0.04
				Average	1,1

Tab.2: BuGG Green Roof National League version 2: sorted by green roof area per inhabitant ("Green Roof Index").Source: BuGG"

Growth of this market not only translates to significant impacts on climate resilience, but real and substantial employment and job creation benefits. The design and implementation of green roof projects involves a range of multidisciplinary professionals - from specialized consultants, civil engineers, and planners; to contractors, installers, and other trades; to horticulturalists, nursery staff, and maintenance professionals. Similarly, exploration of additional benefits and integration opportunities supports a broad landscape of research professionals and institutions. Researchers around the world are exploring tools and methods to enhance performance and mainstream technologies, enhance biodiversity, develop community capacity, and improve circular economy networks. Furthermore, countless entrepreneurs and innovators are deploying new technologies and solutions such as remote sensing and monitoring, greywater circulation systems, drone-based evaluation and maintenance solutions, biocide free materials, recycled component use, and much more.

3D model of Vienna, green vision
Credit: Meixner Vermessung, Edit: GrünStattGrau

The green roof market has a tremendous economic impact and potential, delivering paybacks from the site scale up to the ecosystem level, and supports thousands of professionals and economic activity globally, alongside the multitude of sustainability and resilience impacts it provides both locally and in aggregate. A study in Spain showed that the perception of green roof technologies and their benefits are well known, still some business areas could be improved- such as grey water, disaster prevention, economics, and food production.

5.2. MARKET TRENDS FOR ROOFTOP SOLAR PROJECTS

Since the year 2000, global solar markets have experienced unprecedented growth as their capacity for renewable, low carbon, and high profit energy generation has been recognized. Globally, installed PV generation capacity surpasses 2.2 terawatt peak (TWp); and ST heating capacity surpasses 560 gigawatts thermal (GWt), a testament to the technology's rapid advancement and increasing adoption.

The European Union's (EU) solar markets have experienced remarkable growth, more than quadrupling over the past decade, driven by the urgent need to transition to independent and decentralized renewable energy and enhance energy security. In 2024, the EU set a new growth benchmark for PV installations, fueled by rising energy demands and increased investments in renewable infrastructure - identifying solar deployment as a key priority across the block.

This growth has been further supported by reductions in equipment and construction costs driven largely by financial incentives, supportive policies, and revised renewable energy targets from EU member states. However, the market also faces a number of challenges such as grid capacity limitations, permitting delays, and fluctuating consumer demand driven by energy prices and high

Solar green roof, Germany
Credit: BuGG

inflation rates. Despite these challenges, the EU's solar market is on track to meet the REPowerEU target of 750 GWDC/600 GWAC (gigawatts direct current / gigawatts alternating current) by 2030, with projections suggesting a total operating solar capacity of 816 GW by 2030 in the EU.

The installation of solar energy generation systems not only contributes to a cleaner environment, but also capitalizes on a thriving market and supply chain. With declining costs as technologies develop and the expansion of supportive policies, solar energy generation is a financially sound and sustainable investment.

5.3. MARKET TRENDS FOR SOLAR GREEN ROOF PROJECTS

Although both solar and green roof markets independently have seen a great deal of growth over the last ten years, many roadblocks to implementing a combination of the two technologies still exist. Many of these roadblocks originate from conflicting municipal policy, such as mandated green roofs or solar, but not a combination; a lack of technical guidance for designers and installers; and early implementation failures stemming from a lack of technical competence in design, installation, and maintenance, which have nonetheless discouraged further adoption.

Market adoption of integrated solar green roofs is still in a nascent stage, particularly relative to the adoption of the individual technologies. That said, some organizations, such as the Austrian Green Roof Association, have begun to track market growth of integrated systems, and in 2022 reported over 90,000 m^2 (96,8752 ft^2) installed, which is equivalent to about 6% of the total annual market. Once the above roadblocks have been removed and governance is harmonized, implementation and market growth are likely to follow, as has been observed with both the solar and green roof markets.

6. REGULATIONS AND POLICIES

Even in these early stages of recognizing the benefits of integrating solar and green roof technologies, there are already a number of policy measures in place worldwide that encourage their implementation. Policy-makers are increasingly recognizing the importance of multi-faceted solutions, and the power of these sustainable technologies to address the myriad challenges of addressing climate change. While many local governments have acted to support these technologies, we need senior governments to increase investment and policy support in order to scale up these technologies.

The following is an overview of some of the policies, regulations, standards, guidelines, and incentives globally that promote the combination of these technologies. Policy-makers are encouraged to avoid either-or scenarios in their roofing policies and building codes, and to encourage the adoption of integrated systems. Similarly, advocates are encouraged to take inspiration from the work that has already been accomplished to shorten the road to implementing high level solutions in their region. Below is a selection of policy measures that regard green roofs, solar technology, or a combination of the two, organized by the type of policy - directives, guidelines, regulations, or technical standards.

Title & Link	**Scope**	**Type**	**Summary**
Vorarlberg´s Solar Green Roof Initiative	Austria - National	Directive	Federal state of Vorarlberg direction on solar green roof integration supported with knowledge on: planning, failure prevention, installation and maintenance, costs and subsidies.
Energy Performance of Buildings, 2024	European Union	Directive	Includes green roofs as an integration with solar systems and stresses considerations of structural integrity. Member states have to adopt nationally until 2026.
Climate & Resilience Law	France - National	Directive	For non-residential buildings with a surface area of 500 m². Inclusive of new buildings, major renovations and extensions with an obligation to plant vegetation or install a renewable energy system on at least 30% of the roof surface (up to 50% in 2027) then for all buildings concerned from 2028 (including existing buildings)

Title & Link	Scope	Type	Summary
Law for Renewable Energies	France - National	Directive	Bill to accelerate the production of renewable energy obligating green roofs or renewable energy.
Solarguideline Vienna, 2021	Austria - Municipal	Guideline	Comprehensive technical guideline for projects eligible to receive the city's subsidy for Investments in Solar Green Roofs, covering green roofs and walls, PV, solar thermal, or a combination.
PV- Roof garden Case study	Austria - Municipal	Guideline	Implementation concept for innovative PV roof gardens on school buildings of the City of Vienna
Green Roof Guideline City of Vienna 2020	Austria - Municipal	Guideline	Technical guideline covering solar green roofs as well as biodiverse green roofs.
FLL-Green Roof Guidelines	Germany - National	Guideline	Guidelines for the planning, construction, and maintenance of green roofs recognized as a benchmark set of guidelines. Has served as the basis for a number of international policy approaches.
BuGG-Fachinformation Solar-Gründach	Germany - National	Guideline	Technical information for planning and implementation summarizing the most important principles and instructions for permanently functional extensive green roofs in combination with solar energy systems. Applies to flat roofs with a pitch of up to 5 degrees.
BuGG-Fachinformation Leitfaden kommunale Förderinstrumente Dach- und Fassadenbegrünung sowie Entsiegelung und Hofbegrünung	Germany - National	Guideline	Summary of existing funding instruments for the greening of buildings in Germany. Importantly, describes the determination of solar green roofs at municipal, federal and state level.

Title & Link	Scope	Type	Summary
GRO Code	United Kingdom - National	Guideline	Published by GRO incorporating specific information and design considerations for biosolar roofs.
Raumbuch Public Buildings, Vienna	Austria - Municipal	Regulation	Regulates that on public buildings, schools, and kindergartens, biodiverse green roofs (including solar use) must be applied for new buildings and refurbishments. Performance qualities included.
San Francisco Better Roofs Ordinance	United States - Municipal	Regulation	Mandated construction standard requiring 15-30% of roofing space on new construction projects to incorporate solar panels, green roofing, or a combination of the two, with some exceptions
Denver's Green Building Ordinance	United States - Municipal	Regulation	Ordinance requiring the implementation of green roofs or solar panels on new, retrofit, or addition construction, although rather than taking a roof percentage, this policy looks at a buildings gross floor area, issuing the requirement for buildings over 25,000 square feet.
New York City Climate Mobilization Act	United States - Municipal	Regulation	Local Laws 92 and 94 which mandated the use of green roofing, photovoltaics with a capacity of at least 4 kilowatts, or both on the roof. These requirements apply to all new construction, as well as any roof alterations of existing buildings where the entire existing roof deck or roof assembly is replaced.

Title & Link	Scope	Type	Summary
Solar Green Roof subsidy Vienna	Austria - Municipal	Subsidy	Funding for solar green roof investments for private entities covering new and retrofit projects of extensive and also PV-roof garden installations. Minimum project size 1kW peak and maximum subsidy per project is 250€. The roof must comply with the ÖNORM L1131 for green roofs and can not contradict the Solar guideline of the City.
ÖNORM L1131 green roofs, 2010/2025	Austria - National	Technical Standard	The technical standard currently under revision, the updated version 2025 will give specific design criteria, greening objectives and technical regulations regarding the installation and maintenance of solar green roofs.

Solar green roof on a residential building, Berlin
Credit: Optigrün International AG

7. CASE STUDIES

The Case studies presented show a diverse application of solar green roofs for different clients: public, private and businesses.

7.1. ZURICH OPERA HOUSE, ZÜRICH, CH

Zurich opera house
Credit: Elisabeth Weiss-Tessbach

The project entered the planning phase in 2017 and is special in every respect. Thanks to the innovative approach, it was possible to increase the originally projected output by around 20%. The opera house itself only consumes ten per cent of the energy it produces, with the main output being fed into the grid. The contract was split and the substructure was not awarded to the solar installer as usual, but to the roof greening company. The green roof maintenance is carried out by 4 mowing robots, which can visually recognise the biodiversity areas and drive around them. They trim the succulent-herbaceous vegetation growing under the panels, their energy need is directly covered by the system installation. All cables and other disruptive elements must be buried so that they can make their rounds unhindered. The housing of the robotic mowers must also be modified so that no unmown edges remain. Without these innovative robotic mowers, the large roof would have to be weeded out by hand three to four times a year.

Details

- Type: Extensive Biosolar roof
- Built 2019
- Ownership: public
- Building use: public
- Technical specifications:
- 825 kWp, 2.660 Solarpanels; 740 000 kWh electricity/year
- 7.700 m² extensive, biodiverse green roof (Swiss Standard SiA 312)
- Mounting: Butterfly, integrated
- Orientation/Shading: East/west
- Specials: Mowing Robot, Biodiverse plots higher
- Cost: 900.000 CHF installation cost; 7500 CHF maintenance cost/year
- Contact: Solarspar, ZinCo

Additional figures:

- 5 sand islands with piles of branches
- 9 ecological compensation areas with substrate mounds
- 20 types of plant seedlings
- 220 kg sedum sprouts
- 360 kg seed
- 618 m³ substrate
- 12 km of cable
- 25 inverters
- 310 Wp power/module

7.2. EICHGUT RETIREMENT HOME, WINTERTHUR, CH

Eichgut retirement home
Credit:Elisabeth Weiss-Tessbach

Details

- Type: Solargreen roof, Vertical bifacial, Research unit
- Built 2017
- Ownership: public
- Building use: residential home
- Technical specifications:
- 10,8 kWp
- Mounting: vertical-bifacial, integrated
- Orientation/Shading: East/west
- Specials: research plot, +16% output of solar panels, 80% annual precipitation retained
- Maintenance: 1-3/year
- Contact: Solarspar, ZHAW

Together with a team of researchers from the ZHAW, a sophisticated system was developed that provides new insights into the optimal utilisation of green roofs in combination with solar energy generation. Stadtwerke Winterthur is supporting the pilot project with the consumption of the solar power produced. With the solar system on the planted Eichgut roof, a completely new approach based on problem solving was achieved at the time. Previously, there was no way to simulate yield and effect. For the first time, a prototype was used to measure how a vertically mounted solution with smaller bifacial modules would perform in practice. If both sides of the solar cells are exposed to the sun and an east-west orientation is selected, the maximum yields are achieved in the early morning and afternoon. This is when conventional systems, which produce the most electricity at midday, are less effective.

A light-coloured substrate with silvery-leaved plants - such as sunflower and thyme - and white decorative gravel favours the reflection of sunlight and leads to an increased yield in solar power production. However, because standard 60-cell PV modules can only be installed at large distances from each other due to the shadows they cast and because vertical installation places a heavy load on the statics in windy conditions, the initiators have decided to install customised small modules with 20 cells on a substructure from Zinco at the retirement home. Additionally, the optimized snow performance should be mentioned. The pilot project is supported by the Climate Fund of Stadtwerke Winterthur, which provided a contribution of CHF 49,000 in June 2017 to analyse the research results and manage the project. The results are continuously published.

7.3. LØREN SKOLE, OSLO, NO

Loren Skole
Credit: Over Easy Solar

Details

- Type: Extensive Solar green roof, Vertical bifacial
- Built 2023
- Ownership: public
- Building use: school
- Technical specifications:
- Capacity: 46.2 kWp, expected annual production: 42.400 kWh
- Mounting: vertical-bifacial, self- ballasting overlay
- Orientation/Shading: East/west, South
- Specials: cassette based sedum mats, no connection to green roof, aerodynamically optimized self-ballasting system, installation time 1 day, optimized for own-consumption
- Subsidy: Oslobygg KF
- Contact: Over Easy Solar

Building 7 at Løren school was completed in 2019 with an extensive sedum roof. In 2022, a test facility of vertical, bifacial, South-West/North-East oriented panels was installed which was expanded to a full-scale facility in 2023, with the new panels oriented in a South-East/North-West direction. Both facilities were supported by Oslo Municipality's Smart Oslo initiative. Over Easy Solar, a Norwegian start-up established in 2021, supplied their unique flat-roof PV solution which consists of high efficiency heterojunction bifacial solar panels pre-mounted on a frame. In this way installation has been shown to be more than 10x faster than the installation of a conventional ballasted system. The installation and commissioning was done by the PV system installer Solenergi FUSen based in Oslo. The support from the Smart Oslo initiative was given to evaluate the implementation and performance of the Over Easy Solar technology on a extensive sedum green roof. One of the observations was that the sedum underneath the initial test system thrived better than the sedum around the system during a particularly dry summer. Performance of the system has also been good.

The initial test facility consisted of 52 units totalling 5.06 kWp while the full system built in 2023 consisted of an additional 206 units of an updated product from Over Easy Solar. The full system has a total capacity of 46.2 kWp.

7.4. VIENNA INTERNATIONAL SCHOOL, VIENNA, AT

Details

- Type: Extensive Solargreen roof
- Built 1984/2022
- Ownership: private
- Building use: school
- **Technical specifications:**
- 446 solar panels integrated system, 23,000 kilowatt-hours (kWh in May 2023)
- 2.500 m^2 extensive green roof
- Mounting: integrated
- Orientation/Shading: South
- Specials: renovation
- Contact: Bauder; Vienna International School

Vienna International School
Credit: VIS/Bauder

The Federal Ministry of the Republic of Austria on Climate Action, Environment, Energy, Mobility, Innovation and Technology, has handed Vienna International School (VIS) a certificate for our sustainable contribution by saving 60,18 Tonnes of Carbon dioxide release into the atmosphere this year. This is the result of the great school effort made through the development of 3000 sq. meters of green roof, including areas of photovoltaic installations.

This project has been fully implemented in 2021 and is currently generating about 15% of the electricity our school uses every day. There are a total of 446 solar panels on the roof, covering an area of more than 800m2 and generating an estimated annual savings of 76.000 kg of CO2 emissions.
In May 2023, the PV (Photovoltaic) system achieved a remarkable feat by generating an astounding total of over 23,000 kilowatt-hours (kWh) of electricity. To put this achievement into perspective, this amount of energy is equivalent to the typical monthly household electricity consumption of 110 households. Based on an average annual consumption of 2,500 kWh per household, our PV system‘s output in May demonstrated its exceptional capability.

The outstanding performance of our PV system is a testament to its efficiency and effectiveness in harnessing solar power. By generating such a substantial amount of electricity, our PV system was able to offset approximately 40% of the schools total electricity consumption for the month of May (excluding the school's catering facility). This impressive contribution clearly showcases the significant role our PV system plays in reducing our dependence on conventional power sources and moving towards a more sustainable energy future.

This project is an important part of our ECO School initiative, in terms of taking responsibility and finding alternatives that help us reduce the Carbon footprint. In our journey, we need to adapt to new ways of life to help support the sustainability of our planet. In addition to saving operating funds is also a great way for our students to learn about alternative energy. Our school is committed to involving our students in caring for the environment and understanding sustainable energy alternatives, and the solar energy project exemplifies this commitment.

7.5. RESIDENTIAL HOUSING SOCIAL COOPERATION, HOUTEN, NL

Residential housing, solar green roof
Credit: Sempergreen

Details

- Type: Extensive Solargreen roof, Ballast PV system with green
- Built 2021
- Ownership: Social Housing Corporation
- Building use: Residential Housing
- Technical specifications:
- 2500 m2 green roof
- 378 PV panels
- 143 kWp
- 130.000 kWh p/y
- Mounting: Mounting system green ballast
- Orientation/Shading: East/west, South
- Specials: Renovation, new green roof, no anchoring on waterproofing, ballast by substrate and pregrown sedum blankets
- Subsidy: Postcoderoosregeling
- Contact: Sempergreen

Loren Skole
Credit: Sempergreen

7.6. THE VILLAGE DELAGE ECOQUARTIER, FR

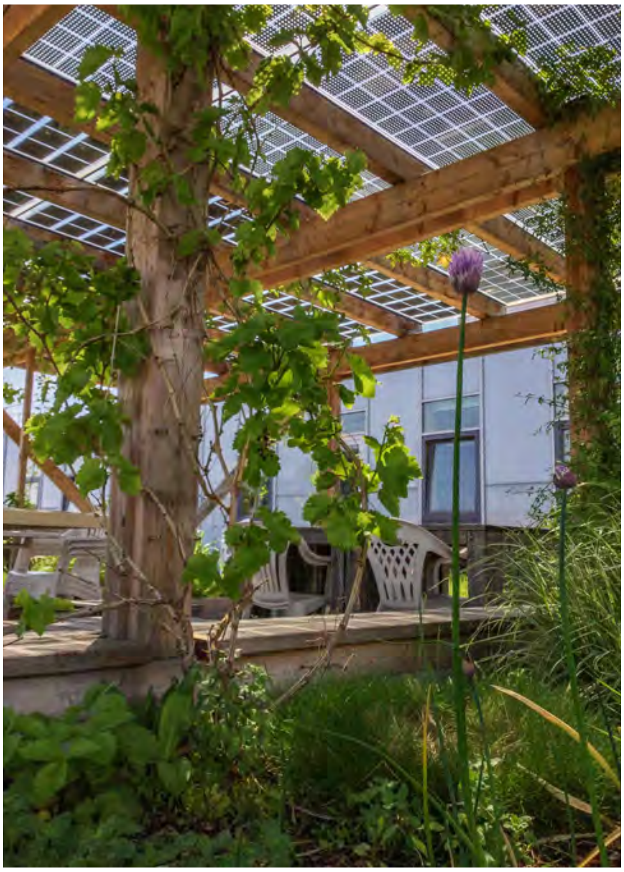
Villa Delage at Spring time
Credit: Topager

Details

- Surface area: 2,350 m²
- Location: Courbevoie (near Paris)
- Completion dates: 2018-2021
- Client: BNP Parisbas Real Estate
- Architect: MFR Architecture
- Greening designer and greening contractor: Topager
- Waterproofing contractor: SMAC
- Load-bearing element: concrete with 0 to 3% slope
- Waterproofing complex: two-layer elastomer (Axter)
- Vegetation complex:
  - Drain: drainage with water reserve
  - Filter: filter integrated into drainage
  - Semi-intensive subsoil 20 to 30 cm
  - Plant layer: sedum seedlings, shrubs, perennials, climbers
- Thermal solar:
  - Surface of the collector : 210 m² divided in 3 buildings (almost 192 apartments)
  - Each collector is 2.3 m² and they are grouped by 3 or 4
  - for water heating

The Village Delage EcoQuartier is an urban development project that Courbevoie (near Paris) has been running since 2013 on an industrial zone where the former Delage automobile factories were located. The site includes economic and commercial activities as well as 1,200 housing units. Solar panels have been installed in non-accessible areas to combine biodiversity and energy production and their co-benefits. Studies have been carried out to determine the plants and parameters most conducive to plant development: species of shade and appropriate irrigation are needed to ensure quality plant cover.

7.7. PV-ROOFTOP GARDEN, BOKU VIENNA



Structure with semi-transparent modules
Credit: Dusty Gedge

Producing renewable energy, compensating for increasing surface sealing, improving the microclimate, reducing CO2, storing rainwater and extending the service life of the roof cladding - a combined system on the roof should achieve all of this. For the first time, competing roof uses were analysed on an interdisciplinary basis. This could only be achieved by a co-operative research team and implemented in real projects. Due to the growing importance of renewable energy generation on buildings, building-integrated photovoltaics increasingly played a key role. Many flat roofs of new and old buildings were currently underutilised and therefore represented a significant resource for improving living conditions in urban regions. The 'PV roof garden' project focussed on people and proved that the 'm²' flat roof can be used simultaneously for people, plants and energy areas. The results have been published in the form of a handbook for interested replicators.

Details

- Type: semi-intensive to intensive Biosolarroof including a Pergola
- Built 2014
- Ownership: public
- Building use: public (University)
- Technical specifications:
- 80 m^2 of 40% semi-transparent glass-glass modules; 10,000 kWh
- 55 m^2 extensive, semi-intensive to intensive green roof (ÖNORM L1131)
- Mounting: on Pergola
- Orientation/Shading: flat
- Specials: Focus on easy refurbishment of unused terraces, creating amenity spaces and productive areas at the same time, Production yield: herbs and vegetables for Institute kitchen.
- Cost: €90.000.- (Research project, estimation; €1.200-€1.400/m^2)
- Contact: Institute Soil- Bioengineering BOKU Vienna,
- How to: Vienna Energy Department study on PV Rooftop gardens

PV roof garden
Credit: Dusty Gedge

7.8. IKEA WESTBAHNHOF, VIENNA, AT

IKEA rooftop terrace
Credit: Hertha Hurnaus - querkraft

Based on the demands of the municipality, the privately financed new city store provides private open spaces and communal areas, all of which are tailored to the preferences of local residents and users and designed to be accessible without barriers.

There is a publicly accessible 1800-square meter rooftop terrace where IKEA and the hostel operators also offer gastronomy services, but there is no obligation to consume. The idea of creating an urban „park structure“ was well received by the Municipality of Vienna as well as the neighbourhood. A total of 160 trees on the building contribute to a more pleasant microclimate and have been installed utilizing intensive green roof technology in XXL size plantainers. The photovoltaic pergola´s are fitted to the frame structure of the building and provide additional shade for rooftop users. On a hot day, they can cool the neighborhood by up to -1.5°C. Additionally, they improve the air quality in the surroundings by converting carbon dioxide into oxygen, for example, through dust absorption, air cooling, and humidification.

Details

- Type: intensive green roof top garden with partial cover and recreation area, shaded by PVs
- Built 2022
- Ownership and building use: private(IKEA)
- Building use: private (IKEA)
- Technical specifications:
- Overheads PV Installation on Rooftop creating shade for visitorskwH
- Intensive Green roof system in XXL Plantainers (Trees), Rainwater irrigation
- Mounting: mounting rails on on HEA 300 beams
- Orientation/Shading: flat
- Specials: Publicly accessible Rooftop without consummation need
- Cost: N/A
- Contact: Querkraft Architects, Green4Cities

IKEA rooftop terrace
Credit: Christina Häusler - querkraft

The irrigation system uses rainwater collected from the roof to water the plants in the building's community garden, reducing water consumption and the strain on the city's water resources. The project has won a large number of international prizes from innovation to sustainability, neighbourhood friendliness and for its special approach to architecture. This is the worldwide first IKEA in a city centre and it has no car parking options, deliveries to home are arranged with electric vehicles. Still it is a highly profitable store.

8. SUMMARY

The climate emergency which we currently face requires the implementation of a number of mitigation and resilience strategies. Urban communities are especially vulnerable to the impacts of this crisis, particularly as urban populations and densities continue to grow. The production of decarbonized and decentralized energy; management of severe weather events such as extreme heat and rain; and the erosion of habitat and biodiversity are all of critical importance to our long term survival.

Solar green roofs are a practical and proven solution to many of these challenges, and thanks to their multi-functional nature, they can meet these challenges by taking up space on underutlized roofs.

This guide has explored the many benefits derived from the integration of solar energy generation and green roof systems, both as individual building systems as well as combined sustainability technologies. It has reviewed existing solutions and explored the areas by which their combination can maximize benefits, outlining the many possibilities available to stakeholders. It has identified technical considerations and conditions for optimal operation and pathways towards maximizing returns. It has explained the design factors which influence the financial costs and benefits involved, and has detailed a growing number of policies currently in place to develop and support the development of solar green roof projects. . Finally, it has presented a number of real world case studies to serve as concrete and inspiring examples.

With this Resource Guide, we hope that all stakeholders - public authorities, developers, urban planners, architects, designers, engineers, suppliers, installers and maintenance professionals - will be inspired and empowered to act towards a more sustainable future, and make our spaces all the more resilient. It is no longer a question of choosing between greening buildings or producing decarbonized energy, but of how to combine them to yield the best results, in the most efficient way, for the greater good.

Biodiversity on solar green roofs
Credit: Elisabeth Weiss-Tessbach

APPENDIX I - GLOSSARY

When discussing the integration of solar energy and green roofs, it is important to establish terminology to accurately identify systems being used and their components.

Auxiliary sowing
A maintenance measure carried out on green roofs where seeds or cuttings of the desired vegetation are sown to increase the vegetation cover.

Bifacial panel
Bi-facial modules generate electricity from direct radiation on the module front and from (indirect) light on the back of the module. The rear side of bi-facial modules is transparent. The solar cells are designed to generate energy from both sides.

Bifacial panels on a green roof, Switzerland
Credit: Weiss-Tessbach

Biosolar roof - A subcategory of solar green roofs, which refers to an integrated solar green roof system with an emphasis or focus on supporting biodiversity through the establishment of microclimates and habitat spaces for local flora and fauna.

Blue-Green Roof - This type of green roof can be extensive or intensive but with the added capacity to detain additional rainwater and allow for its controlled release, in excess of the normal water retention capacity of the plants, drainage and growing medium. Water is typically stored underneath the substrate.

Combination roof
A green roof combined with a solar system.

Establishment period
A period of approx. 1-3 years after installation of a green roof where the vegetation requires regular maintenance to establish itself sufficiently on the roof.

Extensive Green Roof - This type of green roof typically uses only 8 cm of growing medium (in some regions even less) and features low-growing plant species, including succulents, mosses, herbs and grasses. They are low maintenance, light weight is 80 to 150 kg/m^2 and often not designed to be accessible by building occupants or the general public. This type of system is typically used in combination with solar technologies

Flexible photovoltaic modules
The special structure of flexible PV modules allows them to be bent; examples are arched roofs (on caravans or boats) and roll-up shading elements.

Glass-glass modules
In glass-glass PV modules, both the front and rear layers on the outside of the module are made of glass. With the stronger protective effect of the glass layers on either side, glass-glass modules are more robust and have a longer service life. Moreover, they are designed to let sunlight shine through the module, illuminating the area below.

Growth mass
Made in a green roof where the vegetation takes root and draws water and nutrients from.

Intensive Green Roof
This type of green roof is at least 20 to 30 cm (or more) thick and thus heavier in weight than extensive systems, but designed to support a wide variety of plants, including small trees and shrubs. These systems are higher maintenance, will require irrigation and provide amenity space for building occupants and/or the general public.

Monofacial panel
One-sided, used for solar panels that only produce electricity on one side the panel.

Photovoltaic (PV)
Method of utilizing the energy of the sun as electrical power. In this procedure the electromagnetic radiation is converted to electric current.

Photovoltaic modules (standard)
At the core of a PV module are the solar cells, which are connected to each other. To protect the solar cells against mechanical impact, weather and humidity, modules are made up of several layers. In standard modules, the outermost layer consists of glass.

Rooftop Agrivoltaic
A subcategory of solar green roofs which combines a solar array with agricultural production located beneath the panels, either at or above grade, providing protective benefits to agricultural production in harsher rooftop environments. Solar panels are often placed high enough above the substrate and plants to allow for easy access for farming, for example utilizing pergolas or other mounting structures.

Greened residential building in Graz, Austria
Credit: GrünStattGrau

Runoff
The ability of a system (e.g. a green roof) to retain rainwater to avoid overloading drainage systems.

Sedum cassette
A type of green roof consisting of „boxes“ with sedum and associated drainage layers and growth masses that are placed next to each other on the roof to create a continuous cover of sedum.

Sedum mats
Ready-made sedum vegetation established in mat systems

Semi-Intensive Roof
This type of green roof system is characterized by small herbaceous plants, ground covers, grasses and small shrubs, requiring moderate maintenance and occasional irrigation. A typical growing medium depth is 12 - 30 cm. Though higher in maintenance compared with extensive roofs, this green roof system also provides the potential for a formal garden effect and/or potentially greater ecological benefits, is a more resilient system and is able to retain more storm water.

Solar green roof, Switzerland
Credit: Elisabeth Weiss-Tessbach

Solar cells
The smallest unit in a PV module is the solar cell, which converts sunlight to electrical energy. The module is made up of a number of interconnected solar cells.

Solar Green Roof
Refers to any combination of solar collectors (thermal and pv) and vegetative roofing systems. This term encompasses a variety of systems, layouts, and technologies utilized.

Solar Photovoltaic
Refers to the collection and conversion of solar energy into direct current electricity by semiconductive materials such as silicon or other photoreceptors.

Solar Thermal
Refers to the collection and conversion of solar energy into thermal energy, heating water or air which is then distributed for use by a system of pumps or fans.

APPENDIX II - RESOURCES

Austrian Qualification programme on Greening buildings

- Modular training system for all persons who want to complete a quality-assessed competence extension in the field of building greening (roof, façade and interior greening) and green/ blue infrastructure in the context of buildings/ settlements/towns
- https://gruenstattgrau.at/leistungen/weiterbildung/

Biosolar Best practice Design guide

- Design guide for the implementation of biosolar roofs by the United Kingdom's GRO
- https://ikogroup.co.uk/wp-content/uploads/2024/07/Green-Roof-Organisation-GRO-Biosolar-Best-Practice-Design-Guide.pdf

Biosolar green roofs guide, Summer 2025

- Guidance document for implementing biosolar green roof systems
- https://www.adivet.net/ressources/bibliographie

Biosolar and Solar Green Roof Database

- Database on Biosolar and Solar Greenroof and other Projects, Professionals and Products hosted by InnoLab GRÜNSTATTGRAU
- https://gruenstattgrau.at/netzwerk/datenbank/

BOKU Planning Handbook for PV-Rooftop-garden Projects

- University of Life Sciences Vienna
- https://boku.ac.at/fileadmin/data/H03000/H87000/H87400/VT/PV-Dachgarten_Planungshandbuch.pdf

City of Vienna Solar Energy Handbook

- Described the integration of Biosolar and Solargreenroofs and linked city strategies, policy, funds and examples
- https://www.wien.gv.at/stadtentwicklung/energie/pdf/solarleitfaden-en.pdf

City of Vienna Green Roof Guideline

- Technical specifications and as well linked strategies, policies, funds and examples
- https://www.wien.gv.at/umweltschutz/raum/pdf/gruendaecher-leitfaden.pdf

City of Vienna Concept Study on PV Rooftop-gardens

- Publication of a concept study completed by the City of Vienna on the benefits of PV Rooftopgardens
- https://www.wien.gv.at/spezial/studien/ma20/pvdachgartenkonzeptmappe.pdf

Combining Green Roofs and Photovoltaics Guide

- Green roof and photovoltaic guide by Energieinstitut Vorarlberg
- https://www.energieinstitut.at/gruendach-pv

EFB free Webinar Series

- Regular free webinar series on biosolar roofs and other green building topics, also recorded and available on Youtube
- https://efb-greenroof.eu/trainings_seminars/

Green Roof Energy Calculator

- Calculator designed to compare the annual energy performance of a building with a vegetative green roof to the same building with either a dark roof or a white roof .
- https://greenroofcalculator.sustainability-innovation.asu.edu/grcalc_v2.php#retain

Green Roof Guidance Documents

- Collection of green roof and green wall guidance documents by Bundesverband GebäudeGrün e. V. (BuGG), The German Federal Association for Greening Buildings
- https://www.gebaeudegruen.info/wissen-und-ressourcen/broschueren-und-downloads/broschuerenuebersicht/

Green Roof Professional (GRP) training program

- North American green roof design and installation accreditation program
- https://www.greenroofs.org/green-roof-professional

GreenRoofScore, 2023

- The framework for assessing the ecosystem services of green roofs 2023
- www.greenroofscore.fr

Journal of Living Architecture

- Peer reviewed scientific journal dedicated to green infrastructure research
- https://livingarchitecturemonitor.com/latest-journal

Living Architecture Monitor

- Free quarterly online publication by Green Roofs for Healthy Cities
- https://livingarchitecturemonitor.com/

Living Architecture Performance Tool

- Rating system and resource, designed to certify that green roofs and walls are designed to achieve certain measurable and replicable performance benefits.
- https://greeninfrastructurefoundation.org/lapt

Measurable Benefits of Green Roofs

- Free publication compiling studies of the measurable benefits of green roofs, walls and indoor greenery by EFB
- https://efb-greenroof.eu/2025/03/19/introducing-the-new-efb-publication-benefits-of-green-buildings-green-roofs-green-walls-and-vertical-indoor-greenery/

North American Green Roof and Wall Policy Guide

- Guide to source supportive policies and programs for green roof and wall installation across North America.
- https://www.greenroofs.org/policy-resources

Professional rules for design and implementation of the green roofs - 3rd edition - 2018

- Jointly established by Adivet, CSFE (French Waterproofing Trade Union), Enveloppe Métallique du Bâtiment (formerly the National Union of Flat Steel Product Profilers
- https://www.adivet.net/ressources/bibliographie

PV Greenroof Garden for Schools Handbook

- Guidebook for the implementation of pv roof gardens on schools by the City of Vienna
- https://www.wien.gv.at/spezial/studien/ma20/pvdachgartenumsetzungskonzept.pdf

Solar Green Roof Integration training course

- Course that explores the basic principles and functionalities of the two, identify areas of synthesis, and explore how to maximize benefits and returns in projects that incorporate both.
- https://livingarchitectureacademy.com/p/introduction-to-solar-green-roof-integration

Technical recommandations for urban agriculture on roofs, 2018

- Guidance for the implementation of rooftop urban agriculture systems
- https://www.adivet.net/ressources/bibliographie

Toitures vivantes, 2024

- Book covering how to implement vegetation on the buildings
- https://www.editions-eyrolles.com/livre/toitures-vivantes

APPENDIX III - LIST OF TABLES

APPENDIX IV - SOURCES

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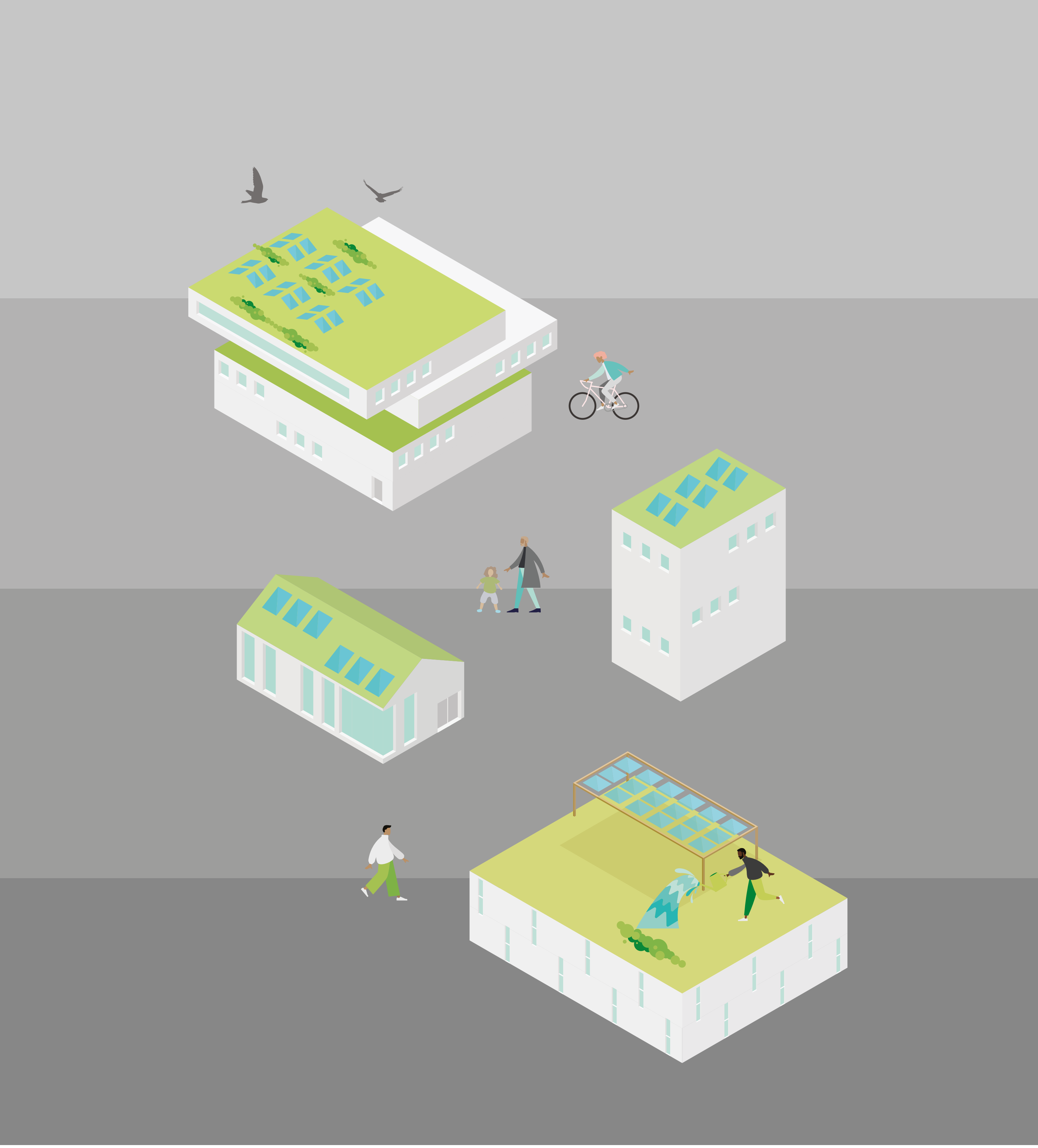

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